Simulating Bike-Transit Trips Using BikewaySim and TransitSim

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract

Planners and engineers need to know how to assess the impacts of proposed cycling infrastructure projects, so that projects that have the greatest potential impact on the actual and perceived cycling safety are selected over those that would be less effective. Planners also need to be able to communicate these impacts to decision-makers and the public. This research addresses these problems using the BikewaySim cycling shortest path model. BikewaySim uses link impedance functions to account for link attributes (e.g., presence of a bike lane, steep gradients, the number of lanes) and find the least impedance path for any origin-destination pair. In this project, BikewaySim was used to assess the impacts of using time-only and time with attribute impedances, as well as two proposed cycling infrastructure projects, on 28,392 potential trips for a study area in Atlanta, Georgia. These impacts were visualized through bikesheds, individual routing, and betweenness centrality. Two metrics, percent detour and change in impedance, were also calculated. Results demonstrate that BikewaySim can effectively visualize potential improvements of cycling infrastructure and has additional applications for trip-planning. An expanded study area was also used to demonstrate bike + transit mode routing for four study area locations. Visualizations examine the accessibility to TAZs, travel time, and the utilized transit modes for each location. Compared to the walk + transit mode, the bike + transit mode provided greater access to other TAZs and reached them in a shorter amount of time. The locations near the center of the transit network where many routes converge offered the greatest accessibility for both the bike + transit and walk + transit modes. The difference in accessibility was greatest for locations near fewer transit routes. This research demonstrated how BikewaySim can be used to both examine the current cycling network and show changes in accessibility likely to result from new infrastructure. Both BikewaySim and TransitSim are open-source Python based tools that will be made available for practitioners to use in bicycle network planning. Future research will focus on calibrating link impedance functions with revealed preference data (cycling GPS traces) and survey response data (surveys on user preference for cycling infrastructure).

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Simulating Bike-Transit Trips Using BikewaySim and TransitSim

A National Center for Sustainable Transportation Research Report

April 2024

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ABM – Activity based model

ARC – Atlanta Regional Commission

DOT – Department of Transportation

GPS – Global positioning system

GTFS – General transit feed specification

MARTA – Metropolitan Atlanta Rapid Transit Authority

MAZ – Micro analysis zone

MPO – Metropolitan planning organization

MRS – Marginal rate of substitution

NACTO – National Association of City Transportation Officials

OD – Origin-destination

OSM – Open Street Map

RAPTOR – Round based public transit optimized routing

TAZ – Traffic analysis zone

TDM – Travel demand model

Simulating Bike-Transit Trips through BikewaySim and TransitSim

EXECUTIVE SUMMARY

Planners and engineers need to know how to assess the impacts of proposed cycling infrastructure projects so that projects that stand to have the greatest impact on the actual and perceived safety of cycling are selected over those that would be less effective. Additionally, they need to be able to communicate these impacts to decision-makers and the public. This research addresses these problems by outlining a framework for assessing new and existing infrastructure through BikewaySim, a shortest path calculator for cycling. This research also demonstrates how BikewaySim can be extended to model bikes as a first and last mile mode (referred to as the bike + transit mode in this report) using TransitSim, a shortest path calculator for transit. The first half of this report covers the framework while the second half reports the model results for the bike + transit mode.

BikewaySim is used to calculate the shortest path for 28,392 potential trips for a study area in Atlanta, Georgia. BikewaySim uses link impedance functions that consider link attributes (e.g., the presence of a bike lane, steep gradients, the number of lanes) to find the least impedance path for any origin-destination pair. Impedance in BikewaySim represents the cost of traversing a link; impedance is relative and can be in units of time or cost (it can also be unitless). The impact of new infrastructure is the change in impedance.

For this report, two impedance functions were used. The first impedance function considered only the travel time cost of a link (time-only impedance). The second impedance function adds other considerations that can either reduce or increase the original travel time cost impedance of a link. Bicycle infrastructure and low-speed (< 25 m.p.h.) streets reduce link impedance (lowering the cost of cycling on that link), while more vehicle lanes and higher speed limits increase link impedance (increasing the cost of cycling on that link).

Using these two impedance functions, the 'shortest path' (i.e., the lowest impedance path) was calculated for 28,392 potential trips. These trips were all possible origin-destination pairs of traffic analysis zone centroids from the Atlanta Regional Commission's activity-based travel demand model (ABM). The shortest paths were then re-calculated to assess the impacts of two proposed cycling infrastructure projects. The impacts of these projects were visualized through changes in bikesheds, individual trip routing, and network link betweenness centrality. Two metrics, percent detour and change in impedance, were also calculated.

The analytical results demonstrate how BikewaySim and the accompanying set of visualizations and metrics can be used as a framework for assessing new cycling infrastructure. The second set of analyses demonstrate how BikewaySim can be extended to model bike + transit mode trips. Using an expanded study defined by a 2.5-mile buffer around all the Metropolitan Atlanta Rapid Transit Authority's (MARTA) rail and bus stops, four locations were examined to see how bike + transit mode trips expanded accessibility to destinations from walk + transit mode trips.

The bike and walk portions of trips were modeled using Dijkstra's algorithm with a travel-time-cost-based impedance, while the transit portion was routed using the RAPTOR (round-based public transit optimized routing) algorithm from the Transit-Routing Python package. These two algorithms were used to find TAZs that were accessible within 60 minutes of the four trip origin locations. The path taken, including the transit routes and streets traversed, were saved and used to create three visualizations. The first visualization compared the accessibility of the bike + transit mode to the walk + transit mode. In general, the bike + transit mode expanded accessibility. This observation was more pronounced for the locations that were far from rail service. The second visualization examined travel times. For areas accessible by both bike + transit and walk + transit modes, bike + transit provided reduced travel times. The third visualization examined the transit mode(s) taken for bike + transit mode trips.

The analytical results demonstrate that BikewaySim can effectively visualize the improvements of cycling infrastructure, and it has additional applications for trip-planning. Modeling bike + transit trips through BikewaySim and TransitSim in the second set of analyses demonstrated how bicycles could be modeled as a first and last mile mode to or from transit. Future research will focus on calibrating the link impedance functions for BikewaySim with data from revealed preference data (cycling GPS traces) and survey response data (surveys on user preference for cycling infrastructure).

As more cities seek to invest in cycling infrastructure, tools like BikewaySim and TransitSim will be essential for communicating the projected impacts of cycling infrastructure to the decision-makers and the public. Both tools are open-source and transferrable to any study area with access to street network and GTFS data.

Introduction

According to the 2017 National Household Travel Survey (NHTS), about 46% of all single occupancy motor vehicle trips in the U.S. are three miles or less; yet NHTS survey results indicate that only 1% of all trips are accomplished by bicycle (Federal Highway Administration, 2017). This mismatch is suspected to be in part due to the real and perceived danger imposed on cyclists when they share the same right-of-way with motor vehicles (Pucher & Buehler, 2012). This danger is also revealed in safety statistics. According to NHTSA projections, 985 cyclists died on U.S. roads in 2021, a 5% increase from 2020 (NHTSA's National Center for Statistics and Analysis, 2022). Past estimates of cycling fatalities per 100 million kilometers cycled show the U.S. well above peer European countries like the U.K., the Netherlands, and Germany (Pucher & Buehler, 2012).

Cyclists are particularly vulnerable because their chances of surviving if struck by a car or truck dramatically decrease when vehicle speeds exceed 30 mph (Groeger, 2016). Separated cycling facilities are one proposed solution to make cycling safer and more accessible. The literature suggests that separated cycling infrastructure can decrease crash risk (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017). The literature also suggests that people, regardless of cycling frequency or ability, state that they would be more willing to try cycling on roads with bicycle infrastructure that provides a buffer or separation from car traffic (Clark, Mokhtarian, Circella, & Watkins, 2019). Not only do cities with more cycling infrastructure tend to have higher cycling ridership (McKenzie, 2014; Schoner & Levinson, 2014), one can predict ridership increases within these cities via the presence and network density of newly constructed cycling facilities (Fields, Cradock, Barrett, Hull, & Melly, 2022).

With new bike design guidelines from NACTO and the forthcoming newest edition of the AASHTO Bike Guide (NACTO, 2014; Toole Design, n.d.), resources are available to design high-quality, separated cycling infrastructure. However, planners and engineers need to know what infrastructure would be most effective, and in which locations the infrastructure should be placed, to increase both the actual and perceived safety of bicycling to facilitate safe travel and make cycling more accessible. To that end, this research provides a framework for assessing how new cycling infrastructure contributes to decreasing traffic stress and increasing bikeability (i.e., the attractiveness of, and accessibility provided by, cycling); so that infrastructure alternatives that stand to have the greatest impact are selected over those that would be less effective. This framework utilizes BikewaySim to calculate the shortest route through a network, given the preferences that people have for road attributes (e.g., traffic speeds, cycling infrastructure, hills, traffic signals, etc.). In addition, this research extends the use of BikewaySim to model cycling as a first and last mile mode for transit (henceforth referred to as the bike + transit mode) by using it in conjunction with TransitSim, a transit shortest path calculator. For clarity, this research is split into two parts: the first covers the framework and BikewaySim while the second covers modeling bike + transit mode trips with TransitSim.

This report begins with a literature review on the limitations of using travel demand models for cycling, followed by general findings from cycling route choice literature, current efforts to make cycling shortest path models, and the visualizations and metrics employed with shortest path modeling. The research methodology is then discussed. Two impedance functions are developed for calculating shortest paths for a study area in Atlanta, GA. Using these impedance functions, visualizations and performance metrics are used to evaluate the impact of two cycling infrastructure improvements. These results are discussed, followed by limitations, and future research discussions.

The second chapter of the report provides background information on bike + transit mode trips, starting with how suburban sprawl reduces the effectiveness of the walk + transit mode, due to long walking distances, and how bicycles have the potential to increase the accessibility of transit. The TransitSim study methodology is then introduced. The study area from the first half of this report is expanded to include the full potential service area of public transit, and four origin locations are used to compare the bike + transit and walk + transit modes’ access to destinations and travel times. The results are discussed, followed by limitations, and future research areas. The report concludes by tying the analyses from the two chapters together in the conclusions section.

BikewaySim and TransitSim

To accomplish the technical analyses done in this report, two shortest path calculators from the Python-based modeling suite TransportationSim were used. The first, BikewaySim, was for cycling shortest path calculation. This model uses Dijkstra’s algorithm to find the lowest impedance path between any origin-destination pair given user-specified link impedance functions (Dijkstra, 1959). BikewaySim also post-processes shortest path results to generate visualizations and metrics. The second, TransitSim, uses the round based public transit routing (RAPTOR) algorithm in conjunction with Dijkstra’s algorithm at the beginning and end of the transit trip to find least impedance path from any origin to any destination given a departure time and allowed number of transfers (Delling, Pajor, & Werneck, 2014). TransitSim also post-processes shortest path results to generate visualizations and metrics. Both of the tools are open-source and are available for download (see data summary section for DOI number).

Assessing Cycling Infrastructure Improvements with BikewaySim

Traditional tools used by transportation planners and engineers to model the impacts of infrastructure projects, such as travel demand models (TDM), do not effectively model the impacts of cycling infrastructure. This is in part because most TDMs do not use an all-paths network or impedance functions that account for cyclists' preferences for road attributes (RSG, 2019). All-paths networks are rarely used in TDMs because they dramatically increase model computational burden by expanding the number of potential routes between origin-destination pairs for long-distance car trips (Madkour, Aref, Rehman, Rahman, & Basalamah, 2017). TDMs also need to be run iteratively to account for congestion, further increasing model run-time. In contrast, cycling trips are typically short (median trip distance of about two miles (Goel, et al., 2021)), and congestion is assumed to have a minimal impact on cyclist travel time, which suggests that incorporating bicycle routing into TDMs would not increase model computational burden for vehicle trips. In addition to providing cyclists with more route options, all-paths networks include links with attributes that cyclists may prefer.

Most TDMs employ relatively simplified approaches to predicting bicycle trips. Cycling trips may appear in the iterative trip generation, trip distribution, and mode choice process. However, in trip distribution steps, cycling may be limited to intra-zonal travel or travel to adjacent traffic analysis zones (TAZ). In mode choice steps, cycling utility algorithms may be less complex than those for other modes. Cycling trips are also usually excluded from subsequent route assignment steps (assuming that the mode does not contribute to nor is affected by congestion, which is the primary purpose of iterative traffic assignment using Frank Wolfe or dynamic traffic assignment (DTA) algorithms).

Over the past ten years, many researchers have utilized GPS-recorded cycling trips to investigate cyclists revealed positive and negative preferences for particular road attributes, such as the presence of a bike lane (positive), presence of on-street parking (negative), speed limit (negative for higher speed limits), and number of lanes (negative for more lanes). These studies have used discrete choice modeling to assess how cyclists choose routes based on trade-offs in utility for particular road attributes (Menghini, Carrasco, Schüssler, & Axhausen, 2010; Hood, Sall, & Charlton, 2011; Broach, Dill, & Gliebe, 2012). Collectively, these studies show that cyclists on average choose a route that is longer than the shortest path distance route by 8-18% (Ghanayim & Bekhor, 2018). These studies also show that cyclists prefer routes that are shorter, have fewer steep hills, have a higher percentage of bicycle infrastructure (both separated infrastructure and traditional bike lanes), and have fewer turns (especially left turns). All of these factors provide benefits or reduce costs in the cyclist route decision-making process.

Results from cycling route choice models are interpreted by converting model coefficients into average marginal rates of substitution (MRS). MRS values represent how much more of or less of an attribute a cyclist would trade for a one unit increase in another attribute. Typically, the MRS is calculated with respect to distance so that a change in an attribute is seen as a distance reduction or addition. One way to express this is equivalent percent change in distance, as shown in the equation below (Broach, Dill, & Gliebe, 2012).

$$\text{Equivalent }\%\Delta\text{ distance} = \left(e^{\Delta_{\text{attribute}} \frac{\beta_{\text{attribute}}}{\beta_{\ln(\text{dist})}}} - 1 \right) * 100$$

This equation finds the “equivalent percent change in distance” given the coefficients from a cycling route choice model and a change in a route attribute. A negative value corresponds to a reduction in equivalent percent change in distance. Using the coefficients from the Broach et al. 2012 non-commute model, a one-hundred percent increase in the proportion of a route on a bike path (i.e. a route with no bike paths compared to a route that is entirely on bike paths), corresponds to an equivalent percent change in distance of -26% ($\Delta_{attribute} = 1.00$, $\beta_{proportion\ bike\ path} = 1.57, \beta_{\ln(dist)} = -5.22$). A route that is entirely on bike paths is equivalent in utility to a route that is 26% shorter. In other words, a cyclist would prefer to ride up to 26% further or longer than the shortest distance or shortest time route if it meant taking a route entirely composed of bike paths. To further illustrate, a cyclist would perceive a 1.0 or mile or 7.5 minute (assuming a cycling speed of 8.0 m.p.h.) ride on a route that is entirely composed of multi-use paths to be only 0.76 miles or 5.7 minutes (Table 1).

Conversely, a positive value corresponds to an increase in equivalent percent change in distance. Using the coefficients from the Broach et al. 2012 non-commute model again, an additional turn per mile corresponds to an equivalent percent change in distance of 7.4% ($\Delta_{attribute} = 1,\ \beta_{turns\ (mile)} = -0.371,\ \beta_{\ln(dist)} = -5.22$). A route with one more turn per mile is equivalent in utility to a route that is 7.4% longer. In other words, a cyclist would avoid adding an additional turn per mile unless it reduced the trip distance or travel time by 7.4% or more. To further illustrate, a cyclist would perceive a 1.0-mile or 7.5-minute route with one turn per mile to be 1.07 miles or 8.3 minutes (Table 1).

Table 1. Example equivalent percent change in distance calculations

Example	Equivalent %Δ distance for $\boldsymbol{\Delta_{attribute} = 1}$	Actual Distance (Actual Travel Time)	Perceived Distance (Perceived Travel Time)
Route entirely on bike paths	-26%	1.0 miles (7.5 minutes)	0.76 miles (5.7 minutes)
Route with one turn per mile	7.4%	1.0 mile (7.5 minutes)	1.07 miles (8.3 minutes)

Deriving the marginal rate of substitution using the beta coefficients for various treatments defined in the literature also provides a way to compare the potential response of cyclists to treatments across cities (Fitch & Handy, 2020), subject to the limitations of data and combinations of variables employed across these studies.

Route choice utility models are not ideal for use in TDMs because they are complex and require modelers to generate large route choice sets within the model. Recent efforts in the literature have instead focused on translating findings from route choice models into link impedances that can be used in TDM shortest path modeling. Existing methods include creating stress modification factors based on MRS values (Lowry, Furth, & Hadden-Loh, 2016) and scaling route choice utility function coefficients by the shortest distance route (Broach & Dill, 2016). The focus of this paper is on using link impedance to effectively convey new bike infrastructures' impact on bikeability. The assessment of impacts generally involves monitoring changes in four metrics from the literature:

- *Directness:* Directness refers to the physical distance reduction provided by an infrastructure improvement (reduced circuity). Increasing the directness of cycling networks makes cycling more attractive by shortening the trip distance to places people want to go (CROW, 2016; FHWA, 2018). Thus, using change in trip directness can be a way of prioritizing projects (Cabral, Kim, & Shirgaokar, 2019). Studies in places with high cycling ridership like Davis, CA and Amsterdam, NL have lower detour rates likely due to their cycling network design and availability of direct and safe routes (Ton, Cats, Duives, & Hoogendoorn, 2017; Fitch & Handy, 2020).

- *Impedance:* Infrastructure improvements are usually deigned to reduce cyclists' travel costs by reducing travel time and a variety of perceived costs associated with the trip (e.g., physical exertion costs, convenience costs, experience costs, safety costs, etc.). Cyclists are assumed to want to reduce their overall travel costs; hence, infrastructure improvements can be prioritized by finding the projects that provide the greatest decrease in impedance for the highest number of origin-destination pairs (Nassir, Ziebarth, Sall, & Zorn, 2014; Hood, Sall, & Charlton, 2011). Impedance can be in units of time or money but can also be unitless. Impedance is relative, meaning that once a choice is being made, the relative difference in impedance across alternatives is more meaningful than the impedance value itself.
- *Betweenness Centrality:* Betweenness centrality refers to how often a link appears across all shortest paths (Alattar, Cottrill, & Beecroft, 2021; Freeman, 1977; Newman, 2008). A high betweenness centrality indicates that a transportation network link provides an important connection for many trips. Cycling infrastructure improvements on links with high betweenness centrality may further enhance cycling travel, and cycling facilities connected to these links are more likely to be used than facilities connected to links with lower betweenness centrality (Lowry, Furth, & Hadden-Loh, 2016). Changes in betweenness centrality can be used to assess the addition or removal of cycling infrastructure, restrictions on what links can be traversed, and changes in impedances. For example, if cycling infrastructure designed to reduce link impedance is added to high-stress links, betweenness centrality will likely increase for these links. If the impedance reduction is large enough, these links will appear in more shortest path routes. In Seattle, betweenness centrality was used to model the effect of adding cycling infrastructure to a bridge (Lowry, Furth, & Hadden-Loh, 2016).
- Destination Access*ibility:* Destination accessibility refers to whether or not people can reach key destinations (e.g. hospitals, grocery stores, dentists, restaurants, workplaces) within specified tolerances. This method requires the implementation of thresholds that define whether a trip is considered feasible. Lowry et al. (2016) created a basket of key destinations (destination basket) and assessed whether every trip origin had access to at least two of each type of key destination. The overall cycling trip distance allowed was two miles and stress tolerances were created to reduce the effective bikeshed of origins. Infrastructure improvements can then be evaluated by seeing how they increase access to destinations. A similar approach was taken by the online People for Bikes Bicycle Network Analysis (BNA) tool (People for Bikes, n.d.).

Methodological Framework for Bicycle Routing

This section presents the basic functionalities of BikewaySim, how BikewaySim can be used to assess new cycling infrastructure, and insight into future research to support cycling shortest path modeling. BikewaySim is a shortest path model that takes in a network graph with link attributes, allows a user to specify custom impedance functions, and then outputs metrics and visuals for the ‘shortest’ paths (lowest impedance paths) between any origin-destination pair. The analyses in this paper build on existing cycling route choice and shortest path modeling literature by presenting a methodology for assessing both the impact of changes in link impedance and the provision of new dedicated cycling infrastructure on shortest path (lowest impedance) routes.

Analyses were performed for a 12-square-mile study area in the City of Atlanta, Georgia, USA (Figure 1). The case study area includes the Atlanta neighborhoods of Midtown, Piedmont Park, Morningside, Virginia-Highlands, Old Fourth Ward, Ansley Mall, Atlantic Station, and the Georgia Institute of Technology campus.

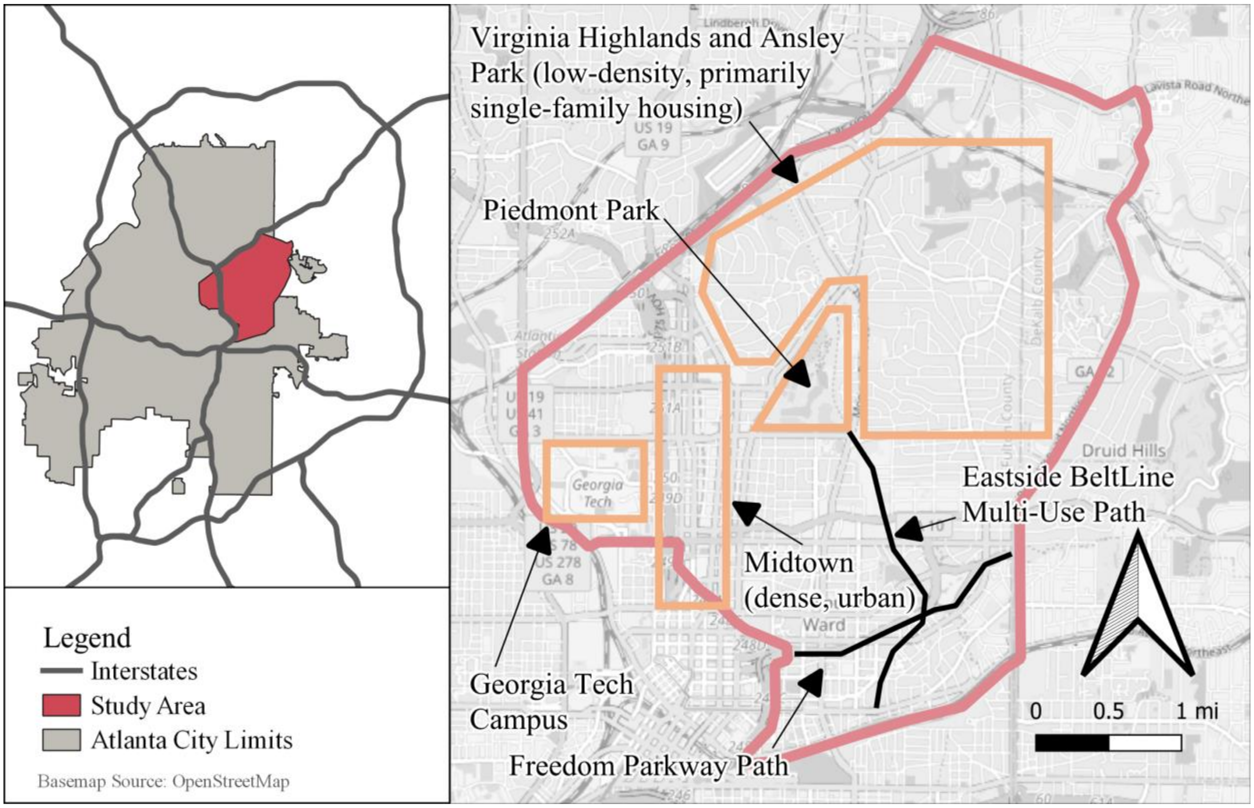


Figure 1. Study area in relation to Atlanta city limits and the Interstate Highway System

This small study area was selected because it was familiar to the researchers, making it easier to litmus test shortest path outputs. The study area also includes a variety of land uses, bike infrastructure (see NACTO (2014) for an overview on the different types of cycling infrastructure), and road types, as shown in Figure 2. These data were sourced from OpenStreetMap and the ARC. Major cycling infrastructure includes two multi-use paths that run north-south (BeltLine) and east-west (Freedom Parkway) within the study area. Georgia Tech campus and Piedmont Park each have an interconnected network of wide sidewalks that are used as multi-use paths. However, there is limited infrastructure in the northeast section of the study area, and there are gaps between infrastructure throughout the study area. Thus, two improvements were proposed for case study analysis as shown in Figure 2 and highlighted in red; a new multi-use path along an existing road in the western half and a new multi-use path that adds connectivity in the northeastern quadrant.

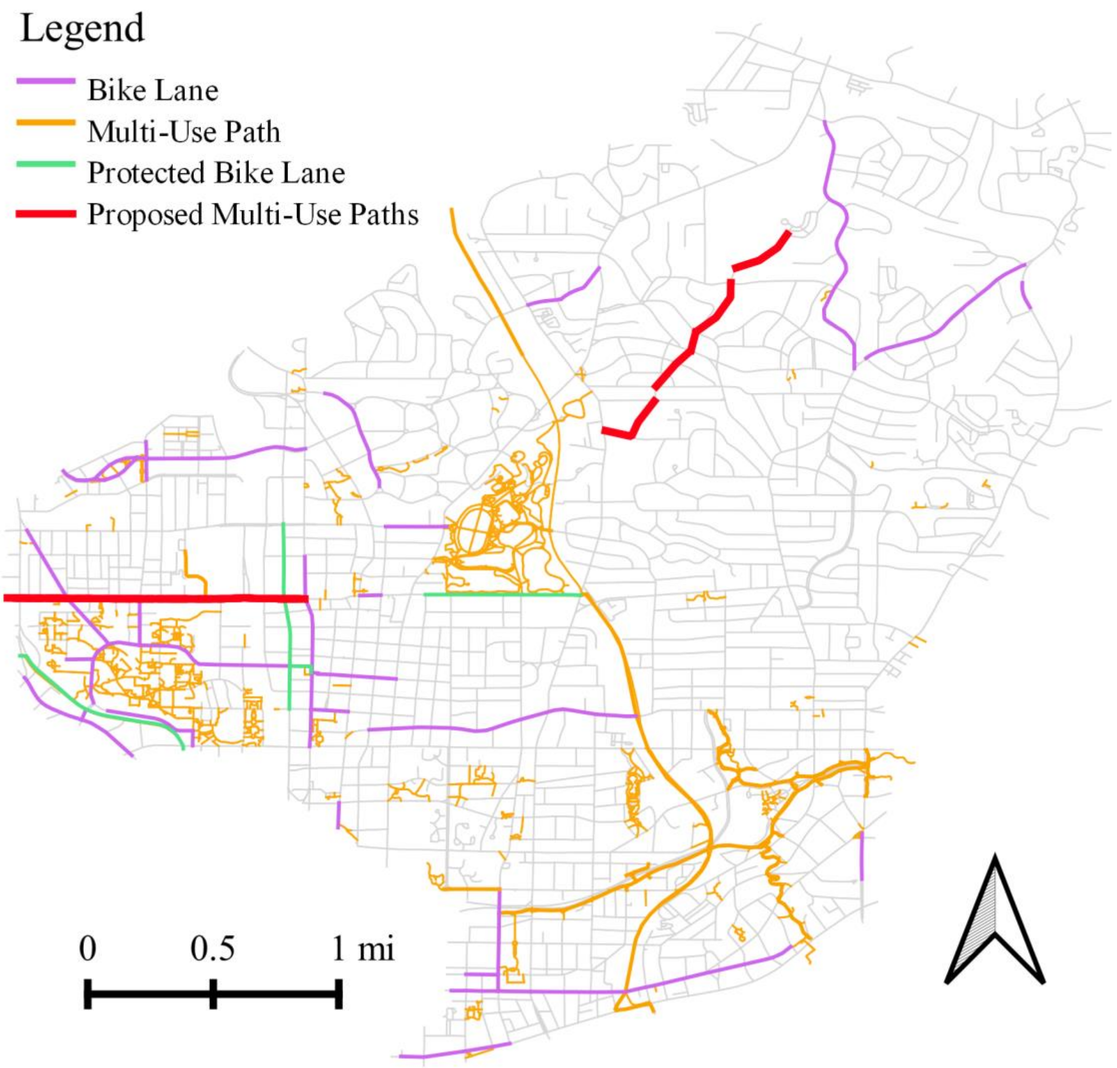


Figure 2. Existing cycling facilities by type and proposed multi-use paths

Link Impedance Functions

To calculate the shortest path, BikewaySim relies on link impedance functions. Impedance, expressed in minutes, represents the friction associated with travel (i.e., travelers want to minimize impedance). For this paper, edges and vertices for graph network terminology will be referred to here as links and nodes, respectively. Once link impedances are calculated, BikewaySim returns the path with minimum total impedance using Dijkstra's algorithm (Dijkstra, 1959). For this paper, two impedance functions were used. The first impedance function was a travel time-based impedance based upon link distance (l_i) and average cycling travel speed (v) as expressed in the equation below.

$$C_{i,time} = \frac{l_i}{v}$$

The second impedance function was a time + attribute based impedance (see equation below). $\mathrm{C_{i,time}}$ and $\mathrm{C_{i,time\,+\,attributes}}$ represent the impedance costs from traversing link i in a network graph with E total links. The variables l_i and v are the length of link i and the assumed average speed of the cyclist (8.0 mph for this study). In the second equation, k represents an attribute in the set of K attributes for link i, where β_k is the coefficient that represents the effect of attribute k, and $x_{k,i}$ is the k_{th} attribute value for link i.

$$C_{i,time\,+\,attributes} = \frac{l_i}{v}\left(1 + \sum_{k \in K} \beta_k x_{k,i}\right)$$

The second impedance function, based on Lowry (2016), accounts for cyclists' preferences for link attributes. Its linear form allows for clear attribute coefficient interpretability. For example, a bike lane attribute coefficient of -0.5 would reduce a link's impedance by half its travel time. Any alternative impedance functions can be implemented into BikewaySim, as long as the impacts are reasonable and reflect the impact of the impedance on route decision making. Additionally, all link impedance values must be greater than zero per the requirements of Dijkstra’s algorithm (Dijkstra, 1959).

The attributes included in the second impedance function were link distance, bike facility presence (by type), speed limit, and number of lanes. These attributes were chosen because of their significance in past MNL models and the availability of data. Specifying coefficients for these attributes requires the analysis of cycling ridership data and is a computationally expensive process (Schweizer, Rupi, & Poliziani, 2020). The research team plans to derive attribute coefficients using the MRS approach outlined above applied to various cycling route choice studies reported in the literature. However, initial efforts indicate that this will be a challenging research task. Controlling for differences across studies with respect to the variables employed and the intercorrelation of variables affecting route choice will be statistically challenging. Thus, while attribute coefficients shown in Table 2 below are informed by the literature using MRS values as shown earlier in Table 1, these are by no means the final values that will be employed in the Atlanta model. These coefficients are illustrative in nature, to show the reader how the approach will be employed and to highlight the applications of shortest path modeling; they are not currently recommended for application in planning or prioritizing cycling infrastructure at this time because MRS values are highly dependent on the local data collected in each literature study and the variables included/excluded from those studies.

Table 2. Coefficients for attribute impedance function

Attribute Type	Coefficient Symbol	Full Variable Name	Coefficient Value	Attribute Value
Bike Facility	$\beta_{bf\ none}$	No Bike Facility	0.00	0 or 1
	$\beta_{bf\ bl}$	Bike Lane	-0.25	0 or 1
	$\beta_{bf\ pbl}$	Protected Bike Lane	-0.95	0 or 1
	$\beta_{bf\ mup}$	Multi-Use Path	-0.95	0 or 1
Speed Limit	$\beta_{sl\ >30}$	> 30 mph	1.00	0 or 1
	$\beta_{sl\ 25-30}$	25 to 30 mph	0.30	0 or 1
	$\beta_{sl\ <25}$	< 25 mph	-0.25	0 or 1
	$\beta_{\mathrm{sl\ mup}}$	Multi-use path (speed limit is NA)	0.00	0 or 1
Number of Lanes per Direction	$\beta_{nlpd\ \geq 4}$	4 or more lanes per direction	1.00	0 or 1
	$\beta_{nlpd\ 2\ or\ 3}$	2 or 3 lanes per direction	0.30	0 or 1
	$\beta_{nlpd\ 1}$	1 lane per direction	0.00	0 or 1
	$\beta_{\mathrm{nlpd\ mup}}$	Multi-use path (lanes per direction is NA)	0.00	0 or 1

The complete formula for calculating link impedance is shown below. The attribute values accompanying each coefficient are all dummy variables corresponding to the presence or absence of an attribute. No one network link can possess more than one of each attribute type (bike facility, speed limit, number of lanes). Additionally, not all network links will exhibit one of each attribute. For instance, multi-use paths prohibit motorized vehicle travel and thus the attribute values for speed limits and the number of lanes are all zero. Similarly, road links without bike facilities would feature attribute values of zero for all bike facility types.

$$
\begin{aligned}
C_{i,time+attributes} &\\
= \frac{l_i}{v}\big(1 &+ \beta_{bf\ none}x_{bf\ none,i} + \beta_{bf\ bl}x_{bf\ bl,i} + \beta_{bf\ mup}x_{bf\ mup,i} + \beta_{sl\ >30}x_{sl\ >30,i} \\
&+ \beta_{sl\ 25-30}x_{sl\ 25-30,i} + \beta_{sl\ <25}x_{sl\ <25,i} + \beta_{sl\ mup}x_{sl\ mup,i} + \beta_{nlpd\ \geq 4}x_{nlpd\ \geq 4,i} \\
&+ \beta_{nlpd\ 2\ or\ 3}x_{nlpd\ 2\ or\ 3,i} + \beta_{nlpd\ 1}x_{nlpd\ 1,i} + \beta_{nlpd\ mup}x_{nlpd\ mup,i}\big)
\end{aligned}
$$

The negative coefficients in Table 1 allow the functions to illustrate findings from MNL models; cyclists often detour to access cycling infrastructure (Misra, 2016). However, all negative coefficients were limited to -1.0 to prevent the generation of negative link impedances, as negative link impedances are not permitted in shortest path calculation using Dijkstra's algorithm (Dijkstra, 1959). Negative link impedances would also be counterintuitive, as the model would essentially indicate that users were being paid to traverse a link. Factors that increase impedance (coefficient values greater than zero) generally have a larger effect on calculated impedance than the factors that reduce impedance (coefficient values less than zero), such as bike infrastructure presence and low speed limits. However, this falls in line with the main idea behind traffic stress (Mekuria, Furth, & Nixon, 2012), where the most stressful attribute defines the level of traffic stress.

One advantage of using impedance functions is that attribute coefficients can be modified to see their impact on link impedance. Figure 3 depicts the difference in calculated link impedance when going from the time-only impedance function to the time + attributes impedance function. In this analysis, all road links saw an increase in link impedance relative to the time-only impedance, because very few links had bike facilities and many arterials had speed limits greater than 30 mph. Multi-use path links all yielded a decrease in impedance because they do not have positive attribute values for any of the speed limit and number of lanes attributes and the bicycle facility impedance function is negative (given the attractiveness of this type of facility to cyclists). Because all links were affected by one or more changes in the impedance coefficients employed in the analyses (Table 2), no link impedance remained unchanged in this example.

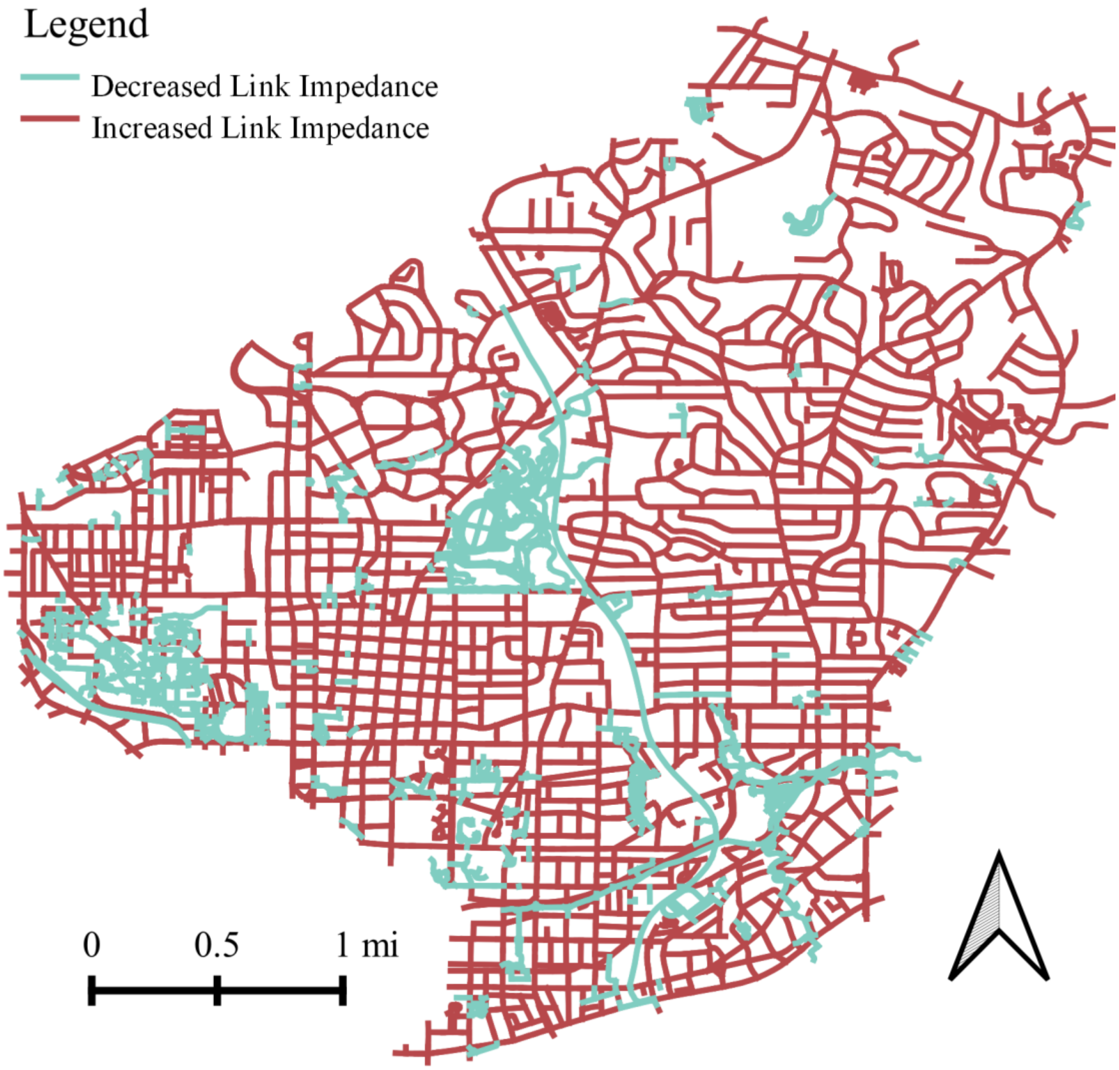


Figure 3. Link impedance changes after adding in additional impedances for attributes

Data Employed in the Analyses

The network data used for the study area is sourced from OpenStreetMap (OSM), the Atlanta Regional Commission (ARC), and HERE. OSM data are open-source and were retrieved using OSMnx (Boeing, 2017). The ARC's network data are available upon request from the ARC, and HERE map data can be licensed from HERE. The researchers conflated these three networks because each network lacked various attributes or features that others contained (Passmore, Watkins, & Guesnler, 2021). Restricted access roads (e.g., Interstates and access ramps), sidewalks (unless bicycles were explicitly permitted), and service roads (e.g., driveways and parking lots) were removed from the network. The final network had 7,469 links, 6,010 nodes, and 265 total network miles. This is a small network in comparison with most regional models. However, BikewaySim can scale to larger networks (the network size in the second portion of this report has 400,000+ links and 180,000+ nodes) though computation times and storage requirements will increase.

Traffic analysis zones (TAZs) from the Atlanta Regional Commission's 2020 Activity Based Model run acted as potential origin-destination pairs. The 169 TAZs in the study area yielded 28,392 total unique origin-destination pairs. BikewaySim can account for access distance to the network as an impedance (e.g., traditional travel demand models implement a travel time on the ABM centroid connector). However, this feature was disabled for these analyses. Instead, TAZ centroids were snapped to the nearest network node, which would add only a minor travel distance and time. Once micro analysis zones (MAZs) begin to be employed in bicycle route choice modeling, there may be a need to better account for the travel from the centroid to the network for some of the larger TAZs (RSG, 2019).

Metrics and Visualizations

For the 28,392 possible origin-destination pairs, shortest paths were calculated using the two impedance functions and the two networks (existing and with infrastructure improvements). Using a computer with a 10-core 3.70 GHz processor and 32 GB of RAM, the run-time for each scenario (all origin-destination combinations) was about 12 minutes. A larger network would result in a longer run-time. Most of this time was spent exporting shapefiles for each trip.

Four visualizations are explored in subsequent sections of this paper: bikesheds, individual routing, betweenness centrality, and zonal statistics. In addition to these visualizations, two metrics are reported. The first is the percent detour, calculated using the equation below:

$$\%\ detour = \frac{X_{time+attributes} - X_{time}}{X_{time}}$$

$\mathrm{X}_{\mathrm{time}}$ and $\mathrm{X}_{\mathrm{time+attributes}}$ represent the total distance of a path generated by the time-only and time + attribute impedance, respectively. The closer the time + attribute impedance path are in distance to the time-only impedance path (i.e., closer to 0% detour), the better. At 0% detour, the preferred path (time + attributes) is also direct, a desirable property for effective cycling infrastructure (CROW, 2016). The second metric is total impedance, which is the sum of all the link impedances in a route:

$$C_{total,imp} = \sum_{i \in P_{imp}} (C_{i,imp})$$

$\mathrm{C}_{\mathrm{total,imp}}$ is the total impedance of path P derived from the impedance function. Using the time-only impedance, this metric represents the total travel time of a route. Using the time + attribute impedance, this metric is more akin to a perceived travel time of a route, as it factors in cyclists' preferences for attributes. This metric is most effectively used when calculating the difference in total impedance after adding in a network improvement. This difference is the relative improvement from new cycling infrastructure.

Bikesheds

Bikesheds represent the extent of destinations one can access by bike within specified constraints. For this study, the bikesheds were limited to every location that one could reach in ten minutes at a speed of 8.0 miles per hour. In the future, BikewaySim's network graph for Atlanta will be expanded to calculate larger bikesheds. Bikesheds are measured in linear network miles (i.e., the total length of all unique traversable links within a bikeshed).

Figure 4 shows bikesheds before and after adding attribute-based impedance to the time-based impedance (i.e., creating the time + attribute impedance). The time-only impedance bikeshed size was 35 network miles, and the time + attribute impedance bikeshed size was 78 network miles. This large increase in bikeshed is entirely due to the impedance beta coefficient for multi-use facilities being set to -0.95, which significantly increases the willingness of cyclists to travel longer trip distances and longer trip times. While this beta coefficient may be too large for commute to work travel (where route directness is a high priority), the large beta coefficient may be reasonable for recreational and non-commute travel (the team plans to conduct additional research in this area). Hence, even though the network impedance increased on many roads as indicated in Figure 3, the presence of multi-use paths with much lower impedance greatly expanded the bikeshed. The map at the bottom of Figure 4 shows how the bikeshed expands in some areas and contracts in other areas due to the changes in impedance across various facility types. Links that have been added and removed from the bikeshed in moving from the time-only impedance to time + attribute impedance are shown in blue and red, respectively. When links are removed, either the links removed or the links leading up to the links that were removed had a higher impedance when attribute impedance was included (reaching these links may involve traversing high-stress links). When links are added, the new links or the links leading up to these new links, had a lower impedance when attribute impedance was included. For example, reaching these links may involve traversing dedicated multi-use paths, streets with cycling infrastructure, or low-speed streets (i.e.; links that people may be willing to travel further on compared to high-stress links). The expansion in the south area of the bikeshed is due to the presence of the Atlanta BeltLine and Freedom Parkway multi-use paths (shown earlier in Figure 2).

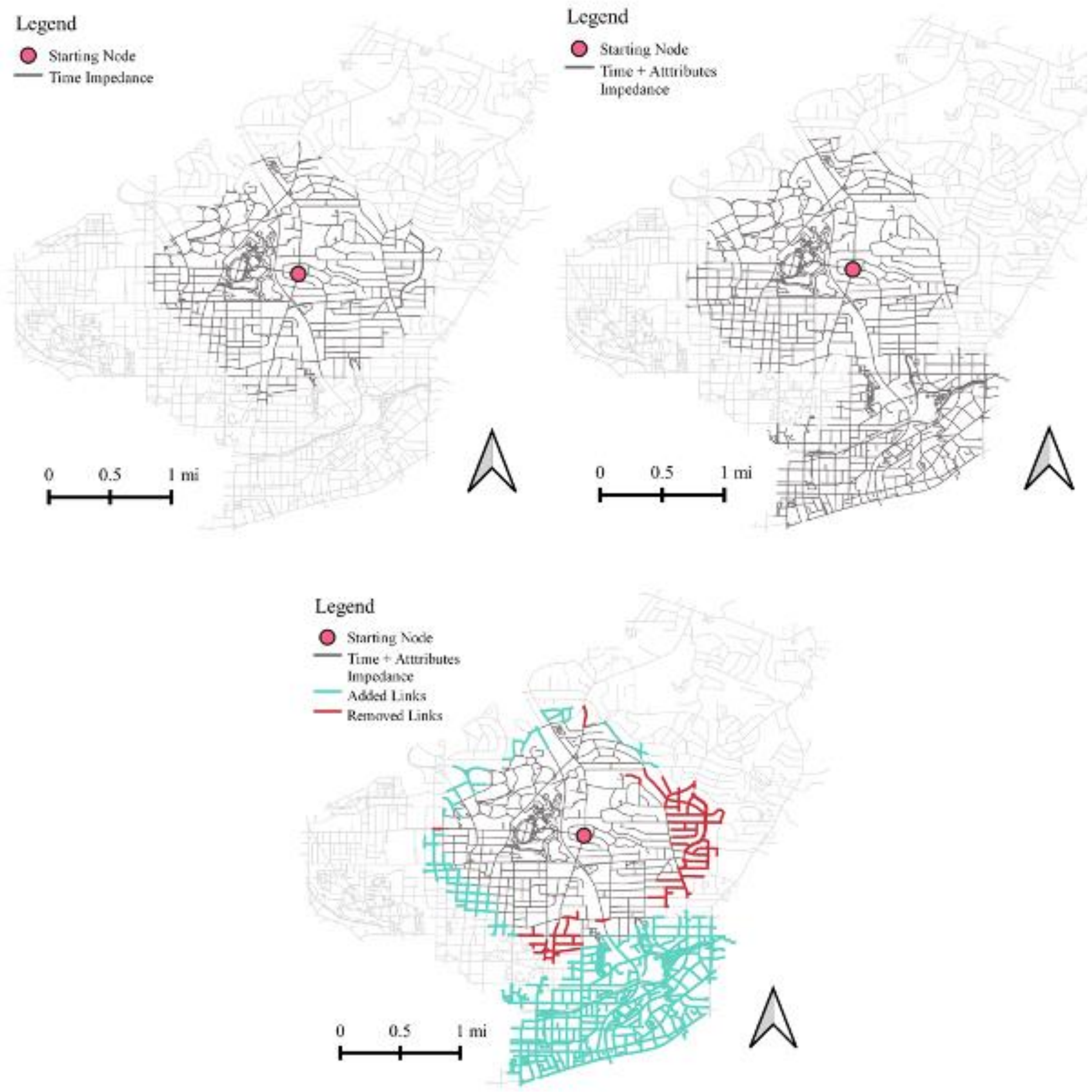


Figure 4. 10-minute bikesheds for time impedance (top-left) and time + attribute impedance (top-right), and links added and removed after adding attribute impedance (bottom)

The bikesheds were then re-calculated to include two major network improvements. The orange lines in Figure 5 represent links added for two multi-use paths (cross-hatched). The size of the resulting bikeshed increases to 104 miles. As discussed above, the addition of any multi-use path to the study area, because the impedance coefficient is set to -0.95, will significantly increase the bikeshed. In this example, the multi-use path in the eastern half added more miles than the one in the northeastern quadrant because there are few bike facilities in the northwestern quadrant to which the multi-use path will connect.

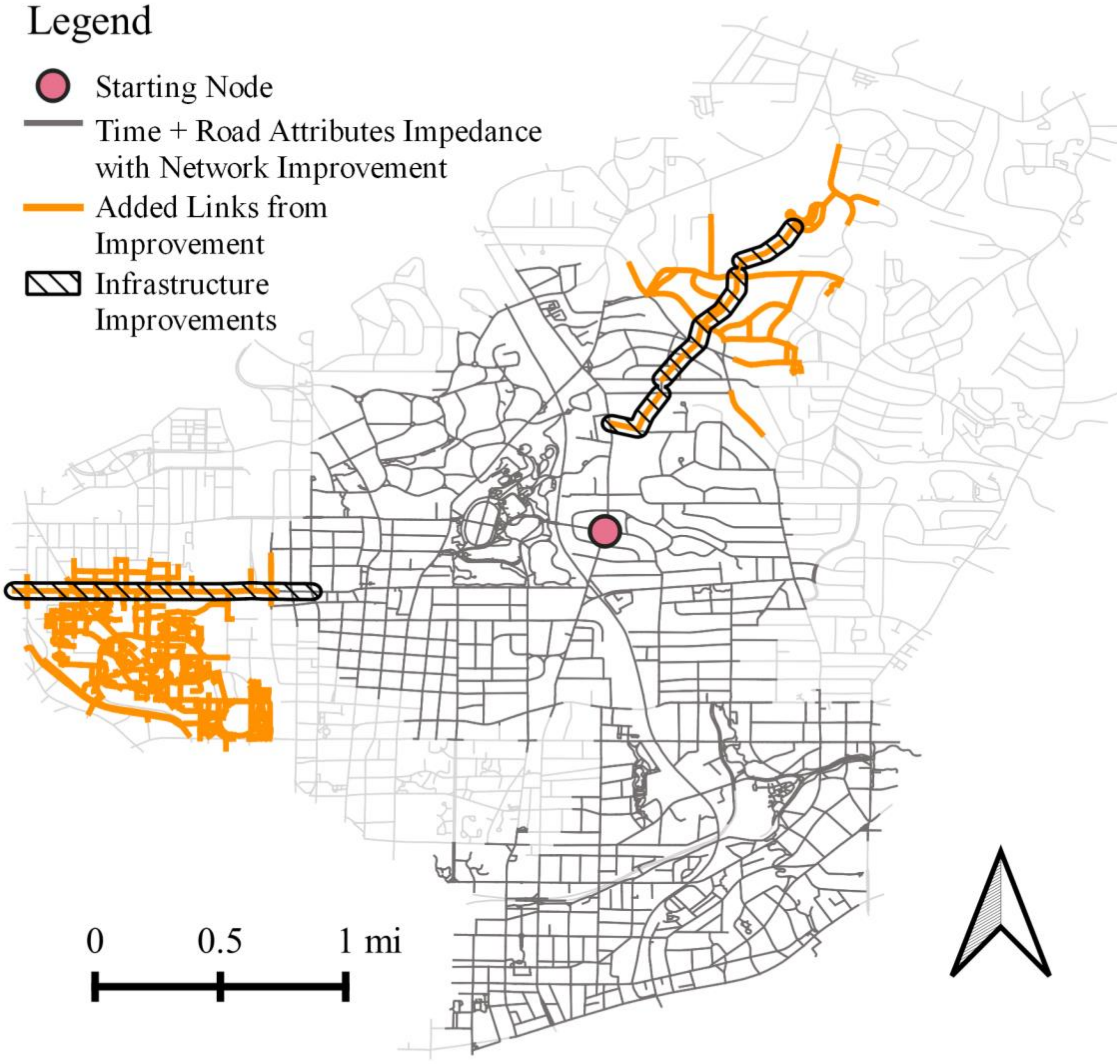


Figure 5. Change in the time + attribute impedance 10-minute bikeshed after two multi-use paths were added to the network

This example highlights how bikesheds can be used to assess the impacts of infrastructure improvements on bikeability. These bikesheds also demonstrate the potential effects of reduced speed limits and various traffic calming measures derived from literature modeling coefficients. In addition, limits could be placed on exposure to the most stressful of attributes (Lowry, Furth, & Hadden-Loh, 2016). For instance, in recommending bicycle infrastructure, one could further penalize distance traveled on 40 mph roads to address safety concerns, which would restrict the size of the bikeshed. In addition to these transportation planning contexts, these bikesheds can be used as a tool on an individual level, similar to WalkScore (Walk score, n.d.). A person could look up their residence and see all the locations within a safe 10-minute time-only-impedance-equivalent bike ride.

Individual Routing

This section illustrates how routing may change with the integration of attribute impedance by presenting the routing for two origin-destination pairs. The first example, shown in Figure 6, demonstrates how the time + attribute impedance yields a comparable, yet less direct route, compared to the time-only impedance route. In this case, the percent detour (extra distance) from the time-only impedance is 62%, due to the presence of the BeltLine multi-use path. This large percent detour is higher than typical literature review values (Ghanayim & Bekhor, 2018), but may be reasonable for recreational travel given the attributes of the BeltLine multi-use path. The time + attribute impedance route diverts to the BeltLine multi-use path (see Figure 6); whereas, the time-only impedance route traverses several arterial roads with high vehicle speeds and up to four lanes of traffic (see Figure 7, where green and red circles represent the origin and destination, respectively). The very large percent detour also highlights the lack of adjacent North-South cycling infrastructure in the study area (see Figure 2). Even if this more circuitous path is not consistent with observed cycling behavior, current cyclists may have a much higher attribute tolerance for these high impedance roads (i.e., willingness to operate on these major arterials) than do the more vulnerable users (e.g., children, older adults, inexperienced cyclists, etc.). Indeed, this is a research area in which this team has begun to explore.

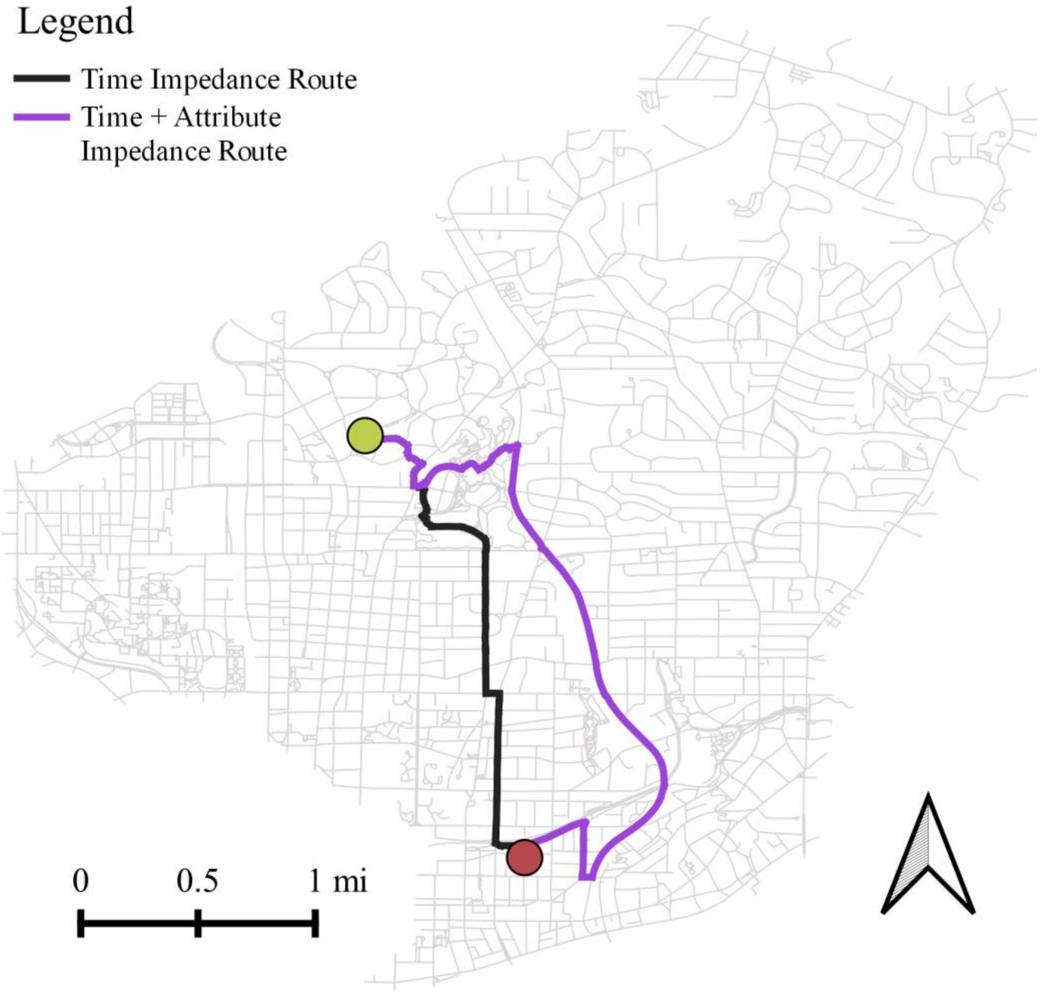


Figure 6. The change in routing when adding additional impedances

Figure 7. Google Street View images of (left) Boulevard Ave, a 4-lane arterial, and (right) the Beltline multi-use path

The second example, shown in Figure 8, demonstrates how the new multi-use path, displayed with cross-hatches, modifies the routing (the green and red circles represent the origin and destination, respectively) using time and time + attribute impedance. The percent detour from the time-only impedance route before improvement was 12%; the percent detour with the improvement was reduced to 0.4%. The preferred route is now essentially as direct as the time-only impedance path. This suggests that cycling is now a more attractive option.

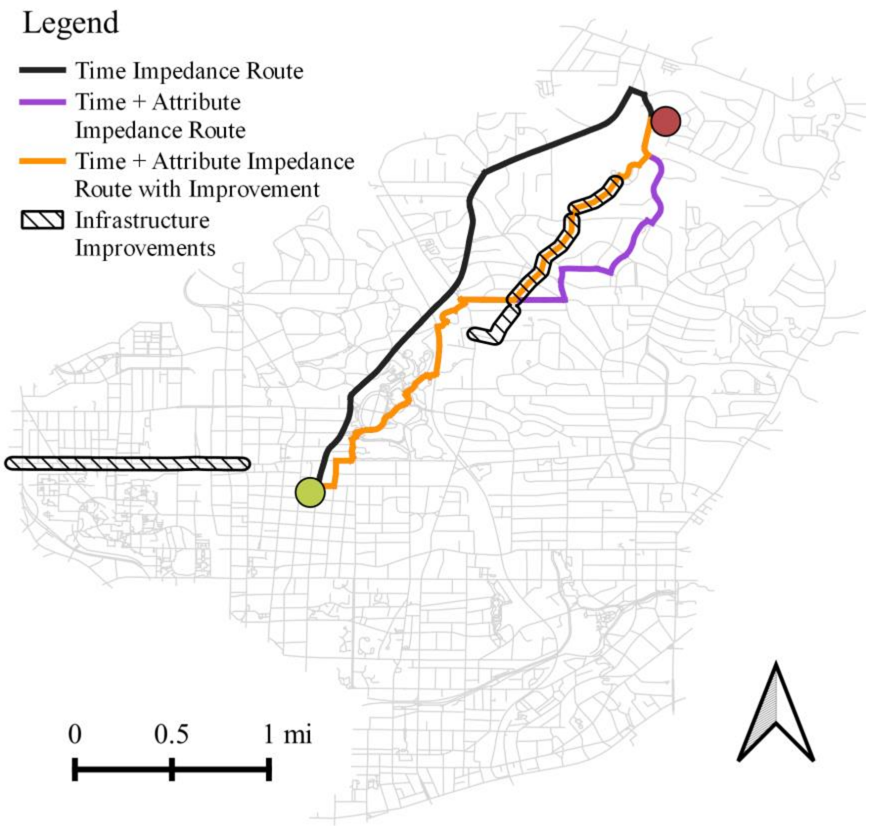


Figure 8. Route showing the effect of infrastructure improvements

In addition to testing the results of the impedance functions and calculating percent detours, routing can be used for trip planning apps such as Google Maps, Apple Maps, or Bing Maps. MPOs or cities could also use these results to reduce automobile dependence for short trips, by providing curated cycling routes through neighborhoods to reduce percent detour to destinations.

Betweenness Centrality

Betweenness centrality represents the number of shortest path trips that shared a link. A high betweenness centrality signifies that a link is a crucial connection. The betweenness centrality resulting from the two impedance functions is shown in Figure 9a and Figure 9b. The differences between the two are highlighted in Figure 9c. Like percent detour, when the difference in betweenness centrality for two impedance functions is close to zero, the most direct link possesses preferable attributes. Change in link betweenness centrality was calculated by subtracting the time + attribute impedance centrality from the time-only centrality. A negative difference indicates that fewer trips utilized that link because it and other links around it had a higher impedance than before. A positive difference indicates the link's attributes and the attributes of surrounding links make it worth the detour. Negative links became less important than before. It appears that betweenness centrality is more dispersed in Figure 9a than in Figure 9b. The BeltLine multi-use path becomes a critical corridor in the time + attribute impedance network. This is reflected in the differences shown in Figure 9c. Next, the betweenness centrality using the time + attribute impedance was calculated after the network improvement as seen in Figure 9d. The effects of the added multi-use paths show that the shortest path routing near them has shifted, and the multi-use paths have become critical links.

The betweenness centrality figures currently weights all origin-destination pairs as having an equal contribution to the measure of link betweenness centrality. In reality, some origin-destination pairs have more trips between them than other pairs. When weighting link betweenness centrality by the number of trips between origin-destination pairs, links that are part of the shortest path between origin-destination pairs with many trips between them will have a larger link betweenness centrality than they would if origin-destination pairs were equally weighted.

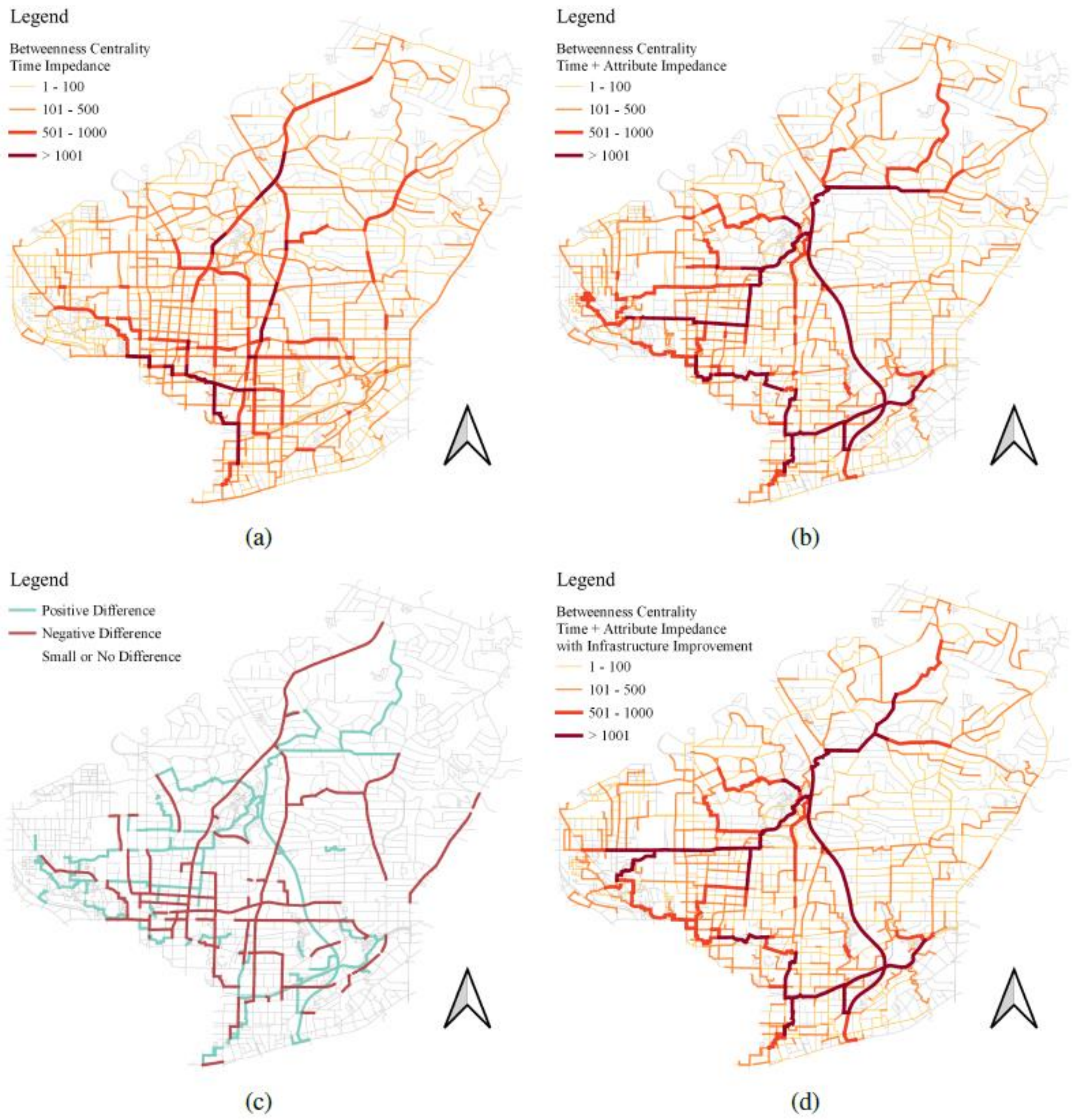


Figure 9. a) Betweenness centrality using time impedance, b) Betweenness centrality using time + attribute impedance, c) Change in betweenness centrality, and d) Betweenness centrality using time + attribute impedance with network improvements

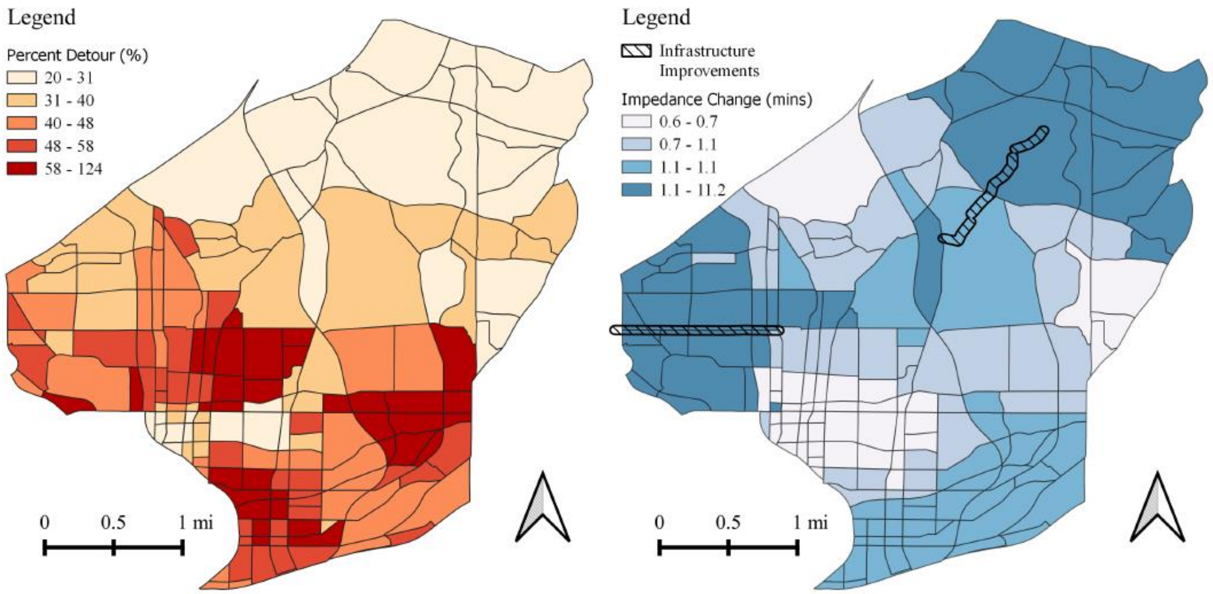
Planners can use betweenness centrality to sketch out the most important corridors for cycling. Transportation plans can prioritize cycling infrastructure on routes with a high time-only impedance betweenness centrality but a low time + attribute impedance betweenness centrality. Betweenness centrality could also be cross-referenced against observed cycling data to see if these expectations match reality.

Zonal Statistics

The last visualizations are aggregated percent detour and change in impedance from network improvements. For the former, the percent detour was calculated for all 28,392 possible OD pairs and aggregated by origin. The mean percent distance per TAZ is visualized in Figure 10a. The minimum percent detour for a TAZ was 20%. This is larger than literature values (8-18%), but average detour rates have been noted to be as high as 30% for this study area in past research (Misra, 2016). The mean and median detour rates for all trips were 46% and 30%, respectively. TAZs with average detour rates above literature values might indicate unrealistic routing. It could also mean a high presence of high-stress streets that necessitate longer detours if a cyclist was brave enough to travel at all.

There is a clear divide between the northeast TAZs and the rest of the TAZs in the study area. Most of the low average percent detour origin TAZs are on the northeastern side of the map. Figure 2 shows that there is less bike infrastructure in this area, and Figure 3 shows that most link impedances increased in this area with the introduction of attribute impedance. Most of the streets in this area are residential (one lane per direction, 30 mph), so the impedance functions don't cause detouring towards lower-impedance cycling infrastructure as they would in other parts of the study area. Additionally, there are more one-way streets and multi-lane streets in the western TAZs that likely make normally short-distance trips longer than expected.

Figure 10b shows how the average impedance changes after adding the proposed cycling facilities. The scale is organized into quantiles where each bin represents 25% of the data. As expected, the areas with the largest change in impedance were adjacent to the infrastructure improvements. However, there was also an impedance reduction in the south section of the map, presumably because these areas had access to existing multi-use paths. This demonstrates that network improvements can impact areas with existing cycling infrastructure that are separated by distance from the improvement. This metric can be used to prioritize different cycling infrastructure projects by assessing which improvements provide the largest change in time + attribute impedance.



(a) (b)

Figure 10. a) Average percent detour from time-only impedance path by TAZ and b) Change in impedance after infrastructure improvements

Limitations and Future Work for the Framework and BikewaySim

The main limitation of the analyses presented in this study was the use of the literature-informed attribute beta coefficients for the time + attribute impedance function. A detailed dissertation study is currently being undertaken to reconcile MRS-derived beta coefficients across literature studies that employ significantly different data sets and use different combinations of explanatory variables (many of which appear highly correlated) that affect the magnitude of attribute beta coefficients within each study. The resulting routes derived in this study may be unrealistic if the current attribute beta coefficients are incorrect. Some potential avenues to rectify this include generating stress factors from MRS values or scaling MNL coefficients (Lowry, Furth, & Hadden-Loh, 2016; Broach, Dill, & Gliebe, 2012), but further research is needed in this area. The researchers are investigating a method for calibrating link impedance through revealed preference data (cycling GPS traces) and survey response data (surveys on user preferences for cycling infrastructure).

Some other limitations include the lack of impedance values associated with other attributes that were available in other cycling route choice studies, such as left turns across traffic and the influence of road grade. The network used for this project was conflated using a semi-automated process, so there could be potential errors in network conflation. To support bicycle planning, cities, DOTs, and MPOs will need to commit to the development of complete-paths networks that carry as much attribute information as possible.

The visualizations and metrics generated by BikewaySim can serve as information for decision-makers, but BikewaySim is not meant to supersede other elements of the infrastructure planning process. Care should still be taken concerning public input and local context. Cities, DOTs, and MPOs need to implement cycling volume measurement programs to assess BikewaySim's predicted behavior against the actual observed behavior of cyclists. Care should always be taken to ensure that the needs of potential cyclists (individuals who are currently not cycling for various reasons) are accounted for in planning; existing cyclists may have higher tolerances of stressful attributes. As such, engagement of the public (focus groups, outreach, co-planning, etc.) should be considered in the transportation planning process and development of project prioritization systems.

The cost of cycling infrastructure was not addressed in this study, but cost-effectiveness could be implemented as a metric in BikewaySim to compare the dollar per minute in impedance reduction of different projects.

The bikeshed and routing tools also have applications outside of infrastructure planning. In particular, the shortest path functions can provide local bicycle commuters with route suggestions based on their preferences. Researchers could recruit cyclists to try the routes generated with BikewaySim's impedance functions, and then these people could provide feedback about the bikeability of the route. Not only would this benefit BikewaySim by providing input on how to modify attribute impedances, but could also benefit new bicycle commuters.

Lastly, only potential origin-destination pairs were considered and a limited study area network graph was used. In the next research application of this report, the research team uses an expanded network graph to assess cycle plus transit modes. A full regional network complete paths network would allow Georgia Tech researchers to use BikewaySim and its impedance functions to estimate the current distribution of route impedances from more than 2.1 million potential origins (residential parcels) to classes of activity in ARC’s -based travel demand model activity-specific destinations (grocery stores, hospitals, restaurants, job centers, etc.) using the PACE supercomputing cluster (Partnership for an Advanced Computing Environment, n.d.).

Modeling the Bike + Transit Mode

First and last mile (FLM) connectivity is a major barrier to public transportation, particularly in low-density suburban settings where disconnected and circuitous streets create long distances to transit stops. One study in the Metro Atlanta area found that the average difference in travel time between driving and taking public transit was 72 minutes for a selection of 2,082 GPS traces, which corresponded to a Transit Capacity and Quality of Service Manual (TCQSM) (Zuehlke, 2007). Another study of 5,472 trips routed through Google Maps' routing API found that the average travel time by public transit was more than twice the travel time by automobile (Wu, 2017).

Bicycles can effectively extend the service coverage area of a transit stop or station. While the TCQSM sets walking distances for transit service coverage at 0.25 and 0.5 miles for buses and rail, it sets biking distances at 1.25 and 2.5 miles for bus and rail (Transit Cooperative Research Program, 2017). People can reach transit stops faster on a bicycle than they could by walking; they can cycle to transit routes with higher service frequency, they can avoid transfers, and they can cycle to routes that have dedicated right of way (such as heavy rail).

In addition, the bike + transit mode is often more flexible than park-and-ride (i.e., drive and park car at a transit station) style journeys in that a bike can be parked at the transit station or brought on board the transit vehicle for use at the destination transit stop. The transit system studied in this report was the Metropolitan Atlanta Rapid Transit Authority (MARTA). MARTA's stations also have elevators and wide gates that allow for bikes to be carried through the heavy rail stations. MARTA's buses are equipped with a bike rack that holds two bikes, and there are no restrictions for bringing bicycles aboard its heavy rail vehicles.

In contrast, systems like Washington D.C.'s Metro restrict bringing bicycles aboard during peak hours, and older systems like N.Y.C.'s subway may not have large fare gates and elevators that allow users to bring bicycles into the station. Even if the station is accessible, heavy rail cars may not have a spot to secure bicycles to prevent them from moving during the trip, which means owners may need to hold their bicycle for the entirety of the transit trip. Additionally, bikes placed on bus bike racks are not locked and can be stolen when the bus stops.

For this report, the bike FLM mode will be referred to as the bike + transit mode. There are several common combinations of these trips:

1) Bike to a transit station, park bike, take transit, and walk to the destination
2) Bike to a transit station, bring bike on-board transit, and bike to the destination
3) Bike to a transit station, park bike, take transit, use bikeshare or parked personal bike to bike to the destination
4) Walk to a transit station, take transit, use bikeshare or parked personal bike to bike to the destination

While existing trip planning applications such as Google Maps and OpenTripPlanner (OTP) are capable of outputting the shortest paths for bike + transit trips, these types of trips are not considered in most travel demand models (TDMs). According to the literature, the only North American MPO that includes these trips is Phoenix's Maricopa Association of Governments (MAG) (RSG, 2019).

In the Atlanta Regional Commission's 2019 Regional On-Board Survey, about 1% of MARTA riders used micromobility (i.e., bicycles, scooters, skateboards, etc.) to access transit compared to 87% by walking and 13% by shared or personal vehicle (The Atlanta Regional Commission, n.d.). This small access mode share may be due to the lack of safe micromobility facilities, unawareness of the bike + transit mode, lack of secure bicycle storage options at the transit station or destination, or other reasons.

This work serves as an extension to previous work done on determining the feasibility of transit trips in metro Atlanta by understanding how bicycle + transit trips can improve the effectiveness of public transit (Zuehlke, 2007; Wu, 2017). BikewaySim will model bike routing to transit facilities based on physical attributes and safety preferences. TransitSim handles the transit portion of the journey, routing users from any origin to any destination via the transit path with the lowest travel time and the fewest number of transfers.

The objective of this chapter is to join these two models so that for each origin, destination, and departure time, the shortest path will include bicycle transit access and bicycle travel from the last transit stop to the final destination. This approach can be applied to bike-share and scooter-share trips as well, greatly expanding the potential to understand the costs and benefits of multimodal trips. Overall, these tools can be used for planning new bicycle facilities or transit services and seeing their projected impact on transit access throughout a region.

This calculator can be used to understand how new bike facilities around transit facilities or new transit services are likely to affect overall bike FLM shortest path routing, travel time, energy usage, and emissions.

Methodology for the Bike + Transit Mode

For this report, the walk + transit mode is compared to the bike + transit mode. Cycling trips were modeled with bikes brought on board the transit vehicle. The methodology for this report is split into sections that describe the expanded study area, the street network and transit data, the transit routing algorithm, and finally, the routing settings.

Expanded Study Area

The study area used earlier in the report was not large enough to adequately model the bike + transit mode because transit trips can serve a much larger area for a given travel time, so the study area was expanded for the analyses that will follow. The expanded study area used for this section was delineated by buffering each MARTA bus and rail stop by 2.5 miles, the TCQSM's bicycle service area. This expanded study area is depicted in Figure 11. The bus lines are shown with black lines and the rail lines are shown with white lines with black borders. The City of Atlanta borders are crosshatched in grey and the cycling study area used earlier in the report is crosshatched in red; MARTA's potential bike + transit service area extends far beyond these borders.

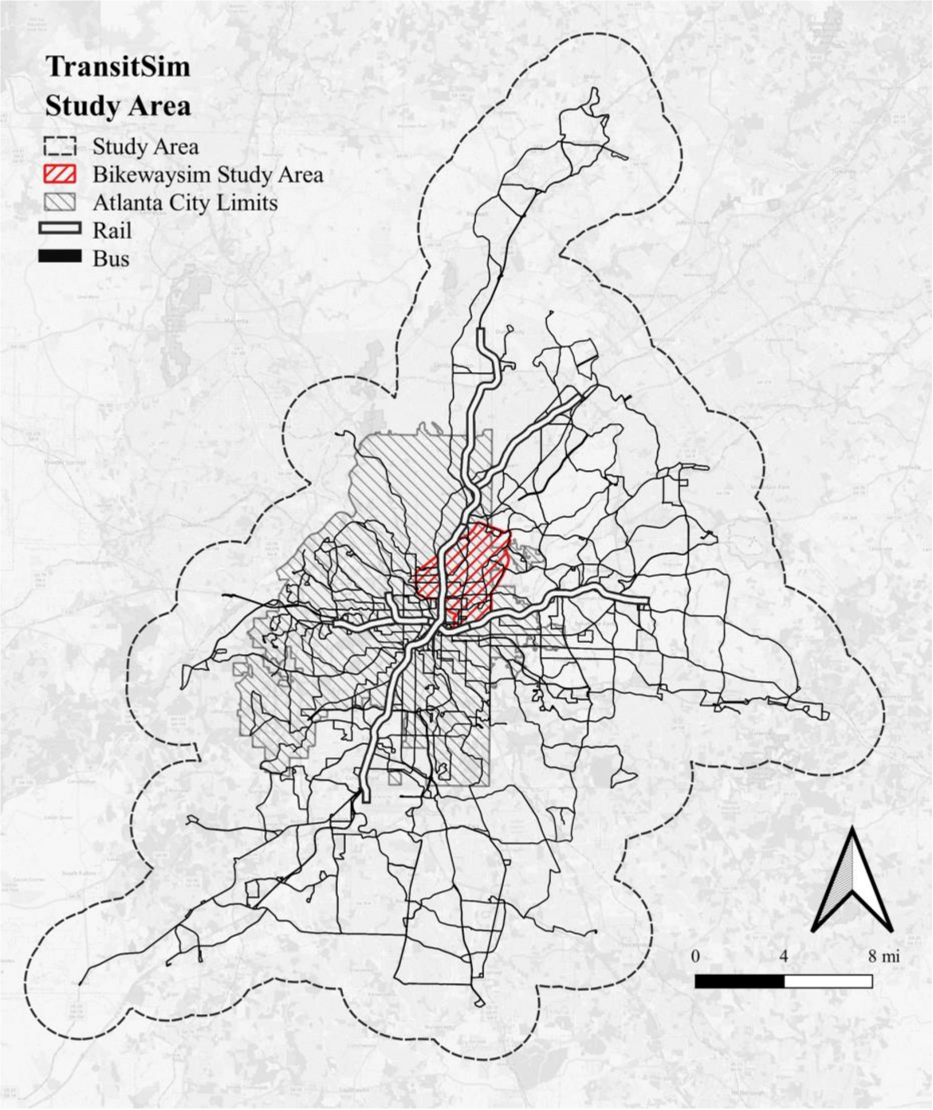


Figure 11. Expanded study area using a 2.5 mile buffer around all MARTA's transit stops

Data Employed in Analyzing the Bike + Transit Mode

The street network for the larger study area was reconciled using ARC, Open Street Map, and HERE data, using the same process as presented earlier in the report. The street network was similarly expanded to fill the extent of the entire study area. The final network was composed of 413,628 links and 181,070 nodes. In this analysis, all possible pairings of traffic analysis zones (TAZs) from the ARC's Activity Based Model were used as origin-destination pairs. Lastly, the MARTA network for the dates 2022-09-10 thru 2022-12-16 was retrieved from MARTA's GTFS feed (Open Mobility Data, n.d.).

Transit Routing Algorithm

Before integrating BikewaySim and TransitSim, several issues had to be addressed. The first was to update TransitSim's shortest path routines for transit. TransitSim initially used a time-expanded Dijkstra's algorithm to handle shortest path routing (Li, 2018). This method was inefficient because every trip stop in the transit network is modeled as a node; hence, a route consisting of five stops and ten trips would require 50 nodes and 40 links, and the links needed for transfers to and from other routes.

At the time TransitSim was developed, this was the state of the practice method. Now, there are more efficient methods used by services such as Google Maps and OpenTripPlanner (OTP). The former uses transfer pattern based routing (TPBR), while the latter uses round-based public transit optimized routing (RAPTOR) (Delling, Pajor, & Werneck, 2014). For TransitSim, RAPTOR was selected in part because the open source algorithm developer offered to work directly with the research team on streamlining the integration. In the future, additional approaches that may reduce the computational burden will be explored.

RAPTOR is not a traditional graph-based routing algorithm like Dijkstra's algorithm. It utilizes a transit system's property of fixed routes to instead focus on finding the earliest arrival time for each stop that can be reached from a source transit stop, given a specified number of transfers. Each round is split into two phases, the first phase searches for stops along a route, while the second phase searches for footpaths to the final stop. Every stop along a route is visited exactly once per round, and the earliest arrival time at a stop is updated if an earlier arrival time is found. For a detailed description of the algorithm, see Delling et al. (2015).

The existing Python module, Transit-Routing, was adapted into TransitSim's code to implement RAPTOR (Agarwal & Rambha, n.d.). This involved processing MARTA's GTFS data and generating footpaths for allowing walking transfers between transit routes. The maintainers of Transit-Routing typically use the OSM network to generate network walking distances between stops, but Euclidean distance was used in place of network walking distance to speed up computational time.

The Bike + Transit Mode and Walk + Transit Mode Routing Constraints

This study examined the bike + transit mode configuration where the owner brought their bicycle on board. Both MARTA's heavy rail and bus routes were considered. A one-hour period on a weekday schedule (when service is most frequent) was used for assessing transit travel times. The assumed walking and biking travel speeds were 2.5 mph and 10.0 mph, respectively. One issue that has made modeling the bike + transit mode difficult in the past has been the vast number of permutations one can take to accomplish a trip. To limit the number of bike-to-transit trips, a series of constraints were implemented, based on engineering judgment and lived experience with bike + transit trips.

- Origin-destination pairs that are under the transit access thresholds (0.5 miles for walking and 2.5 miles for biking) are not considered for transit routing

- For each transit route, a person will board at the closest stop servicing that route even if there are other stops servicing the same route within the access threshold
- No transfers are made from bus to bus (only bus-to-rail, rail-to-bus, or rail-to-rail)
- No more than one mile of walking or five miles of cycling is allowed
- 60 minutes is set as the maximum travel time

Bus-to-bus transfers were not considered on the grounds that they would be behaviorally unlikely. Bus routes within the study area operate on low frequency schedules, making it difficult to time transfers. Additionally, cyclists have similar average speeds to many bus routes (meaning they would avoid unnecessary bus segments), and bicycle storage on buses in the study area is more limited than the heavy rail service.

The one-hour period was split into four departure times, and the average travel time across the four was taken. The actual departure times used were 9:00 am, 9:15 am, 9:30 am, and 9:45 am. These times were simply selected to account for the different frequencies and arrival times of the routes. For trips where there were fewer than four travel times (i.e., the max travel time was exceeded for one or more departure times), the average of the available travel times was taken.

The Bike + Transit Mode and Walk + Transit Mode Routing Procedure

The bike/walk and transit portion of each journey were modeled separately. In the bike/walk portion, three runs of Dijkstra's algorithm were completed to determine the least impedance path. The first was from each TAZ to all other TAZs to eliminate origin-destination pairs that were too close together according to the set access thresholds. The next run was to find the least impedance path from each TAZ to all candidate transit stops within the access threshold. TransitSim calculates the arrival time at each candidate transit stop using these paths. The last run was from each transit stop to all TAZs within the access threshold. This step must be run separately, because path directionality often matters (i.e., the least impedance path **to** a transit station won't always be the same as the least impedance path **from** a transit station).

For walking and cycling, the impedance used for routing was travel time. In the future, additional impedances will be added to account for cyclists' preferences for road attributes.

In the transit portion, all the possible starting and ending transit stop combinations for each OD pair were used from the bike/walk portion. For each OD pair, there could be many potential transit combinations. The RAPTOR algorithm outputs the start and end stop with the least travel time given the transfer and time constraints given in the previous section. Note that the transit portion was re-run for each departure time tested.

Origin Test Locations

For this study, four origin locations were selected to represent the variability in transit service and land use throughout the expanded study area. These origins included:

1. Midtown - This commercial center is composed of mixed-use dense development and features several MARTA heavy rail stations that serve as terminus points for many of MARTA's bus routes.
2. West Atlanta - This relatively new neighborhood in northwest Atlanta has access to several bus routes and the Bankhead MARTA station (via the Proctor Creek multi-use path).
3. Medical Center – This MARTA station is located near the Interstate 285/GA-400 interchange. This area has many medical services including pediatrics, gynecologists, and a hospital. Many of the MARTA rail stations in this area are surrounded by commercial development and parking (for park-and-ride) instead of residential/mixed-use development. Additionally, many of the surrounding streets in this area are large multi-lane arterials with high vehicle speeds and volumes.
4. Greenbriar near Campbellton Road (Campbellton) - This location was selected because of its proximity to the Campbellton bus line, which has high ridership and frequent service. However, this area is still largely composed of low-density single-family homes which increase required walking distances.

Results

Using a desktop with a 10-core 3.70 GHz CPU, 32 GB RAM, and a 1024 GB NVMe, the mean run time for a location was 107 minutes for the bike + transit mode and four minutes for the walk + transit mode. The significantly longer computation time for bike + transit mode shortest path calculations was expected because the higher travel speed and stop access thresholds for cycling resulted in more trip combinations to examine than for the walk + transit mode. Similarly, origin TAZs that were near more transit routes and other TAZs took longer to route. As an example, the midtown TAZ took 216 minutes for bike + transit. In the near future, the team will apply the RAPTOR algorithm to evaluate more origin/destination pairs and larger geographic areas. In the next sections, three visualizations (accessibility, travel time, and public transit modes utilized) illustrating the results of these analyses are presented for each study location.

Midtown

Three figures show the results for the Midtown location. Figure 12 shows a comparison of the walk or bike to transit accessibility within 60 minutes for the Midtown location. Although more TAZs can be reached by the bike + transit mode (light red areas), there are still many TAZs that can be reached by the walk + transit mode (light green areas). This is expected as the origin location is a short walking distance to both rail and bus routes, and MARTA's network layout prioritizes transporting people to and from this business center. However, it is also clear that the maximum walking distance (1 mile) and maximum travel time (60 minutes) imposed in the analyses restrict access to those TAZs located near the bus and train routes.

Figure 13 illustrates the travel time to the accessible TAZs for the bike + transit mode (left) and the walk + transit mode (right). The origin dot (white) is bounded by a dotted border on the left map. The small white dots within this area are TAZ centroids that are under the transit access threshold (0.5 miles for walking and 2.5 miles for cycling) and were therefore not considered for transit routing. This border is also present in the walk + transit mode map; it is just covered by the origin TAZ dot. Outside of this border, accessible TAZs are color-coded according to travel time; non-accessible TAZs are a very light grey. TAZs that are accessible for both the walk + transit and bike + transit modes can be reached in less time with the bike + transit mode.

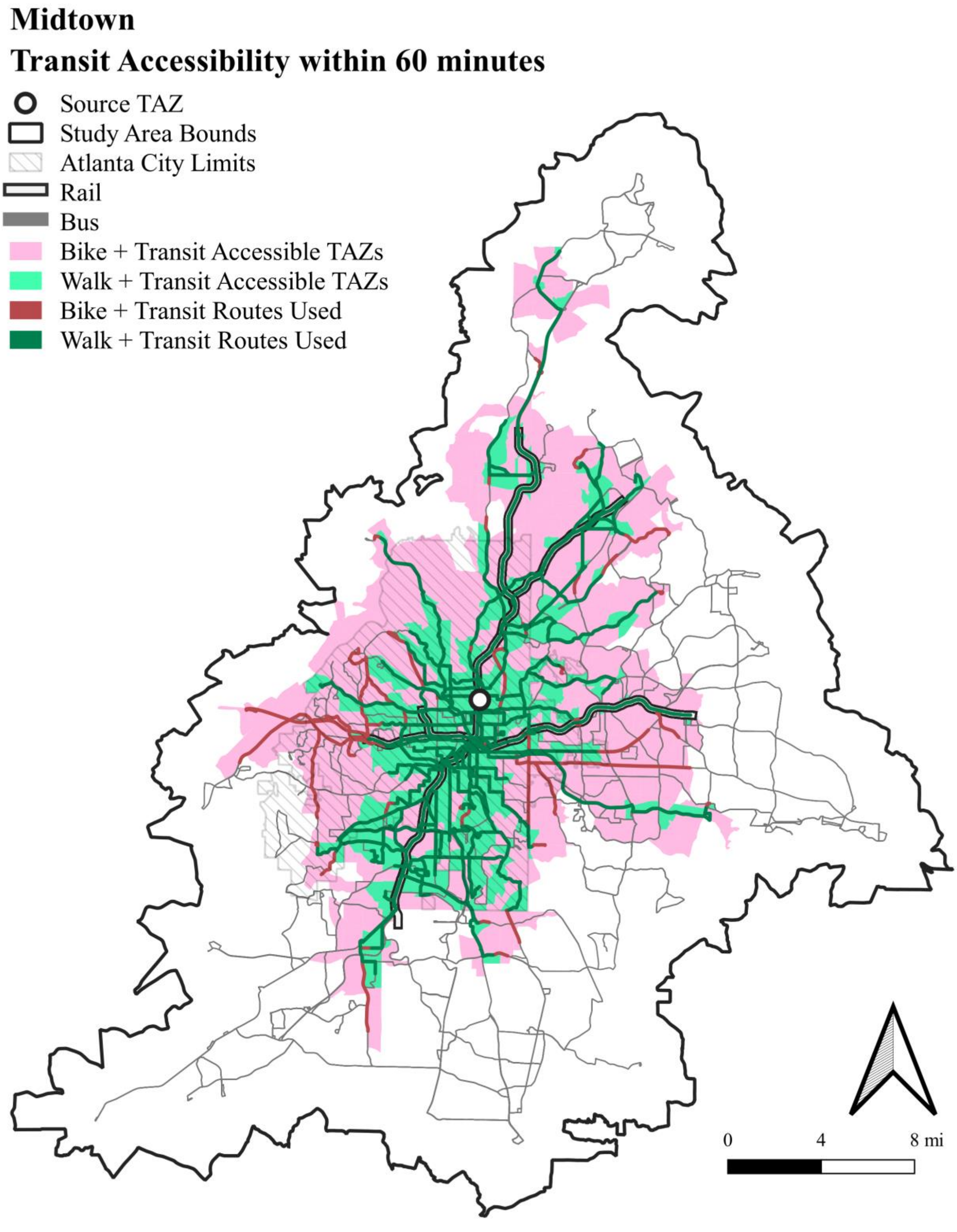


Figure 12. The accessible TAZs and utilized transit routes from the Midtown TAZ

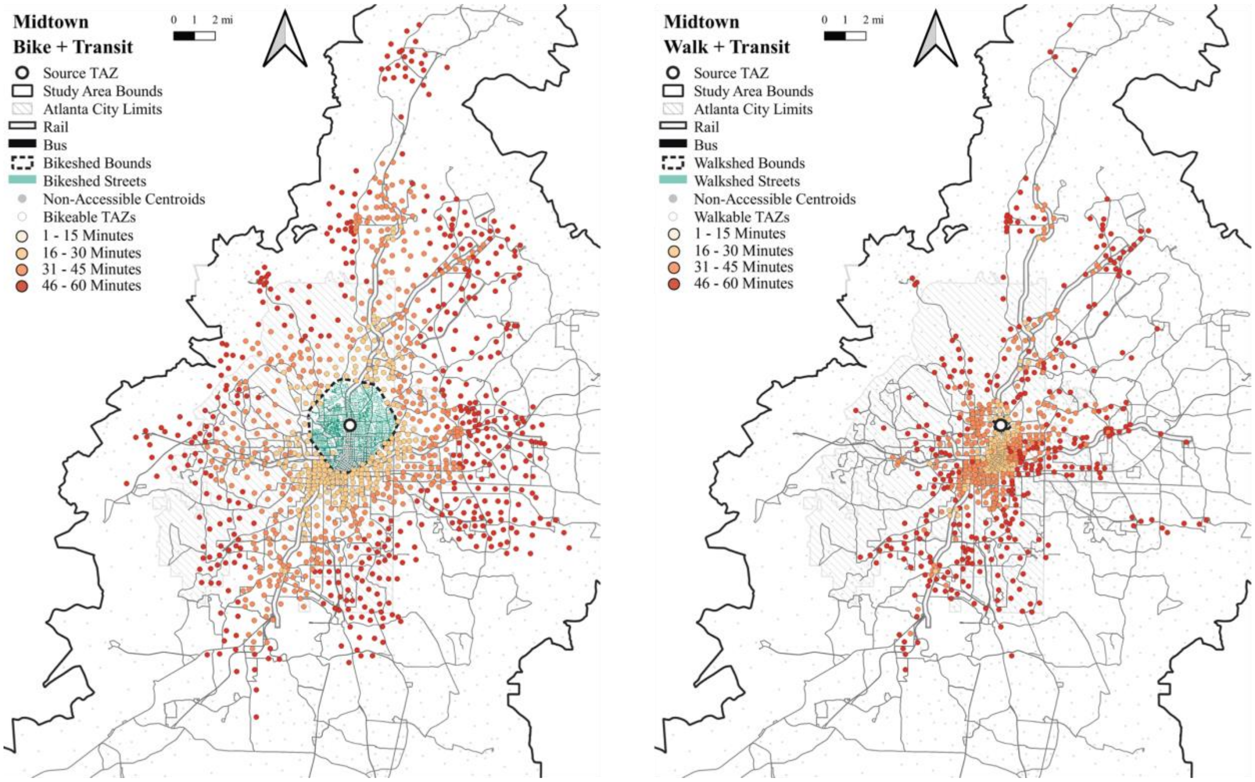


Figure 13. Dot plots showing travel time from the Midtown TAZ to all other TAZs

Lastly, Figure 14 shows the combination of transit modes used to access a TAZ from the source TAZ. For simplicity, only the results for one departure time, 9:00 AM, are displayed; in reality, the fastest transit mode combinations change with changing departure times. For instance, at one time it may be faster to bike and then take bus + rail, while at another time it may be faster to just bike directly to the rail station.

As depicted in Figure 14, biking directly to rail is the fastest way to travel to TAZs lying near the North-South rail lines. For TAZs lying near the East-West rail lines, taking bus service or connecting to rail via bus service is the fastest way to travel. This is of note because one might assume that transferring at Five Points (the intersection of the rail lines) would be the best way to access destinations along the rail lines that run East-West. However, transferring at Five Points is only fastest for the yellow-colored TAZs at the Western terminus of the rail lines that run East-West. Figure 14 also shows that rail or rail with connecting bus service is the fastest way to reach TAZs furthest from the source TAZ. This is expected as rail service features higher travel speeds and frequency than bus service, and rail service has dedicated right-of-way.

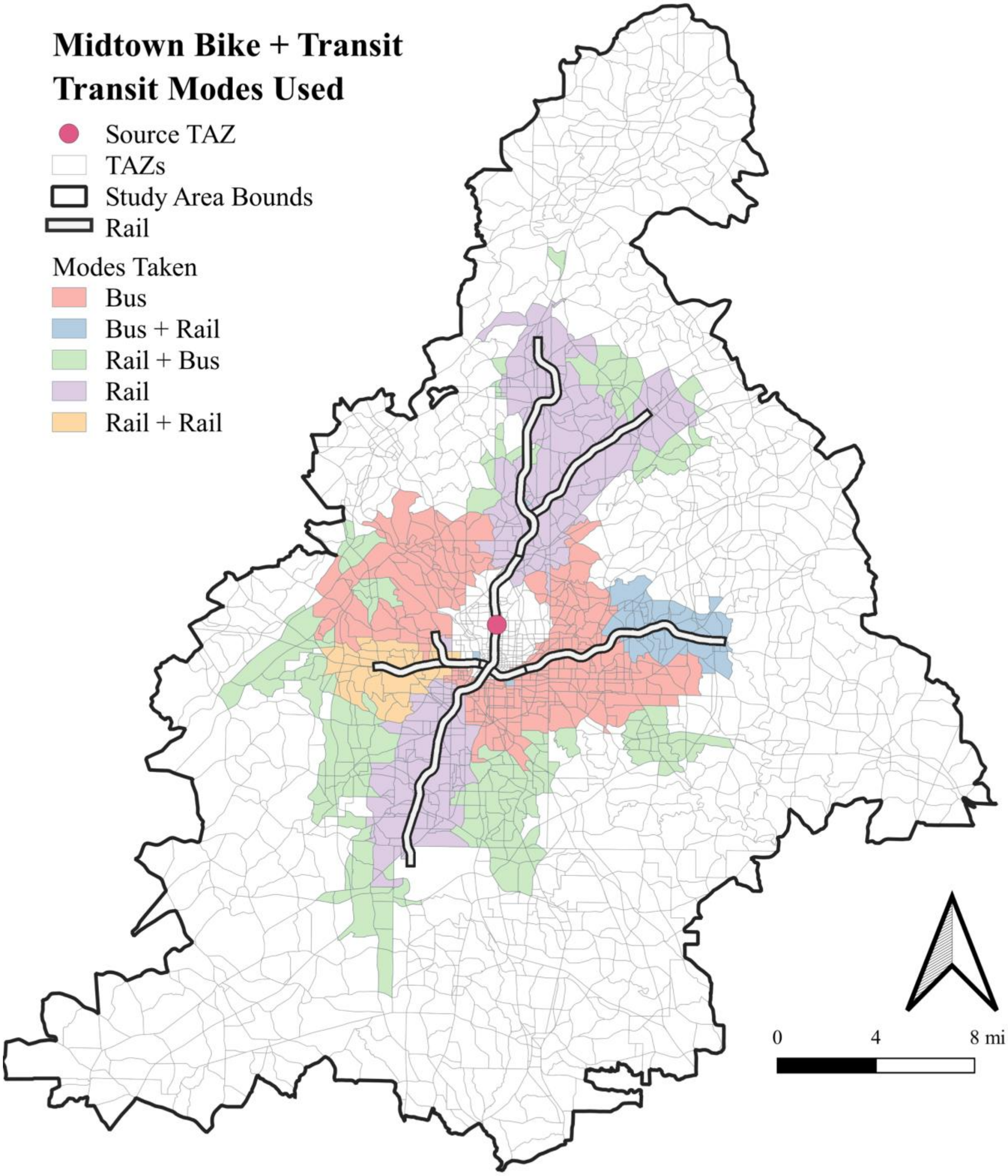


Figure 14. Fastest transit mode(s) to accessible TAZs from the Midtown TAZ at 9:00 A.M

West Atlanta

For the West Atlanta location, three similar figures are presented, showing slightly different accessibility. Figure 15 shows the TAZs that are accessible within 60 minutes for West Atlanta. In comparison to the Midtown location, fewer TAZs can be reached from this location. This is especially true for the walk + transit mode, where access is mostly limited to TAZs that are adjacent to the few accessible transit routes. The walk + transit mode appears to be limited to transit routes that are accessible from the closest bus route, while the bike + transit mode has access to bus routes that are further away. The effect of MARTA's network layout on accessibility is more apparent in this location. Because bus service facilitates travel to and from the rail stations, there are no bus routes that extend past the rail lines (a transfer to another bus is needed). As such, there are few accessible TAZs east of the rail lines that run North-South. The presence of Norfolk Southern's Inman Rail Yard as a barrier to direct connectivity, and this area's limited local road connectivity, also play into reducing the number of accessible TAZs from the West Atlanta location.

Figure 16 illustrates the travel time to the accessible TAZs for the bike + transit mode (left) and walk + transit mode (right). As in the previous case, there appears to be a reduction in travel time for TAZs that are accessible by both modes. However, fewer TAZs can be reached from the West Atlanta TAZ in the 16 - 30 minutes bin than from the Midtown location for both the bike + transit and walk + transit modes. This is likely due to the lack of proximal access to rail and the low frequency of the available bus service.

As shown in Figure 17, most of the accessible TAZs in this area were reached by bus, although there are a few TAZs near Five Points that were accessible by transferring from bus to rail. It is of note that this origin location experienced the largest variation in the number of accessible TAZs. Many of the TAZs that were accessible via transferring from bus to rail service in Figure 15 were not accessible for a 9:00 am departure time.

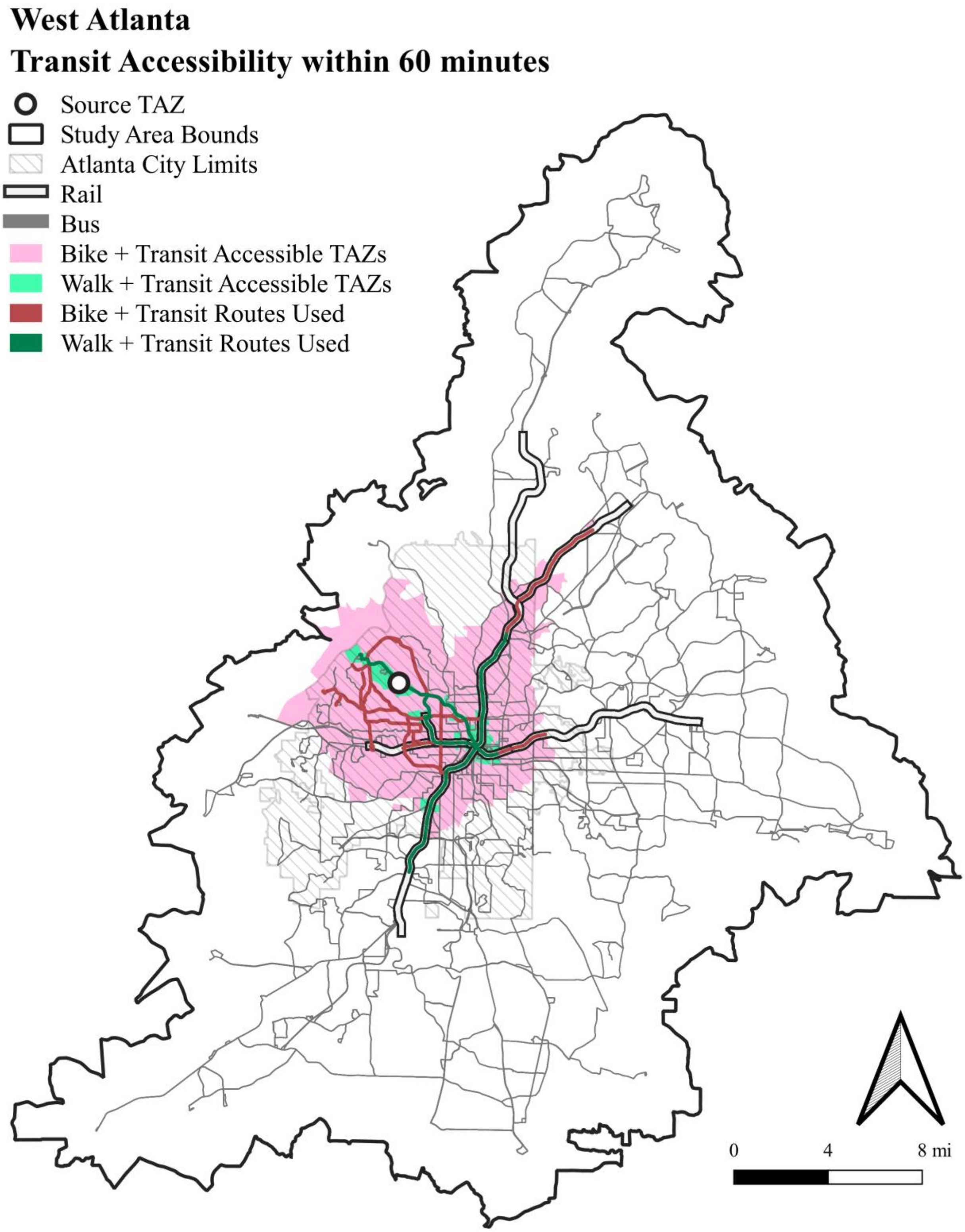


Figure 15. The accessible TAZs and utilized transit routes from the West Atlanta TAZ

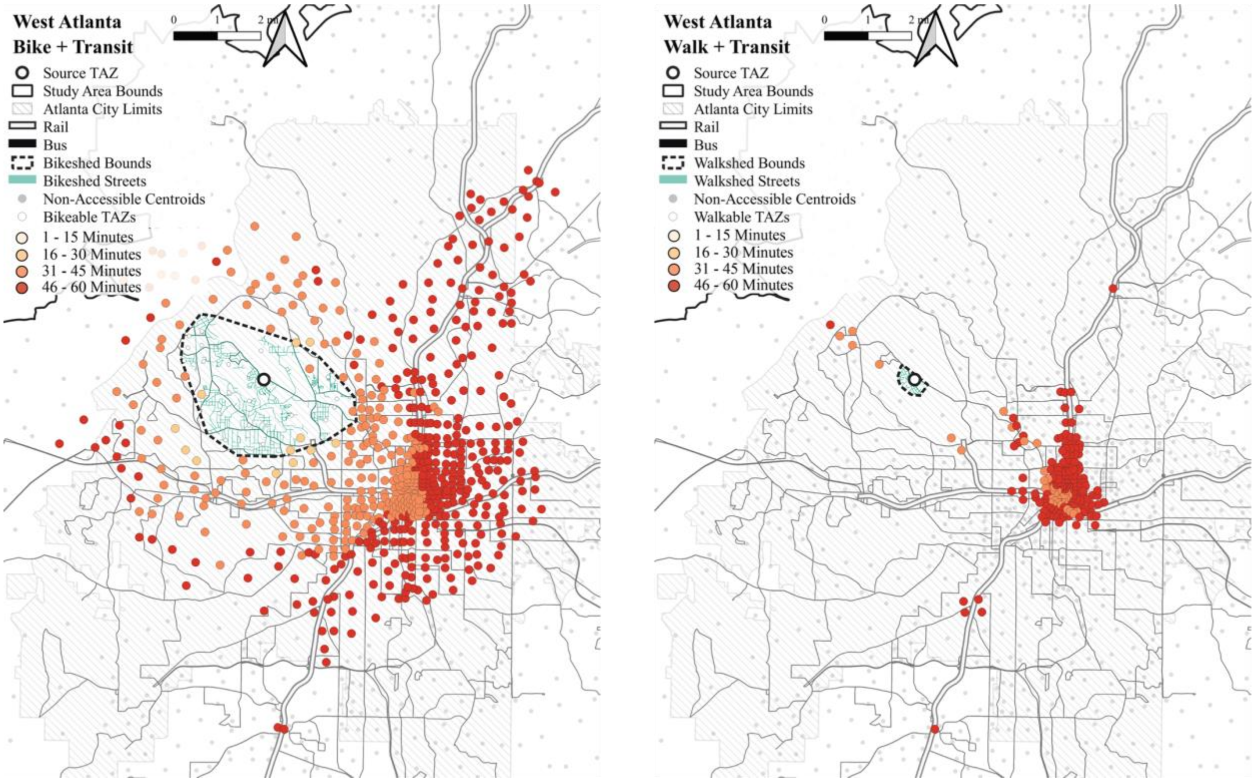


Figure 16. Dot plots showing travel time from the West Atlanta TAZ to all other TAZs

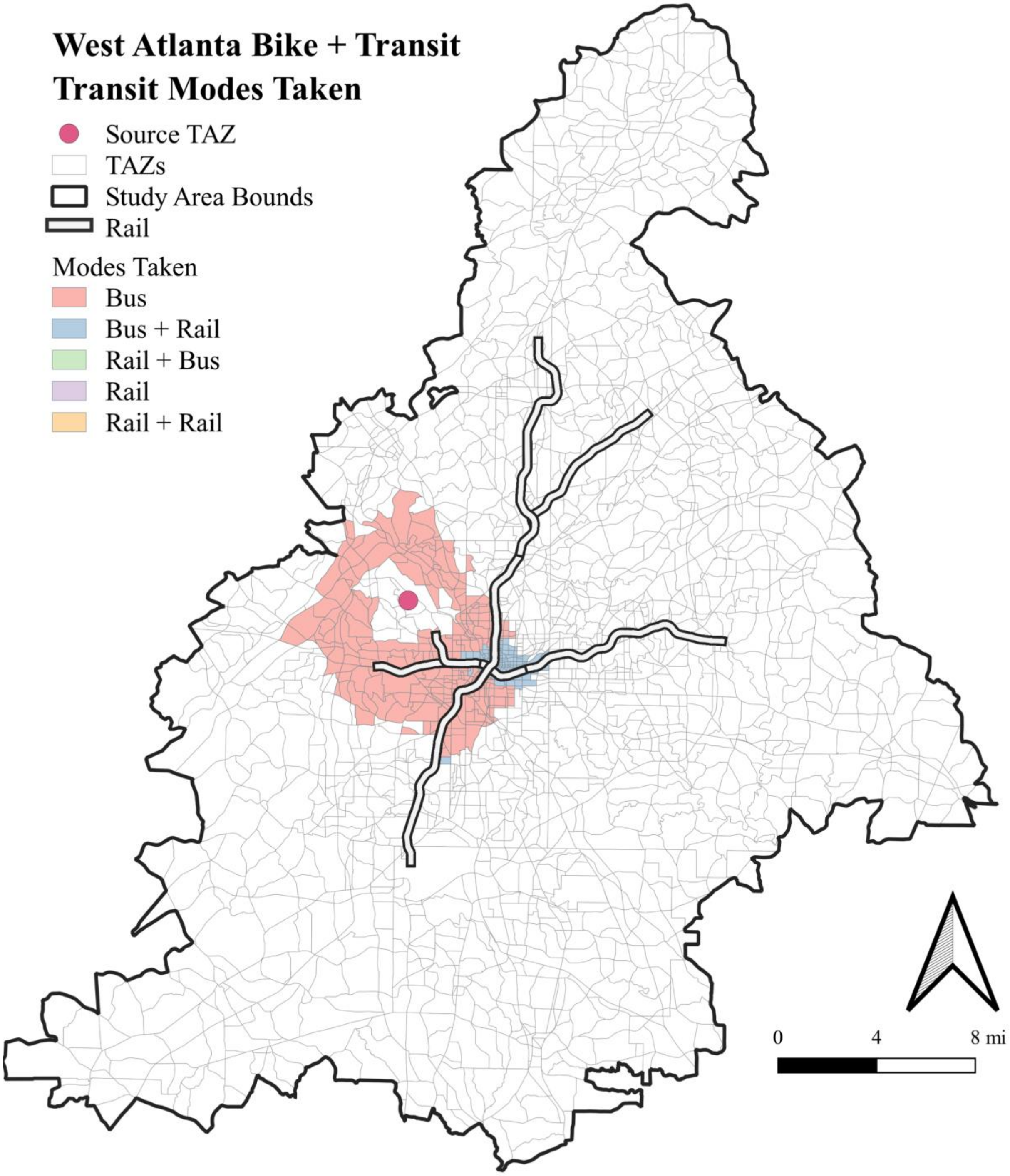


Figure 17. Fastest transit mode(s) to accessible TAZs from the West Atlanta TAZ at 9:00 A.M

Perimeter

Figure 18, Figure 19, and Figure 20 show the results for the Perimeter location. As with the West Atlanta location, Figure 18 shows there are fewer accessible TAZs from the Perimeter location than from the Midtown location. Similarly, the walk + transit mode accessibility is limited to areas directly adjacent to rail or bus lines. In contrast to the West Atlanta location, this location's proximal access to a rail station elongates the accessible area for both the bike + transit and walk + transit modes. Additional TAZs can be accessed in this area by transferring from rail to bus service.

Figure 19 illustrates the travel time to the accessible TAZs for the bike + transit mode (left) and walk + transit mode (right) for the Perimeter location. Unlike the West Atlanta location, more TAZs can be reached by the bike + transit mode in 16 - 30 minutes; this is not true for the walk + transit mode. Figure 19 depicts a disparity in the number of accessible TAZs between the bike + transit and walk + transit modes that is similar to the West Atlanta location. This is likely due to the long walking distance required to access the Medical Center rail station near the Perimeter TAZ.

The Perimeter location had more variability in the transit modes used to accomplish bike + transit trips as shown in Figure 20. As expected, most of the TAZs were accessed with rail as the starting transit mode apart from a few of the TAZs that were accessed using only bus service (shown in red). The TAZs to the north of the starting TAZ were accessed via rail + bus because only buses service that area. Unlike the other locations, many TAZs from the Perimeter location were reached via rail-to-rail connections: along the northeast segment of rail, the far west segment of rail, and the far east segment of rail.

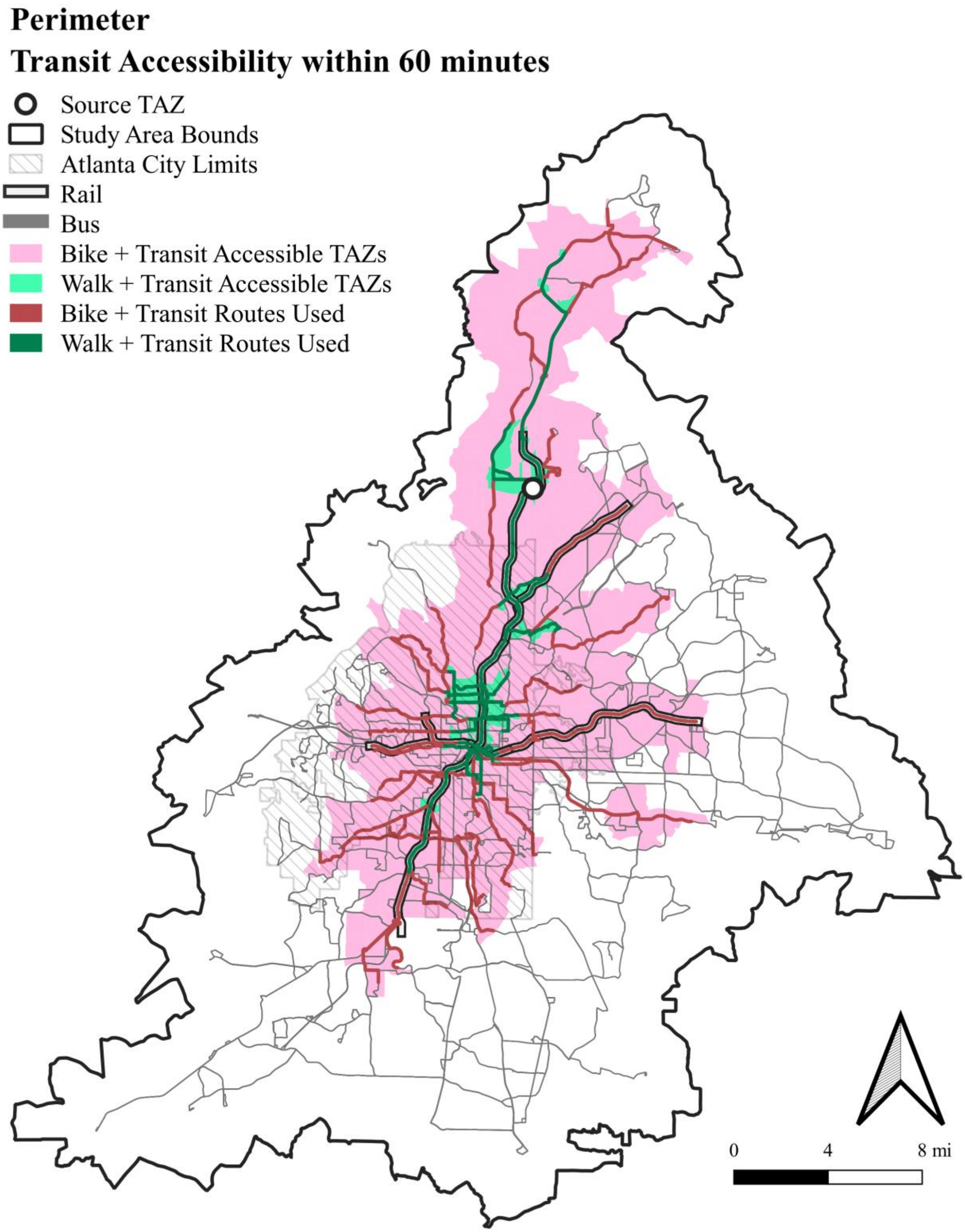


Figure 18. The accessible TAZs and utilized transit routes from the Perimeter TAZ

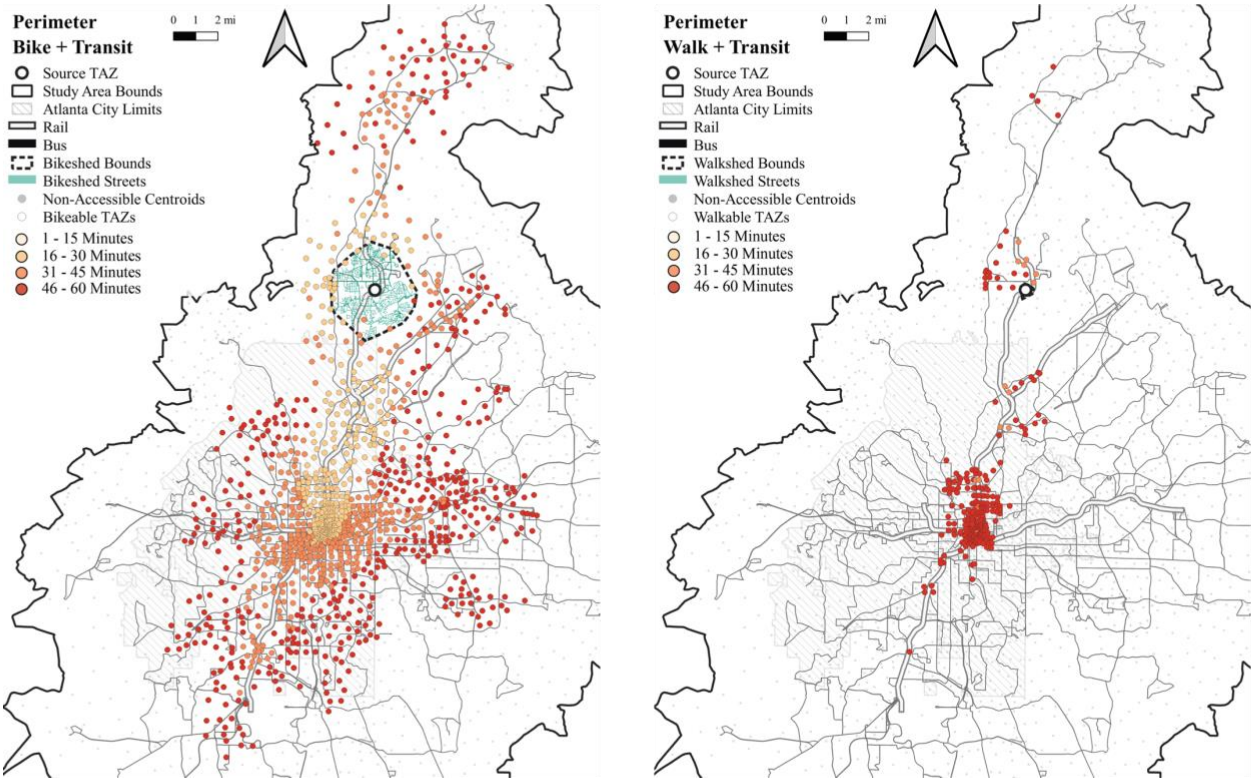


Figure 19. Dot plots showing travel time from the Perimeter TAZ to all other TAZs

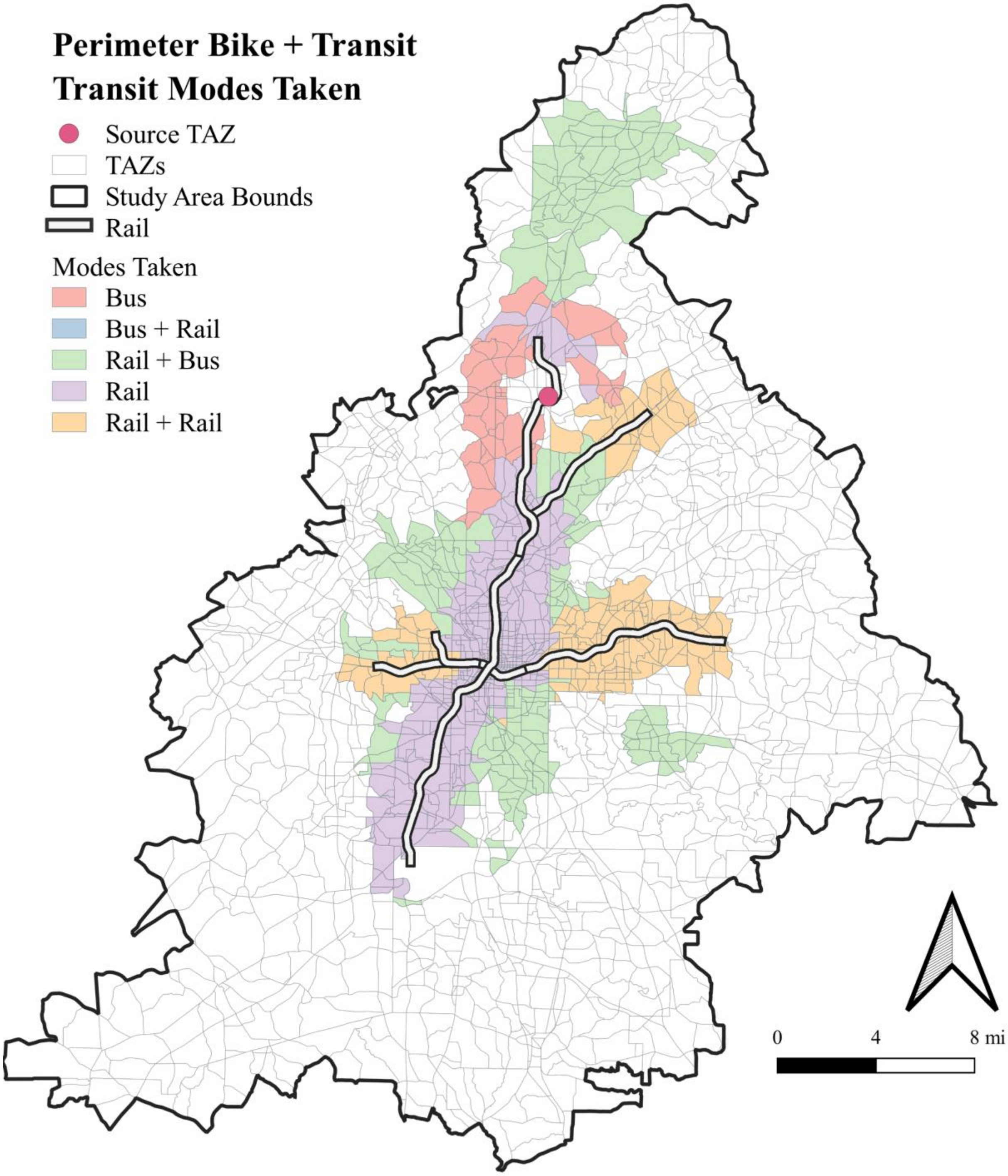


Figure 20. Fastest transit mode(s) to accessible TAZs from the Perimeter TAZ at 9:00 A.M

Campbellton

The final location assessed was Campbellton. Figure 21 shows the accessibility within 60 minutes for Campbellton. As with the West Atlanta and Perimeter locations, there is a clear disparity in access between the walk + transit and bike + transit modes, and despite access to a high-frequency bus route, access to TAZs appears to be comparable to the West Atlanta location. The effect of MARTA's network layout is comparable to the West Atlanta location as well. The lack of bus routes that pass through the rail lines that run North-South limited access to TAZs east of those rail lines.

Figure 22 shows the travel time to the accessible TAZs for the bike + transit mode (left) and walk + transit mode (right) for the Campbellton location. While fewer TAZs are in the 16-30 minutes bin than with the Midtown location, there are more TAZs in the 16-30 minutes bin than with the West Atlanta location due to the higher concentration of TAZs in this area and the presence of a high frequency bus route. Also, as with the previous locations, there is a reduction in travel time for TAZs that are accessible for both the walk + transit and bike + transit modes.

Figure 23 shows that the bike + transit accessible TAZs from the Campbellton location were accessed via bus or bus + rail. This was expected given the lack of nearby rail service. Figure 23 shows that most of the TAZs directly surrounding the origin TAZ were reached via bus, including areas that were adjacent to the southern segment of the rail line that runs North-South. However, bus + rail was the fastest way to reach TAZs north of Five Points (where the rail lines intersect).

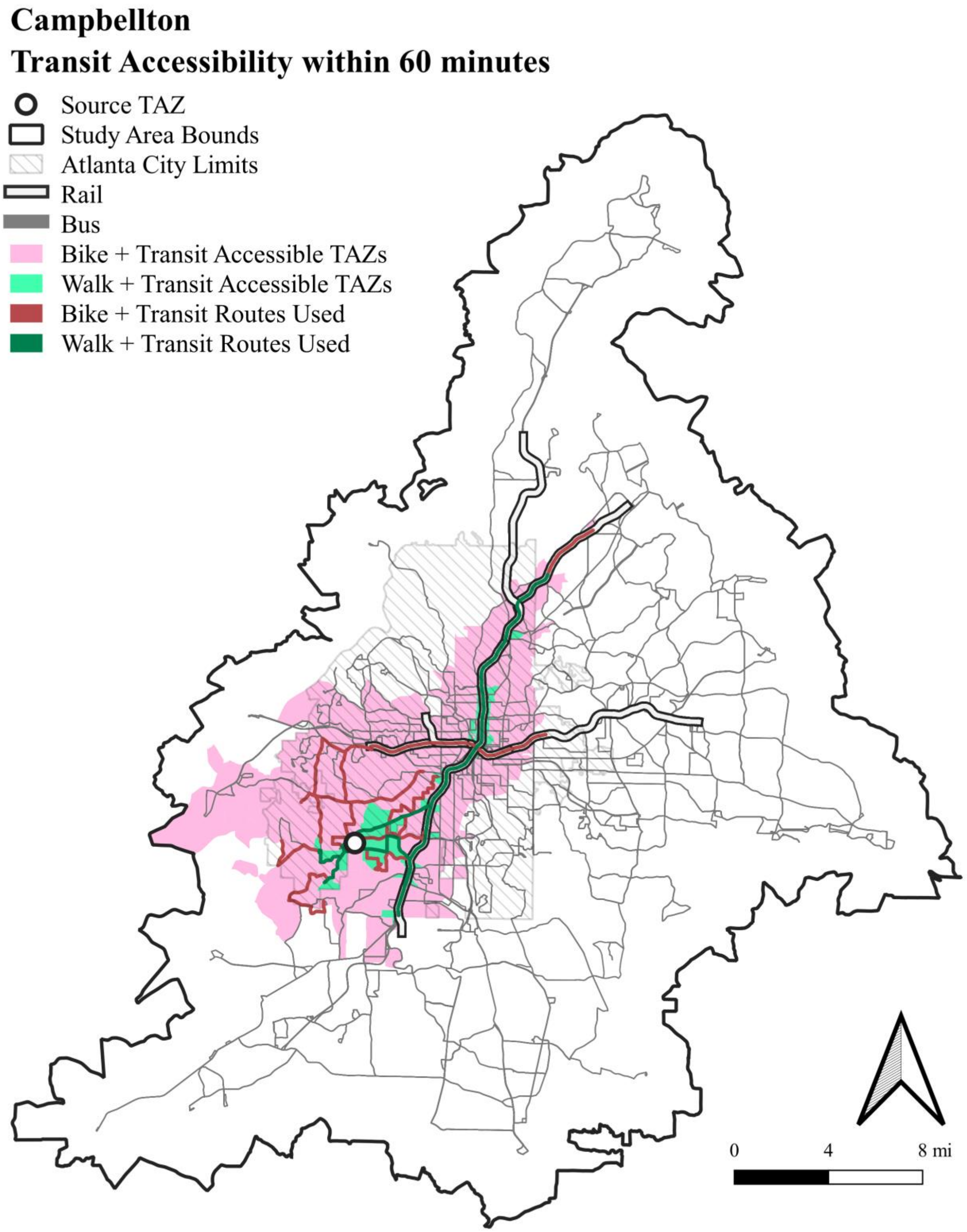


Figure 21. The accessible TAZs and utilized transit routes from the Campbellton TAZ

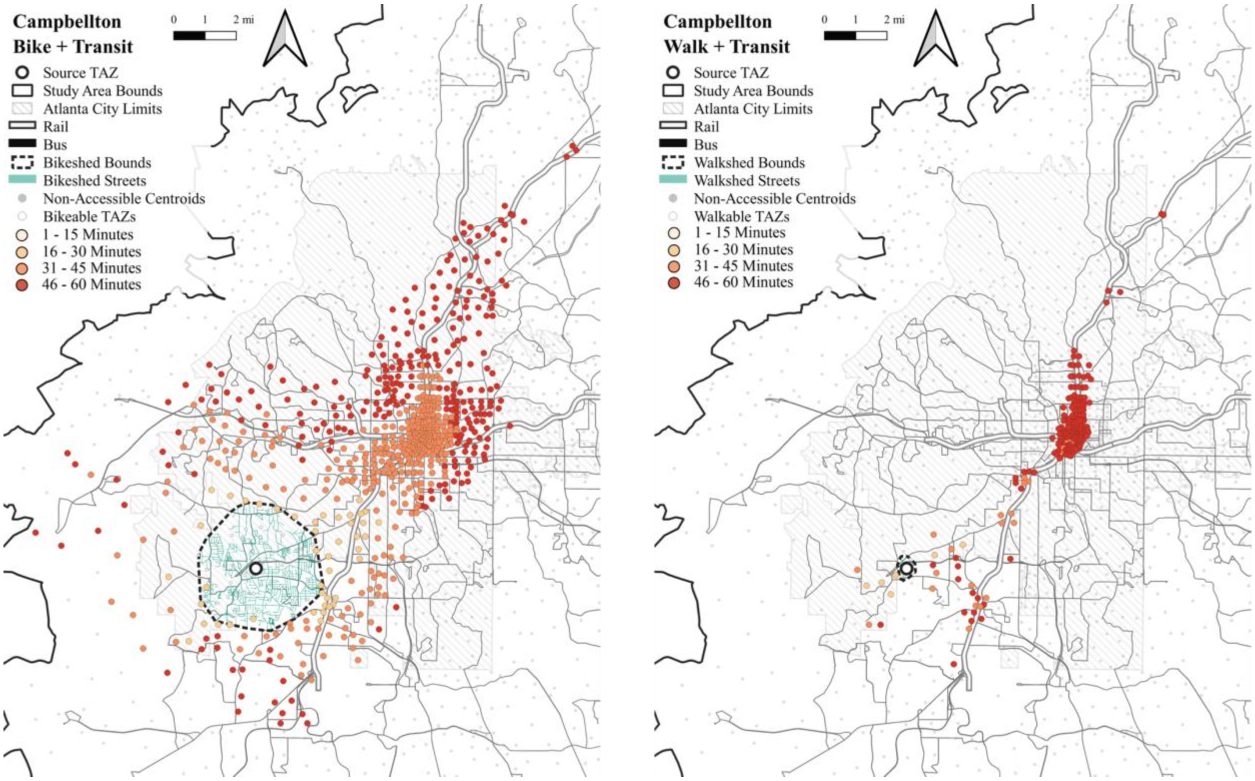


Figure 22. Dot plots showing travel time from the Campbellton TAZ to all other TAZs

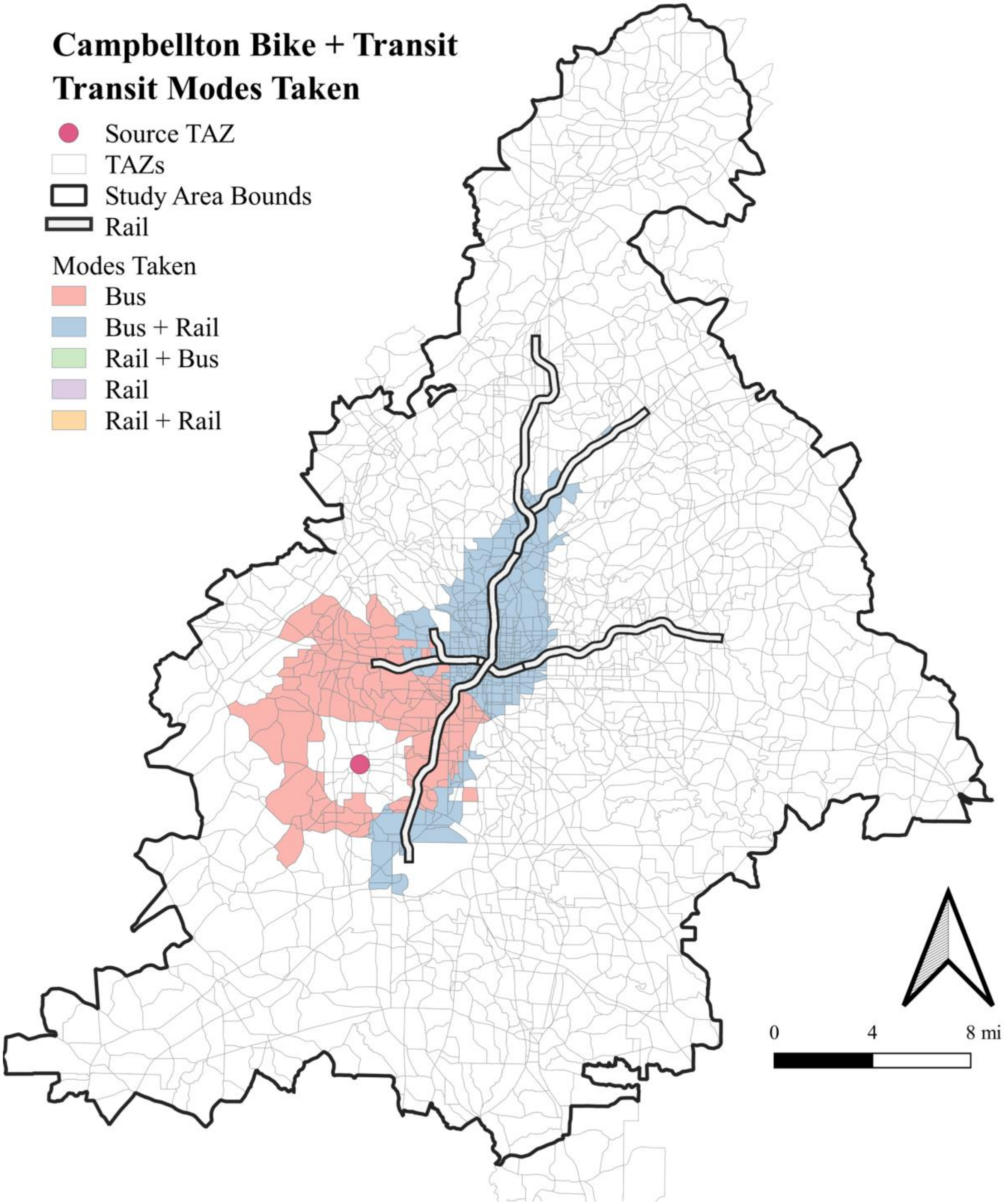


Figure 23. Fastest transit mode(s) to accessible TAZs from the Campbellton TAZ at 9:00 A.M

Limitations of the Bike + Transit Mode Analyses and Future Work

These initial results demonstrate how TransitSim and BikewaySim can effectively model the bike + transit mode. These initial analyses also demonstrate the potential gain in the accessibility of the bike + transit mode over the walk + transit mode. In these analyses, the impedance used for bike routing only considered travel time, leaving out a number of potential attributes that cyclists consider in choosing a route. Locations further away from the urban core such as West Midtown, Perimeter, and Campbellton lack cycling infrastructure and a connected network of slow residential streets. As such, there would likely be fewer accessible areas than presented. Once these impedances are added, new cycling infrastructure projects can be evaluated based on how they improve the accessibility of the bike + transit mode.

Cycling-specific impedances will also need to be balanced against a set of impedances for public transit (which is currently set as a time-only impedance). For example, even with two transit routes that provide an equivalent total transit link travel time, the route with the shorter wait time will likely be scored by users as having lower impedance (most users penalize wait time in their mode choice decision-making). Additionally, if the bike route to access the transit route with the shorter waiting time had a higher impedance than the other transit route, some users may endure the higher impedance bike route to access the route with shorter wait time. Cyclists may have public transit specific preferences that can also be accounted for in estimating impedance, such as a preference for rail service over bus service. More research is needed to bring in specific mode impedances for transit and walking into overall impedance calculations.

In this report, the transit schedule and routes were not modified. However, one future application of an integrated BikewaySim and TransitSim is evaluating transit network re-designs. New transit networks or schedules can be fed into RAPTOR in GTFS form to see how bike + transit accessibility changes with changes in bus and rail infrastructure.

The constraints used in this report were designed to model reasonable walk + transit and bike + transit trips, but individuals may have preferences for rail, an aversion to transfers, or be willing to bike or walk further than the set thresholds. Future work could include analysis of the variability across different first and last mile mode combinations (i.e., bikeshare after taking transit or parking bike at a transit station).

Lastly, in the future, intra-study area origin-destination pairs from actual travel diaries (the ARC collects 10,000 household travel diaries) should be examined rather than stopping at all possible combinations of TAZs pairs used in this study. These actual reported origin and destination locations within TAZs could be used to compare the mode taken in the travel diary to a bike + transit mode alternative. This would give insight into the feasibility of the bike + transit mode for accomplishing real trips.

Conclusions

The first half of this report presented how BikewaySim, a shortest path model, could be used to systematically assess infrastructure improvements through visualizations (bikesheds, individual routing, betweenness centrality, and zonal statistics) and route metrics (percent detour and change in impedance). Two impedance functions were used to calculate the least impedance paths between 28,392 potential origin-destination pairs. Bikesheds were created to show how two network improvements improved bikeability. Showing individual routes demonstrated how impedance functions affected routing. The betweenness centrality maps showed the difference in high betweenness centrality routes for the two impedance functions. Lastly, each trip's percent detour and change in impedance were aggregated to its respective origin TAZ. For percent detour, this showed that trips starting in TAZs in the southeast part of the study area had a higher average percent detour. For change in impedance, analyses showed that the proposed network improvements had the greatest impact on nearby areas and areas with existing cycling infrastructure.

The second half of this report demonstrated how BikewaySim, in conjunction with TransitSim, could model the bike + transit mode. Four locations were evaluated to see how proximity to different transit modes with varying frequencies and coverages changed accessibility and travel time using TAZs. Further applications of bike + transit mode modeling include adding transit-specific impedances and changing transit networks to show service improvements.

Rising cycling and micro-mobility fatalities and injuries have put increased pressure on cities to expedite their plans to construct cycling networks outs (Freishtat, 2022; Deere, 2019). Cities will build infrastructure, but there is a need for systematic planning of safe and connected cycling networks. While BikewaySim does not create the most optimal bicycle network, it can inform decision-makers about the effects of potential infrastructure improvements. The bicycle infrastructure funding process needs political and public buy-in; cycling facilities can be met with strong opposition, especially in cases that require removing on-street parking or vehicle lanes. Such opposition can result in cycling infrastructure being built in places that are politically feasible, but not as effective in encouraging ridership, or, in worst-case scenarios, can lead to cycling infrastructure being placed in dangerous locations or not being built at all.

Cities also need to consider how new cycling infrastructure or modification to transit service can improve the accessibility of bike + transit trips; designing for these types of trips could increase the effectiveness of public transit and reduce the number of car trips.

Lastly, existing route choice models, based on existing cyclists, do not consider the needs of potential cyclists. BikewaySim can be used to both consider current cycling ridership and potential cyclists. Cycling design guidelines are shifting towards providing increased separation of cycling from vehicles when traffic volumes or vehicle speeds are high. BikewaySim can be programmed to account for these design guidelines and assess infrastructure accordingly. Overall, the objective of BikewaySim is to work towards building a connected bike network that is bikeable for all.

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Data Summary

Products of Research

Three GIS datasets containing roads and road attribute information were acquired for this study: the Atlanta Regional Commission activity-based model network, HERE streets data, and OSM network data. The other products of this research include Python code for BikewaySim and TransitSim.

Data Format and Content

The three GIS datasets used are in standard GIS data formats. The Atlanta Regional Commission activity-based model network data are in Geodatabase format and contain 75,289 roadway links and 27,524 nodes for the Atlanta metropolitan region. The streets data licensed from HERE are in shapefile format and contain 7,600 roadway links for the study area. The OpenStreetMap data are in GeoJSON format and contain 10,157 roadway links with OSM street data (a variety of tags) for the study area.

The Python scripts are stored as PY files. The scripts are for performing the shortest path routing and producing shapefiles to create the visualizations in a GIS program.

Data Access and Sharing

The Atlanta Regional Commission makes their activity-based travel demand model (ABM) documentation, certain model code, and many of their model scenario input and output files available online at: https://doc.arcgis.com/en/dashboards/latest/create-and-share/download-data.htm. For any ARC proprietary data not shared online as open source data, potential users need to contact the Atlanta Regional Commission, who often provide the data upon completion of a data user agreement. HERE street data must be licensed directly from HERE. OpenStreetMap data can be acquired using the Overpass API.

The Python scripts are available from the following places :

- Version used for this project: https://doi.org/10.5281/zenodo.8097954
- Latest Version: https://github.com/gti-gatech/BikewaySim

Reuse and Redistribution

As noted above, public domain data associated with Atlanta Regional Commission activity-based model data are available online from the Atlanta Regional Commission (ARC); any proprietary data must be requested from the ARC upon execution of a data user agreement. HERE data were provided under a limited use license for this research project only and did not come with re-distribution rights. The general public should contact HERE to license similar data for research or application purposes. OpenStreetMap data have an Open Data Commons Open Database License and can be reused and redistributed so long as OpenStreetMap and its contributors are credited.

The Python scripts used to process data for this report are open data and can be reused and redistributed so long as the researchers in this report are credited. The following citation is recommended:

- Passmore, R., K. Watkins, and R. Guensler (2023). Supporting Code for NCST Report: Simulating Bike-Transit Trips using BikewaySim and TransitSim. Zenodo. https://doi.org/10.5281/zenodo.8097954
- Reid Passmore, Kari Watkins, & Randall Guensler. (2021). BikewaySim Technology Transfer: City of Atlanta, Georgia. Zenodo. 10.5281/zenodo.5750140