MEASURING LOW STRESS BIKE ACCESS TO MARTA

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by

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To the Wi-Fi at Cypress Street Pint and Plate

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LIST OF SYMBOLS AND ABBREVIATIONS

MARTA	Metropolitan Atlanta Rapid Transit Authority
BCI	Bicycle Compatibility Index
BLOS	Bicycle Level of Service
LTS	Level of Traffic Stress
MTI	Mineta Transportation Institute
AADT	Annual Average Daily Traffic
TOD	Transit Oriented Development
ACS	American Community Survey
GDOT	Georgia Department of Transportation
NACTO	National Association of City Transportation Officials
NRI	Network Robustness Index
FTA	Federal Transit Administration
ARC	Atlanta Regional Commission

SUMMARY

Level of Traffic Stress (LTS) is a bicycle quality of service measure originally developed by the Mineta Transportation Institute (MTI) that categorizes road infrastructure into four levels based on amount of traffic stress perceived by a bicyclist (Mekuria, Furth, & Nixon, 2012). The concept builds on research indicating that bicyclists can be grouped based on their comfort level. Riders identifying as *strong and fearless* as well as *enthused and confident* bicyclists represent most of the current users of the bicycle network across the US. However, there is a large group of *cautious and concerned* bicyclists that might be more likely to bike if the bicycle infrastructure were less stressful. This research uses a case study approach to show how LTS methodology can be used to define a low stress bicycle network.

This research applies the LTS methodology to quantify low stress bicycle access around the West End, Oakland City, and Lakewood/Ft. McPherson (Metropolitan Atlanta Rapid Transit Authority) MARTA rail stations. The Equitable Transit Oriented Development (TOD) typology analysis conducted by Reconnecting America identified these station areas as highly vulnerable with lagging markets (Reconnecting America, 2013). Additional analysis compares the existing low stress network, improved low stress networks, and the entire (low and high stress) bike network. Ultimately this work can serve as a model for both transportation planners interested in improving bike access both in general and specifically to transit.

CHAPTER 1

OBJECTIVE

The objective of this research was to use a bicycle quality of service methodology to evaluate bike infrastructure improvements around select Metropolitan Atlanta Rapid Transit Authority (MARTA) stations. Existing definitions of catchment areas often rely on a simple radial distance measure. When considering bike access to transit, it is important to realize that not all bicyclists are comfortable on all roads. Limiting bike use to low stress infrastructure can dramatically limit bike access.

The Level of Traffic Stress (LTS) methodology used in the case study analysis was developed, in part, as a response to the word defining rider typologies. Rider typology has been defined, according to comfort level, into five types: *strong and fearless, enthused and confident, interested but concerned, comfortable but cautious,* and *no way no how.* CHAPTER 2 discusses the trend in bicycle planning efforts across the country as well as in the Atlanta regions specifically have emphasized the importance of planning for the less confident rider (Alta Planning + Design, 2013). This means that when defining bike access to transit, it is essential to consider only the portion of the road network that has a very low quotient of traffic stress.

There are several models for determining the bicycle level of service and the Bicycle Compatibility Index (BCI) and Bicycle Level of Service (BLOS), and LTS methodologies are discussed in detail in CHAPTER 3 (Furth & Mekuria, 2013; Harkey, Reinfurt, & Knuiman, 1998; Huff & Liggett, 2014; Landis, Vattikuti, & Brannick, 1997; Mekuria et al., 2012; Sprinkle Consulting, 2007). Based on the effort to prioritize planning efforts for the less confident riders, the Level of Traffic Stress (LTS) methodology was selected as the means for defining low stress bike access to transit.

The LTS methodology identifies each link and intersection as LTS 1-4, low to high stress. The network defined by the LTS 1 and LTS 2 infrastructure are defined as the low stress network. The average existing bicyclist is likely comfortable at a LTS 3 or even LTS 4. However, to promote bicycling among all existing and potential riders, it is important to plan for the low stress network. After all, a very confident rider requires very little bike infrastructure in order to have a high degree of bike access. The LTS methodology adapted in this research is based on a second iteration of the original LTS methodology. The original work was conducted by the Mineta Transportation Institute (MTI) and was later modified to incorporate data available in the Atlanta region (Furth & Mekuria, 2013; Mekuria et al., 2012; Mingus, 2015).

The LTS methodology used to define the low stress network involved separate methodologies for physically separated bicycle infrastructure, links (streets), and unsignalized intersections. Physically separated bike infrastructure was always identified as low stress. Links were classified according to several criteria: the presence of a standard bike lane, the presence of a buffered bike lane, the presence of on street parking, number of through lanes, annual average daily traffic (AADT) volume, functional classification, and posted speed limit. The LTS of unsignalized intersections was evaluated based on the number of lanes and the speed limit of the street being crossed.

To assess the amount of access to transit based on the low stress bike network, measures of total network length, effective bike-able area, and effective population with bike access were identified for each network. The 2010 census block data was used to define the accessible area and population. A census block was determined accessible if the low stress bike network intersected or ran along its edge.

To demonstrate this application the LTS methodology, a case study analysis was conducted in South West Atlanta. The West End, Oakland City, and Lakewood/Ft. McPherson MARTA rail stations were selected for the case study analysis based on the equitable Transit Oriented Development (TOD) recommendation for investing in station area infrastructure and strengthening community assets (Reconnecting America, 2013).

The research presented here shows how this LTS methodology can be used to define the low stress bike network, evaluate the impact of proposed improvements, and identify key gaps in the low stress network. Access was then evaluated and compared across four bike networks: existing low stress network; low stress network based on proposed improvements; low stress network based on additional key improvements; and the entire bike network (low and high stress infrastructure).

The additional key improvements were identified through a visual analysis of barriers in the other low stress network. For instance, given the maximum network distance of 3 miles, if a portion of the service area was extending for less than a mile, then there was a major barrier at that point. Establishing a process for defining the level of bike access based on specific networks and proposed networks would help planners better conceptualize the regional impact of each individual bicycle infrastructure improvement. Ultimately, this case study analysis can demonstrate to both bike and transit planners the benefits of considering comparing specific bicycle infrastructure investments within the larger context of the low stress bicycle network.

Finally, this paper recommends the future research required in order to establish LTS as a statistically valid tool for evaluating bicycle infrastructure and recommending infrastructure improvements. Ultimately, with further refinement, LTS could become a tool for identifying small scale infrastructure improvements along specific links. This specificity would allow for low cost, high impact investments to prioritize bicycle connectivity throughout an entire metropolitan region.

CHAPTER 2

THE BICYCLIST

The ultimate goal of this work is to demonstrate an application of the LTS methodology for evaluating, comparing, and prioritizing bicycling infrastructure improvements. Before addressing the specifics of the LTS methodology, it is important to understand who is biking in cities and what infrastructure they prefer. With an improved understanding of bicyclists, potential bicyclist, and the infrastructure they prefer, city planners can better define local and regional goals regarding bicycle infrastructure and culture. Historically, the bicyclist has been conceptualized as a professional white male and in 1997, the average bicycle commuter in North America was a 39-year old male who rode an average of 10.6 months each year and had a household income over $45,000 (US median income in 1997 was $37,005) (Moritz, 1997; US Census Bureau, 1998). However, both the demographics of bicyclists in the US and bicycle infrastructure priorities are shifting. This chapter provides a discussion of the demographic characteristics of the existing and growing bicycle population across the US; a description of bicyclist typology; and a demonstration of how these trends have influenced the definition of the design bicyclist within the context of bicycle planning in Atlanta.

Demographics

There are many relevant and important ways of describing a population's demographics. As an introduction to the topic of biking typology, this section on bicycling demographics is limited to a brief discussion of gender, age, income, and race.

The bicycling population in the US is male dominated and in large cities across the US, ¾ of bicyclists are male (Susan Handy, Gil Tal, & Marlon G. Boarnet, 2014), with bicycle commuting rates at 0.8% among male workers and 0.3% among female workers (McKenzie, 2014). However, in the Netherlands and Germany the gender split is far more even. In the Netherlands 45% of bicyclists are male and in Germany 51% of all bicycle trips are conducted by men (Linda Baker, 2009). Despite this gender disparity, the gender profile of the US bicyclists is changing and from 2007 to 2011, there was a 56% increase in the number of women biking to work (The League of American Bicyclists & Sierra Club, 2013).

Another population group that is of increasing interest to bike planners is the aging population. With the aging population largely living in auto oriented built environments, mobility for aging communities is becoming a major focus of planning efforts. A survey found that 82% of adults over 65 years old are worried that they will be entirely un-mobile when they can no longer drive (Neal et al., 2006). In the US only 0.4% of bike trips are conducted by adults over 65 years, while in the Netherlands 25% of trips are conducted by adults over 75 years and, in Germany, 7% of trips are conducted by adults over 75 years old (Pucher & Renne, 2003). Based on the bicycling behavior of aging populations in Europe, with proper planning, the bicycle could provide an opportunity for aging populations in the US to remain active while maintaining mobility.

According to the 2008-2012 American Community Survey (ACS) census, the total number of bicycle commuters is highest for those with an income between $50,000 and $74,999 (orange bars, Figure 1). Taken alone, the orange bars show that there are more middle to high income bicycle commuters than low income bicycle commuters. However, Figure 1 also shows that the proportion of commuters that commute by bicycle (number of bicycle commuters / total commuters) decreases with an increase in income category (blue bars). Although there is a larger total number of bicycle commuters in the middle to high income categories, there is a higher percent of commuters in lower income categories that ride bikes.

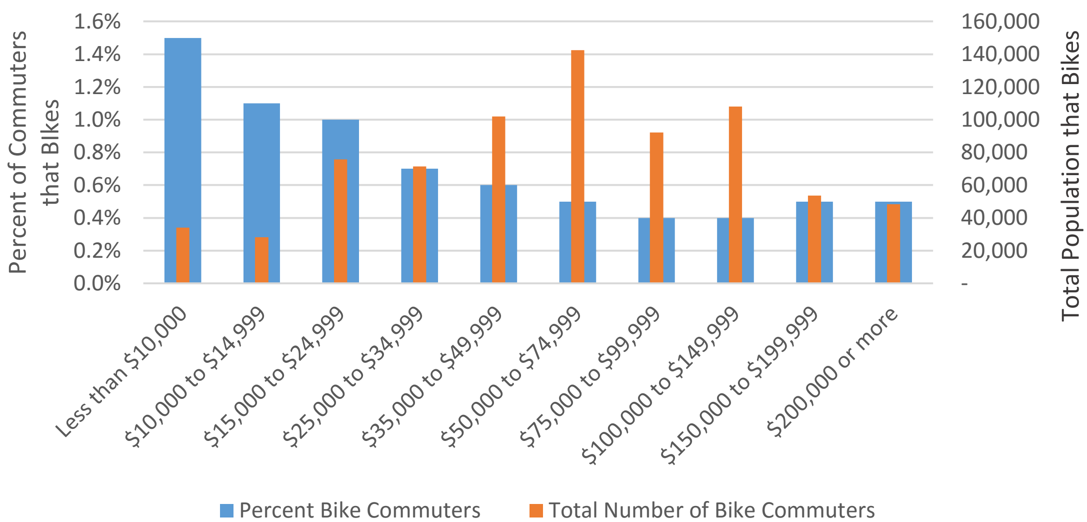


Figure 1: The proportion of bicycle commuters (blue bars, left axis) and the total number of bicycle commuters (orange bars, right axis) by income category. (Source: ACS 2008-12)

The proportion of the national population with a household income under $10,000 has the highest rates of bicycle commuting at 1.5% (Figure 1, ACS 2008-12). This is higher than the combined average percentage of bicycle commuters for the 50 largest cities in the country (1.0%), equal to the bicycle commuting rate in Austin, TX (1.5%), and just shy of that in Boston (1.7%) (McKenzie, 2014).

To better understand the household income makeup of the bicycle commuter as compared to the overall population, Figure 2 shows the percent of bike commuters that fall into broad income categories (blue bars) next to the total percent of the working population that falls into each income category (orange bars). The lowest two income categories, representing households below $50,000, are proportionally more represented among bike commuters than they are among the overall population. In other words, households with household incomes below $50,000 per year are overrepresented among bike commuters. This is particularly true for households with incomes below $25,000.

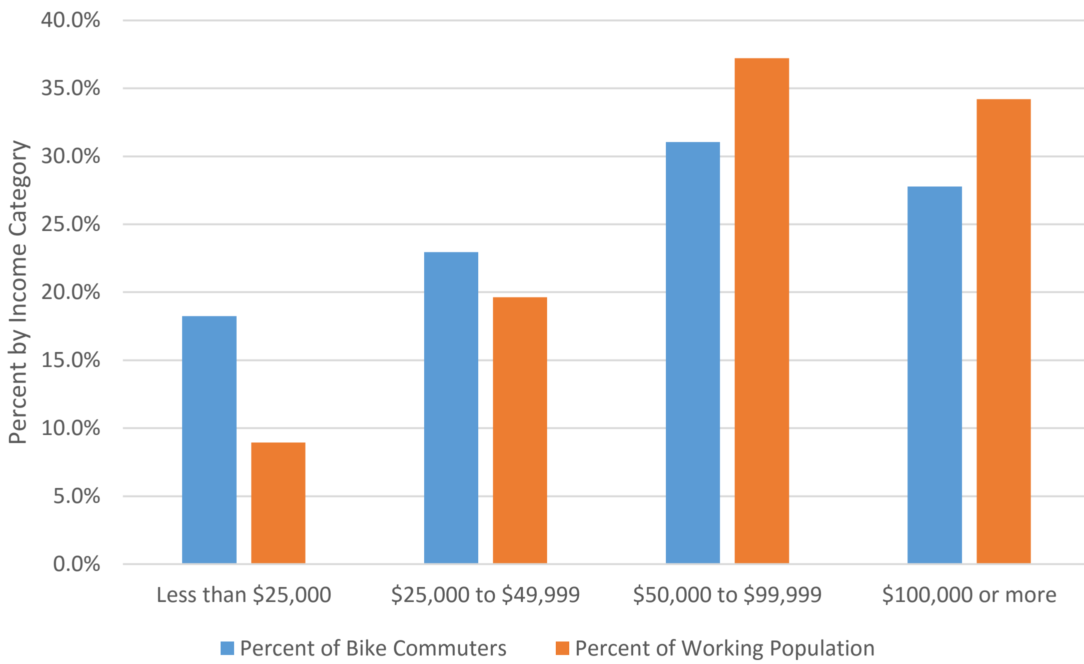


Figure 2: The percent of bicycle commuters by income category (blue bars) and the percent of the total population (orange bars) by income category. (Source: ACS 2008-12)

According to the ACS 2008-2012 5-year census estimates, the majority of bicycle commuters in the US identify as white alone (69%, Figure 3). However, this is only a slight over-representation of the white population (67% of the total population, Figure 3) and although observed at smaller rates overall, Hispanic/Latino, Asian, and multiracial populations are also each over-represented among bike commuters (Figure 3).

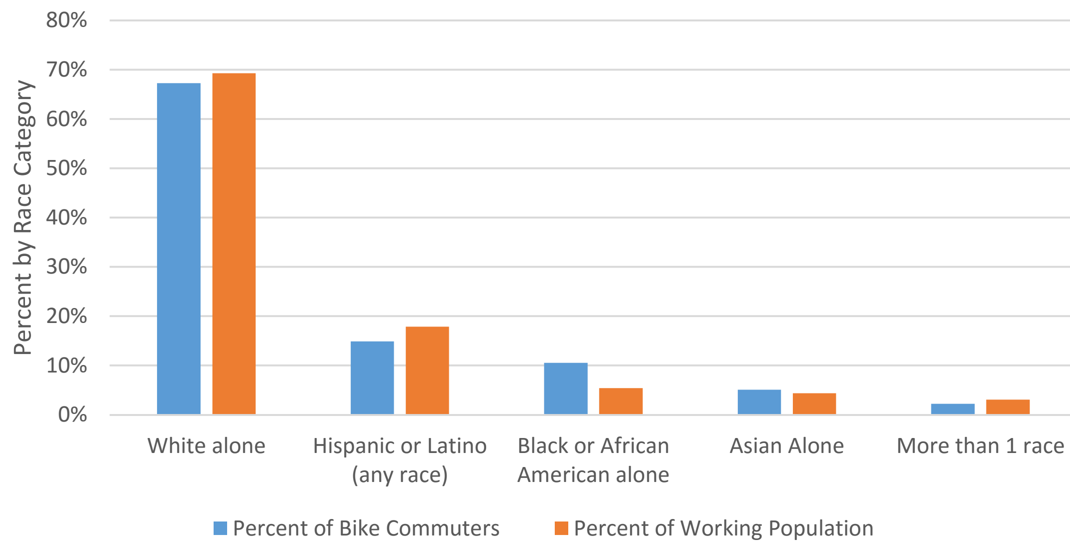


Figure 3: The percent of bicycle commuters by race category (blue bars) and the percent of the total population (orange bars) by race category. (Source: ACS 2008-12)

Recent trends in the demographic makeup of the biking population across the US has shown the largest increases in biking among non-white bicyclists (Figure 4). The Equity Report conducted by the League of American Cyclists identified several studies supporting the notion that people of color (defined as Hispanic, African American, Asian, Native American, and mixed or other race) were more likely to ride more with infrastructure improvements. The 2012 Princeton Omnibus Survey found that 26% of people of color would be more likely to bicycle if they weren't worried about traffic safety (compared to only 19% of white survey respondents) (The League of American Bicyclists & Sierra Club, 2013).

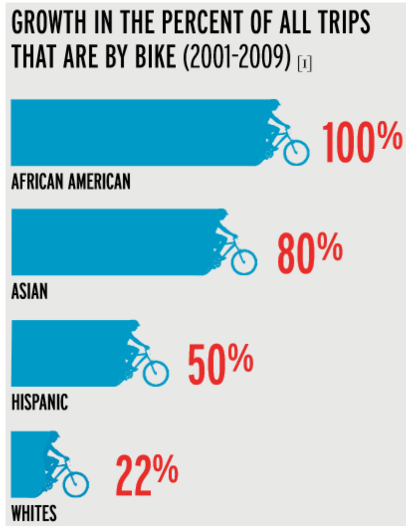


Figure 4: Percent increase in bike trips by race category; (The League of American Bicyclists & Sierra Club, 2013)

Research has supported the fact that there are generally two kinds of bicyclists. A study surveying bike commuters in Guelph, Canada found that 26% of participants demonstrated a strong preference for local roads and trails, while 46% of participants preferred direct, high traffic, major roads (Aultman-Hall, Hall, & Baetz, 1997). Preferences in this study were inferred based on the percent that a self-reported bicycle trip was conducted along roads of specific functional classifications (Aultman-Hall et al., 1997). Investments in high quality bicycle infrastructure would serve to benefit existing riders while also attracting new riders. The installation of a bike lane along South Carrollton Street in New Orleans was shown to be associated with a 115% increase in female riders and a 51% increase in African American riders (Parker et al., 2013; The League of American Bicyclists & Sierra Club, 2013).

Overall, the trend in bicycle planning is to shift away from planning infrastructure improvements aimed at existing rider types. Instead, there is an effort to consider bicycle infrastructure from the perspective of potential users. To further conceptualize these potential users, riders have been classified into rider typologies based on bicycle comfort level.

Rider Typology

Perceived safety is often cited by non-bicyclists as the primary reason for not riding (Geller, 2007). However, this is not a feature of bicycling, but a feature of bicycling within close proximity of motor vehicles. Based on the fact that current bicyclists are, in fact, bicycling, it is clear that not all people have the same safety threshold. Even among current bicyclists, individuals maintain different perceived safety thresholds. For example, some bicyclists might ride exclusively on paths and trails (e.g. Atlanta Beltline), others might avoid high traffic streets regardless of bike infrastructure (e.g. Ponce de Leon with the bike lane), while some may even be comfortable riding along high speed, multi-lane arterials (e.g. Northside Drive or Buford Highway). To best plan for all potential and existing bicyclists, planners must first attempt to identify the different potential users.

Out of frustration with the perceived danger of bicycling among non-bicyclists in Portland and an interest in identifying the potential market for bicycle users, Geller identified four types of Portland bicyclists: *Strong and Fearless*, *Enthused and Confident*, *Interested but Concerned*, and *No Way No How* (Geller, 2007). These four typologies were initially defined "based on the professional experience of one bicycle planner" (Geller, 2007). Although this typology was enthusiastically accepted by planning communities across the country, it was not validated until 2013 (Dill & McNeil, 2013). The validation study was conducted based on a phone survey of adults in the Portland region that asked respondents their comfort level based on a set of bicycle infrastructure categories.

Strong and fearless riders identify the bicycle as their preferred mode and would bicycle regardless of the amount of bicycling infrastructure. This group was identified by Dill and McNeil as respondents that were very comfortable on non-residential streets without bike lanes. Based on the premise that the majority of the US has minimal to no bicycling infrastructure, Geller approximates the number of riders in this group based on national bike commuter rates. Given that approximately 1% of people in the US commute by bicycle, it can be inferred that approximately 1% of the population falls into the *strong and fearless* category(Geller, 2007). However, based on the Dill and McNeil analysis, 6% of the City of Portland and 4% of the region fall into the *strong and fearless* category (Dill & McNeil, 2013).

Geller approximates the *enthused and confident* rider group to represent approximately 7% of the population. This approximation includes the majority of current riders plus an adjustment factor to account for people who fall into this category but do not have access to the necessary environment. Although the initial estimation by Geller was very approximate, the results from the phone survey were similar. The phone survey defined *enthuse and confident* riders as those that were comfortable with bike lanes and estimated this group to be 9% of the population (both among the City of Portland and the region) (Dill & McNeil, 2013).

Geller's classification identifies the remaining 73% of Portland residents as either *interested but concerned* or *no way, no how,* while Dill and McNeil classify 75% of the City of Portland population (87% of the regional population) as either *interested but concerned* or *no way, no how*.

Initially, Geller guessed that approximately 1/3 of residents would fall into the no way, no how category and 60% into the *interested but concerned* category. This was also supported by the phone survey for which 25% of respondents from the City of Portland and 37% of respondents from the region indicated that they were very uncomfortable on paths, not interested, and/or not physically able to cycle (Dill & McNeil, 2013). Another survey of 20,000 Portland households conducted as part of the Smarttrip program (under the Portland Bureau of Transportation) found that 33% of respondents strongly agree that "it is unlikely that I would ever ride a bike to work" (Geller, 2007). The same survey found that 30% of Portland residents do not own a bicycle (Geller, 2007).

A mobility study conducted in the Netherlands found that, if given the choice between car and bicycle for a 7.5km trip to work (4.7mi), 31% of respondents would always chose car (Ministry of Transport, Public Works and Water Management & Expertise Centre for Cycling Policy, 2009). Given the advanced state of bicycling infrastructure in the Netherlands, it is likely that there is a remarkably high barrier to riding for this 31% which represents a typology similar to the *no way no how* rider. These results suggest that depending on culture, between 25 and 37% of the population falls into the *no way no how* typology.

Research conducted based on an Atlanta cycling smart phone application, Cycle Atlanta, added a *comfortable but cautious* group that is expected to include primarily bicyclist that would, under Geller's methodology, have been identified as *interested but concerned* (Misra, Watkins, & Le Dantec, 2015). Based on Dill and McNeil's validation work, the *interested but concerned* group comprises 60% of the City of Portland population and 56% of the regional population (Dill & McNeil, 2013). This is the group was initially conceived as a potential market group, currently not biking, but likely to start biking or bike more if conditions were more favorable. However, the phone survey results indicate that although the *interested but concerned* group bicycles less often than the *enthused and confident* and *strong and fearless* groups, each of these three groups demonstrated similar rates of bicycling as defined by the development of "some pattern of cycling for transportation that extended beyond the past month" (Dill & McNeil, 2013).

The addition of the *comfortable but cautious* typology was based in the hypothesis that the *interested but concerned* group was composed of people with different degrees of pro-bicycle attitudes. The *comfortable but cautious* group was split from the *interested but concerned* group to better describe people that are actively interested in bicycling, but exercise caution when bicycling under the current conditions (Misra et al., 2015).

According to the Atlanta research, the *strong and fearless* and *enthused and confident* groups are both significantly more likely to be younger and male, while the *comfortable but cautious* and *interested but concerned* riders are more likely to be older and female (Misra et al., 2015). Despite these demographic and behavioral differences between groups, there is an overwhelming preference for bike lanes and separate facilities and no consistent difference in preference (or lack thereof) for heavy traffic and high speeds across rider types (Misra et al., 2015). As a result, although the biking behavior and specific comfort levels is likely different for each of these rider types, planning facilities aimed at the *comfortable but cautious* and *interested but concerned* riders will benefit all riders.

The efforts made to diversify bicyclists with regard to rider type supports efforts to diversify the rider with regard to demographic categories. Planning efforts focused around high quality infrastructure will benefit both the existing riders as well as potential riders that may currently not have access to a low stress bicycle network. These demographic categorizations as well as the rider typologies can help a design bike user. The design user is a transportation engineering concept used to promote safety through designing for a reasonable worst case scenario.

Design Bike User

Transportation engineers do not design for the best, most experienced driver on the road. Instead, roads are designed for the 90th percentile driver. Given this engineering design standard and commitment to safety for all users, it follows that bicycle infrastructure should, also, not be designed for the *strong and fearless* or even the *enthused and confident* rider. According to the rider typology breakdown, the 90^{th} percentile user would identify as somewhere between *interested but concerned* and *comfortable but cautious* (Dill & McNeil, 2013; Geller, 2007; Misra et al., 2015). In 2008, Furth identified the design user as the “traffic intolerant easy riders” that can be conceptualized as the commuting older adult or high school student on their way to school (Furth & Mekuria, 2013). It follows that, in most US cities, the design bicyclist is likely not currently an active bicyclist, but would become one with improved infrastructure.

The most recent Atlanta bicycling study conducted in 2012-2013 identified the design user groups: women, parents and their children, college students, seniors and older adults, minorities, youth (school age children), city residents and workers that commute to job centers or to or from MARTA stations by bike (Alta Planning + Design, 2013). The study explicitly states that bicycling in Atlanta should be comfortable for all people regardless of age, gender, income, and experience levels (Alta Planning + Design, 2013).

This discussion of bicyclist demographics, rider typology, and the design bicyclists each supports a shift away from bike sharrows and towards cycle tracks and side paths. However, the description of current riders, potential riders, and future riders has only generally defined the ideal infrastructure as high quality and low stress. To move forward with these ideals within a planning context, it is necessary to define the low stress bike network beyond the mere presence and absence of bike lanes. The next chapter (CHAPTER 3) discusses ways in which each the BCI, BLOS, and bicycle LTS can be used to define the bicycle network and why LTS is the most applicable methodology given this interest in planning for a low stress network.

CHAPTER 3

DEFINING THE BICYCLE NETWORK

In 1994, Sorton and Walsh created a categorization system that identified the level of stress a bicyclist would experience on a given road segment. Stress levels were defined based on traffic volumes, traffic speeds, and curb lane width. The authors categorized bicycle infrastructure into one of five stress levels based on a combination of engineering design guidelines and bicyclist feedback responses. The design criteria was based on the concept that substandard motor vehicle design would be even worse for bicyclists. The stress levels were then validated based on feedback from volunteer bicyclists. Volunteers were asked to watch a set of videos and rate them according to traffic stress (Harkey et al., 1998; Sorton & Walsh, 1994).

The bicycle level of stress methodology provided the groundwork for subsequent studies to further develop statistical strength in defining bicycle level of service. The BCI and BLOS models each used stepwise regression methodology to define statistically significant variables for predicting bicycle comfort level. BCI and BLOS have utility in planning and design applications, but they both rely on very precise, design-oriented (vs planning oriented) data and do not directly consider potential differences in riding comfort based on rider typologies (Harkey et al., 1998; Landis et al., 1997; Sprinkle Consulting, 2007).

As a direct response to these criticisms, as well as in response to the general shift in the bicycle planning community to focus on the low stress bicycle network, MTI developed a set of LTS criteria. The LTS criteria define the bicycle network specifically available to riders with different levels of stress tolerance. LTS was intended to be easily applied at a municipal level and enable planners to identify and improve the low stress bicycle network (Furth & Mekuria, 2013; Mekuria et al., 2012). More recently, in her master's thesis work, Charlene Mingus modified the LTS criteria by tailoring the methodology for the data available in Atlanta (Mingus, 2015).

This chapter first discusses the development of BCI and BLOS models and the limitations of each model that led to the development of the LTS methodology. The original and Atlanta LTS methodologies are presented in parallel.

Level of Service – BCI and BLOS

Bicycle Compatibility Index

The BCI model was developed with the intention of providing a practical evaluation tool that identified (1) roads that could accommodate bicycles and motor vehicles, (2) specific design improvements required for accommodating bicycles and motor vehicles, and (3) design elements required of upcoming projects to prioritize a network that can accommodate both bicycles and motor vehicles (Harkey et al., 1998).

To develop the BCI model, researchers videotaped 67 sites with a range of design characteristics including lane widths, traffic speeds, and traffic volumes (Harkey et al., 1998). Researchers asked 202 study participants (ages 19-74, 60% male), with varying bicycling experience, to rank the bicycling comfort level for each video according to a 6 point comfort scale (Harkey et al., 1998). Participants ranked each video 4 separate times based on (1) traffic volumes alone, (2) traffic speeds alone, (3) width of space available for the bicyclist alone, and (4) overall experience (Harkey et al., 1998).

The BCI model was defined through a step wise regression analysis using design variables to predict the BCI. Only variables significant at 0.1 were left in the model (Harkey et al., 1998). The base BCI model included 8 primary design variables: Presence of a bicycle lane; bicycle lane (or paved shoulder) width; curb lane width; type of roadside development; directional curb lane volumes; directional other lane(s) volume; 85th percentile speed; presence of parking lane with more than 30% occupancy (

Table 1) (Harkey et al., 1998). The variables generally describe four features (1) bike operating space, (2) land use patterns, (3) traffic volume, and (4) traffic speed (

Table 1).

Table 1: BCI regression model (Harkey et al., 1998).

	BCI Model Variables	Documented Study Range	Coefficient
	Intercept		3.67
Bike Operating Space	Presence of a bicycle lane	no=0, yes=1	-0.966
	Bike lane (or paved shoulder) width (m)	0.9 – 2.4m (3 – 8ft)	-0.41
	Curb Lane Width (m)	3 – 4.7m (10-15ft)	-0.498
Land Use	Type of Roadside Development	residential = 1; other = 0	-0.264
	Presence of parking lane with more than 30% occupancy	no=0, yes=1	+0.506
Traffic Volume	Curb Lane Volumes by direction (veh./hr.)	2,000 – 6,000 veh./day	+0.002
	Other Lanes' Volume by direction (veh./hr.)		+0.0004

Traffic Speed	85th Percentile Speed (km/hr.)	40-89km/hr. (26-55mph)	+0.022
			$R^2 = 0.89$

There was also a significant increase in overall comfort level based on the presence of trucks (an increase of 0.5), vehicles pulling in/out of on-street parking spaces (an increase of 0.6) and the presence of right turning vehicles (an increase of 0.1) (Harkey et al., 1998). These scenarios were not tested with varying design conditions and so were not included in the regression model. However, adjustment factors were developed based these results. The tested conditions were considered the worst case scenario conditions and the adjustment factors were scaled based on the observed impacts of each feature (Table 2) (Harkey et al., 1998).

Table 2: Adjustment factors and criteria for BCI (Harkey et al., 1998).

Condition	Condition Level	Adjustment Factor
Curb Lane Truck Volumes (vehicles/hour)	≥ 120	0.5
	60 - 119	0.4
	30 - 59	0.3
	20 - 29	0.2
	10 - 19	0.1
	<10	0.0
Parking Time Limit (min)	≤ 15	0.6
	16 - 30	0.5
	31 - 60	0.4
	61 - 120	0.3
	121 - 240	0.2
	241 - 480	0.1
	>480	0.0
Right Turn Volume (hourly)	≥ 270	0.1
	<270	0.0

To ease application to planning and design projects, the BCI was converted into a 6 point level of service (A-F) metric based on the distribution of BCI for the 67 research sites. The sites used in the analysis were chosen because of the range of traffic and design features and so the minimum and maximum scores found in the study (1.24 and 5.49 respectively) were taken as the extreme BCI values (Harkey et al., 1998). The level of service cut points were then determined somewhat arbitrarily based on percentiles splits: 5th percentile, 25th percentile, 50th percentile, 75th percentile and 95th percentile (Figure 5) (Harkey et al., 1998).

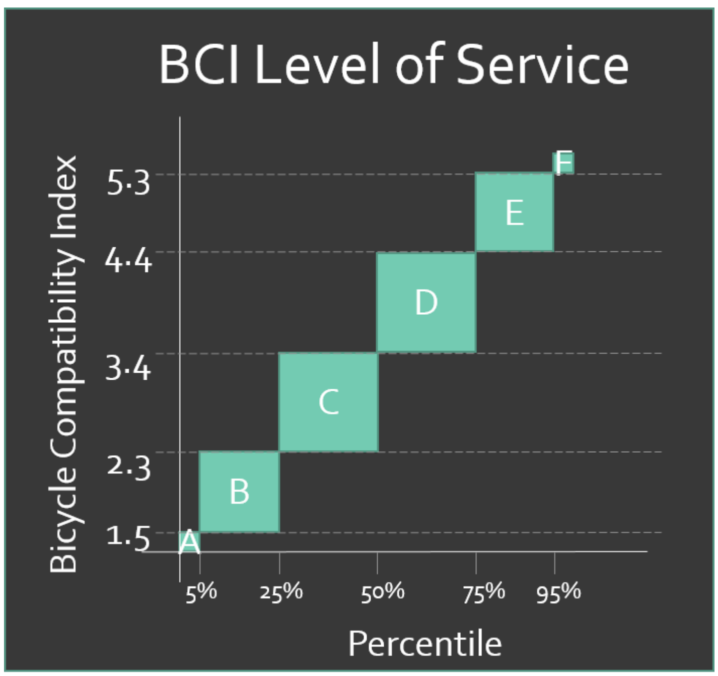


Figure 5: Definition of Bicycle Compatibility Index level of service cut points (Harkey et al., 1998)

Bicycle Level of Service

The BLOS model was inspired by the lack of statistical robustness among previously existing models used to quantify a bicyclists perception of safety, hazards, and stress (Landis et al., 1997).

The BLOS model was defined with stepwise regression and used design variables to predict the average BLOS score identified by research participants (Landis et al., 1997). The study included 150 participants each of whom biked through a predetermined course and rated each road section from 1-6 (A-F). The course included a range of different developments/densities, lane widths, bicycle infrastructure, and traffic volumes. The research participants were 47% female, with the majority of participants were between 30 and 45. Even though recruiting efforts were focused on less experienced riders, the least experienced bicyclists included in the study bicycled 161 km (100 mi) annually (Landis et al., 1997). This amount of bicycling could be experienced as a single 13 km (8mi) ride in a month or a few 4km (2.6mi) rides each month. Although this is less than a standard bicycle commuter, it still demonstrates a fairly high degree of comfort on a bicycle. For example, if someone participates in an activity once or twice a month (book club, golf, haircut), then, over time, she would become fairly comfortable and familiar with the activity.

The original BLOS model was defined based on a linear regression analysis. Independent variables were selected if they correlated to the BLOS rating. If a variable was correlated to BLOS but showed strong collinearity to a variable that was more strongly correlated to BLOS, it was dropped from the analysis (Landis et al., 1997). Based on the correlation analysis the following variables were excluded from the model:

presence of curbing, through-movement green time/cycle length ratio, number of directional lanes (Landis et al., 1997). To determine the best BLOS model, several variable transformations were considered based on a stepwise regression analysis and the model with the highest R^2 (0.73) was chosen to best predict BLOS based on various transformations of directional 15-minute volumes, number of lanes, posted speed limit, percent heavy vehicles, commercial land index, frequency of driveways and on-street parking spaces, pavement surface condition rating, and average effective width of the outside lane (Table 3) (Landis et al., 1997).

Table 3: Original BLOS model, independent variable transformations and HCM 2010 updated BLOS model (Huff & Liggett, 2014; Landis et al., 1997; Sprinkle Consulting, 2007)

Variable	Abbrev	Original Model			HCM 2010 Model	
		Transform	Coeff.	t-stat	Transform	Coeff.
Directional 15 min. volume	Vol_{15}	$\ln(Vol_{15}/L)$	0.59	6.7	$\ln(0.25*Vol_{15}/L)$	0.51
Total number of directional through lanes	L					
Motor Vehicle Speed	S	ln(S(1+HV))	0.83	2.4	$(1*\ln(S - 20)+0.8) * (1 + 10 * HV)^2$	0.20
Proportion of heavy vehicles	HV					
Commercial land index	COM15	ln(COM15*NCA)	0.019	0.65	Eliminated	---
Driveway/on-street parking frequency	NCA					
Pavement Surface Condition	PC	PC	6.4	4.0	$1/PC^2$	7.1
Bicyclists Space: Width of outside lane + paved shoulder	W_e	$(W_e)^2$	-0.01	-8.1	$(W_e*)^2$	-0.005
Constant			-1.57	-1.5		0.760
		$R^2 = 0.73$				$R^2 = 0.77$

* The W_e calculation in the HCM 2010 model differs based on presence of on-street parking, hourly volumes, and overall bike lane width

Over time, applications of the BLOS model led to slight modifications that were eventually adopted by the 2010 Highway Capacity Manual (HCM) (Huff & Liggett, 2014; Sprinkle Consulting, 2007). One of the major differences between the original BLOS model and the HCM model is the complexities added to determining W_e (bicycle space). In the original model, W_e was calculated as the sum of the width of the outside lane and the width of the paved shoulder minus the sum of the effective width reduction (Huff & Liggett, 2014; Landis et al., 1997).

Table 4 shows the various condition specific calculations required by the HCM BLOS to calculate the amount of available bicycle space (W_e) (Huff & Liggett, 2014; Sprinkle Consulting, 2007). The conditions eliminate the inclusion of shoulder width when there is on-street parking, increase the effective space available under low volume conditions, and when the bike lane is particularly narrow (or non-existent) the effective total width is reduced proportionally to the rate of occupied on-street parking (

Table 4). But it is very difficult to intuit the impacts of specific design decisions on the value of either W_e or the overall BLOS score.

Table 4: Condition specific calculations and transformations for variables for the HCM 2010 BLOS model (Huff & Liggett, 2014)

Condition	Variable When Condition Is Satisfied	Variable When Condition Is Not Satisfied
$p_{pk} = 0.0$	$W_t = W_{ol} + W_{bl} + W_{os}^*$	$W_t = W_{ol} + W_{bl}$
$v_m > 160$ veh/h or street is divided	$W_v = W_t$	$W_v = W_t(2 - 0.005\ v_m)$
$W_{bl} + W_{os}^* < 4.0$ ft	$W_e = W_v - 10\ p_{pk} \geq 0.0$	$W_e = W_v + W_{bl} + W_{os}^* - 20\ p_{pk} \geq 0.0$
$v_m(1 - 0.01\ P_{HV}) < 200$ veh/h and $P_{HV} > 50\%$	$P_{HVa} = 50\%$	$P_{HVa} = P_{HV}$
$S_R < 21$ mi/h	$S_{Ra} = 21$ mi/h	$S_{Ra} = S_R$
$v_m > 4\ N_{th}$	$v_{ma} = v_m$	$v_{ma} = 4\ N_{th}$

Notes: W_t = total width of the outside through lane, bicycle lane, and paved shoulder (ft);
W_{ol} = width of outside through lane (ft);
W_{os}^* = adjusted width of paved outside shoulder; if curb is present $W_{os}^* = W_{os} - 1.5 \geq 0.0$, otherwise $W_{os}^* = W_{os}$ (ft);
W_{os} = width of paved outside shoulder (ft);
W_{bl} = width of bicycle lane = 0.0 if bicycle lane not provided (ft);
W_v = effective total width of outside through lane, bicycle lane, and shoulder as a function of traffic volume (ft);
p_{pk} = proportion of on-street parking occupied (decimal);
v_m = midsegment demand flow rate (veh/h);
P_{HV} = percent heavy vehicles in the midsegment demand flow rate (%), and
S_R = motorized vehicle running speed (mi/h).

An additional statistical enhancement based on a statewide application of the model in Delaware led to the replacement of the speed limit/heavy vehicle term: ln(S(1+HV)), with a more complicated speed/heavy vehicle adjustment factor: $[1.1199 \ln(S - 20) + 0.8103] * (1 + 10.38 * HV)^2$ (Huff & Liggett, 2014; Sprinkle Consulting, 2007).

In both equations S refers to the posted speed limit and HV refers to the proportion of heavy vehicles. With these updates, the overall fit of the model improves by 5%, R^2 increases from 0.73 to 0.77 (Table 3) (Huff & Liggett, 2014; Sprinkle Consulting, 2007). It is not obvious whether or not the complexities introduced in the HCM version of the BLOS model are justified by a 5% increase in overall model fit –

especially given the relatively high fit of the BCI model with minimal variable transformations ($R^2 = 0.89$,

Table 1).

The complexity of the variable transformation in the BLOS model and the specificity of the data required for the model make it difficult for many jurisdictions to apply this model as a planning tool. The BLOS model requires intensive data collection efforts at specific locations to be able to quantify how a particular piece of infrastructure is performing. This is a valuable tool; however, it is not a tool fit for large scale bicycle network planning efforts.

Strengths and Limitations

The focus of the BCI and BLOS models is on specific engineering design characteristics. As a result, the models can be useful in evaluating specific road designs for the degree to which they are compatible with bicycle use. However, when evaluating an entire network, these variables are difficult to obtain.

In the example calculations discussed in the original BCI paper, AADT was used to estimate *curb lane volume* and an *other-lane volume* based on standard peak hour volumes, directional splits, and the proportion of vehicles traveling in the curb lane (Harkey et al., 1998). The manipulation of variables frequently collected at the network level, such as AADT, into specific design oriented variables such as curb lane volume relies either on local data collection or gross generalizations. Similar variable manipulations would be required to implement the BLOS methodology on a system wide level.

The BCI and BLOS models were developed based on precise measures of traffic and design. An application of either model on a small scale level with thorough data collection and analysis would provide a level of service classification that could be compared across the region or nation. This emphasis on data collection is also seen the motor vehicle intersection level of service methodologies that require specific turning movement counts and lane configurations. However, as a result of this precision, the BCI and BLOS models are less appropriate for a system wide evaluation of the bike-able network.

Another feature of the BCI and BLOS models is their effort to define the level of service for the average user. The BCI and BLOS methodologies do not directly incorporate the idea that different rider typologies may perceive level of service differently. The BCI study found that "casual recreational" bicyclists were less comfortable (overall average rating of 3.1) than "experienced recreational" and "experienced commuter" bicyclists (with overall overage ratings of 2.7 and 2.6 respectively) (Harkey et al., 1998). However, the authors modeled BCI based on the average rating across all users (Harkey et al., 1998).

The emphasis of both the BLOS and BCI methodologies was to create a single metric for determining the overall level of service perceived by the average bicyclist. The motivation, purpose, and application of BCI and BLOS are not directly in line the recent emphasis on improving the bicycle network for *all* rider types. The discussion in CHAPTER 2 showed that a design user falls into the *interested but concerned* and *comfortable but cautious* typologies. These riders demonstrate a preference for high quality, physically separated and low stress biking environments. The LTS methodology discussed in the next section of this chapter defines a framework for beginning to capture differences in comfort level and perceived traffic stress across rider types.

Level of Traffic Stress – LTS

The LTS methodology creates a framework for identifying the perceived traffic stress for each street in a network. The LTS concept and the original criteria to determine LTS were defined by researchers at MTI in response to the difficulties in applying the BLOS and BCI metrics for large scale planning purposes (Furth & Mekuria, 2013; Mekuria et al., 2012). The LTS methodology was intended to be a straightforward metric for evaluating the bicycle network at a municipal or regional scale. The LTS methodology identifies streets as LTS 1-4, with 4 representing the highest and 1 the lowest stress streets. Each rider can then identify her highest level of stress tolerance and that LTS value defines her bicycle network. For example, if a rider is comfortable with LTS 2 streets, but not with LTS 3 streets, then the bicycle network available to her would be defined by the LTS 1 and LTS 2 streets.

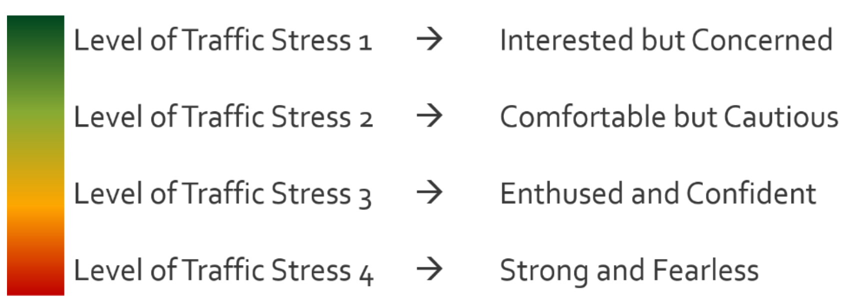


Figure 6 LTS categories and estimated rider type stress tolerance

The LTS concept supports the idea that current and potential bicyclists have a range of confidence levels and identifies each road in the network as LTS 1, 2, 3, or 4. These LTS categories correspond roughly to the 4 rider types identified by the Cycle Atlanta application: *interested but concerned, comfortable but cautious, enthused and confident, strong and fearless* (Figure 6). LTS 1 is defined as suitable for all riders (regardless of age, experience, and comfort level) and LTS 2 defines the infrastructure that is suitable for most adult cyclists. The combined network of LTS 1 and LTS 2 represents the bicycle network available to the design user. The LTS 3 infrastructure is suitable for the majority of current bicyclists in US cities when such infrastructure includes features such as bike lanes along busy arterials. Finally, the LTS 4 infrastructure includes the rest of the network included wide, high traffic, high speed arterials—this network is only considered bike-able to the *strong and fearless* rider type. A low stress network, defined as LTS 1-2 approximates the network available to the *interested but concerned* and *comfortable but cautious* rider types and is used to define the low stress bike network (Furth & Mekuria, 2013; Mekuria et al., 2012; Mueller & Hunter-Zaworski, 2014).

The specific LTS methodology discussed below includes the original methodology (original LTS) and any modifications made in a recent application of LTS in the Atlanta region (Atlanta LTS). The modified Atlanta LTS methodology was created to enhance the classification system by refocusing the criteria around data easily available for the region. One of the touted benefits of the LTS methodology is that the data are more easily obtained than for other level of service methodologies. However, this is regionally dependent and the Atlanta methodology was generally more appropriate for the Atlanta Case Study presented in CHAPTER 6. The final section of this chapter identifies the specific LTS methodology used to define the bike network in the Atlanta case study (CHAPTER 6).

The LTS methodology is based on an interpretation of existing literature and the data used to determine LTS includes features and conditions that were statistically significant in the BCI and BLOS models. However, the specific LTS criteria and thresholds for each level have not been statistically validated. The LTS methodology (both the original methodology and the Atlanta methodology) is discussed below in four sections: (1) Physically Separated Bike Infrastructure and Trails, (2) LTS for Links, (3) Unsignalized Intersections, and (4) Signalized Intersections. The chapter closes with a discussion of how LTS will be applied to define bike-ability in the CHAPTER 6 case study analysis.

Physically Separated Bike Infrastructure and Trails

The original and Atlanta LTS methodologies categorized physically separated bicycle infrastructure slightly differently. The original LTS methodology considered all trails and other bicycle infrastructure that was physically separated form motor vehicle traffic as LTS 1 regardless of the type of separation (curb, bollard, parking, etc.) (Furth & Mekuria, 2013; Mekuria et al., 2012). The Atlanta LTS also categorized trails as LTS 1, but due to potential driveway conflicts, classified side paths and cycle tracks as LTS 2 (Mingus, 2015). The application of the LTS methodology in the CHAPTER 6 Case Study analysis merged these two concepts and considered off road infrastructure (trails and side paths) as LTS1 and physically separated on-road infrastructure as LTS 2. Even though side paths have potential driveway conflict points, they are generally designed for users of all ages and comfort level and were classified as LTS 1 in the CHAPTER 6 case study. However, these subtle differences had no bearing the case study results, because the methodology identified the low stress network as LTS 1 and 2.

LTS for Links

Criteria – Streets with Bike Lanes

The original LTS criteria for bike lanes was based on street width (number of lanes), bicycle operating space, motor vehicle speeds, and bike lane blockage with different criteria thresholds with and without on-street parking (

Table 5 and Table 6). The measure of bicycling operating space was collected based on field observations and online map measurements as part of the input criteria with narrower bike lane widths corresponding to a higher LTS. Each link was given an overall LTS based on the most stressful criteria. For example, if a street with a bike lane and no on street parking had 1 through lane per direction, over 15ft bike lane including shoulder space, rare bike lane blockage rates, but a speed limit of 40 mph, the link would be classified as LTS 4 (

Table 5).

Table 5: Original LTS criteria for bike lanes alongside on-street parking (Furth & Mekuria, 2013; Mekuria et al., 2012)

	LTS 1	LTS 2	LTS 3	LTS 4
Through lanes per direction	1	*(no effect)*	≤ 2	*(no effect)*
Sum of bike lane and parking lane width (includes marked buffer and paved gutter)	≥ 15 ft.	14 – 14.5ft*	≤ 13.5 ft.	*(no effect)*
Speed limit or prevailing speed	≤ 25 mph	30 mph	35 mph	≥ 40 mph
Bike lane blockage (typically in commercial areas)	Rare	*(no effect)*	Frequent	*(no effect)*

**If speed limit <25 mph or Class = residential, then any width is acceptable for LTS 2*

Table 6: Original LTS criteria for bike lanes *not* alongside on-street parking (Furth & Mekuria, 2013; Mekuria et al., 2012)

	LTS 1	LTS 2	LTS 3	LTS 4
Through lanes per direction	1	1*	≤ 2**	(no effect)
Sum of bike lane and parking lane width (includes marked buffer and paved gutter)	≥ 6 ft.	≤ 5.5 ft.	(no effect)	(no effect)
Speed limit or prevailing speed	≤ 30 mph	(no effect)	35 mph	≥ 40 mph
Bike lane blockage (typically in commercial areas)	Rare	(no effect)	Frequent	(no effect)

**2, if directions are separated by a raised median*
*** more than 2 if directions are separated by a raised median*
(no effect) = factor does not trigger an increase to this level of traffic stress

The Atlanta LTS methodology also included separate criteria thresholds for bike lanes with on-street parking, and bike lanes without on-street parking (Table 7 and

Table 8). Information regarding bike lane width did not exist on a system wide level in Atlanta, but the Atlanta bicycle network dataset did include a variable indicating if a bike lane was buffered or not buffered. Instead of collecting lane width data, the Atlanta LTS methodology created a separate set of criteria specifically for buffered bike lanes (as compared to bike lanes striped with a single stripe) (Table 9 and

Table 10) (Mingus, 2015). The data required for both types of bike lanes was the same, but for a given LTS, tolerable traffic speeds and functional classifications were higher for a buffered bike lane (Table 7 vs Table 9).

Table 7: Atlanta LTS criteria for bike lanes *not* along on-street parking (maximum criteria indicated for each LTS criterion) (Mingus, 2015)

	LTS 1	LTS 2	LTS 3	LTS 4
Through lanes per direction	1	1	≤ 2	Any
Traffic Volume (AADT)	≤ 6,300	≤ 14,000	≤ 27,000	Any
Functional Class	Local	Collector (or less)	Minor Arterial (or less)	Principal Arterial (or less)
Speed Limit	≤ 25 mph	30 mph	35 mph	≥ 40 mph

Table 8: Atlanta LTS criteria for bike lanes along on-street parking (maximum criteria indicated for each LTS criterion) (Mingus, 2015)

	LTS 1	LTS 2	LTS 3	LTS 4
Through lanes per direction	1	(no effect)	≤ 2	Any
Traffic Volume (AADT)	≤ 3,000	≤ 6,300	≤ 14,000	Any

Functional Class	Local	Local	Collector (or less)	Minor Arterial (or less)
Speed Limit	≤ 25 mph	≤ 30 mph	≤ 35 mph	Any

Table 9: Atlanta LTS criteria for buffered bike lanes *not* along on-street parking (maximum criteria indicated for each LTS criterion) (Mingus, 2015)

	LTS 1	LTS 2	LTS 3	LTS 4
Through lanes per direction	1	1	≤ 2	Any
Traffic Volume (AADT)	≤ 6,300	≤ 14,000	≤ 27,000	Any
Functional Class	Collector (or less)	Collector (or less)	Minor Arterial (or less)	Principal Arterial (or less)
Speed Limit	≤ 30 mph	≤ 35 mph	Any	Any

Table 10: Atlanta LTS criteria for buffered bike lanes along on-street parking (maximum criteria indicated for each LTS criterion) (Mingus, 2015)

	LTS 1	LTS 2	LTS 3	LTS 4
Through lanes per direction	1	1	≤ 2	Any
Traffic Volume (AADT)	≤ 3,000	≤ 6,300	≤ 14,000	Any
Functional Class	Local	Collector (or less)	Minor Arterial (or less)	Principal Arterial (or less)
Speed Limit	≤ 25 mph	≤ 30 mph	≤ 35 mph	Any

Both the original and Atlanta LTS methodology have more sensitive thresholds for bike infrastructure alongside on-street parking primarily because of two potential conflict points (

Table 5 vs Table 6; Table 7 vs

Table 8; and Table 9 vs

Table 10). The first is the conflict between a bicyclist and a driver or passenger opening her car door into the bike lane. The second is between the bicyclist and a driver either entering or exiting the parking space. Both of these events would likely increase the level of traffic stress for a bicyclists and this is incorporated into the methodology by adjusting the criteria thresholds for each LTS. Lower traffic volumes and lower speed limits are required for a bike lane with on-street parking to classify as LTS 2 with the Atlanta methodology than a bike lane without on-street parking (Table 7 vs

Table 8).

Another difference in the data required for the original LTS and the Atlanta LTS is the inclusion of rate of bike lane blockage in the original LTS. Bike lane blockage is a major issue across the US and in Atlanta (Rebecca Serna, 2014). Despite this growing frustration, there is very little data identifying the degree to which these violations occur and the authors of the original LTS include only the distinction between a bike lane "rarely" being blocked and a bike lane "frequently" being blocked. The MTI research posited that bike lane blockage would be "frequent" on commercial blocks and "rare" on non-commercial blocks. Despite the inclusion of bike lane blockage in the description of the methodology, the original application of LTS was unable to obtain the appropriate commercial data and so instead, based on anecdotal experiences, deemed all streets "rarely" blocked.

The Atlanta LTS methodology omitted this criteria because of the difficulty in accurately determining this blockage. It could also be argued that, because the issue is a result of illegal parking, the stress is not an innate condition of the link, but instead a law enforcement issue.

The original LTS study indicated that traffic volumes were too difficult to obtain and were omitted from the analysis. However, in the Atlanta region, AADT data is available for the entire network through the Georgia Department of Transportation (GDOT). The statistical significance of traffic volumes in the BCI and BLOS methodology supports the inclusion of AADT as a criterion for all road types (with and without bike lanes) in the Atlanta LTS methodology (Harkey et al., 1998; Landis et al., 1997; Mingus, 2015; Sprinkle Consulting, 2007). For the Atlanta LTS methodology, the LTS for each road condition is based on the same input criteria: lane number, AADT, Functional Classification, and posted speed limit.

The application of LTS used in the CHAPTER 6 Case Study uses a direct application of the Atlanta LTS methodology for evaluating the LTS for streets with bike lanes.

Criteria – Shared Travel Lanes

The data required to categorize links with bike infrastructure according to the original LTS methodology is time intensive. It was not feasible to collect this data for the entire road network, and so the original LTS criteria for shared travel lanes was limited to widely available data: speed limit and number of travel lanes (Table 11). The Atlanta LTS methodology for streets with bike infrastructure required field observations to identify if a bike lane included a buffer or if there was on-street parking alongside of a bike lane. However, the criteria used in determining the LTS were widely available and, as a result, were able to be similarly applied to shared travel lanes (

Table 12).

Table 11: Original LTS criteria for shared travel lanes (Furth & Mekuria, 2013; Mekuria et al., 2012)

	Street Width		
Speed Limit	2-3 Lanes	4-5 Lanes	6+ Lanes
≤ 25 mph	LTS 1* or 2*	LTS 3	LTS 4
30 mph	LTS 2* or 3*	LTS 4	LTS 4
≥ 35 mph	LTS 4	LTS 4	LTS 4

** Use lower value for streets without marked centerlines or classified as residential and with fewer than 3 lanes use higher value otherwise*

Table 12: Atlanta LTS criteria for shared travel lanes (maximum criteria indicated for each LTS criterion) (Mingus, 2015)

	LTS 1	LTS 2	LTS 3	LTS 4
Through lanes per direction	1	1	≤ 2	Any
Traffic Volume (AADT)	≤ 2,000	≤ 6,000	≤ 14,000	Any
Functional Class	Local	Local	Collector (or less)	Arterial (or less)
Speed Limit	≤ 25 mph	≤ 30 mph	≤ 35 mph	Any

<u>Limitations</u>

The method for determining LTS based solely on the most stressful criteria creates a simple, transparent, and accessible methodology for municipalities and planning agencies without requiring technical capacity. However, its simplicity may underrepresent the cumulative effects of traffic stress. For example, (using the Atlanta criteria) a road without a bike lane, with 1 travel lane per direction, a daily traffic volume of 500 vehicles per day, a local functional classification, and a 35mph speed limit would be classified as LTS 3, but might be perceived as less stressful than a road with 2 lanes per direction, 13,999 vehicles per day, with a speed limit of 35 mph that is classified as a collector (also LTS 3). Both these conditions would be rated LTS 3, but in the first scenario only the speed limit was causing the LTS to increase from 1 to 3 and in the second scenario each individual criteria met the threshold for LTS 3. To better understand the nuance between the potential interaction effects of these criteria, the perception of traffic stress, for bicyclists of a range of comfort levels, would need to be identified. CHAPTER 7 further discusses the way in which this research may be conducted.

The application of LTS used in the CHAPTER 6 Case Study uses a direct application of the Atlanta LTS methodology for evaluating the LTS of shared travel lanes.

Unsignalized Intersections

Criteria

To identify the traffic stress associated with crossing a street at an unsignalized intersection, the characteristics of the street being crossed were applied to the approaching link. Then each approach was given the maximum LTS score between the LTS calculated for the approach and that based on the characteristics of the street being crossed. The original LTS and the Atlanta LTS align closely for unsignalized intersections (

Table 13 and Table 14). The Atlanta LTS was developed as a modification of the original LTS criteria that adds an additional distinction above a speed limit of 35mph.

The application of LTS used in the CHAPTER 6 Case Study uses a direct application of the Atlanta LTS methodology for evaluating the LTS of unsignalized intersections.

Table 13: Original LTS criteria for unsignalized intersections (Furth & Mekuria, 2013; Mekuria et al., 2012)

		Street Width		
		2-3 Lanes	**4-5 Lanes**	**6+ Lanes**
Speed Limit	**≤ 25 mph**	LTS 1* or 2*	LTS 3	LTS 4
	30 mph	LTS 2* or 3*	LTS 4	LTS 4
	≥ 35 mph	LTS 4	LTS 4	LTS 4

** Use lower value for streets without marked centerlines or classified as residential and with fewer than 3 lanes use higher value otherwise*

Table 14: Atlanta LTS criteria for unsignalized intersections (Mingus, 2015)

		Street Width		
		≤ 3 Lanes	**4-6 Lanes**	**> 6 Lanes**
Speed Limit	**≤ 25 mph**	LTS 1	LTS 2	LTS 4
	30 mph	LTS 2	LTS 2	LTS 4
	35 mph	LTS 2	LTS 3	LTS 4
	≥ 40 mph	LTS 3	LTS 4	LTS 4

Note: number of lanes refers to the entire street

Limitations

The current set of criteria limits the evaluation of the LTS of crossing a street at an unsignalized intersection to the number of lanes being crossed and the speed limit along that link. Future iterations of this methodology should attempt to incorporate some measure of traffic volume for the street being crossed. As the method currently stands, a very high speed street or a very wide street would be categorized as high stress regardless of how frequently a vehicle passes. In reality, the ease of crossing at an unsignalized intersection is likely a function of gap frequency and length. Incorporating a measure of traffic volume (e.g. AADT) into this set of criteria could serve as a surrogate for a gap analysis.

Signalized Intersections

Criteria

The original LTS criteria identified a set of design criteria for signalized intersections with right turn only lanes. There are separate criteria for cases in which (1) the bike lane approaches the intersection between a through lane and a right turn only lane (a pocket bike lane) and (2) there is no bike lane (either because it is dropped at the intersection or there was no bike lane along the approach) (

Table 15). The potential conflict between through bicyclists and right turning drivers can cause increased traffic stress. These criteria attempt to capture this stress. The Atlanta LTS modifies these criteria slightly and includes an additional set of criteria for bicycle left turn movements (

Table 16 and Table 17).

Table 15: Original LTS criteria for signalized intersections with right turn only lanes (Furth & Mekuria, 2013; Mekuria et al., 2012)

	Configuration	Level of Traffic Stress
With pocket bike lane	Single right turn lane up to 150 ft long, starting abruptly while the bike lane continues straight, and intersection angle and curb radius such that turning speed is ≤ 15 mph.	2
	Single right turn lane longer than 150 ft starting abruptly while the bike lane continues straight, and intersection angle and curb radius such that turning speed is ≤ 20 mph.	3
	Single right turn lane in which the bike lane shifts to the left, but intersection angle and curb radius are such that turning speed is ≤ 15 mph.	3
	Single right turn lane with any other configuration; dual right turn lanes; or right turn lane along with an option (through-right) lane	4
Without pocket bike lane	Single right turn lane with length ≤ 75 ft; intersection angle and curb radius limit turning speed to 15 mph.	(no effect on LTS)
	Single right turn lane with length between 75 and 150 ft; intersection angle and curb radius limit turning speed to 15 mph.	3
	Otherwise	4

Table 16: Atlanta LTS criteria for signalized intersections with right turn only lane (Mingus, 2015) image source: NACTO, 2014

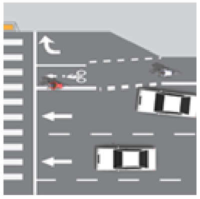
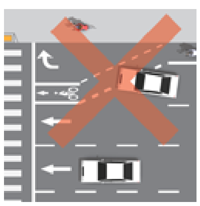
Bike treatment criteria at signalized intersection with right turn only lane		LTS
	Through Bike Lane	LTS 2
	Bike Box (one or more traffic lanes)	LTS 2
	Mixing Zone	LTS 3
	Through Lane Becomes Right Turn Only Lane	LTS 4
	Bike Lane is dropped at the intersection	LTS 4
	Shared Travel Lane	No Effect

Table 17: Atlanta LTS criteria for signalized intersections with left turn bicycle movements (Mingus, 2015; NACTO, 2014)

Bike treatment criteria for left turn bicycle movements at signalized intersection		LTS
 image source: google	Bike Box (extending across all traffic lanes in one travel direction)	LTS 2
 image source: NACTO	Two Stage Turn Queue Box	LTS 2
 image source: NACTO	Bike Lane only (no bike box or two stage turn queue box)	LTS 3
 image source: NACTO	Shared travel lanes with no bike infrastructure	No Effect

The original LTS methodology requires specific design measures including curb radius and right turn lane length. An intersection is considered low stress (LTS < 3) if the approach is low stress and the intersection has a short right turn lane (<150ft with a pocket bike lane and <75ft without a pocket bike lane, Figure 15) (Furth & Mekuria, 2013; Mekuria et al., 2012).

Instead of including specific design measures, the Atlanta LTS methodology for signalized intersections identified different bike lane configurations as different levels of stress. Under the Atlanta LTS methodology, a signalized intersection with a right turn only lane and bike infrastructure was only low stress (LTS < 3) if there was a bike box or a pocket bike lane.

The Atlanta LTS methodology included additional criteria for left turn bicycle movements. For a signalized intersection with a bike lane to be identified as low stress with the Atlanta LTS criteria (LTS < 3), then the intersection needed either a bike box extending across all lanes or a two staged turn queue boxes. For an intersection to be considered low stress under the Atlanta methodology, instances with right turn only lanes must satisfy both sets of criteria for signalized intersections (

Table 16 and Table 17).

Limitations

The original application of LTS admitted that the design data required for the signalized intersection analysis did not exist for their case study area and required manual data collection efforts (Furth & Mekuria, 2013; Mekuria et al., 2012). The researchers evaluated the signalized intersection LTS at a few select intersections, but, for their case study analysis ignored these criteria due to difficulties in collecting the data (Furth & Mekuria, 2013; Mekuria et al., 2012). The Atlanta LTS methodology was also difficult to implement at a network level because the intersection bike treatment designs were not compiled at a network level (Mingus, 2015). Based on the conservative nature of the left turn criteria, signalized intersections with bike treatment would only be low stress with the inclusion of a full bike box or two stage left turn queue boxes. The bike intersection bike lanes identified by the Atlanta LTS methodology are recommended by the National Association of City Transportation Officials (NACTO) guidelines, but the body of research evaluating and comparing these treatments is lacking (NACTO, 2014). Furthermore, design treatments at intersections are very sensitive to the specific conditions of that intersection, including turning movement counts, sight distances, and bicycle volumes.

Perhaps the traffic stress of specific signalized is better addressed on an individual case by case level and the network level LTS analysis will serve to highlight cases in which low stress bicycle infrastructure meets high stress intersections (based on the LTS of each of the approaching links). This is along the line of the observation that many of the signalized intersections identified through the LTS criteria exist on links that are already high stress environments (Furth & Mekuria, 2013; Mekuria et al., 2012). In other words, the LTS of an approach may not increase a result of the intersection.

To further develop the categorization of signalized intersections, research should first be conducted to identify perceived stress for riders of all comfort levels and rider typologies. During this research it is essential that there is an effort to identify features for which data is relatively easily collected/calculated/or otherwise obtained. Design measures are easily calculated, but are rarely tabulated across a network and, consequently, are impractical at a network level.

Due to these challenges in identifying the LTS of a signalized intersection, this portion of the LTS analysis was omitted from the CHAPTER 6 Case Study.

Summary of the Case Study Application of LTS

The case study application of LTS presented in CHAPTER 6 uses the Atlanta LTS methodology for the link and unsignalized intersection analysis. The Atlanta LTS methodology was most appropriate because the data required for the analysis was tailored to the data available for the Atlanta region.

The case study application of LTS does not include any consideration of signalized intersections. The data required for the signalized intersection criteria had to be collected through field research and was, as a result, very time consuming. However, these signalized intersection observations were conducted for the study area included in the case study as an explorative exercise. Interestingly, for this study area, there were no instances of right turn only lanes and two intersections included bike box designs. However, the LTS on the links approaching these intersections was not low stress (LTS >

2) and so the signalized intersection criteria would have had very little impact on the overall low stress network analysis.

CHAPTER 4

EVALUATING BICYCLE NETWORKS

Evaluating network connectivity is a multidisciplinary area of research. Many of the analysis techniques applied to evaluating transportation networks are derived from fields of graph theory, geography, and planning. Included here is a brief discussion of some of the metrics most commonly used to evaluate active transportation.

Network Robustness

A growing area of interest in both geography and planning is focused around network robustness. As extreme weather events continue to become increasingly common, there is a growing desire among cities to evaluate transportation network robustness.

The network robustness index (NRI), a common metric used to define network robustness, has been defined based on a comparison of a network with and without key links (Scott, Novak, Aultman-Hall, & Guo, 2006). The NRI for a specific link, A, is calculated based on the difference in total travel time (the sum, across all links, of the product of travel time and volumes) for the entire network compared to the total travel time across the network after removing link A (Scott et al., 2006; Sullivan, Novak, Aultman-Hall, & Scott, 2010). The strength of the NRI metric is the conceptual simplicity. However, applying this metric requires a complete reassignment of trips to identify changes in travel time and volumes along each link and across the entire network. The field of travel demand modeling has spent decades identifying and criticizing different systems of congestion based trip reassignment and any estimation of the NRI is subject to whatever advantages and disadvantages are associated with the specific trip assignment methodology.

Applying a similar NRI style analysis to the bike network involves re-evaluating the network with and without key infrastructure. Although traffic volumes and signal timing likely have some impact on bicycle travel time, it is reasonable to define bicycle travel time solely as an effect of network distance. As a result, an NRI analysis applied to a bike network could be defined simply based on the accessible distance with and without the key infrastructure.

The complexities of congestion based trip reassignment were not applied to the case study presented here. However, the general comparison of networks based on the overall access or service area of each transit station was compared across different bicycle networks. The case study analysis measured the area that someone can bike to within 3 miles (network distance) of each transit stations and then compared this area to the area someone can bike with an improved network. This type of modified network analysis is common when comparing networks from an active mode perspective. The next section discusses some of the ways networks are evaluated from the perspective of walking and biking.

Connectivity for Active Mode

Network connectivity in traditional planning literature is generally applied to neighborhood level studies interested primarily in improving connectivity for pedestrians and/or bicyclists. Measures such as block length, size, and density provide indirect measures of route directness (Dill, 2004). An urban fabric with very large blocks often requires long, circuitous paths. However, simply identifying block size may not be as important to connectivity as the length and width dimensions of the block (Dill, 2004).

The total length of a network can be compared across very specific situations, but in order to standardize this measure, the total length of the network can be divided by the total area of the network to give a measure of network density. An average network has a density of 1.74km/km^2 with values ranging from 0.03 – 18.67 km/km^2 (Schoner & Levinson, 2014).

Measures that take both the street network and the intersection into consideration can quantify how close an area is to achieving a perfect grid. The link-node ratio is defined as the total number of links divided by the total number of nodes. In a perfect grid, the ratio would be 2.5, although the literature has established a network with a link-node ratio of 1.4 as "well connected" (Dill, 2004).

The connected node ratio which is defined by the number of intersections divided by the number of total nodes (i.e. intersections plus cul-de-sacs) creates a percentage style metric that provides a surrogate metric for the proportion of through streets and the degree of "grid-ness" of a network. A more direct measure of "grid-ness" can be calculated by taking the percentage of intersections that are 4-way intersections (Dill, 2004). A true grid would have a connected node ratio of 1 and 100% of intersections would be 4-way intersections.

Another measure of network connectivity can be defined based on the directness of a route. Route directness is calculated as the network distances divided by the straight line distance between two points of interest (Dill, 2004). The City of Portland uses a pedestrian route directness maximum of 1.5 as a design standard. It is important to note that although a low pedestrian route directness value is “better”, a perfect grid has a pedestrian route directness of $\sqrt{2}$ or 1.4. In practice, grid networks are found to range from 1.4 to 1.5 (Dill, 2004; Randall & Baetz, 2001).

In the original application of the LTS methodology, two points were only considered connected if the trip length along the low stress network was less than 25% longer than with the LTS 4 network (or less than 0.33 miles longer for short trips). The study then evaluated the network connectedness based on the number of work trips possible for each LTS 1, LTS 1-2, LTS 1-3, and LTS 1-4 networks (Furth & Mekuria, 2013).

A metric of walkability that can be applied to bicycling, is the effective walking area. The effective walking area is the ratio of the number of parcels within a network distance and the number of parcels within a straight line distance (Dill, 2004). The effective walking area methodology can also be applied to census population data to define an accessible population

Mueller and Hunter-Zaworski used an expanded concept of effective access area during a comparison of bicycle access around rail stations in Salem, OR (Mueller & Hunter-Zaworski, 2014). Overall connectivity was defined by the network size as determined by the total length of the connected low stress bike infrastructure. Network accessibility was then defined by the population, housing, and employment for census blocks adjacent to the low stress bike network (Mueller & Hunter-Zaworski, 2014).

A second level analysis was conducted with a weighting framework. The authors weighted each of the attributes (population, housing, and employment) based on distance. An inner ring (0-1.2 mi) was multiplied by 3, a mid-range catchment area (1.2 – 2.5 mi) was multiplied by 2, and the outer area (2.5-3.7 mi) was unweighted (Mueller & Hunter-Zaworski, 2014). Although the authors admitted this weighting scheme was rudimentary and arbitrary, they were able to show that if the weighting caused accessibility to decrease (or increase) then a station's initial accessibility metric was relying on faraway population, housing, and/or employment (or on nearby population, housing, and/or employing).

Case Study Application of Network Connectivity

The case study analysis presented here involved the comparison of four networks that built off each other: (1) existing low stress network, (2) low stress network with proposed bike improvements, (3) low stress network with proposed bike improvements plus additional recommended improvements, and (4) the entire bike network including LTS 1-4. Each of these networks is defined for the same study area with a maximum network distance of 3 miles.

The network connectivity measures chosen to compare the networks defined as part of this case study were total network length (by distance from the stations), effective bike-able area (based on accessible census blocks), and effective bike accessible population by age, gender, and race (based on census block population). These measures were most appropriate for comparing the relative size and level of access for the four increasingly connected networks within the same study area. The fact that the networks were centered around the same transit stations and built off each other prevented the need to standardize any of these metrics by creating ratios or density measures.

CHAPTER 5

BIKE TO TRANSIT

The case study presented in CHAPTER 6 demonstrates a possible application of LTS methodology that could enhance neighborhood level bike planning efforts. The case study focuses on the ability to access transit stations by bicycle based on a maximum bike distance of 3 miles. This chapter discusses various methodologies for defining bike to transit catchment areas as well as the importance of bike-to-transit planning in Atlanta.

Defining Catchment Area

In transit accessibility studies, catchment areas are often used to define the potential area from which a user can access transit. People working or living within the catchment area are considered potential transit users. The size of a catchment area likely differs based on land uses, the street network, and local culture. One of the major system benefits of using a bike to access transit is the expansion of the catchment area from a walkable distance to a bike-able distance.

In 2011, Federal Transit Administration (FTA) through the authority of the Department of Transportation, issued a final policy statement indicating that "all bicycle improvements located within three miles of a public transit stop or station shall have a *de facto* physical and functional relationship to public transportation" (FTA, 2011).

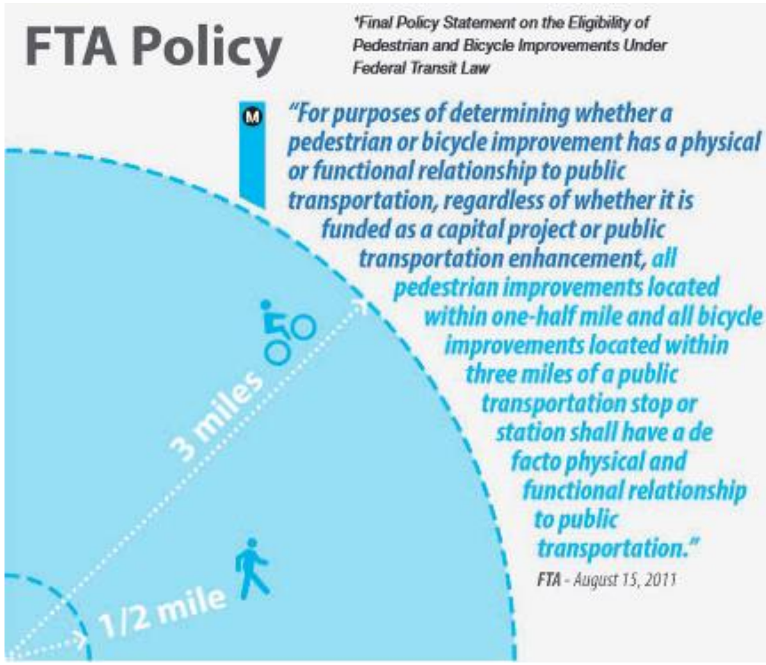


Figure 7: Graphic representation of the catchment area as defined by the FTA (LA Metro & SCAG, 2013)

Within the statement, FTA responds to several comments about the definition of the de facto bicycle influence area. The concerns primarily criticize the catch-all definition that will apply a national standard regardless of local culture, infrastructure, and topography. The FTA's response indicates that for a bicyclist of moderate comfort level, riding at a speed of 10 miles would be able to cover 3 miles in 15 minutes (FTA, 2011). The FTA acknowledges that local development patterns, topography, bicycle culture, and street networks will impact the bicycle catchment area of a specific station. However, the FTA defends its definition as a necessary simplification to ease the process of nationally investing in improving bicyclist infrastructure around transit stations (FTA, 2011).

The catchment area of 3 miles, set by the FTA, is liberal given that it is said to correspond to an average bicyclist traveling at 10 miles per hour for 15 minutes—this would total 2.5 miles. Furthermore, the standard is set as a 3 mile radius, which would generally correspond to a longer bike network trip distance. The 3 mile catchment standard is also in line with the typical catchment area defined by the American Public Transportation Association's (APTA) definition of area of influence for rapid transit (e.g. MARTA rail) as 3 miles (APTA, 2009).

A 3 mile standard buffer is generally used to identify the bicycle catchment area for rapid transit and heavy rail. However, the actual area of access based on the same bike distance is generally only a subset of the radial buffer. By definition, the network distance will always be shorter than the radial distance, but with a high quality network, there will be little difference in the network distance vs the radial distance. However, in cases where there are physical barriers to access and substandard infrastructure, this radial distance may entirely misrepresent the actual catchment area (Figure 8).

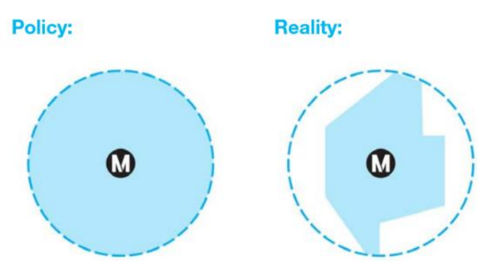


Figure 8: Graphic representation of radial vs network catchment area (LA Metro & SCAG, 2013)

This catchment area as defined by 3 miles is consistent with studies evaluating the bike to transit distances in the Netherlands, Germany, and the UK, where people bike up to 4 or 5 km (2.5 -3.1 mi) to access high speed transit modes (heavy rail) (Martens, 2004). The same study found that people are more likely to both bike to transit and bike longer distances to transit in countries with overall higher levels of bike culture and more established bike infrastructure (Martens, 2004).

Researchers in Philadelphia and San Francisco identified local bicycle catchment areas by surveying bicyclists. In Philadelphia, respondents traveled an average of 2.8 miles (16.6 minutes) and a median of 2.0 miles (15 minutes), while the San Francisco respondents traveled longer distances to reach transit (Flamm & Rivasplata, 2014). The average trip for San Francisco respondents was 5.4 miles (29.7 minutes) and the median trip was 3.3 miles (22.5 minutes) (Flamm & Rivasplata, 2014). This research supports both the fact that the local conditions impact the catchment area and the idea that a 3 mile radial buffer is a reasonable distance to use for bicycle access to transit across the nation.

Atlanta Context

Atlanta has identified bicycle as a priority mode, both in general and specifically with regard to transit access (Alta Planning + Design, 2013; MARTA, 2010). In 2012, the region committed to improving transit access through a Last Mile Connectivity Program allocating federal funding for local investments in the bicycle and pedestrian network (ARC, 2012). The commitment to making the bicycle a more viable mode throughout Atlanta is also demonstrated by the emphasis in the Cycle Atlanta Phase 1.0 plan on promoting biking in all communities with specific mention of commuters who bike to transit (Alta Planning + Design, 2013).

The MARTA TOD guidelines further establish the importance of biking as a means of accessing MARTA stations. The guidelines, define an access hierarchy which ranks passengers arriving by foot as the highest priority MARTA user and passengers arriving by bicycle or feeder bus as the second highest priority passenger (MARTA, 2010). In other words, the TOD guidelines call for design decisions to sacrifice vehicle access and vehicle parking in favor of bicycle infrastructure. In addition to prioritizing the bicycle as a mode of access, the guidelines specifically call for bicycle lanes (5-6 foot minimum width) on all major roads leading to TOD stations (MARTA, 2010).

There is a definite commitment to improving bike access to MARTA stations. There is also an emphasis on promoting high quality bike infrastructure suitable for all rider types. The case study presented in the next chapter provides a detailed demonstration of how measures of network connectivity can be applied to the low stress bicycle network to prioritize improved bike access to MARTA for all rider typologies.

CHAPTER 6

CASE STUDY

The objective of the case study analysis was to demonstrate the utility of using LTS methodology in evaluating the impact of bicycle infrastructure investments. It was therefore important to conduct this demonstration study in a location that has historically seen underinvestment, underscoring the importance of equity when evaluating and improving the regional Atlanta bicycle network. Improving the bicycle network around MARTA stations can directly increase the bike catchment area for that station and, as a result, could substantially change the commute environment around that station.

Defining the Study Area

The most common bike to transit trip is to work and to school and the most common directionality is to use the bike to access transit (not in egress) (Flamm & Rivasplata, 2014; Rietveld, 2000). As a result, it was important for this study to focus on stations in residential areas. Another priority of the study was to focus on transit station areas with vulnerable populations, as defined by the Reconnecting America Equitable TOD study (Reconnecting America, 2013).

Reconnecting America conducted a thorough analysis of the MARTA rail stations with the purpose of prioritizing different stations for different development strategies based on market strength and social equity. To do this, the population vulnerability around each station was plotted against the market strength to identify five different station typologies (Figure 9).

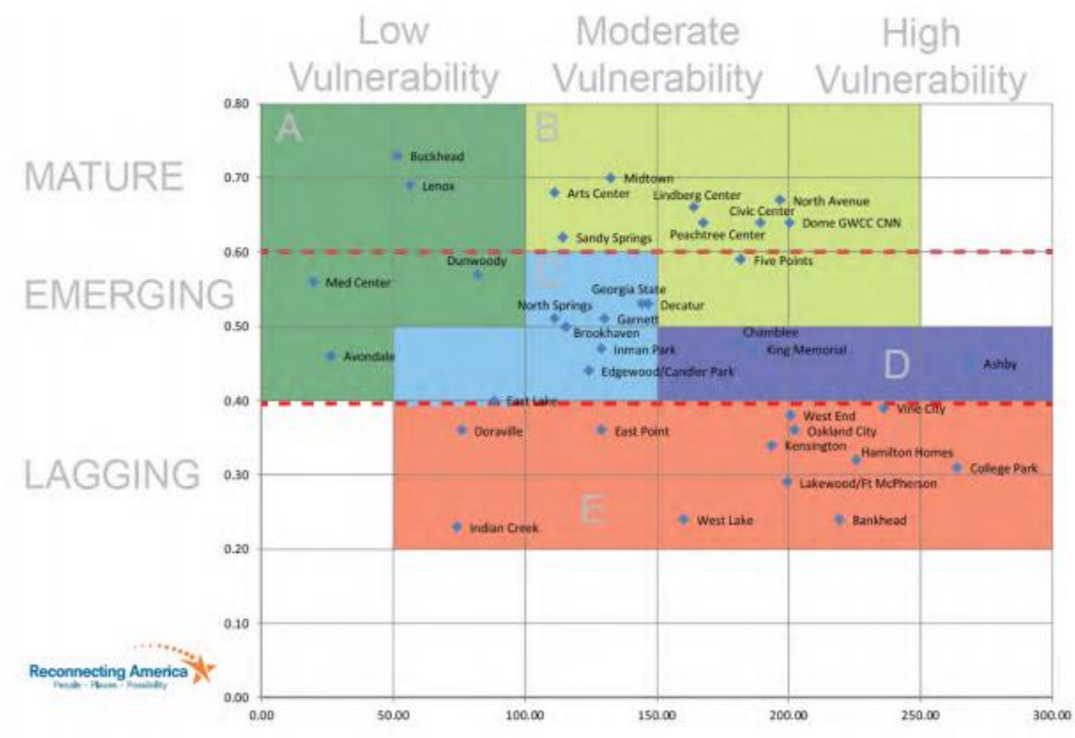


Figure 9: Equitable TOD station typology identification (Reconnecting America, 2013)

Vulnerability was defined based on median household income; percentage of carless households; percent renters; and percent walk, bike, and transit commuters (Reconnecting America, 2013). Market strength was determined by housing density, percent change in population (2000-2012), percent young adult (age 18-34), percent single, median household income, employment density, percent employees earning more than $3,333/mo., total office space (sq. ft.), average office rent, total retail space (sq. ft.), average retail rent, percentage of housing built after 2000, average apartment rents within 1 mile, 2012 number of homes sold within 1 mile, 2012 average sales price (within 1 mile), walk score, nearby barriers, MARTA TOD land, and nearby development land. Stations were categorized based on both a vulnerability score (low, medium, high) and a market score (mature, emerging, emerging potential, and lagging) (Reconnecting America, 2013).

Based on these definitions of vulnerability and market strength, stations were classified into one of five typologies: Type A, B, C, D, and E (Figure 9). Each typology had a specific set of recommended development priorities with Types E and D best suited for this case study (Table 18). Specifically typologies E and D have recommendations to (1) improve job access *to other* station areas (2) investment in station area infrastructure improvements and (3) strengthen community assets. Expanding the bicycle catchment area for all rider types through investment in high quality bicycle infrastructure can directly address the first two recommendations. This investment can also help strengthen community access, as bicycle infrastructure can have traffic calming effects and improve the street and neighborhood environment for all modes.

Table 18: Planning recommendations for each station type (Reconnecting America, 2013)

Type	Affordable Housing Strategies	Diversify Housing Stock	Improve Job Access	Improve Infrastructure	Strengthen Community Assets	Planning/ Visioning
A	Short-Term	Priority	Within station area	Priority	Priority	
B	Short-Term	Priority	Within station area		Priority	
C	Immediate	Priority	Within station area		Priority	Priority
D	Immediate	Priority	To other station areas	Priority	Priority	Priority
E	Long-Term		To other station areas	Priority	Priority	

A closer look at the Type D and E stations and a consideration of proximity was important in identifying the final case study area. There were only three geographically scattered instances of type D MARTA station (Figure 10) and the majority of the 12 Type E stations were located along the southern portion of the red/gold line (every station south of Garnett Station) (Figure 10). A desire to include a study area with consecutive stations led to the selection of West End, Oakland City, and Lakewood/Ft. McPherson as the target stations.

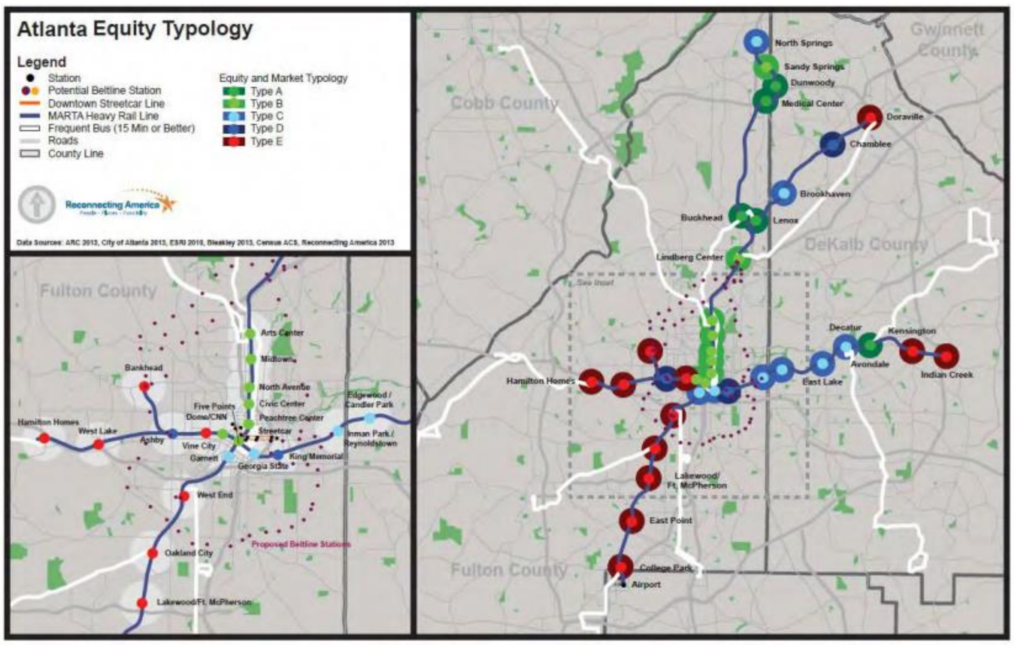


Figure 10: Station typology locations throughout Atlanta. Type E stations are primarily located in South Atlanta.

The catchment area discussion in CHAPTER 5 suggested the use of a 3 mile buffer around the MARTA rail stations to define the bicyle access area. To define the study area for this case study, a 3 mile buffer was drawn around the three station areas of interest (West End, Oakland City, and Lakewood/Ft McPherson) (transparent orange circles, Figure 11). Stations north and south of the stations of interest were also within this original 3 miles buffer. To create a study area that more realisticly represented the catchment area of West End, Oakland City, and Lakewood/Ft McPherson, a line was drawn between East Point and Lakewood/Ft. McPherson as well as between West End and Garnet such that all points along that line were equidsitant from each station pair (black line, Figure 11). The line was then extended a ½ mile beyond the equididistant line to make a more inclusive study area and to best represents the catchment area specifc to West End, Oakland City, and Lakewood/Ft. McPherson (arrows, Figure 11).

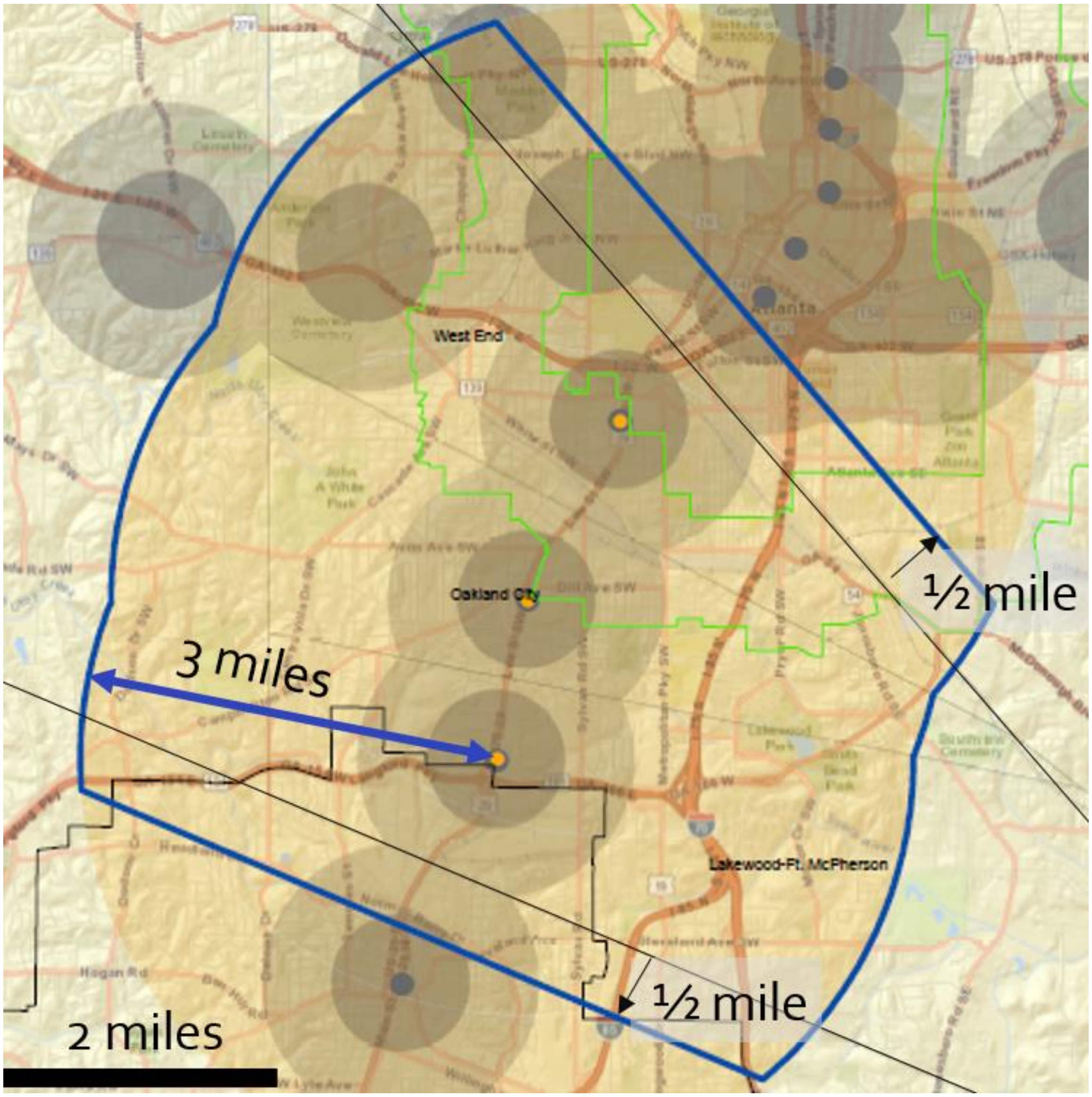


Figure 11: Identification of the Case Study Boundaries (Blue) with study area stations (orange dotes) with the ½ mile and 1 mile grey buffers around transit stations and 3 mile orange buffers around the study area stations. The green outline of the beltline study area is included for context.

Methodology

Data Processing

The LTS analysis required data from 3 main data sources: GDOT road network, Atlanta Regional Commission (ARC) bicycle network, and OpenStreetMap road network. The GDOT data included the street network for the study area as well as the necessary LTS criteria data (number of lanes, AADT, functional classification, and speed limit). The bicycle infrastructure file included the current and planned infrastructure for the region as of 2014 including an indictor variable distinguishing between standard bike lanes and buffered bike lanes (a conditional component in the LTS analysis). This file served as the basis for building the bicycle infrastructure information into the GDOT file. Finally, the OpenStreetMap road network was used to include any additional road infrastructure that may not have been included in the GDOT file. Figure 12 shows the study area with each of these data sources and the relative size of each of the networks that were incorporated into the analysis. The specific sections below provide more detail on the analysis process.

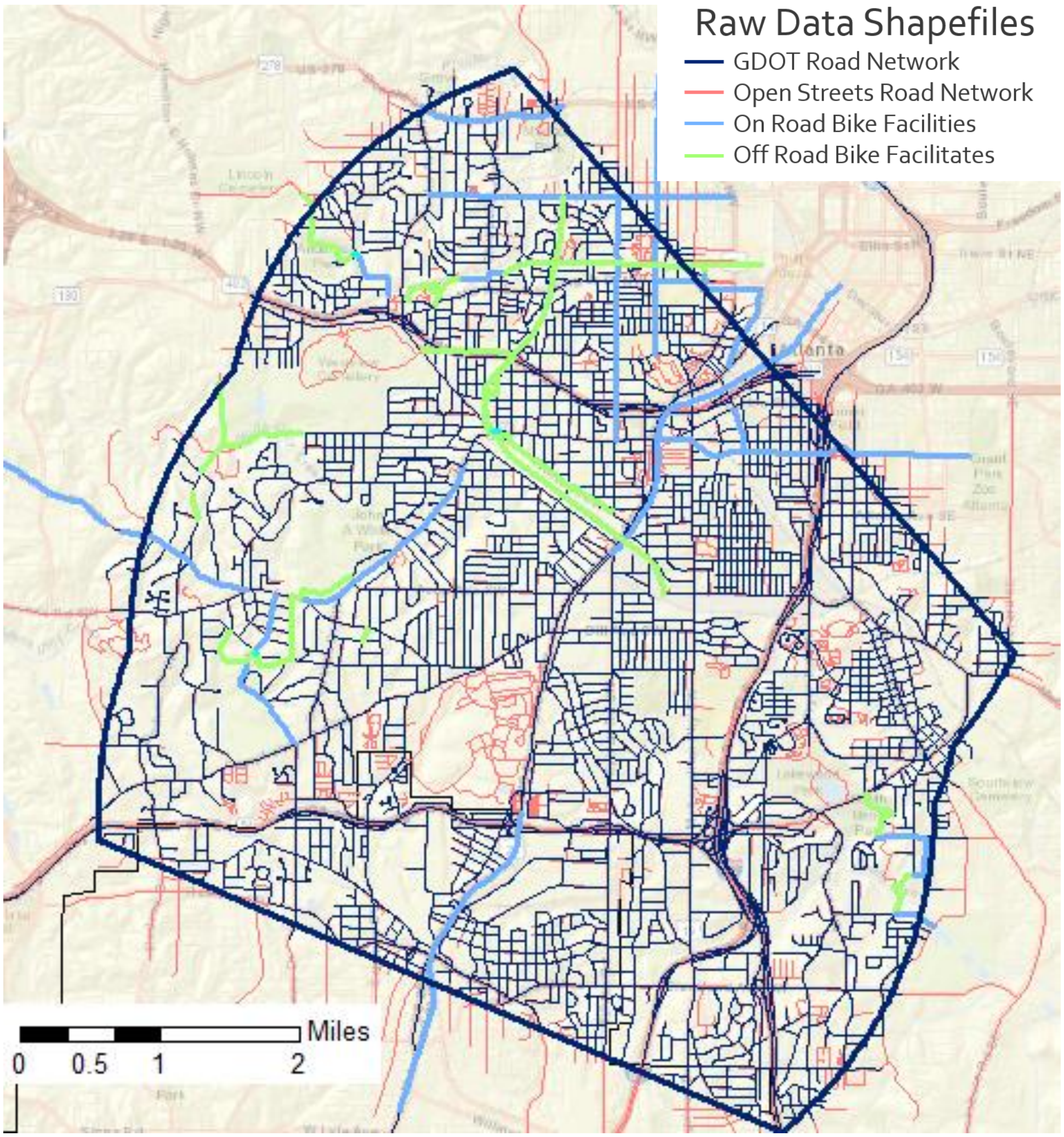


Figure 12: Unprocessed Road and Bike Data.

Link Classification

The modified Atlanta LTS methodology discussed in CHAPTER 3 first required the identification of bicycle infrastructure:

- Separate shared use facility
- Side path
- Cycle track
- Buffered Bike Lane – along on-street parking
- Buffered Bike Lane – without on-street parking
- Bike Lane (with no buffer) – along on-street parking
- Bike Lane (with no buffer) – without on-street parking

The ARC bike data file differentiated between each of the given bicycle infrastructure types required for the analysis, but had no information regarding the presence of on-street parking. To identify the bike infrastructure alongside on-street parking, a visual inspection of google satellite and street view imagery was conducted for each street segment with on street bicycle infrastructure. Given the limited extent of the study area (with relatively few bike lanes), this was a reasonable data processing step. However, for future large scale studies, it would be valuable to determine how important the inclusion of this time consuming data processing step was in determining LTS. If the inclusion of parking is deemed essential to defining the stress level of bike lane infrastructure, it would be beneficial to include the presence of on-street parking during the creation of the bike infrastructure data file.

Once the bicycle infrastructure was identified, the remaining streets were added to the network as shared infrastructure and restricted use streets (e.g. highways) were removed from the network. For all links, LTS was then determined by four variables:

- Through lanes per direction
- Traffic Volume (AADT)
- Functional Class
- Speed Limit

Each of these variables was included in the GDOT road network file acquired for this research. The OpenStreetMap network was used to supplement the GDOT network through the inclusion of connecting links through parking lots and within developments. The links included from OpenStreetMap were given the characteristics of adjacent streets and all added links were classified as LTS 1 or LTS 2 and totaled 15 miles. The bicycle infrastructure was ultimately given LTS scores ranging from 1 to 4 (Figure 13). The LTS of each link was defined according to the Atlanta LTS methodology (Table 7,

Table 8, Table 9,

Table 10, and

Table 12).

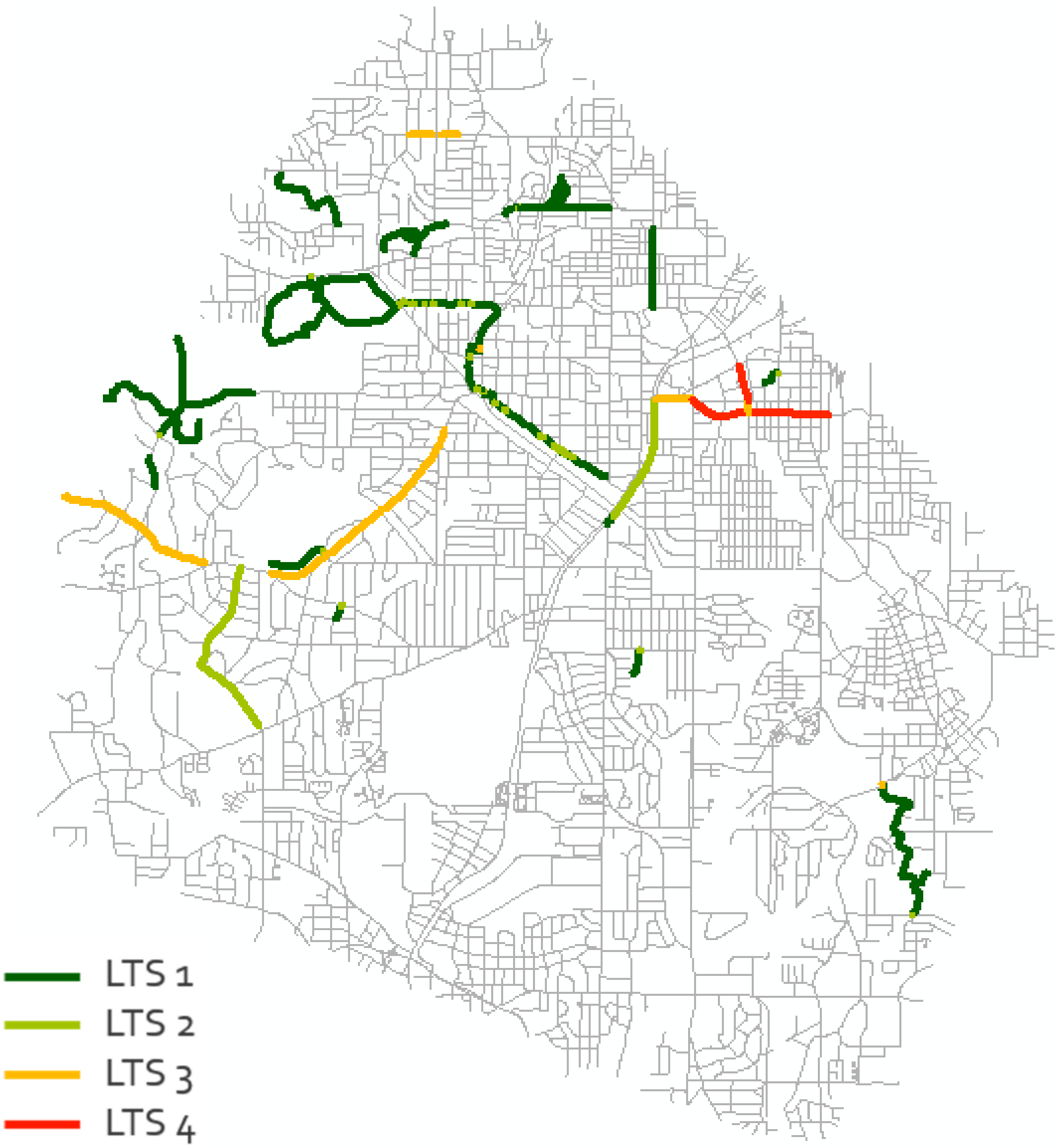


Figure 13: Existing bicycle infrastructure and LTS classification

Unsignalized Intersection Classification

To incorporate the LTS of unsignalized intersections into the network, it was first necessary to locate all the signalized intersections. Signal location data files were obtained from GDOT and ARC. Based on a spot check analysis the combination of these two databases gave a complete representation of the signals in the study area. The network analyst function within Esri ArcGIS software identified the junctions within the network. If these junctions were within 50ft of a signal they were identified as signalized intersections and were omitted from the unsignalized intersection analysis (purple circles in Figure 14). The network was built such that if two links crossed with grade separation, there was no junction (e.g. at an overpass or underpass). However, the list of junctions included any vertex point along a link (blue circles in Figure 14). Junctions were only considered intersections if there were multiple streets (as identified by a unique id for each street) within 30ft of a junction. The attributes of the street being crossed were then used to give each approach an intersection LTS (Figure 14). The maximum LTS between the link LTS and the intersection LTS was then applied the portion of the approach within 30ft of the unsignalized intersection. The unsignalized intersections LTS was defined according to the Atlanta LTS methodology (Table 14).

Figure 14: Close up section of the LTS network and the signalized (purple) and unsignalized (blue) intersections.

In a few instances, side paths with junctions (points at which the link changes direction) alongside streets with LTS greater than LTS 1 were misidentified as unsignalized intersections according to the above methodology (Figure 14). A visual inspection of side paths was conducted to ensure that each side path was correctly identified as LTS 1.

Signalized Intersections

The case study presented here does not include any of the LTS criteria for signalized intersections. In this study area, there were no cases in which there was a bike lane and a right turn only lane at the same intersection and this portion of the signalized intersection methodology would not have impacted the LTS of the study area. Furthermore, there were no low stress approaches at signalized infrastructure with bike infrastructure, so regardless of intersection treatments, the approach LTS would have remained unchanged. This brief analysis of the conditions at signalized intersections in the study area support the discussion in CHAPTER 3 indicating that an evaluation of traffic stress at signalized intersections may not be appropriate in a network level analysis.

Analysis of LTS by Criteria

Before conducting the low stress bike network accessibility analysis, it was first important to understand what components of the LTS criteria were driving the overall LTS. The development of the LTS criteria was grounded in an analysis of existing literature. CHAPTER 7 discusses ways in which the LTS methodology can be further validated, but before applying the methodology here, it was important to understand whether or not any single criteria component was driving the overall LTS designation.

To better understand how each criteria impacted the overall LTS score, the LTS of each link was identified based only on a single criterion and each link was given 4 "LTS by Criteria" scores: Lane LTS, AADT LTS, Functional Classification LTS, and Speed Limit LTS. Figure 15 visualizes each of the four LTS by criteria in three different maps. Each row includes only the links that were scored as a specific overall LTS (2, 3, or 4) based on all the criteria. Each column shows the LTS score according to a specific criterion (by column). For example, all the maps in the Overall LTS 3 row visualize the same links, but each link is colored according the LTS by Criteria. The map in the Overall LTS 3 row and the Functional Classification column shows the LTS as it would have been determined by the Functional Classification of the link (for only links that were given an overall LTS of 3). If a single criterion map in the LTS 2 row is predominantly light green (LTS 2), then that criterion is driving most of the LTS 2 designation. In this case, LTS 2 is driven mostly by the speed limit designation.

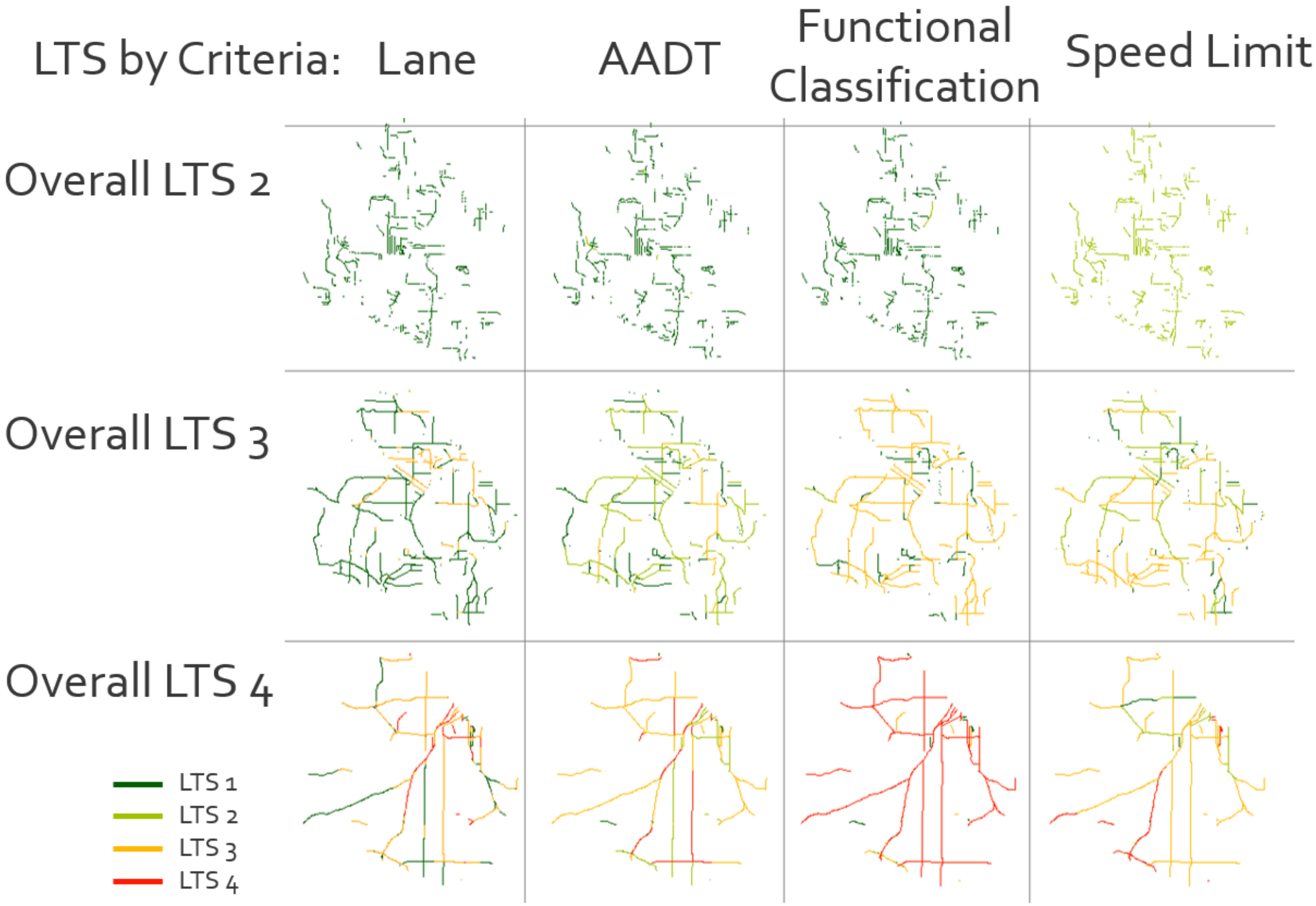


Figure 15: Overall relevance of specific criteria for determining overall LTS

For the low stress bike network analysis, LTS 2 was considered bike-able and LTS 3 was considered too stressful. As a result the specific criteria driving the jump from LTS 2 to 3 are the most meaningful in the analysis. Figure 15 shows that the two criteria that may be driving a link getting categorized as LTS 3 are functional classification and speed limit.

Figure 16 shows the cases in which speed limit and functional classification are the sole determiners of a link being classified as LTS 3 instead of LTS 2.

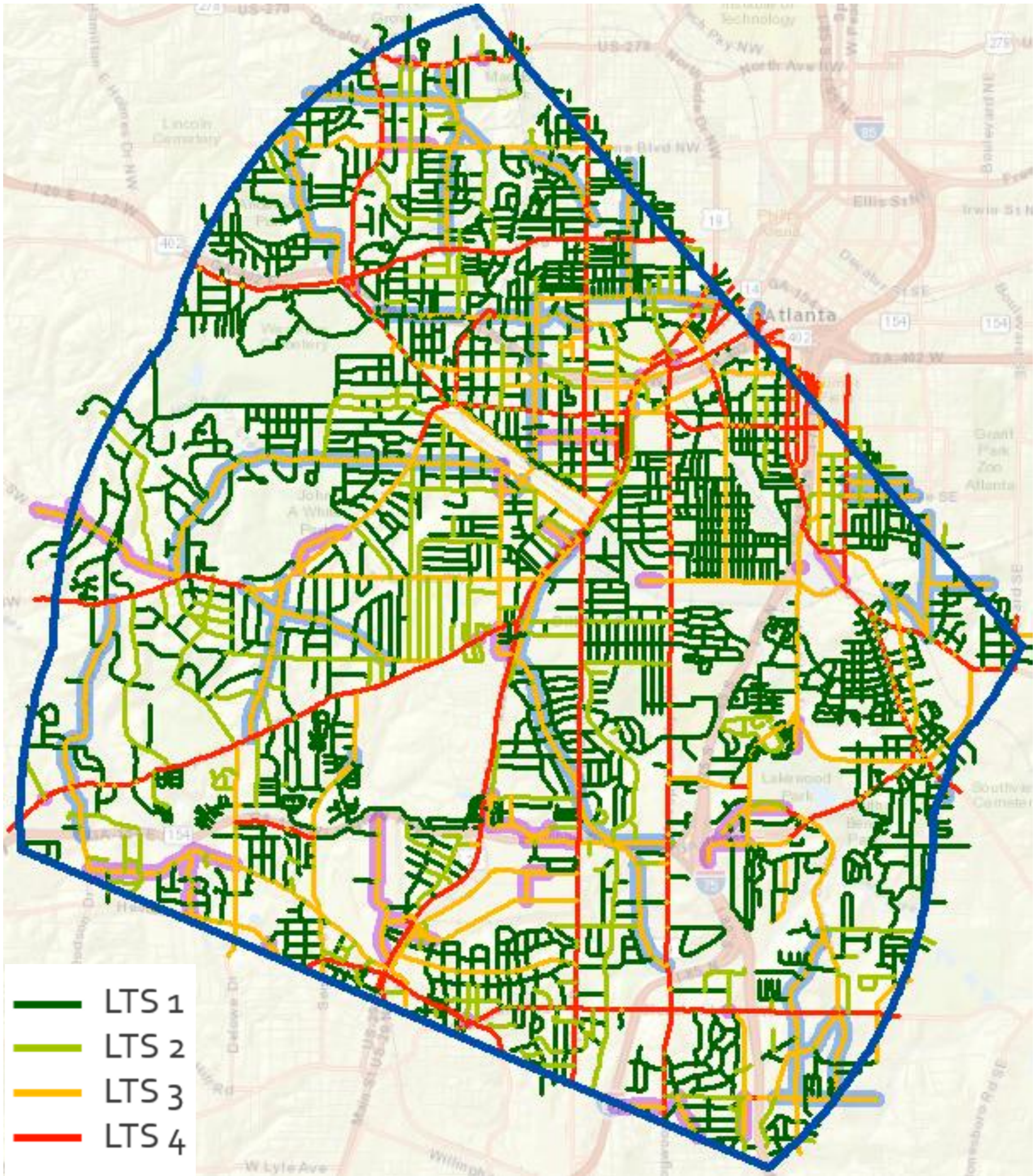


Figure 16: Infrastructure with LTS 3 solely because of speed limit (highlighted in pink) and functional classification (highlighted in blue).

The classification of a link as LTS 3 compared to LTS 2 solely because of the speed limit seems a legitimate upgrade in LTS. The BLOS and the BCI research both show that a bicyclist is able to perceive a difference in speed. The 85th percentile speed of a link in the BCI index will increase the overall BCI by 0.16 for every 5 mile per hour increase in speed (Harkey et al., 1998). The impact of speed limit on BLOS is less obvious as the factor included in the BLOS equation is: $[1.1199 \ln(S - 20) + 0.8103] * (1 + 10.38 * HV)^2$, where HV stands for the proportion of heavy vehicles and S stands for prevailing speed (Huff & Liggett, 2014; Sprinkle Consulting, 2007). It is not obvious what the exact speed limit threshold should be, but it is intuitive that there is one that exists. CHAPTER 7 outlines a proposed future study that would identify threshold limits for each criterion based on data collected from bicyclists of all comfort levels.

It gives pause that links with widths, volumes, and speed limits that classify as LTS 2 should be bumped up to LTS 3 solely because of the functional classification. The functional classification is not included in BCI, BLOS, or original LTS methodologies and it is unclear whether or not this criteria alone should prevent a link from being included in the low stress network. For this study, a visual evaluation of the streets was conducted through google maps street view for all the links that were bumped form LTS 2 to LTS 3 only because of functional class (Figure 17 shows example cases).

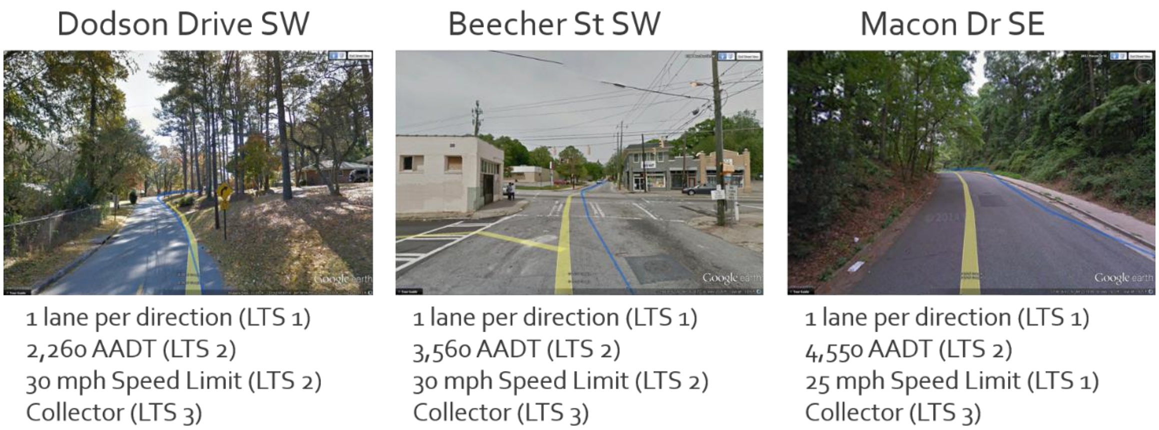


Figure 17: Example cases for which the LTS was defined as LTS 3 only because of the functional classification and was scored as LTS 1 or 2 based on the number of lanes, AADT, and speed limit.

There was not enough evidence from this qualitative analysis to indicate whether or not a link should be classified as LTS 2 or 3. Often these cases seemed to have narrow lanes, low sight distances, designs that promoted speeding, or high volumes of heavy vehicle traffic. Without further research identifying whether or not the functional classification of the road is perceived by bicyclists there is no justification for eliminating this criterion from the analysis. Therefore, the analysis proceeded with all four LTS criteria.

Analysis of Bike Accessibility

The low stress network was defined as LTS 1 and LTS 2. To evaluate the low stress bike networks accessing the West End, Oakland City, and Lakewood/Ft. McPherson MARTA stations, three low stress (LTS 1-2) networks as well as the entire (LTS 1-4) bike network were compared based on total network length, accessible area, and accessible population. The accessible area and population were determined based on the 2010 census blocks that intersected each network. The 2010 census was used instead of the 2009-2013 5-year ACS estimates because the 5-year estimates are only available at the block group level. The study area population was only 1.7% larger based on the 2013 5-year ACS census block group estimates compared to the 2010 census blocks and so the 2010 census blocks were chosen for the analysis to allow higher precision. The block group was not granular enough to provide a precise enough definition of the study area.

The low stress networks analyzed were based on the existing low stress infrastructure, the proposed improvements, and select key improvements based on the LTS analysis. The final entire LTS bike network included the entire bike network and represented the network available to the most stress-tolerant bicyclists. For each of these analyses, the LTS network was converted into a Network Dataset using Esri ArcGIS. The service area tool identified the streets that were within a network distance of 3 miles from each of the study area MARTA stations.

Existing Conditions - Low Stress Network

The analysis of the existing low stress network was restricted to the LTS 1-2 infrastructure. Figure 18 shows the accessible area to each of the study area MARTA stations by network distance.

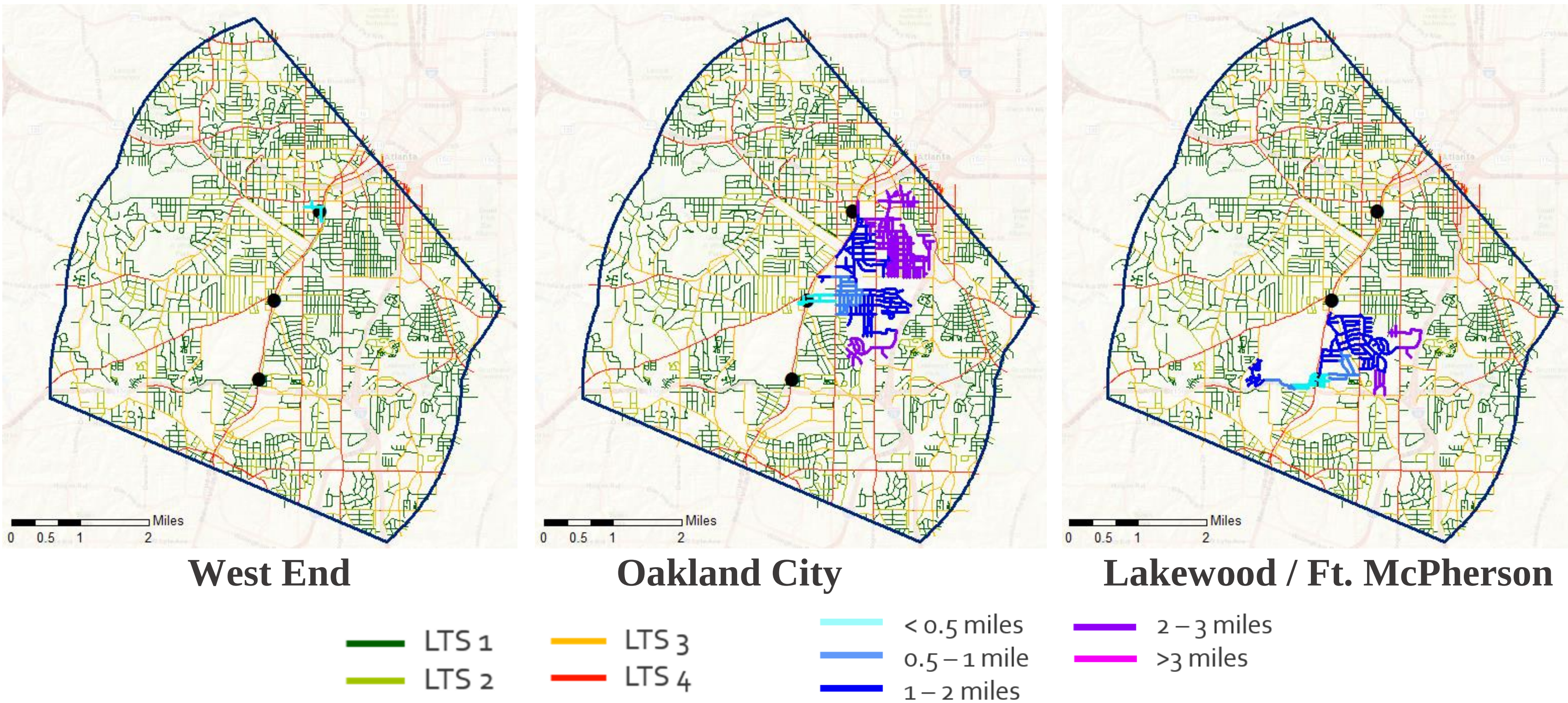


Figure 18: Service area analysis based on existing conditions.

Proposed Improvements – Low Stress Network

The improvements included in this analysis were based on the Cycle Atlanta Phase 1.0 Study Network Map (Figure 19), the infrastructure bond projects identified as complete streets projects (Figure 20), and the planned beltline corridor (Figure 21). Access to the future paved beltline was approximated based on the access points along the interim hiking trail (Figure 21).

Based on the type of proposed improvement, the LTS of a link was manually updated according to the same criteria. Figure 22 highlights the location and LTS classifications for the proposed improvements (the thick line shows the improved LTS and the superimposed thin line shows the original LTS for the same link). The specific improvements are concentrated in around West End MARTA station. The addition of the Southwest portion of the beltline trail and the proposed multi-use trail along Peters Street and Lee Street are the most impactful improvements. Figure 21 shows the bike-able network based on this proposed network, restricted to a 3 mile network distance from each of the study area MARTA stations.

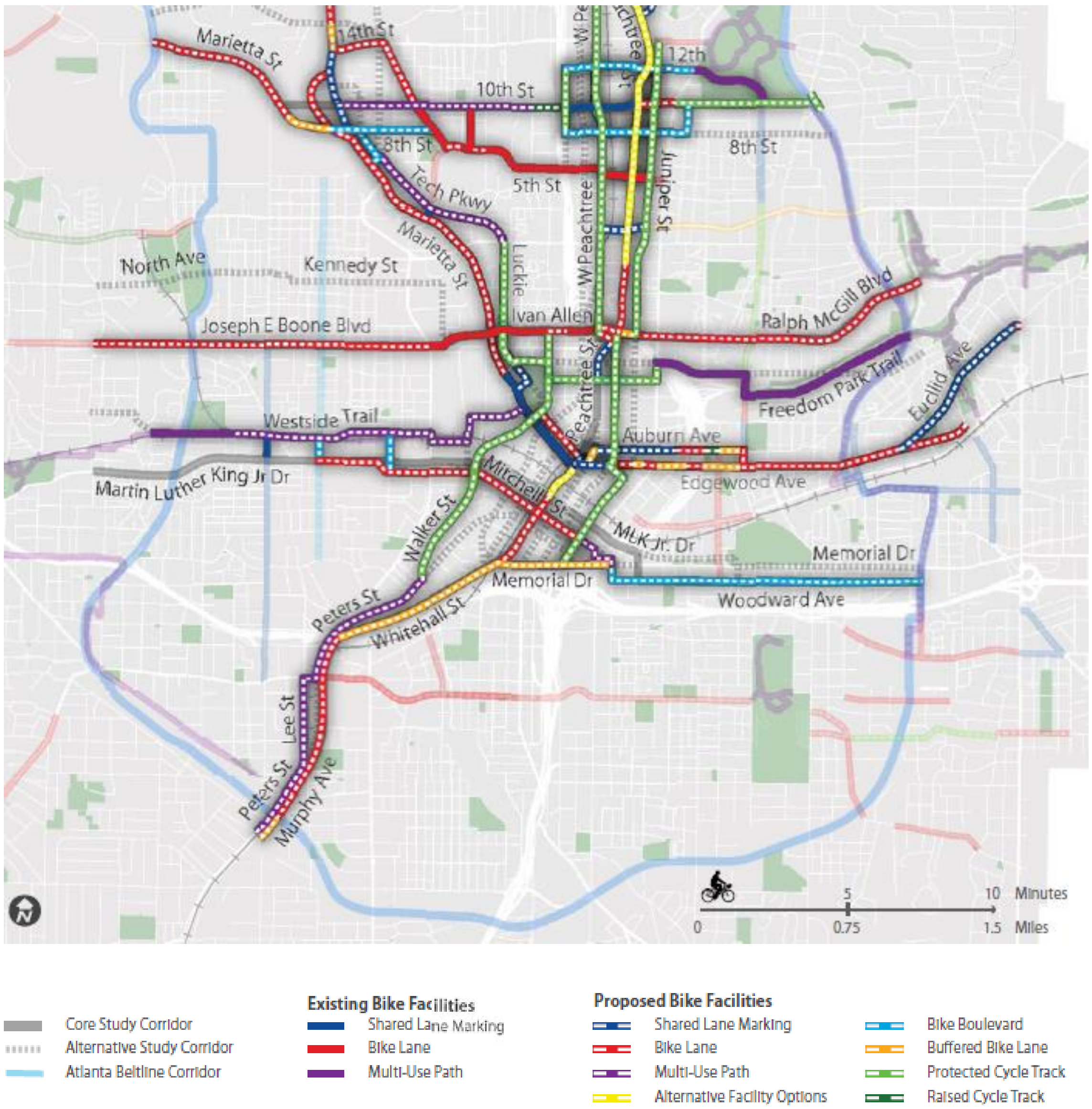


Figure 19: Bicycle Improvements from the Cycle Atlanta Phase 1.0 (Alta Planning + Design, 2013)

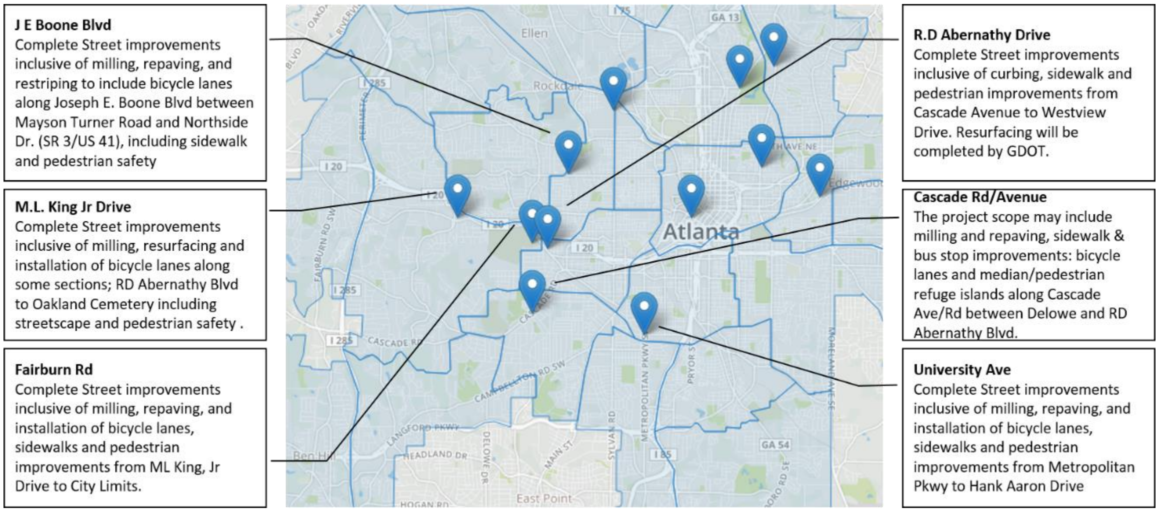


Figure 20: Infrastructure Bond projects that include bicycle improvement (projects within the study area have descriptive call outs) (www.infrastructuremap.org, 2015)

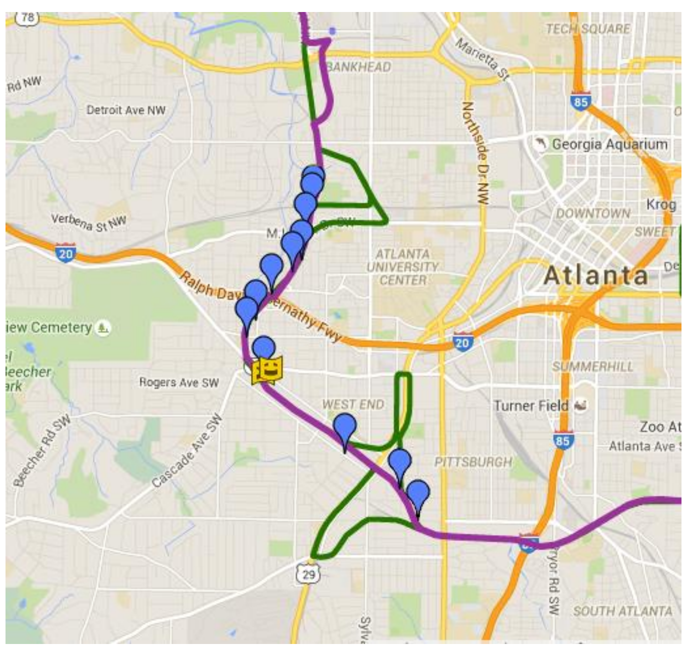


Figure 21: Planned beltline alignment with access points (www.beltline.org, 2015)

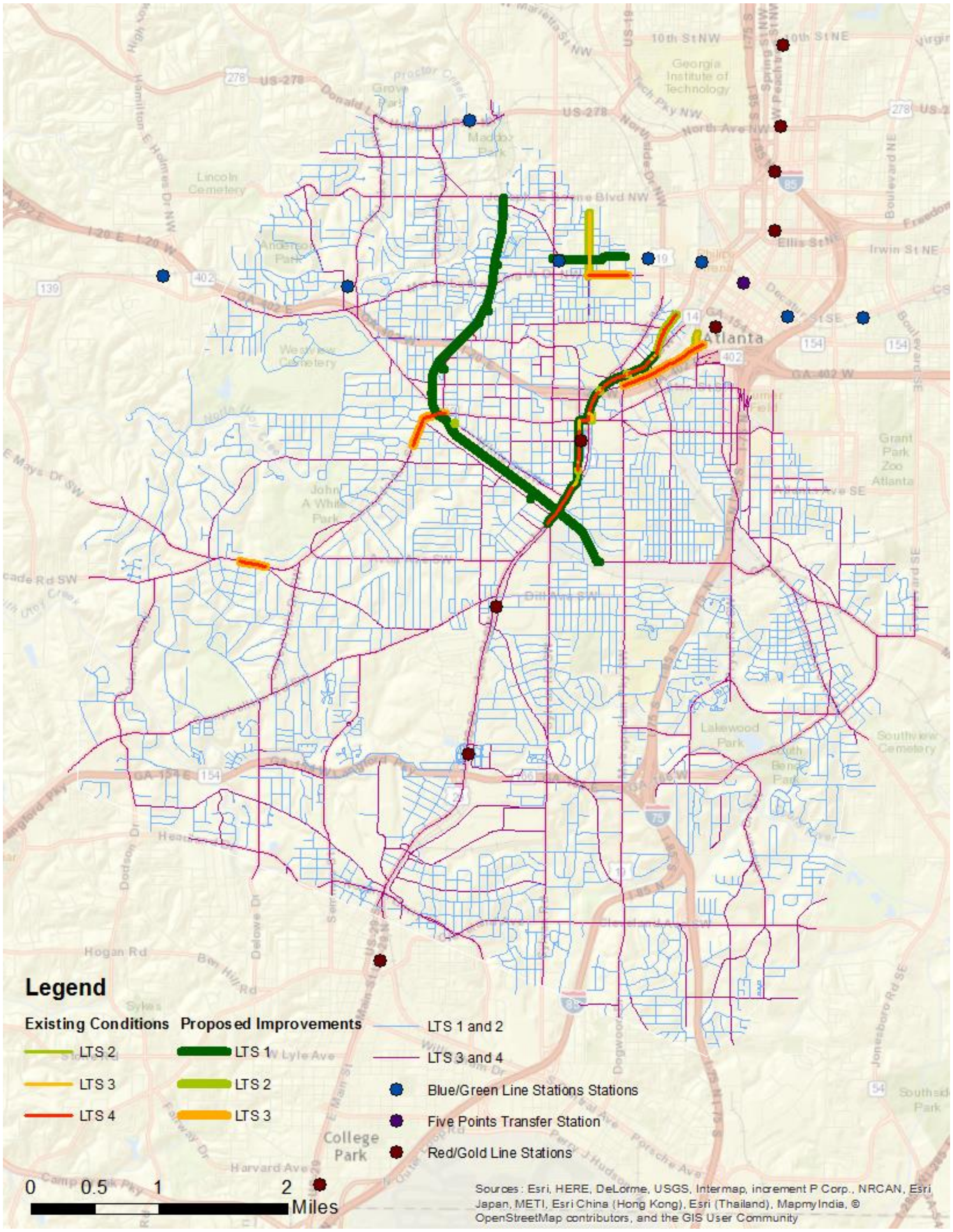


Figure 22: LTS for links with proposed improvements (thick line) and previous LTS (thin line)

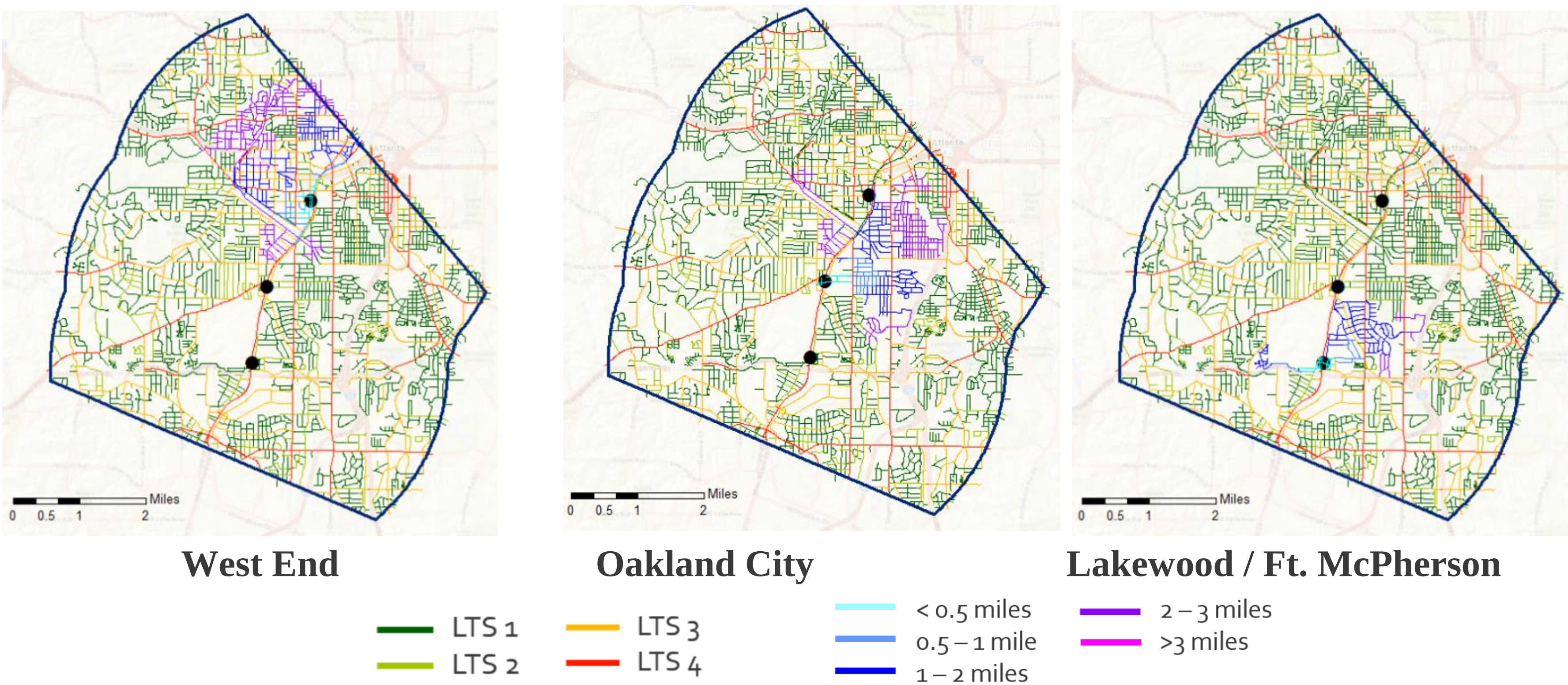


Figure 23: Service area analysis based on proposed improvements.

Select Key Improvements – Low Stress Network

In addition to the proposed improvements network, select key improvements were modeled as a demonstration of how this network analysis could be used to identify priority improvements. Potential key improvement locations were identified based (Figure 24). These key improvements modeled in this analysis serve as an example of how select targeted investments could provide major improvements in accessibility. This simple demonstration includes less than 4 miles of high quality improvements (primarily cycle tracks and/or side paths) (Figure 24, thick blue lines represent these key improvements).

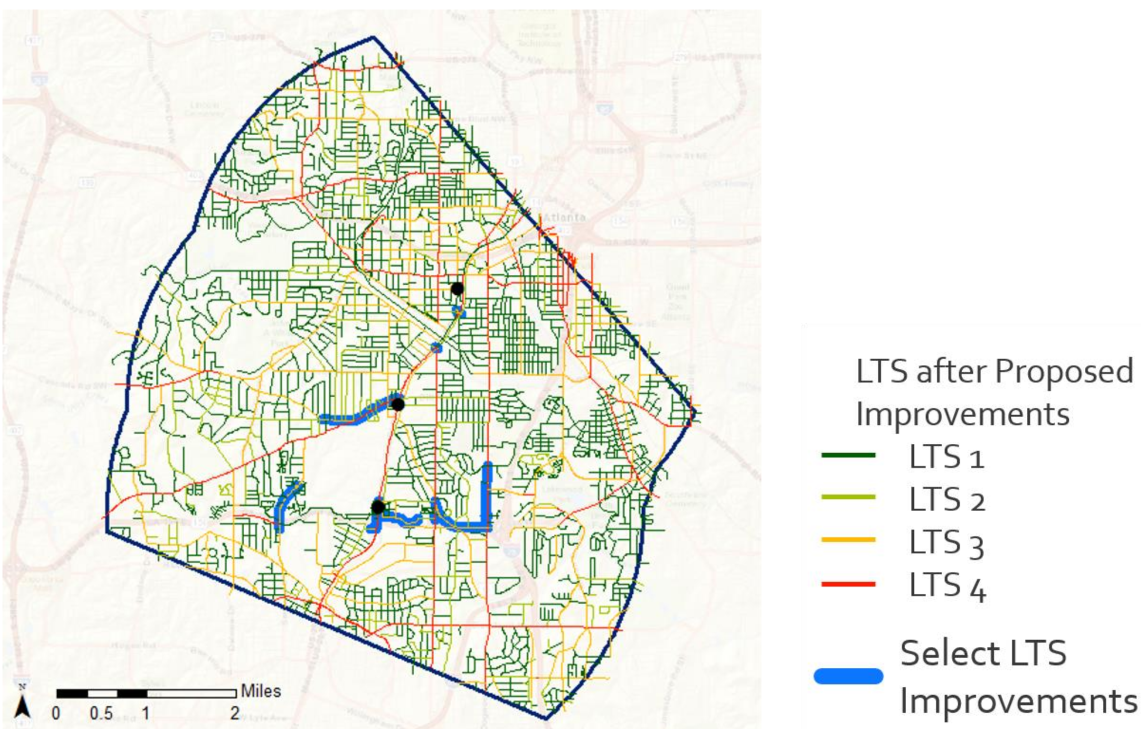


Figure 24: Existing Network with Possible Key Improvements

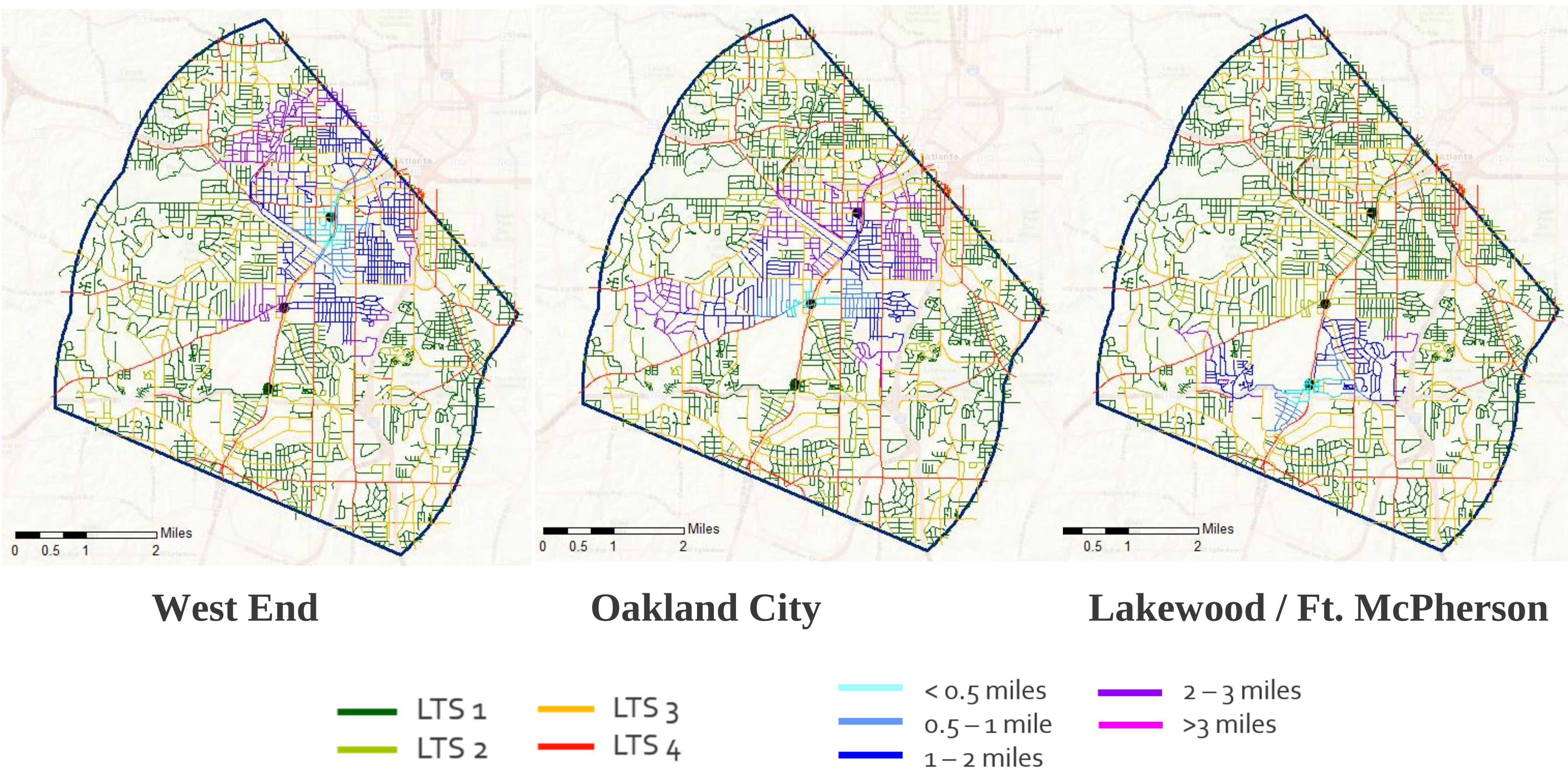


Figure 25: Service area analysis based on select key improvements.

Entire Bike Network

The final network considered as part of this analysis includes the entire bike network. This includes all infrastructure that a bicyclist is legally permitted to use (i.e. the road network excluding highways and restricted access roadways). Figure 26 shows the accessibility by distance to the study area MARTA stations for this high stress bike network (LTS 1-4).

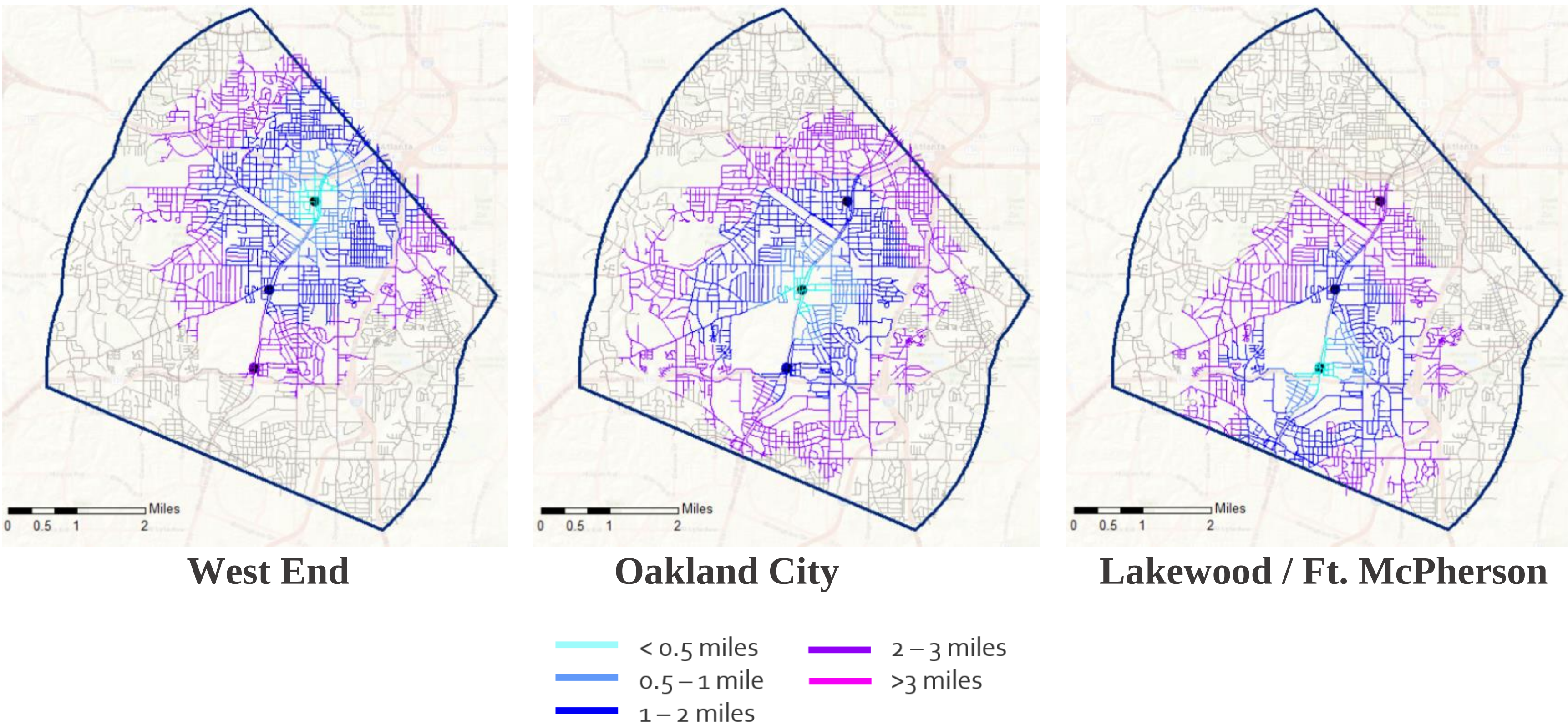


Figure 26: Service area analysis based on entire bike-able network (LTS 1-4)

Results and Discussion

The accessible areas for West End, Oakland City, and Lakewood/Ft McPherson were determined based on a service area analysis with a maximum of a 3 mile network distance. This service area analysis was conducted separately for four different networks: existing conditions LTS 1-2; proposed improvements LTS 1-2; select key improvements LTS 1-2; and the entire bike-able network for *strong and fearless* users (LTS 1-4). Figure 29 shows that as the network improved, the accessible area also expanded.

The tables included within Figure 27 show that the overall network distance increased with improvements in the bicycle infrastructure. Figure 28 shows that there were increases in the relative makeup of each network by distance category. The proposed improvements were associated with the largest increase in accessibility at 2-3 miles (157% increase compared to the existing network, Figure 28). The select key improvements were associated with an additional 149% increase in network length within 0.5 – 1 mile of the stations and an additional 91% increase and 85% increase within 0.5 miles and 1-2 miles respectively. This analysis indicates that in addition to expanding the overall network, the select key improvements were associated with increasing the length of the network specifically within 2 miles of the stations.

Existing Conditions

	Total Network Distance (miles)
0-0.5 miles	4.4
0.5-1 mile	6.4
1-2 miles	25.7
2-3 miles	16.2

Proposed Improvements

	Total Network Distance (miles)
0-0.5 miles	6.0
0.5-1 mile	9.9
1-2 miles	41.9
2-3 miles	41.8

Select Key Improvements

	Total Network Distance (miles)
0-0.5 miles	11.4
0.5-1 mile	24.7
1-2 miles	77.5
2-3 miles	36.4

Level of Traffic Stress 4

	Total Network Distance (miles)
0-0.5 miles	17.2
0.5-1 mile	54.9
1-2 miles	150.9
2-3 miles	109.8

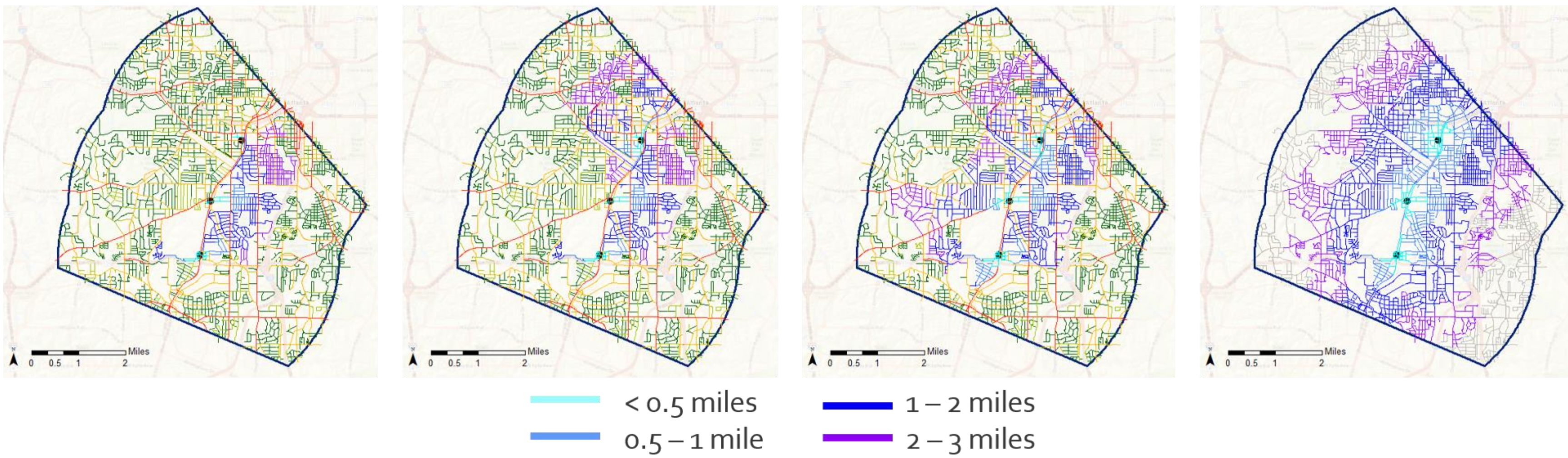


Figure 27: Bike accessibility by network distance for each of the four modeled networks.

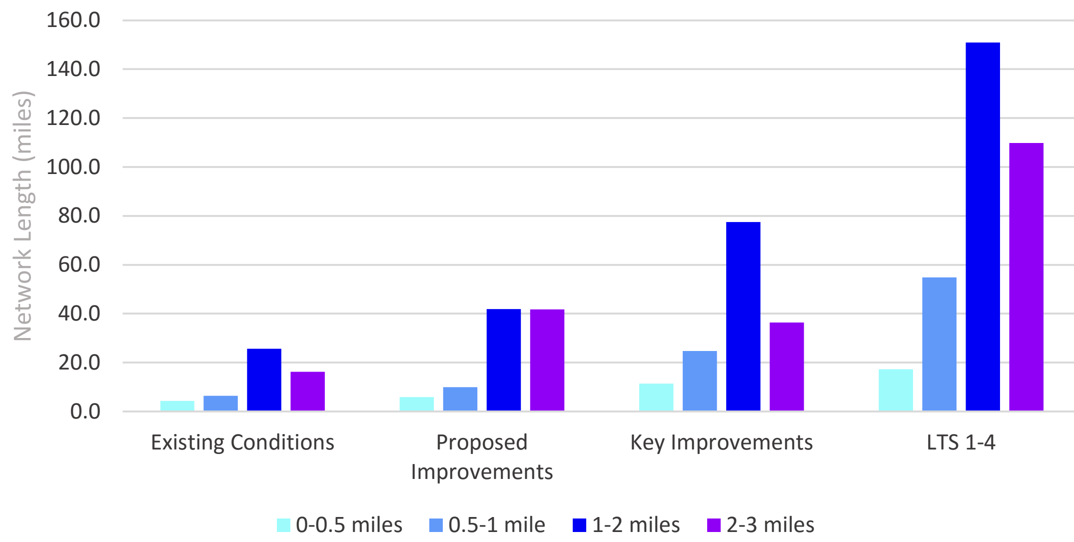


Figure 28: Total network length by distance from the study area stations

To evaluate the accessible population and bike-able area, the census blocks that intersected each network were identified and compared to the entire study area population, area, and network distance (Figure 29). The entire study area network was 443 miles long. The LTS 1-4 network was 333 miles long, representing 75% of the network distance, 78% of the study area, and 84% of the population (Figure 30). Under the existing conditions, the low stress bike-able network was only 53 miles long, representing 12% of the network distance, 13% of the study area, and 15% of the population (Figure 30). The proposed improvements define an accessible network that was 101 miles long and represents 23% of the network length, 23% of the study area, and 22% of the population (Figure 30). The select key improvements added an addition 49 miles to the network length (34% of the total study area network) and provided bike-able access to 50% of the population within the study area (Figure 30).

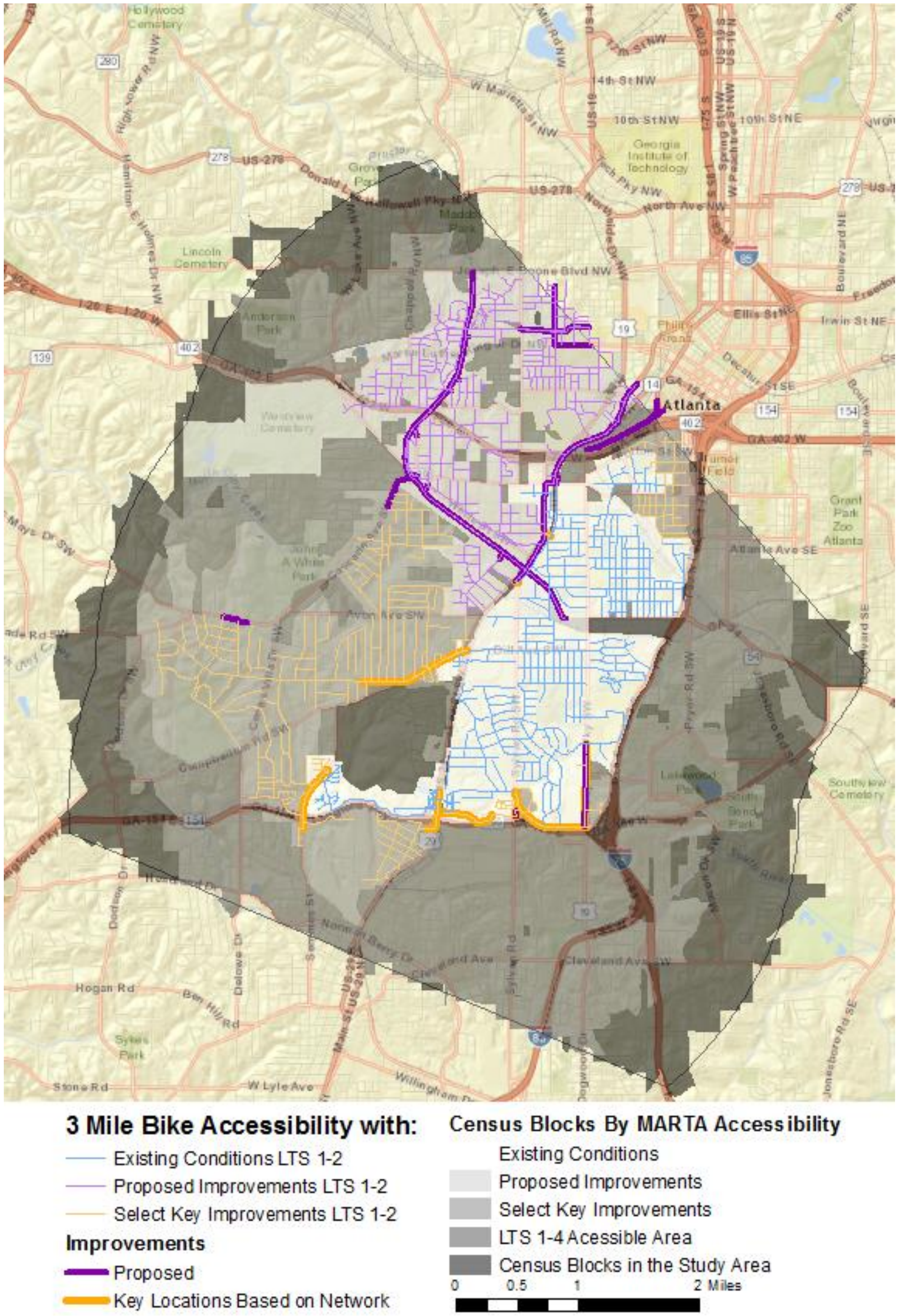


Figure 29: Service area for West End, Oakland City, and Lakewood/Ft McPherson station areas based on existing conditions, proposed improvements select key improvements, and the LTS 1-4 network.

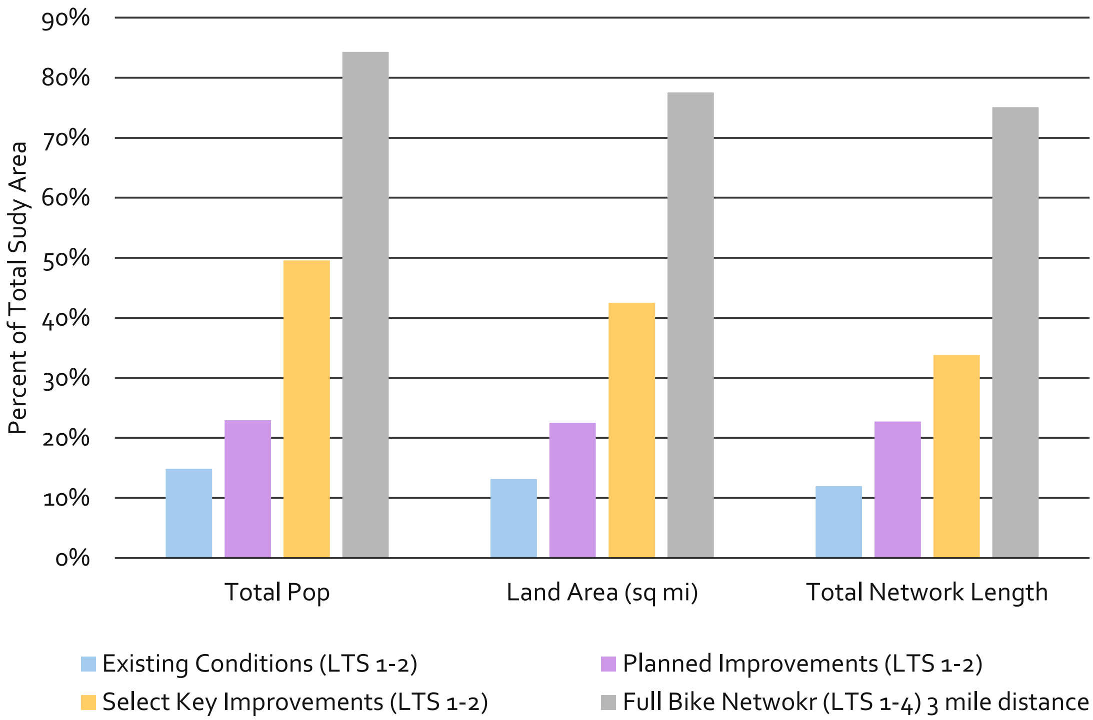


Figure 30: MARTA access based on a 3 mile biking distance for four different bike networks

The proposed improvements increased the population that can access MARTA through a low stress bike network by 55%, while the select key improvements increased the accessible population by an additional 116% (Table 19). There were above average increases in the accessible African American population and the population over 45 years old with the proposed improvements. Comparing the proposed improvements network to the select key improvements network, there were additional, above average increases in the accessible African American population, the under 18 year old population, and (to a much lesser degree) the female population.

Table 19: MARTA access demographics based on a 3 mile biking distance and different levels of stress and proposed bicycle improvements. Percent increases in proposed access is compared to existing low stress conditions and percent increases based on the additional key improvements is compared to the proposed improvements network. Increases in bold are above average increases in population (data: 2010 Census).

	Low Stress Existing Conditions	Proposed Improv.	Select Key Improv.	LTS 1-4	Study Area	Proposed increase in Access	Additional Select Key Improv. Increase in Access
Network Length	53.0	100.8	150.0	332.9	443.3	90%	49%
Land Area (sq. mi)	4.1	7.0	13.1	24.0	30.9	71%	89%
Total Population	14,656	22,649	48,877	83,142	98,597	55%	116%
White Alone	1,120	1,335	2,144	5,059	6,293	19%	61%
Black Alone	12,991	20,516	45,305	74,936	88,192	**58%**	**121%**
Non White/Black Alone	545	798	1,428	3,147	4,112	46%	79%
Under 18 years	3,790	5,629	11,007	19,565	23,607	49%	96%
18-24 years	1,692	2,521	9,393	13,297	14,874	49%	**273%**
25-34 years	2,356	3,435	6,443	11,412	13,493	46%	88%
35-44 years	1,834	2,784	5,305	95,71	11,482	52%	91%
45-54 years	2,001	3,155	6,206	10,862	13,054	**58%**	97%
55-64 years	1,557	2,552	5,248	9,111	10,927	**64%**	106%
Over 65 years	1,426	2,573	5,275	9,324	11,160	**80%**	105%
Female	7,688	11,884	25,912	44,276	52,278	55%	**118%**
Male	6,968	10,765	22,965	38,866	46,319	54%	113%

These results show that the proposed improvements in the study resulted in a considerable expansion of the bike-to-transit access area. These improvements in accessibility resulting from the proposed improvements were exclusively a result of the investment in infrastructure around West End Marta stations. These improvements would result in a disproportionally large increase in the bike to transit access for African American, adult, and aging populations (Table 19). These results show that the stated intentions of the bicycle planning efforts in Atlanta to improve access overall access with specific interest in the minority and aging population is consistent with this analysis of the low stress bicycle network.

The strategic key improvements were identified based on a visual identification of choke points in the low stress network. The improvements resulted in an additional 116% increase in population with low stress bike to transit access. This increase was primarily around Oakland City and Lakewood/Ft McPherson stations with the largest increase in access among 18-24 year olds (273%, Table 19).

Discussion

The existing bicycle network provides very limited access to MARTA from the west side of the study area. Almost all of the existing low stress access to MARTA stations in the study area is from east of the West End and Oakland City Stations. With this very limited network, only15% of the population in the study area can bike along a low stress network to a MARTA station (Figure 30).

The proposed improvements were associated with dramatic increases in low stress bike access to the transit stations, specifically in the area north west of the West End station. Under the existing conditions, low stress bike access to/from the West End station was prevented because high stress arterials surround the study area. However, the proposed improvements along Lee Street and the access to the South West portion of the beltline provided low stress access to the West End station. This access in the area immediately surrounding the station connected to local residential streets which extended north and west, expanding the low stress bike network by 90% and the accessible population by 55% (Table 19).

The select key improvements were identified solely with the intent of expanding the low stress bike access to the MARTA station in the study area. The select improvements were intended to improve low stress bike access to the Oakland City MARTA station from the west side of the study area, improve access to the Lakewood/Ft. McPherson station, and allow low stress East-West connection across the rail corridor (the East-West connections between Oakland City and West End were all categorized as high stress links). These targeted improvements expanded the network by 49% and increased the accessible population by 116% (Table 19). The majority of the improved low stress bike access to MARTA resulting from the select key improvements was to the west of the Oakland City Station.

In addition to expanding the overall network, the select key improvements increased the amount of the network that was 1-2 miles (network distance) from the station and reduced the amount of the network that was 2-3 miles (network distance) from the station (Figure 28). The shift in network distance was a result of adding connections that allow for more direct access to stations.

Despite substantial expansion of low stress bike access to each of these MARTA station with proposed and select key improvements, the *strong and fearless* LTS 4 bicyclist can access the MARTA stations within a 3 mile bike ride from 78% of the study area (by area, Figure 30). This is a substantially greater portion of the study area than any of the low stress networks, as even with the low stress network with select key improvements, only 42% of the study area (by area) can access a MARTA station within 3 miles. This disparity between low stress and high stress bike access to transit emphasizes that a 3 mile catchment area may change dramatically, whether considering a low stress bike network distance, an overall network distance, or a radial distance.

Conclusion

The case study presented here demonstrates that the LTS methodology in conjunction with a simple connectivity analysis can be used to evaluate and compare bike infrastructure investments. The LTS methodology has an advantage in this application over the BCI and BLOS models for two reasons: the LTS methodology relies on easily compiled data and also incorporates a consideration of stress levels based on different rider typologies. This second feature is especially important in Atlanta since there is specific mention of improving bike infrastructure for all rider types (Alta Planning + Design, 2013).

The analysis presented here could also be applied to a comparison of specific bike infrastructure investment alternatives and could help answer questions like: Could more people access transit through low stress bike infrastructure with a 5 mile buffered bike lane on street X, a 2 mile cycle track along street Y, or 6 0.1 miles side paths targeting specific holes in the low stress network? Of course the question is specific to low stress bike access and before making any infrastructure investment, it is important to consider the larger planning context.

The case study analysis demonstrated that a low stress bicycle network analysis can provide a framework for comparing the impact of individual proposed improvements. The results of this specific case study show that relatively minimal, but high quality bike infrastructure improvements along arterial approaches to MARTA stations can provide much needed connections to low stress residential streets. The improvements modeled in this case study analysis that provided direct access to MARTA stations were associated with the largest improvements in access. This case study shows that bridging these gaps in the low stress bike network can dramatically increase the number of people that have low stress bike access.

Overall, the case study was successful in evaluating the low stress bike access to MARTA stations and comparing this access based on different bicycling infrastructure improvements. However, it is important to understand that the LTS methodology itself has yet to be validated through any user studies. Although the specific criteria thresholds defining each LTS level are supported by the literature, they were developed based on the expert opinions of several researchers.

The next steps in this research must be to validate the LTS methodology. The case study analysis shows there is potential value gained from using the current iteration of the Atlanta LTS methodology to compare potential bicycle investments. However, before the method becomes too established in practical applications, it is essential that efforts are made to validate the LTS methodology. The next chapter discusses some potential future research.

CHAPTER 7

FUTURE RESEARCH

At its core, the LTS methodology is grounded in expert opinion and intuition. Before considering the LTS methodology as a potential planning decision support tool, the methodology needs to be validated. The study used to define the BCI used video recordings to determine bicyclists' perception of different design conditions (Harkey et al., 1998). The BLOS equations were based on bicyclists' perception of road conditions along a live course (Landis et al., 1997). Both the video and the live course methodology are strong, but they rely on existing conditions. These alternatives were the best choices in the late 1990's and early 2000's. Recently there has been an interest in adapting driver simulation technology for bicyclists.

With bicycle simulation technology, a set of research participants could be exposed to a large number of very specific design and traffic scenarios. This would allow researchers to adjust, virtually, the lane widths, traffic volumes, prevailing speeds, and road environment conditions (to represent functional class) with different bicycle infrastructure. Researchers will be able to adjust each feature incrementally to identify differences in perceived LTS based on different scenarios. Additional intersection scenarios could be developed to identify the key criteria for evaluating the LTS of signalized and unsignalized intersections.

Technological Opportunity

Three universities currently have bicycle simulation technology appropriate for a study of this nature: Oregon State University, University of Iowa, and the University of Missouri.

Oregon State University

Oregon State University has a bicycle simulator that is linked to a driving simulator so both users can interact with each other (Figure 31). The lab was set up by Dr. David Hurwitz and Dr. Karen Dixon who were both primarily interested in the driving simulator. However, given the context of Portland and the popularity of bicycling, the researchers found it unreasonable to continue studying driver behavior without the inclusion of some evaluation of the more vulnerable bicyclist.

Figure 31: Oregon State University Bicycle Simulator interacts with Vehicle Simulation (Hurwitz Research Program, 2015; Jonathan Maus, 2011)

The driving simulator at Oregon State uses a Ford Focus sedan on a motion-based platform. The vehicle is in front of three angled screens in the front with a rear screen behind (Hurwitz Research Program, 2015; Jonathan Maus, 2011). During the driving simulation, the driver can interact with the person operating the bicycle simulation. The bicycle simulation is located nearby with a bicycle (three sizes are available) facing a single large screen with a rearview mirror screen attached to the handlebars (Hurwitz Research Program, 2015; Jonathan Maus, 2011). The driver and bicyclist can independently see a representation of the other user on the screen in real time (Hurwitz Research Program, 2015; Jonathan Maus, 2011). As the bicyclist approaches the vehicle from behind, the driver will see a bicyclist in the rear screen. Similarly, the bicyclist will see a car in front of them. This setup will allow researchers to begin to study the ways in which drivers and bicyclists interact in real time. However, this micro level study of individual behavior is less relevant to the identification of an LTS network.

Although the interactive technology at Oregon State is not relevant to the LTS research concept, the simulation bicycle can be set up in front of the driver screens and would provide an opportunity to provide a bicyclist with a very high tech quality simulation.

University of Iowa

The Hank Virtual Environment Lab at the University of Iowa has a state of the art bicycle simulator (Figure 32). The bike is positioned 5 ft. from one 10ft x 8ft screen which is orthogonal to two 14.22 ft. x 8 ft. side screens (Calvin Bryant, n.d.). The simulator can control the ease of pedaling to simulate hills and the ambient noise to improve the overall simulation experience.

Figure 32: University of Iowa Bicycle Simulator (Calvin Bryant, n.d.)

The Hank Virtual Environment Lab is housed under the psychology department and includes primarily members of the Department of Psychological & Brain Sciences and Computer Science. The recent work coming out of the lab involving the bicycle simulator primarily focuses on street crossing behavior of children (Babu et al., 2011; Grechkin, Chihak, Cremer, Kearney, & Plumert, 2013; Plumert, Kearney, & Cremer, 2004). The conditions of the road being crossed are adjusted in number of lanes and direction of traffic. Although the research questions proposed by this group are focused around psychology and published in journals like Child Development and Journal of Experimental Psychology there is a rich discussion of wait time and gap choice.

University of Missouri

The University of Missouri has a single screen simulator that is set up with a stationary bicycle (Figure 33). The University of Missouri is working with the City of Columbia, Missouri and Alta Planning + Design to use the bicycle simulator to evaluate wayfinding signage. The study was funded by the Federal Highway Administration in 2014 and is currently ongoing (City of Columbus, Missouri Non-Motorized Transportation Pilot Program, 2014). The goal of the study is to compare specific road markings to identify designs that minimize added stress due to way finding. Similarly, the project is evaluating markings on shared paths to identify the most effective markings for separating bicyclists and pedestrians on a single path (City of Columbus, Missouri Non-Motorized Transportation Pilot Program, 2014).

Figure 33: University of Missouri Bicycle Simulator (Kevin Neill, 2015)

The project includes a second phase that will involve an on-line survey and field testing of the results from the simulation study (City of Columbus, Missouri Non-Motorized Transportation Pilot Program, 2014). This is an essential component of simulation studies as the results must be further validated in the field. However, the simulation is invaluable in the initial stages as it provides the opportunity to collect data from uncommon and geographically distant conditions.

Research Concept

In the BCI and BLOS studies, researchers asked riders of all comfort levels to rank specific road and traffic conditions according to how comfortable they feel, but the LTS methodology was founded in the concept of different rider types having different established comfort levels. As a result, the perceived level of stress should not be averaged across rider types. Instead, this proposed LTS research would involve participants of all rider types. Each participant would first identify her experience level and then self-identify as a rider type. The scenario based questions would then focus on asking the participant if she feels comfortable or would ride along the given conditions. The analysis would then identify conditions that are acceptable to each rider type. This would provide an entirely new body of research, since the majority of previous studies average the perceived level of stress across all rider types. Although the previous studies made efforts to include a wide range of rider types, the majority of participants were often current bicyclists and would likely be comfortable on LTS 3 and LTS 4 infrastructure. The research proposed here would attempt to identify the specific perceived comfort level of potential bicyclists.

As cities across the US attempt to increase the number of bicycle trips, it is essential that the bicycle infrastructure is planned for the less confident user. The LTS concept attempts to identify the bicycle network that would be attractive to these potential users. However, the specific cut points for each criterion have not been grounded in data. This proposed research concept would ground the LTS methodology in hard data. With a more rigorous foundation, the LTS methodology would be better and more easily used by planning agencies to identify the relative value, on a network level, of specific bicycle infrastructure investments.

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