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Understanding the relative attractiveness of alternatives to driving is vitally important toward lowering driving rates and, by extension, vehicle miles traveled (VMT), traffic congestion, greenhouse gas (GHG) emissions, etc. The relative effectiveness of automobile alternatives (i.e., buses, bicycling, and walking) depends on how well streets are designed to work for these respective modes in terms of safety, comfort and cost, which can sometimes pit their relative effectiveness against each other. In this report, the level of traffic stress (LTS) criteria previously developed by two of the authors was used to determine how the streets functioned for these auto alternative modes. The quality and extent of the transit service area was measured using a total travel time metric over the LTS network. The model developed in this study was applied to two transit routes in Oakland, California, and Denver, Colorado.

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Improving Livability Using Green and Active Modes: A Traffic Stress Level Analysis of Transit, Bicycle, and Pedestrian Access and Mobility

MTI Report 12-65

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REPORT 12-65

IMPROVING LIVABILITY USING GREEN AND ACTIVE MODES:

A TRAFFIC STRESS LEVEL ANALYSIS OF TRANSIT, BICYCLE, AND PEDESTRIAN ACCESS AND MOBILITY

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16. Abstract
Understanding the relative attractiveness of alternatives to driving is vitally important toward lowering driving rates and, by extension, vehicle miles traveled (VMT), traffic congestion, greenhouse gas (GHG) emissions, etc. The relative effectiveness of automobile alternatives (i.e., buses, bicycling, and walking) depends on how well streets are designed to work for these respective modes in terms of safety, comfort and cost, which can sometimes pit their relative effectiveness against each other. In this report, the level of traffic stress (LTS) criteria previously developed by two of the authors was used to determine how the streets functioned for these auto alternative modes. The quality and extent of the transit service area was measured using a total travel time metric over the LTS network. The model developed in this study was applied to two transit routes in Oakland, California, and Denver, Colorado.

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EXECUTIVE SUMMARY

Understanding the relative attractiveness of alternatives to driving is vitally important toward lowering driving rates and, by extension, vehicle miles traveled (VMT), traffic congestion, greenhouse gas (GHG) emissions, etc.

The relative effectiveness of automobile alternatives (i.e., buses, bicycling, and walking) depends on how well streets are designed to work for these respective modes in terms of safety, comfort and cost, which can sometimes pit their relative effectiveness against each other. For example, a street network that works well for high-speed vehicle traffic may work well for buses, but not for bicyclists and pedestrians. Until now, little research has been done looking at the quality of the street environment in terms of how it functions for the relative attractiveness of sustainable human-powered (bicyclists and pedestrian) and vehicle transport (bus transit). Building on previous research and the development of an innovative measure of traffic stress, this study reveals the often competing characteristics of safety and comfort against the speed and reliability that can drive the attractiveness of these modes.

In this report, the level of traffic stress (LTS) criteria from MTI report 1005[1] was used to determine how the streets in our study areas functioned for these auto-alternative modes. Specifically, the LTS criteria used for this study include vehicle speeds, number of lanes, presence of parking, presence of bike lanes, and intersection type (whether signalized or unsignalized).

The quality and extent of the transit service area was measured using a total travel time metric over the LTS network. The model developed in this study was applied to two transit routes in Oakland, California, and Denver, Colorado.

The key research findings and recommendations are as follows:

- Higher LTS levels (LTS 3 and 4) networks around transit routes are uncomfortable and unattractive for bicycling and walking—essentially, the traffic becomes a stressful barrier to non-motorized travel—thereby limiting the effective catchment area of the transit service. The recommendations from MTI Report 10052 to make sure connectivity is maintained through the provision of safe crossings to destinations/attractors such as transit stations is again re-emphasized.

- For streets and networks with LTS level 2 or below, bus travel times are comparable to bike riding times to the point that they limit the effective attractiveness of bus transit service for bicyclists who use a bicycle/bus mode. This study suggests that the effective bus transit service catchment area can be constrained to within a one-mile network distance around the transit stops.

- Paradoxically, changes in network LTS can shift the relative attractiveness of once complementary mode pairings (e.g., a bicycle/bus-transit mode choice) toward becoming directly competitive and substitutable with each other (e.g., a bicycle/transit versus a bicycle-only mode choice). For instance, at lower levels of traffic stress (LTS 1 or 2) the choice between a bicycling/bus transit and bicycle-only modes become equally attractive and substitutable, especially if you are a bicyclist outside the one-mile range of a regular service bus stop. In these cases, travel time between a bicycle/bus-transit trip and bicycling-only become more alike, and therefore the choice between the modes becomes interchangeable. Bicycling all the way to the destination becomes more attractive, especially considering transfer penalty, availability of parking, on-board accommodation, and cost, as well as the bicyclist's independence and self-determination regarding the characteristics of their trip (on-demand, route choice, trip chaining, opportunity to exercise, etc.).

- Improving transit mobility and the comfort and encouragement of pedestrians and bicyclists to access a larger service area than traditionally attributed to transit produces the highest livability and increases alternatives for the traveler. Therefore, we recommend that urban areas design and plan for LTS 2 levels, accompanied by enhancements to help transit operate more efficiently in conjunction with pedestrian and bicyclist comfort and safety improvements. Some measures to thoughtfully consider include transit-only lanes, transit priority lanes at the intersections, transit-stop bulb-outs, and integrated networks of pedestrian and bicycle routes throughout the metropolitan area.

I. INTRODUCTION

As on-street, non-motorized travel accommodation has increased among U.S. metropolitan areas, there is a significant need to examine the interaction between transit and non-motorized access modes (walking and cycling) in terms of service area expansion and when competition between the modes may arise.

According to the 2013 Transit Capacity and Quality of Service Manual (TCQSM),[3] the most influential quality of service factors that contributed to overall satisfaction were frequency, wait time, reliability, and access. Transit service is deemed effective when people are able to access it quickly, safely, and economically to reach their desired destination. Effectiveness of a fixed-route transit service may be evaluated from the rider or operator perspectives, but, if not carefully executed, strategies meant to improve service may have negative consequences for one or the other or both. In practice, it is not always possible to completely satisfy one without impacting the other. There is the need for transit operation solutions that balance multiple competing objectives. Attributes of transit service impacting the rider include total travel time (access time, wait time, ride time); amenities such as convenient and safe shelters; traveler (schedule and/or real-time) information; on-board accommodation; and adequate parking. Generally speaking, operators are concerned with providing quality and efficient service, within a limited budget.

Access, in the context of this study, is the distance between trip origins, transit stops and destinations. One strategy for improving access is by providing more stops. However, the impact of increasing the number of stops along a fixed route is increased travel time for those already onboard the vehicle and the operator. This, in turn, impacts the ability to provide frequent service due to budget limitation. Access can also be thought of as the ability to move from the origin of a trip to transit stops safely without discomfort or undue detour. This paper examines the accessibility of transit from the aspects of travel time, safety, and comfort for two important non-motorized modes, walking and cycling.

The outline of the report is as follows. First a brief literature review of relevant research activities on the topic of transit service area and operational modeling is presented. The research methodology follows, including details of the data collection and analysis. Then results and findings are presented, followed by conclusions and suggestions for future research.

II. LITERATURE REVIEW

One can classify transit operational analysis models in terms of their service area, stop density, or location impact assessment. Table 1 shows some common modeling paradigms based on the ways they measure service area access.

Table 1. Access Measure Models

Model	Access Measure	Travel Time Measure
Continuum	Uniform	Fraction of Spacing
	Airline	Based on Euclidean Distance
Discrete	Airline	Based on Euclidean Distance
	Taxi-Cab	Ride time + Projected Walk Time
	Augmented Network	Total Travel Time

Fixed-route transit service is primarily accessed via a discrete number of access points or stops, with the stop service area comprising the neighborhood around each access point. Early research in transit non-motorized service area modeling implemented simplifications to allow the use of calculus-based (closed-form) mathematical solutions to the transit access problem.4 Such simplifications provide a way to avoid the difficulty of accounting, especially for the impact of walking to a transit stop.5 Because digital street network data was rarely available and computation of a large dataset was very expensive, tractable formulae were prepared by flattening the access network to the route geometry and assuming either uniform demand along a route or aggregated demand profiles at each stop. The network was simplified by distilling the access measures into a uniform dataset amenable to solutions based on calculus (continuum) mathematical equations. Researchers such as Wirasinghe et al.6 and Van Ness et al.7 provided very elegant, but highly simplified, continuum models that display the importance of objectives for transit systems operations. While the insights continuum models provided have been useful to highlight important planning-level transit operational strategies such as route spacing, tradeoffs between alternative routes, and alternative transit service types (local, express, short-turning, dead-heading, etc), they are inadequate to account for factors key to pedestrians and bicyclists as they fail in providing practical guidance useful for day-to-day operations. Such details as how to improve service, whether a particular access location is beneficial or not, or what potential impact does relocating a stop have on the user or the operation of the route become impossible to measure.

Another avenue of research has utilized discrete stop models that are more representative of the actual route structure. These models have been used, similar to the continuum models, to varying degrees of success in transit service operational analyses. From the European experience, one of the most prominent model formulations is known as “set covering” and much pioneering work was done by Schobel et al.[8] Discrete models have brought a more realistic view of transit operations due to the fact that transit stops are modeled individually and access and operation impacts are computed discretely, resulting in more realistic analysis. Still, the majority of the research followed generalized airline distance as a service access measure. Such simplifications gloss over route as well as access network complexities.

Other discrete models proposed were designed to be demand sensitive through reflecting variability in one or two dimensions. The first application was using the method of superposition to aggregate the demand along the length of the route. Work done by Furth and Rahbee9 was such a treatment. An extension of the same concept was the addition of a more realistic network walk access model incorporated in the work done by Furth et al.,10 Mekuria,11 and Mekuria et al.12 The identification of barriers to access and a discrete point origin for the demand and its possible distribution over the service area from a network travel perspective was accomplished through the use of spatial analysis. The network modeling concept was later applied to ascertain access based on roadway characteristics generating the Low Stress Network Models analysis built for bicycle travel during MTI project 1005.[13]

Other research on cycling access has examined the ideal conditions that encourage integration between public transit and cycling. Pucher and Buehler[14] pointed out that increased bicycle access shares in several cities in North America may be attributed to those municipalities that provide cycling amenities such as safe access to parking and onboard bike-and-ride facilities at transit stations.[15] Building on Appleyard,[16,17] Cervero et al. provide details regarding how the transit service area increased significantly when Bay Area Rapid Transit (BART) improved bicycle facilities at two stations.[18] Appleyard[19,20,21] show how bicycle amenities, as well as human-scale built-environment/streetscapes and land uses, encourage access for walking and bicycling. Rose and Marfurt's[22] research in Australia provided insights as to how far commuting cyclists traveled and the average commute speeds. Their study found that commute cyclists traveled, on average, 45 minutes at a speed of 22 kph (13.5 mph). Average bus transit speed is 12 mph and the implication of higher cycling speed is that, from travel time considerations, for most urban commutes cycling is preferable to bus transit. The length of cyclist ride time is also much more than what would be expected for transit access time, and most urban commutes would be completed solely by biking if there is access to a safe network.

Cheng and Agrawal describe a tool—TTSAT (Time-Based Transit Service Area Tool)[23] — which assesses transit service areas using a network analysis approach. The tool used by Cheng and Agrawal allows a visualization of the accessible service area within a travel time budget. Interesting results and map visuals were produced to show the comparison between walking and bicycling. The paper estimated that use of bicycles increased the service area by over 700%. The measures used to produce the service area were calculated using one-to-many total travel times and they accounted for access time at both ends, waiting time, and in-vehicle travel time. Several limitations were listed regarding the model used in the study. The model did not use accurate trip times due to lack of availability. With the presence of abundant real-time transit data, that limitation can be more easily addressed now. Also the access network used was an automobile-accessible road network (pedestrian and bicycle paths were not included). The use of transit travel time (trip data) by stop would also increase the accuracy of arrival and departure times, time of day delays, etc. The speed used by Cheng and Agrawal was taken from the large bicycling study by Rose and Marfurt.[25] The reported increase in service area size of over 700% appears to be more than the walk-speed differential warrants. In general, transit trips are assumed to be made within a single municipality or not to exceed 12 miles in length (an hour's travel time by bus or bike). Longer trips that span service areas much larger than those within a single municipality with faster transit service,such as those offered through limited, express or heavy rail transit, may encourage larger service-area increases. Many transit operators cover much larger geographic extents in a single route service spanning over several municipalities (e.g., Valley Transportation Authority Light Rail Route 902 Winchester to Mountain View has a route length of 22.3 miles, spanning four municipalities; Bus Route 22 Palo Alto CalTrain Station to East Ridge Transit Station Route is 25 miles long and spans five municipalities, etc.). Travel time and out-of-pocket cost considerations make these alternatives compete with other modes for the choice rider.

In comparison, TCQSM[26] uses a bike access service area of one mile, or four times the typical quarter mile walking service area. This is largely due to the speed differential between walking and biking. There are other factors considered important from the user's perspective, including the availability of safe and direct access networks. This is an area where more research is needed.

This research examines two access modes to a transit stop, walking and bicycling, on a network classified using the LTS safety criteria developed by Mekuria et al.[27] Access travel times are computed for various LTS levels to investigate the effect on quality of service. The current project adds a unique dimension to pedestrian and bicycle access by introducing the LTS classification to the transit network. The primary contribution of the research is to explore the effect of improving walking and bicycling stress levels in transit service areas. This research assumes that for access and egress to and from transit stops, the access network experienced by cyclists is quite similar to pedestrians' access in terms of street safety at critical crossings. Furthermore, the burden of street crossing for cyclists may sometimes be worse than for pedestrians, who don't share the same right of way with automobiles. Safety statistics found in Hawaii[28] show that although cycling has only a quarter of the mode share compared to walking,[29] cyclists are twice as likely to get injured as pedestrians.[30] While the pedestrian network may also be modeled separately from the bicycle access network, in this research walk access is assumed to parallel bicycle access and the same network is used for both modes.

III. RESEARCH METHODOLOGY

BACKGROUND

In the research literature, various ways of analyzing network access in the transit service area have been proposed. Some have utilized simplified assumptions to reduce the complexity of modeling the access network, such as airline walk distances (as the crow flies) or of a dense grid (Manhattan Grid). This modeling paradigm requires essentially point locations to compute access time regardless of whether there is significant detour required or there is no way to get to the stop location from the origin. It assumes by default that access exists everywhere and employs the simplest distance measures using Euclidean or taxi-cab geometries. In contrast to the above, realistic assumptions follow the actual street network with detailed data including available walking paths, topography, and other barriers such as safety at intersection crossings.

Using the street network to model transit service areas has been successfully demonstrated by Furth et al.[31] Service area analysis with the access street network is both data and computing power intensive, but it reduces the inherent variability in the location and service area analysis. This report utilizes the realistic network model and includes an update to that method by utilizing an access network with the low stress classification proposed by Mekuria et al.[32]

The primary objective of this research is to examine the effect of walk and bike access and comfort on changes in the configuration of transit service areas. The access network is classified using the Low Stress Network classification method primarily for the bicycle mode, and an assumption is made that the walk access also shares similar characteristics. The methodology used in this research also demonstrates a unique transit service operational impact analysis utilizing the most detailed transit data (individual transit trips), realistic street network, and discrete parcel origin/destination data.

A transit access network may be assumed to take a variety of forms according to available data and the level of detail needed in the analysis. Access measures such as airline (Euclidean) distance, grid, or network distances could be used to account for impacts related to location. In recent times, due to the availability of detailed geographic data, it is possible to model walk paths using the actual street access network. Many times such data is readily available through the municipalities or regional transportation entities.

RESEARCH APPROACH

This research examines how the LTS of the street network surrounding a transit service catchment area changes the effective extent of the catchment area (by making it less comfortable for pedestrians or bicyclists), and creating a condition for competition with non-auto modes such as bicycling. Service area variations are mapped, using travel time from individual parcels to the end of the transit line, while the non-transit portion of the trip is made over a stress-level classified network. The service area variations are mapped to reveal the changes in the walk and bicycle mode service area reach. Under such constraints (i.e., travel time and stress-level classified network), there appears to be a threshold distance that governs the extent of the service area.

For the purpose of this study, a street network area that extends over the available spatial network on both sides of a transit route was used to model the combined service area of walking and cycling access to bus transit. Separate analyses were performed to model the changes in service areas, with variations in access speed (walk, bike travel).

Data Collection and Analysis

There are three primary spatial datasets that are used in the course of the data analysis. These include both static transit stops and temporal transit trip data; static parcel and demographic data' and street network data classified according to the LTS criteria. These inputs are utilized to perform the service area and the operational analysis. The street network and roadway performance attribute data could come from either municipal, census- or state Highway Performance Measurement System HPMS-based sources. Attributes such as speed limit, functional class, number of lanes, intersection type (signalized, non-signalized), presence of a bike lane, parking, etc., are used in the weakest link principle of the LTS model to classify the roadway. Parcel/block and demographic attributes such as population, zoning, and area are used to distribute stop-level demand data to the transit service area for the purpose of determining the demand travel paths and times.

In summary, the basic datasets used to model transit access are:

- Street or access network;
- Origins and destinations such as homes and business in the form of parcels or blocks;
- Land use / zoning designations from available municipal sources;
- Census block-level population data; and
- Transit route service points (i.e., transit stops) with transit trip-level service characteristics.

The street network is generally composed of the segments (links) that are used for traveling from origin to destination (modeled as link-node sets) with links attributed with generalized travel time as cost and LTS designation. A short description of LTS is provided in Table 2 and further details are provided by Mekuria et al.[33]

The transit trip and operational data is primarily found from transit agencies. Block-level demographic data was obtained from the U.S. Census, while parcel-level data was downloaded from municipal sources. Street networks with associated attributes were also obtained from regional and municipal sources in data repositories available in the public domain. Some transit-specific data was provided courtesy of Alameda County Transit in the Bay Area of California and the Regional Transit District, Denver (RTD-Denver), Colorado.

MODELING LEVEL OF TRAFFIC STRESS ANALYSIS

The method used in this research models the service using an augmented network of walking, biking and transit travel time over a low stress classified spatial data. The analysis framework taps into network algorithms developed for transit stop spacing analysis and optimization research at Northeastern University[34] and for MTI[35] with extensions to include individual transit trip travel time data as input.

As shown in Table 2, this research builds on a four-level classification scheme anchored by LTS 2, whose criteria essentially mimic Dutch bikeway standards.36 This is the level of tolerance that is mapped to the mainstream traffic-intolerant adult population, those who are “interested but concerned.” Dutch standards have been proven on a population basis to be acceptable to the general traveler, since bikeways built according to those standards attract essentially equal male / female shares and high levels of bicycle use for all age groups.37 (By contrast, cycling in the U.S. is about 70% male, with very low participation rates by older people.) LTS 1, mapped to “eight to eighty four years old” riders, demands greater separation from traffic turbulence and easier crossings, while LTS 3, mapped to Geller’s “enthused and confident” group, allows increased traffic stress comparable to bike lanes on many American arterials. LTS 4, mapped to the “strong and fearless,” corresponds to riding in mixed traffic at 35 mph or more, or in bike lanes or shoulders next to traffic at highway speeds.

Table 2. Levels of Traffic Stress (LTS) Descriptions

LTS Level	Description
LTS 1	Presenting little traffic stress and demanding little attention from cyclists, and attractive for a relaxing bike ride. Suitable for almost all cyclists, including children trained to safely cross intersections. On road sections, cyclists are either physically separated from traffic or are in an exclusive bicycling zone next to a slow traffic stream with no more than one lane per direction, or are in mixed traffic with a low speed differential and demanding only occasional interaction with motor vehicles. Next to a parking lane, cyclists have ample operating space outside the zone into which car doors are opened. Intersections are easy to approach and cross.
LTS 2	Presenting little traffic stress but demanding more attention than might be expected from children. On road sections, cyclists are either physically separated from traffic or are in an exclusive bicycling zone next to a well-confined traffic stream with adequate clearance from a parking lane, or are on a shared road where they interact with only occasional motor vehicles with a low-speed differential. Where a bike lane lies between a through lane and a right-turn lane, it is configured to give cyclists unambigous priority where cars cross the bike lane and to keep car speed in the right-turn lane comparable to bicycling speeds. Crossings are not difficult for most adults.
LTS 3	Offering cyclists an exclusive cycling zone (e.g., bike lane) requiring little negotiation with motor traffic, but in close proximity to moderately high-speed traffic; or mixed traffic requiring regular negotiation with traffic with a low-speed differential. Crossings may be stressful, but are still considered acceptably safe to most adult pedestrians.
LTS 4	Requiring riding near high-speed traffic, or regularly negotiating with moderately high-speed traffic, or making dangerous crossings.

The LTS criteria used for this study is as follows:

- Vehicle speed;
- Number of lanes;
- Presence of parking;
- Presence of bike lane; and
- Intersection type (signalized or unsignalized).

LTS Criteria for Roads with Bike Lanes (with, and without Parking)

Bike lanes are space on the roadway designated for exclusive use by bicycles, except for possible occasional encroachment by motor vehicles to access parking places or intersecting streets and driveways, by markings without any physical barrier. The LTS that bike lanes impose on cyclists can vary over a wide range, and depend heavily on whether the bike lane runs alongside a parking lane.

Criteria for bike lanes alongside parking lanes are given in Table 3; those for bike lanes that are not alongside a parking lane are given in Table 4. Both tables are drawn from Mekuria et al.38 There are criteria along four dimensions: street width, bicycle operating space, speed limit or prevailing speed, and bike lane blockage (e.g., double-parked vehicles). For any given segment, these criteria aggregate following the weakest link principle – the dimension with the worst level of stress governs. For this reason, traffic stress levels in the tables that follow use notations such as "LTS > 2" – meaning that a factor puts a floor on traffic stress at Level 2. For example, if a segment's street width corresponds to LTS > 1, its speed corresponds to LTS > 2, and its bike lane blockage corresponds to LTS > 3, then the segment as a whole has LTS 3.

Table 3. Criteria for Bike Lanes Alongside a Parking Lane

	LTS $\geq$ 1	LTS $\geq$ 2	LTS $\geq$ 3	LTS $\geq$ 4
Street width (thru lanes per direction)	1	(n.a.)[a]	2 or more	(n.a.)[a]
Sum of bike lane and parking lane width (includes marked buffer and paved gutter)	15 ft or more	14 or 14.5 ft See note b.	13.5 ft or less	(n.a.)[a]
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage (typically applies in commercial areas)	rare	(n.a.)[a]	frequent	(n.a.)[a]

Notes: a (n.a.) = factor does not trigger an increase to this level of traffic stress.
[b] If speed limit $\leq$ 25 mph or class = residential, then any width is acceptable for LTS 2.

Table 4. Criteria for Bike Lanes Not Alongside a Parking Lane

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)[a]
Bike lane width (includes marked buffer and paved gutter)	6 ft or more	5.5 ft or less	(n.a.)[a]	(n.a.)[a]
Speed limit or prevailing speed	30 mph or less	(n.a.)[a]	35 mph	40 mph or more
Bike lane blockage (may apply in commercial areas)	rare	(n.a.)[a]	frequent	(n.a.)[a]

Notes: a (n.a.) = factor does not trigger an increase to this level of traffic stress.

LTS Criteria for Roads without Bike Lanes

LTS for bicycling in streets without bike lanes is unaffected by signage (e.g., “Bike Route” or “Share the Road” signs), shared lane markings, or having a wide outside lane. Studies of shared lane markings have shown they have a small beneficial effect, but nothing comparable to the benefit of designating an exclusive bicycling zone by marking a bike lane. Likewise, studies of wide lane conversions (when a wide lane is divided into a travel lane and bike lane) have consistently shown that bicyclists feel less stress when a line formally demarks the bicycling zone, evidenced by the shift in cyclist position away from right-side hazards.[39,40]

Therefore, level of stress when bicycling in streets without bike lanes depends on the prevailing traffic speed and street width (number of lanes); criteria are shown in Table 5, drawn from Mekuria et al.41 In multilane traffic with speeds of 30 mph or greater, LTS is 4. LTS 2 can be achieved only on streets with one lane per direction, consistent with Dutch criteria that do not allow mixed traffic as an acceptable bicycle accommodation for roads with multilane traffic.

Table 5. Criteria for LTS in Mixed Traffic

	Street Width		
Speed Limit	2-3 lanes	4-5 lanes	6+ lanes
up to 25 mph	LTS 1[a] or 2[a]	LTS 3	LTS 4
30 mph	LTS 2[a] or 3[a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

[a] Use lower value for streets classified as residential; higher value otherwise.

MODELING THE TRANSIT SERVICE AREA ACCESS NETWORK

Model parameters that affect the service area for any non-motorized access mode can be walk or bicycle time (using distance traveled and average speed of 12 mph for bicycles and 3.0 mph for walking) to the nearest stop, access network-related measures such as the presence of sidewalks, paths, pavement conditions, traffic stress classification, amenities such as availability of safe bike parking, on-board bike accommodation, as well as grade.

The service area model used in this research follows the parcel-level modeling paradigm where a network Voronoi partitioning minimizes total travel time to the end of the line. Stop service areas are determined by considering the total travel time for a transit patron, and assuming that users choose the stop that minimizes a weighted sum of their walk/bike time and ride time.

Equation (1) shows the major components of the algorithm that assigns parcels to stops. For trips beginning at parcel *k*, the stop chosen is the one that minimizes, over all stops *i*,

$$\mathbf{c}_{w,b} * \boldsymbol{d}_{ki} / \mathbf{u}_{w,b} + \boldsymbol{r}_i \qquad (1)$$

Where $\boldsymbol{d}_{ki}$ = walking/biking distance from parcel *k* to stop *i*, $\mathbf{c}_{w,b}$ = cost of a minute of walking time relative to a minute of riding time (commonly given a value between 1 and 2.5), $\mathbf{u}_{w,b}$ = walking/bike speed, and $\boldsymbol{r}_i$ = running time from stop *i* to the downstream terminal.

Other trip-related factors that affect the mode choice of selection are the length of the trip (the longer the trip is the more likelihood of using transit instead of walk or bike mode), and total travel times, especially during peak-hour operations, as well as perception of walking or cycling safety on the access network.

Transit Vehicle Trip Level Impact Analysis

Modeling transit access involves acquiring detailed data about vehicle trip characteristics and service area networks. Data such as transit travel times, frequency of service, and access networks are some of the desired inputs. Access network connectivity and safety play a critical role in the quality of service provided. The level of analysis possible varies with the available transit data. The case study sites for the project involved two types of transit data. The Regional Transit District (RTD) Denver data included vehicle trip-level travel times and with individual stop-level demand activity. This data is the most detailed data currently available and allows operational analysis at the individual transit vehicle trip level. The data includes stop-level arrival and departure times, making it possible to quantify travel delay and dwell time, as well as interaction with network-level access time. Operational analysis may be performed by aggregating the individual vehicle trips results. The second type of data from Alameda County (AC) Transit included time-point level (at selected stops only) travel time data per individual vehicle trip. Using time-point data, it is required to generate approximate dwell and travel times at each stop if trip-level analysis is desired. The methodology used for AC Transit data was at an aggregated time-period analysis. Generally, service decisions are made over a longer period of time than individual transit trips, and the day is divided into peak and off-peak demand periods. The methodology and tools used for this project are equally suited to individual trip analysis as well as period level (aggregated). Travel time estimates are interpolated for each transit stop (access point). Using period-level analysis, it is possible that within a single period, the number of stops visited could vary by trip. Such instances may require that trip results be aggregated to produce representative sets of stops with approximate travel times during that period. AC Transit raw trip-level data was summarized and interpolated, by stop, into appropriate periods and the analysis methodology was applied to the period-level data.

The transit access network is implicitly assumed when designing and locating a transit service through an area. There may be several considerations that underlie the decision to route a transit service through a neighborhood. The most important being the presence of safe and quick access to the transit line. With the increase in the use of bicycles to access transit and through provision of parking facilities and onboard accommodation, it has become important to examine the service and network fitness around the transit route. This research classifies transit service areas using the LTS model, and examines access in light of those criteria.

DERIVING LTS FROM ALTERNATIVE DATA SOURCES

LTS classification uses network attributes that come from either the census transportation dataset or for the higher classification roadways (such as the National Highway System or NHS) from the HPMS Dataset. Attributes such as roadway functional class (residential, collector, or arterial); the area type (urban or rural), and the posted speed limit are readily available, while number of lanes, intersection type (signalized, non-signalized), presence of a bike lane, and parking may require some effort to acquire. Denver street network data included census-based functional class (detailed enough to identify roadway by class and area type) that includes paths and trails, speed limit, and intersection type.42 Oakland data had street characteristics that are closer to HPMS-based attributes, such as number of lanes and traffic intensity (a measure of traffic activity), bike facility, parking, and speed limit.[43]

Figure 1 shows the Denver-area access network with color-coded LTS designation highlighting the area around RTD-Denver Route 12. Denver appears to provide a much friendlier environment for pedestrians and bicyclists. The amount of green network and the connectivity among the streets is very high. Over three-quarters of the city is connected at LTS 2.

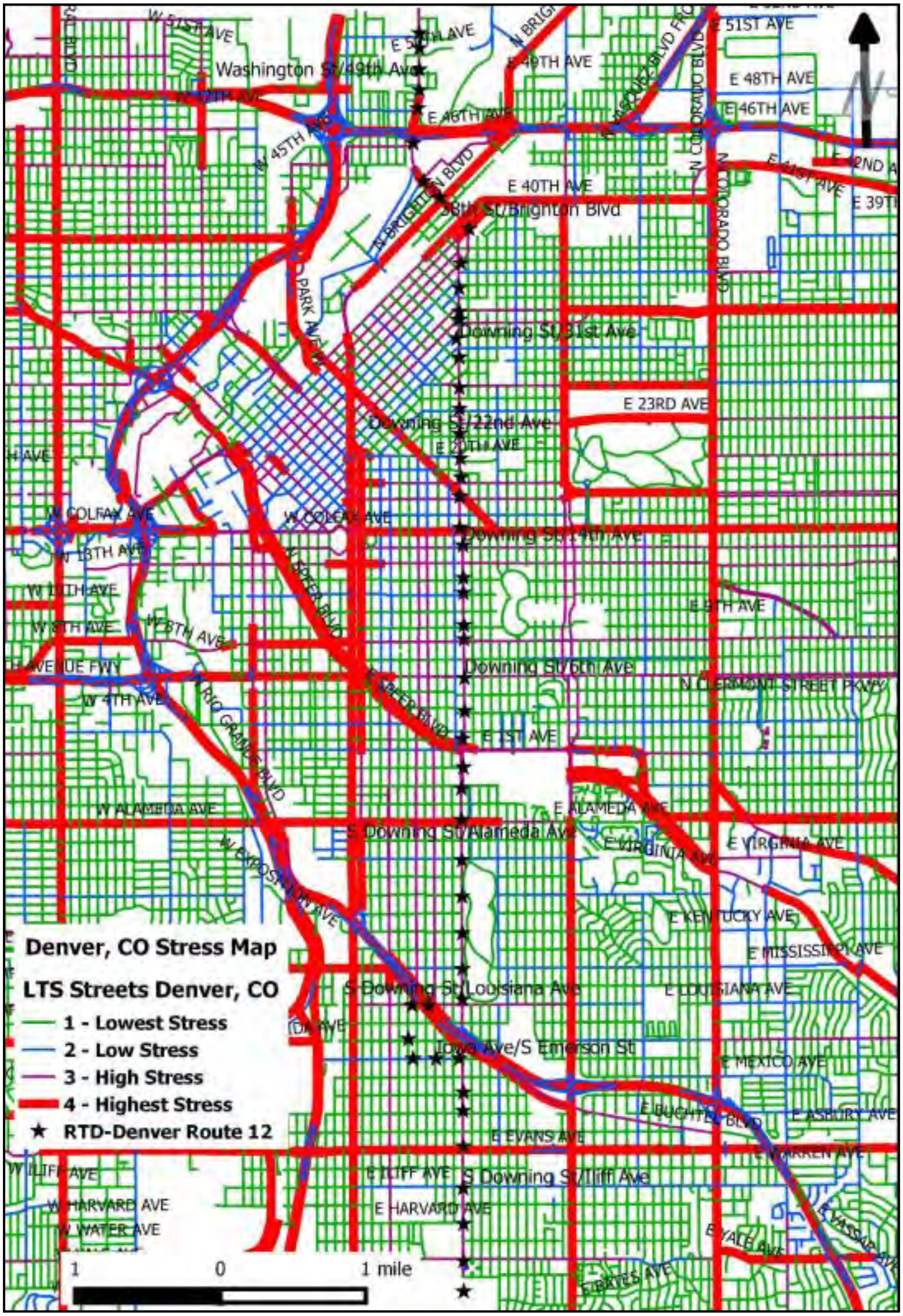

Figure 1. Denver, Colorado, Level of Traffic Stress (LTS) Network and RTD-Denver Route 12

Figure 2 presents the LTS network for Oakland, California, highlighting AC Transit's Route 1.

A comparison of roadway mileage across the four LTS values for the Denver and Oakland study areas are presented in Table 6. Denver provides a noticeably higher percentage of LTS 1 across its network (81%) compared to Oakland (with only 49%).

Table 6. Comparison of Network Mileage and LTS for Denver and Oakland

	Denver		Oakland	
LTS	Mileage	% Mileage	Mileage	% Mileage
1	8,581	81	566	49
2	-	-	252	22
3	1,098	10	233	20
4	871	8	112	10

Figure 3 shows, as an illustrative example, a typical bicycle and/or walking access transit trip path, with transit being the main link between origin and destination in Denver. A generalized trip itinerary is complex and may contain multiple legs and/or modes in practice. However, commute trips are generally composed of one or two legs, primarily to avoid the transit layovers and the potential for delays during transit transfers. For these reasons, the majority of trips in the model are completed using not more than two modes or one transfer.

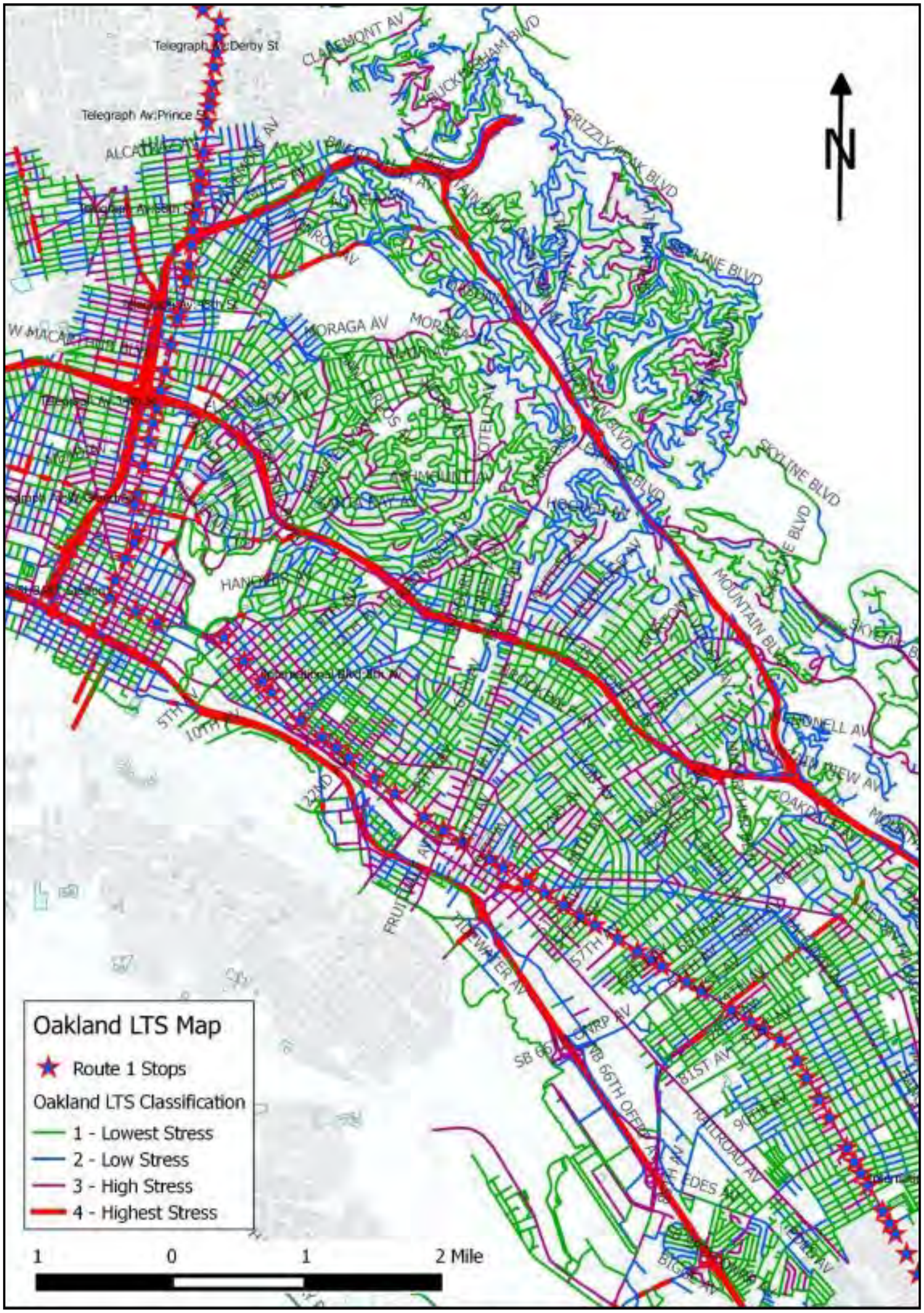

Figure 2. Oakland, California, Level of Traffic Stress (LTS) Network and AC Transit Route 1

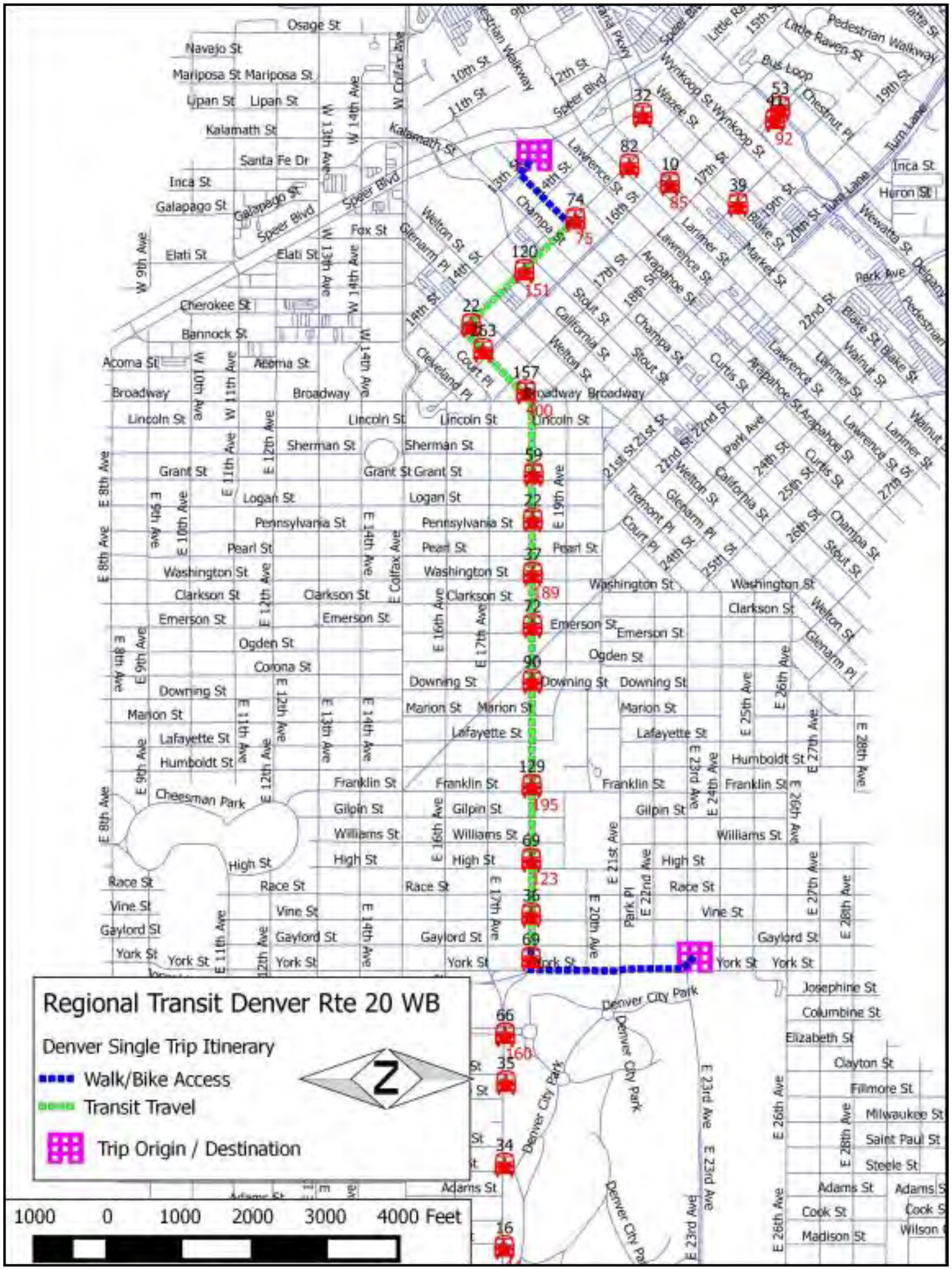

Figure 3. A Sample Multimodal Trip Path in Denver (Stops as Transit Symbols, Highrise, Square Symbols as Origin/Destination, Blue/Green Dotted Path as Trip)

IV. RESULTS AND FINDINGS

The strategy used to determine the service areas was based on the total transit travel time over the LTS network. At LTS 4 (the highest level, and the most stressful to bicyclists and pedestrians), access to all stations is facilitated at the shortest time possible. Any LTS lower than that would be examined for travel time and LTS level.

The walk access service area for bus transit in the U.S. is generally taken to be a quarter-mile radius (about a five-minute walking distance at 3.0 mph) around each stop. For rail transit, the distance doubles to a half-mile radius (10 minute walk). This translates to a bike access service area (12 mph cycling speed) between one to two miles from a transit stop. All of these measures are applicable if reasonable access is provided. Presence of sidewalks, steep grades, bike accommodation including parking, and safe routes affect the access decision.

EXTENDING THE SERVICE AREA FOR BICYCLE ACCESS

The bicycle service area for transit is influenced by a variety of service characteristics including access/egress travel time, onboard transit time, wait times, safety, conveniences such as shelters, traveler information services, onboard amenities such as seating availability, bike accommodation, etc. The single most important factor for bicycle travel is safety.[44] Another important factor for transit access is the length of travel required to access it. Since the speed of travel for a regular bus service is about the same as bicycle speed (average speed of 12 mph),[45] travel time considerations dictate that, when a safe route to the farthest transit stop is available, then riding a bicycle all the way to the stop becomes more attractive. The model results predict that when an individual trip origin is located farther than one mile from a transit stop, the trip maker is better off riding directly to the desired destination.

ACCESS NETWORK CASE STUDY FOR WALK / BICYCLE ACCESS AND LEVEL OF TRAFFIC STRESS (LTS)

The case study routes for this research were selected primarily because these two cities are typical urban routes serving a major city with the density and frequency of transit service large enough that it is suitable for the present analysis. Sufficient transit trip-level data was also readily available to meet the study requirements. The two routes studied were AC Transit Route 1 (Figure 2) in Oakland and RTD-Denver Route 12 in Denver (Figure 1). Both Oakland and Denver Routes 12 are running in the north-south direction, serving the downtown area of both cities where there is considerable traffic throughout the day. The southern half of Route 1 (AC Transit, Oakland) is dominated by industrial and commercial activity with high levels of traffic stress (LTS 3 or above street network). Figure 4 shows the access network from a single location to a transit stop (Route 1 International Boulevard 34th Street Station). Access to this station is limited to a LTS 3 network, and there is no access to this station from an origin within a half-mile radius of the stop at LTS 2 or lower. In contrast, the access network for Route 12 (RTD-Denver) has predominantly low stress networks throughout the city (Figure 1).

Figure 4. Oakland AC Transit Route 1 Stop Service Area LTS Access (Only Accessible at LTS 3)

SERVICE AREA ANALYSIS OF THE TRAFFIC STRESS CLASSIFIED NETWORK

For the purpose of this study, a street dataset for the entire available municipal network was used to model the combined service area of walk and bicycle access to bus transit, and to analyze the overall travel outcomes for the various modes.

Figures 5 and 6 show the quality of access measure for Route 1 in Oakland at LTS 3 and LTS 2, respectively, and these maps are demand-insensitive. The different bands of colors around the stops illustrate the stop service areas and where one stop service area overwhelms another. The map shows that there is access at only one station when the whole area is painted with a single color band. This is illustrated in Figure 5 where there are multiple stops that are covered by a single color band. The stop areas where it is grey/white indicate that access to any stop is impossible. An illustration of this is shown in Figure 6, where between 27th and 5th Avenues in Oakland Route 1 is covered by a single red band, which is due to the intensive mixed industrial character of the streets in the neighborhood. There is access only at the 11th and Madison street stop, and all the other stops are inaccessible beyond that because of higher stress levels on the existing network. The City of Oakland has been aggressively improving the non-motorized access network, especially its bicycle network, including extensive improvements along Telegraph Avenue and International Boulevard. These network updates are not reflected in this assessment.

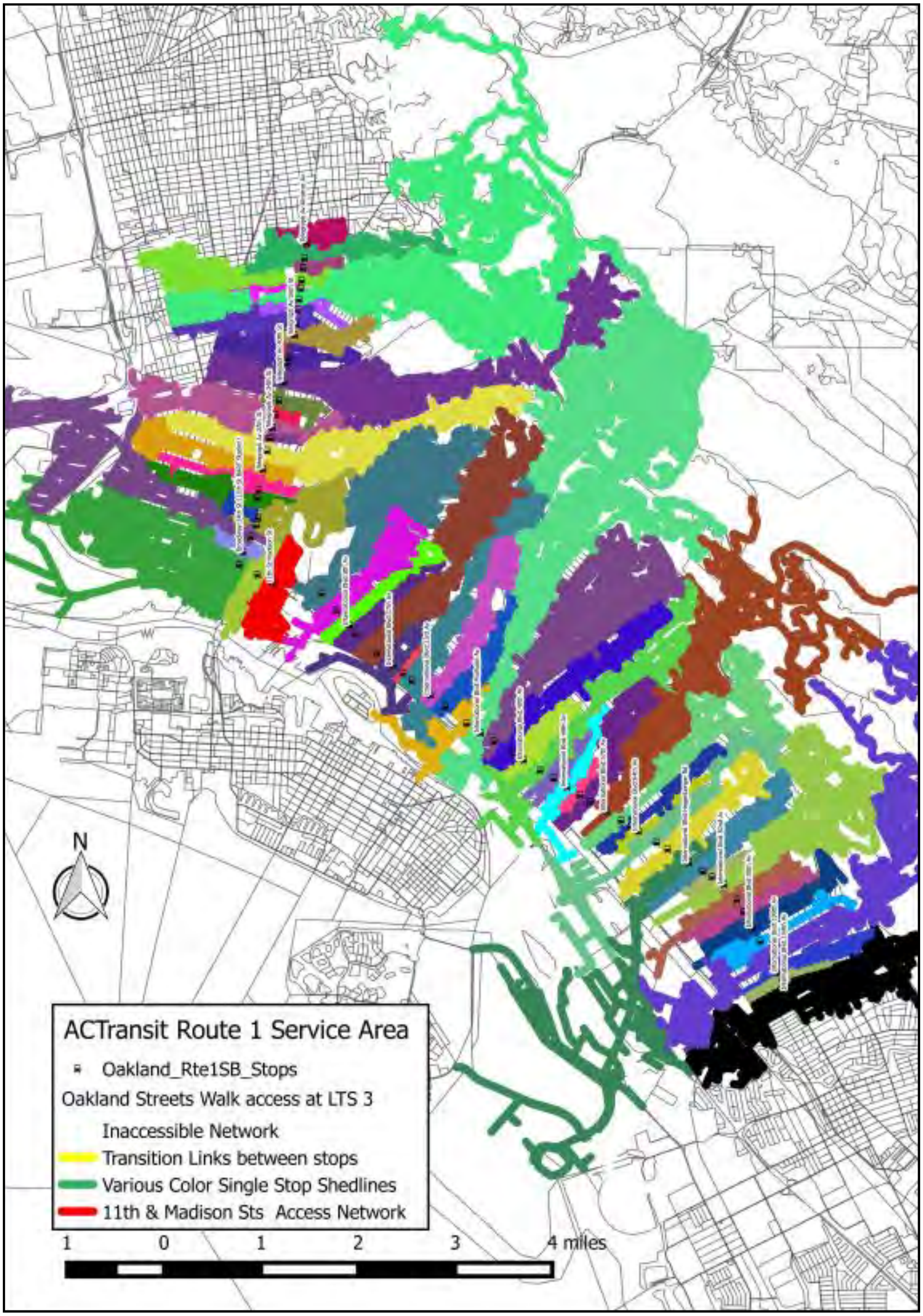

Figure 5. Oakland AC Transit Route 1 Stop Service Area Access at LTS 3

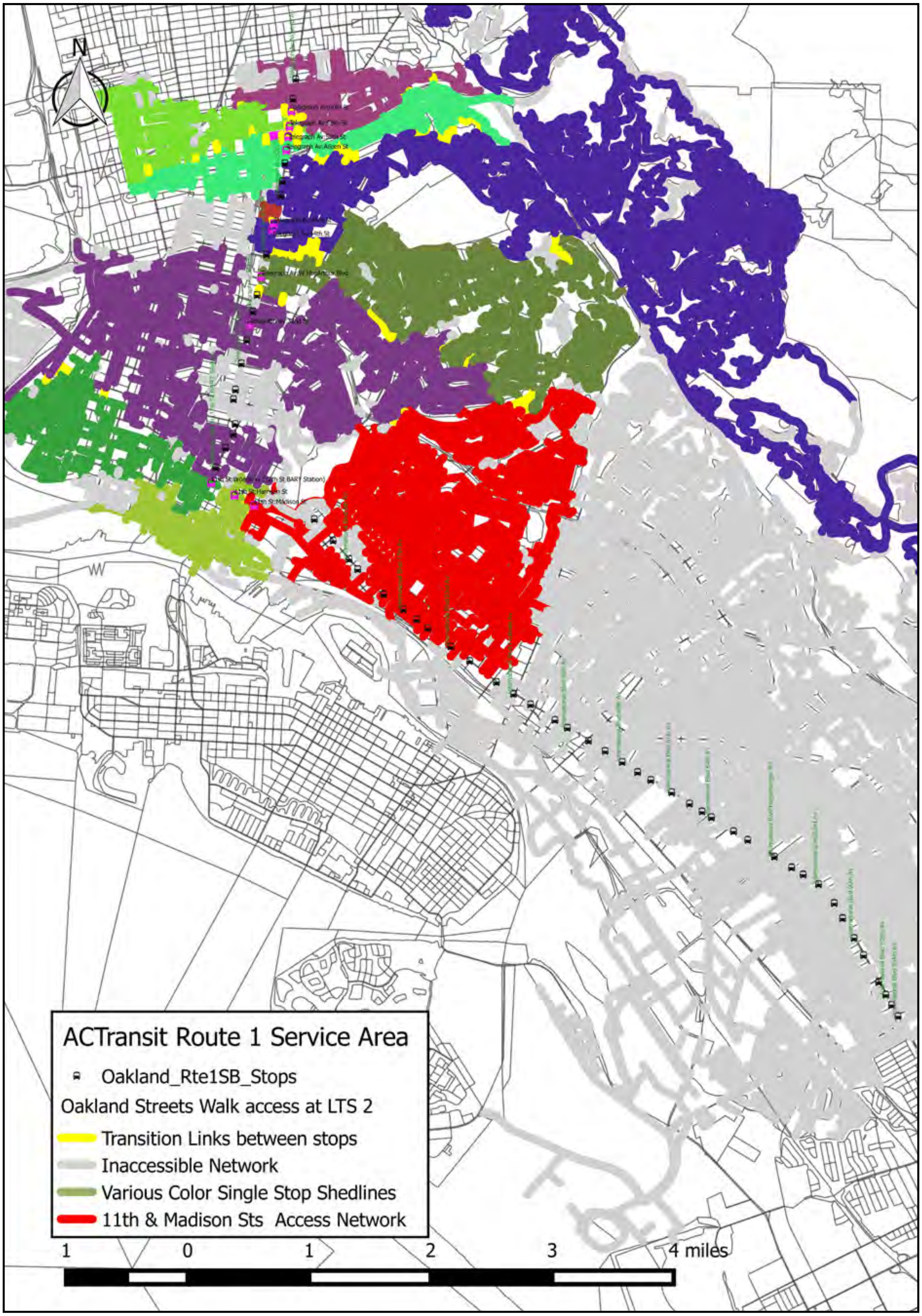

Figure 6. Oakland AC Transit Route 1 Stop Service Area Access at LTS 2

Figure 7 depicts the LTS 4 access network for Route 12 northbound service in Denver. The access network is covered by a distinct color for every stop at this level, showing that the adjacent neighborhood has access to all the stations. The only effect is from the influence of travel time. The effect of the travel time changes the shape of the shedline from the horizontal orientation once the access network is farther than a one-mile buffer. This is particularly evident at LTS 3 (Figure 8) where the service area narrows at the western part of the route.

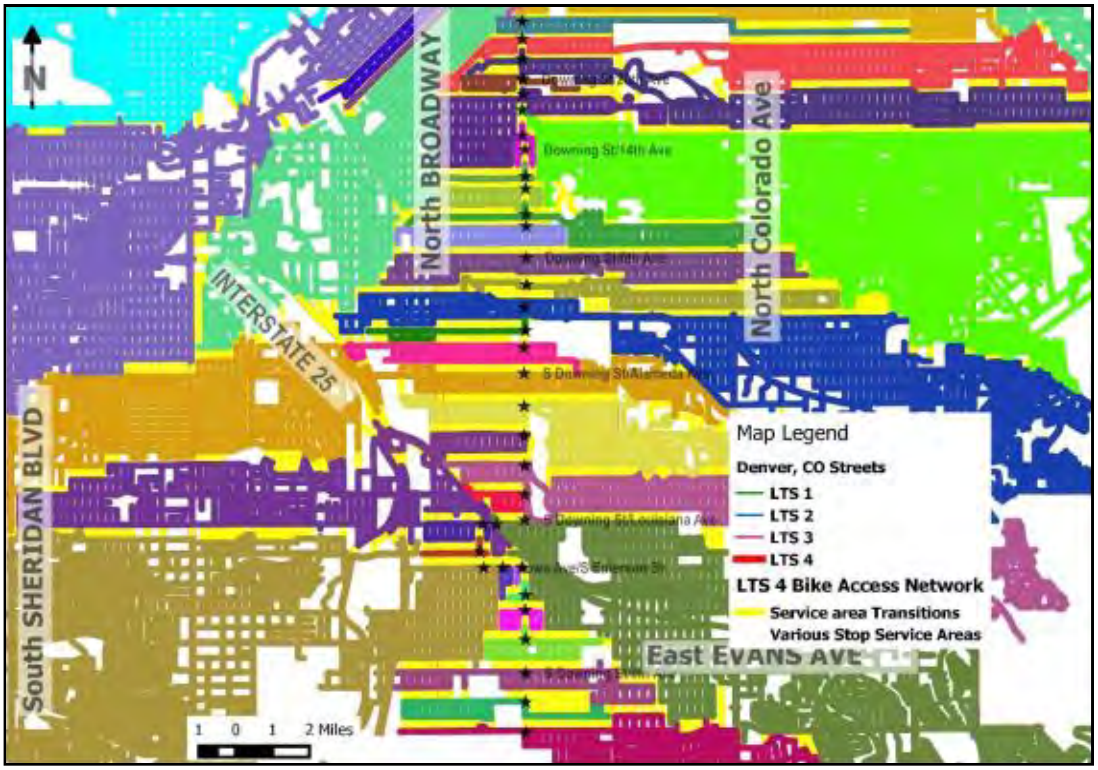

Figure 7. RTD-Denver Route 12 Stop Service Access Network at LTS 4

The Route 12 access network shows the effect of barriers in the western portion of its service area. The light green portion shading of the network displays an almost vertical band in Figure 8. This indicates that access is limited to the transit station only at the northbound edge of the route. The implications are that biking to the farthest station forward is the only option available in that area. The Denver street network is well connected even at LTS 3, and all stops are accessible at this level except the western edge of the city west of Broadway. Interstate 25 acts as a barrier, making Route 12 access difficult and forcing riders to bike much further than at LTS 4. It is true that LTS 4 networks are not accessible to cyclists, and the network connectivity could be improved to provide links to the southwest side of the city.

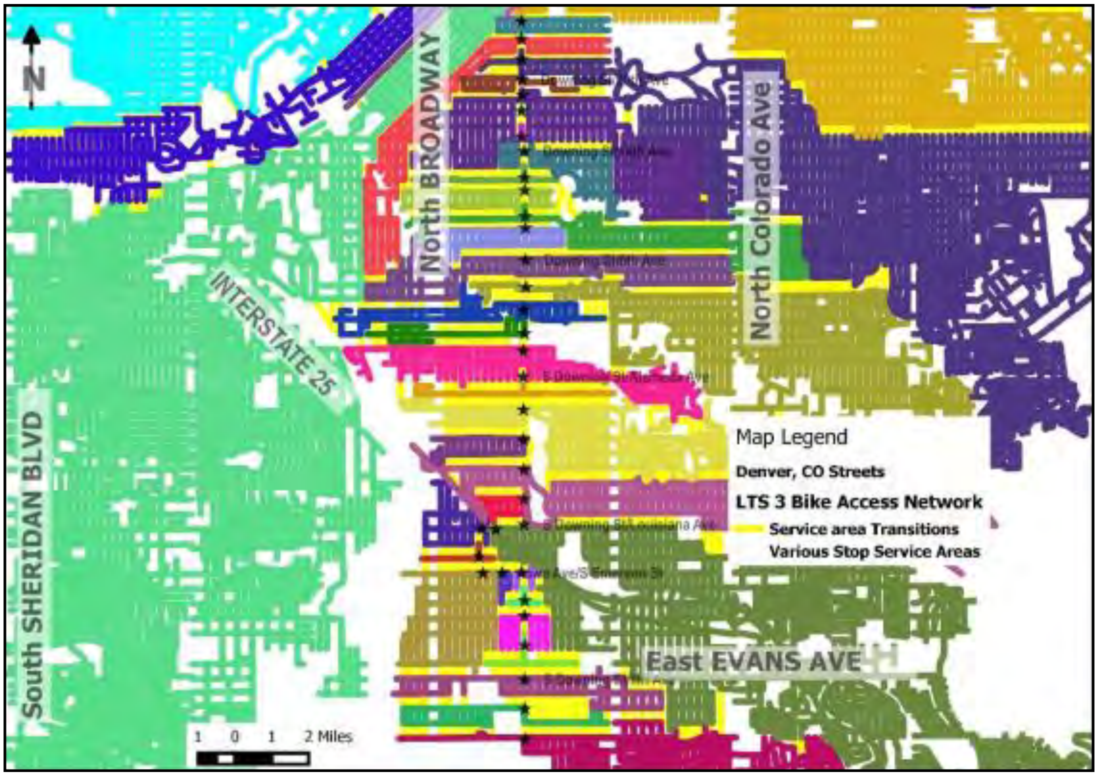

Figure 8. RTD-Denver Route 12 Stop Service Access Network at LTS 3

Figure 9 depicts the LTS 2 access network for Route 12 northbound service in Denver. Each color band on the map shows a single stop service area. When multiple stops are covered by a single band it means one of two things: A stop may not be used because it is not connected at that level, or its travel time is more than another accessible stop at that access speed.

The access network is still well connected (about 75% of the network), but not all the stops are accessible and not all accessible stops are utilized due to travel time merits. Only five out of the 50 stops, five bands of color are being accessed at LTS 2. Virtually all stations after Alameda Avenue are skipped due to travel time considerations (i.e., it is faster to ride all the way to the end than try to use a bicycle and access the closest transit service). The favorability of biking to the furthest station forward has grown considerably and the one-mile barrier disappears. The network connectivity of the southwest side of Denver is cut off completely.

The Denver street network is shown to be very well connected, and simple, safe crossing access improvements could make it even better. Connectivity studies such as what was examined here could provide a deeper insight into making transit more accessible for all patrons.

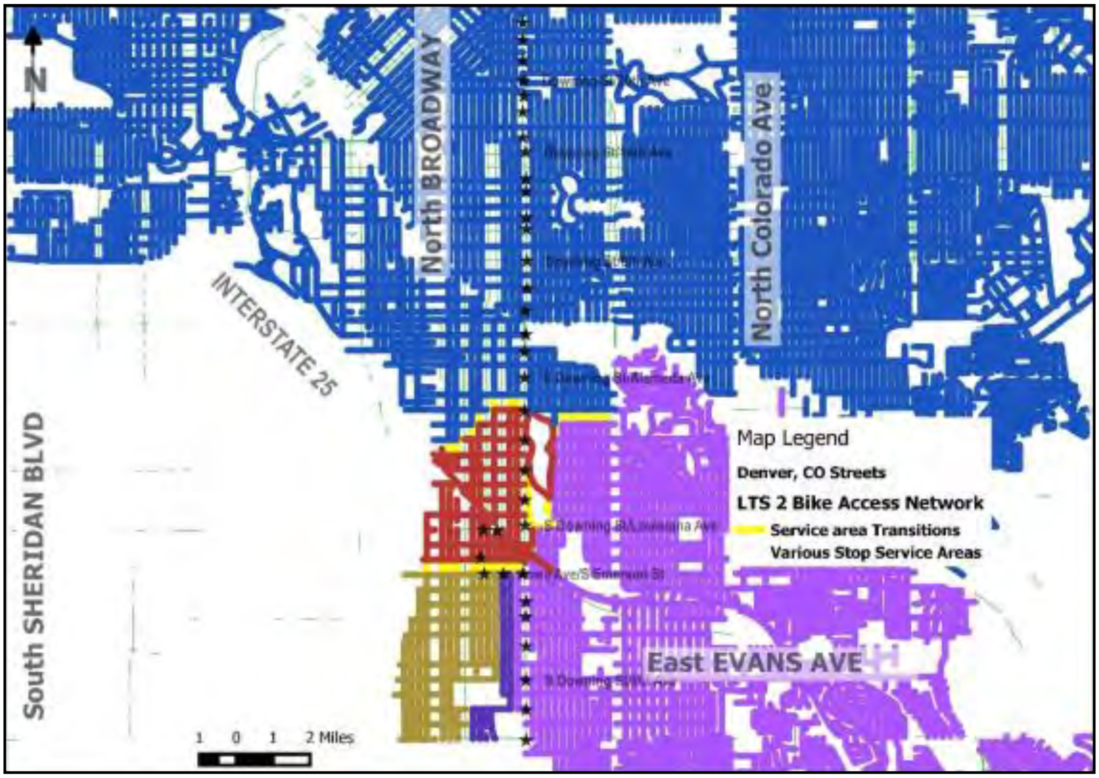

Figure 9. RTD-Denver Route 12 Stop Service Access Network at LTS 2

COMPETITION BETWEEN BUS TRANSIT AND BIKE TRAVEL

Two factors that contribute to making transit more attractive for cyclists are faster transit service and improved network access. Both factors are external to the traveler and can be toolkits at the disposal of the transit agency. This is especially critical for short rides that are under six miles (within 30 minutes of travel time). Figure 9 showing Denver Route 12 as having a single band of blue for half of the trip length depicts that it is covered by only one stop service area. The implication is that all the other stops are bypassed and are deemed ineffective with regards to travel time and also access barriers. In order to further reduce the bypassing of half the stations, the two strategies for improving the service area could be applied. With the implications based on the preceding analysis, it is possible to infer that use of bicycles might be an alternative to transit for trips that are within a 30-minute ride (six-mile threshold for 12 mph speed), given the current state of the network.

MULTIMODAL TRANSIT SERVICE AREA ACCESS NETWORK: TRANSIT VS. BICYCLE

The route access network with the stress level classification from LTS 2 to LTS 4 was used to examine bike access using speeds of 10, 12 and 14 mph.[46] The three access speeds correspond roughly to three levels of bike networks; of LTS 3 (busy streets with bike lane or wide shoulder lane), LTS 2 (mixed traffic on local streets with bike lanes) and LTS 1 (trails, cycle tracks, bike boulevards, and quiet residential streets), respectively. Twelve scenarios were run for each combination of LTS levels 2, 3, 4 against a single walk and three bike speeds for the AC Transit Route 1 Southbound AM peak trip-level data with a total of 65 stops. The number of stops utilized by each scene is shown in Table 7 below.

Table 7. Stop Utilization for Walk/Bike Access For AC Transit Route 1 (65 Stops)

Access Mode	Speed (MPH)	LTS Measure 2	3	4
Walk	2	11	65	65
Bike	10	11	64	63
	12	11	59	59
	14	11	59	59

The number of stops utilized is affected by both access speed and the LTS network. It is instructive to consider that access at LTS 2 is dramatically different from access at LTS 3, showing the importance of safe access networks for both pedestrians and cyclists. The safety-improved network could also produce less usage of transit stops, as depicted in the utilization of stops at the higher access levels of LTS 3 and 4. There is virtually little difference between LTS 3 and 4 and, in fact, LTS 3 has a slight advantage at 10 miles per hour over all cases involving LTS 3 and 4. This advantage is because of the travel time limitation that restricts cyclists from going farther to access a transit stop. Figures 10 and 11 show the access network for LTS 2 and LTS 3 with the 10 mph access speed.

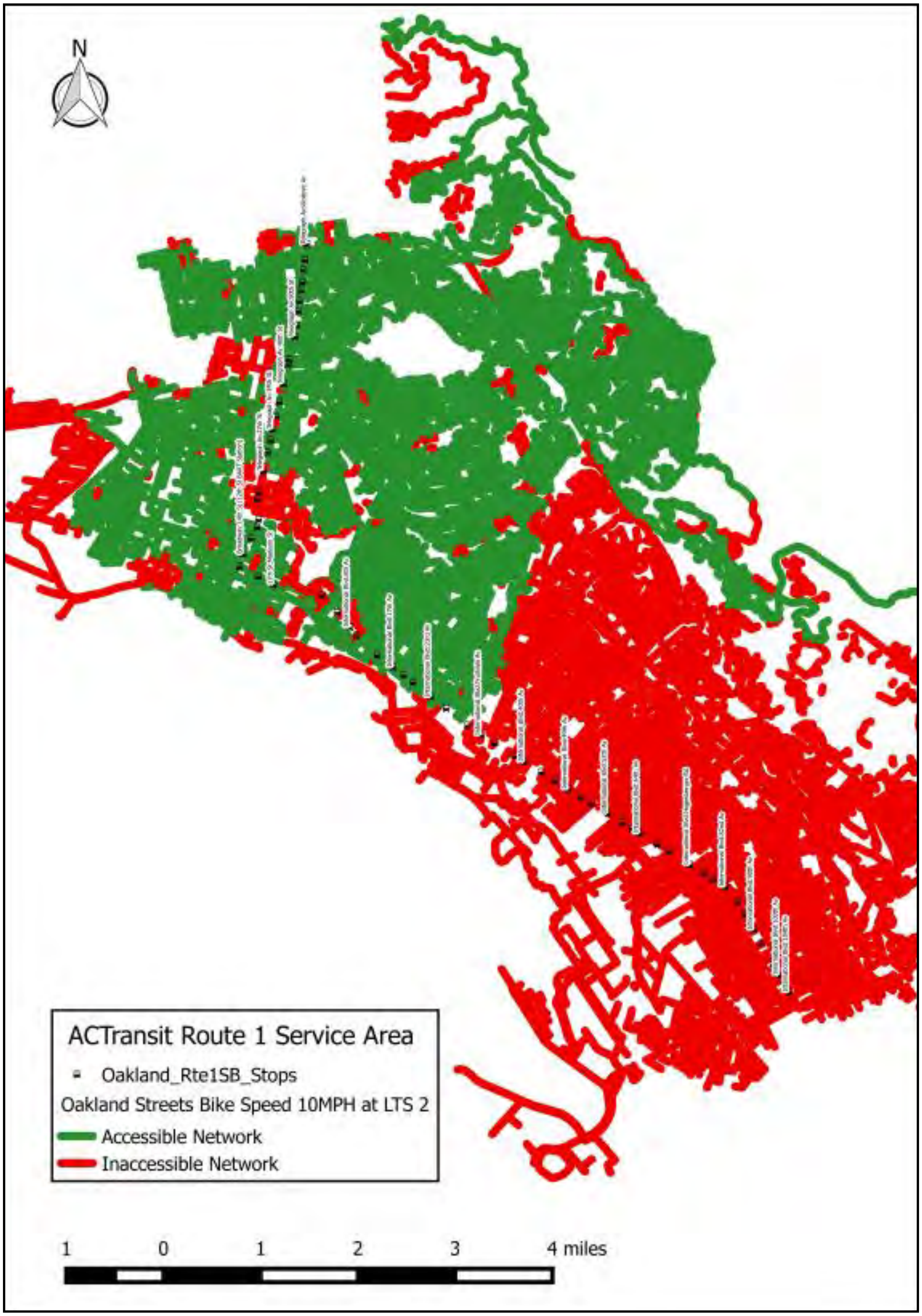

Figure 10. AC Transit Route 1 Stop Service Access Network at LTS 2

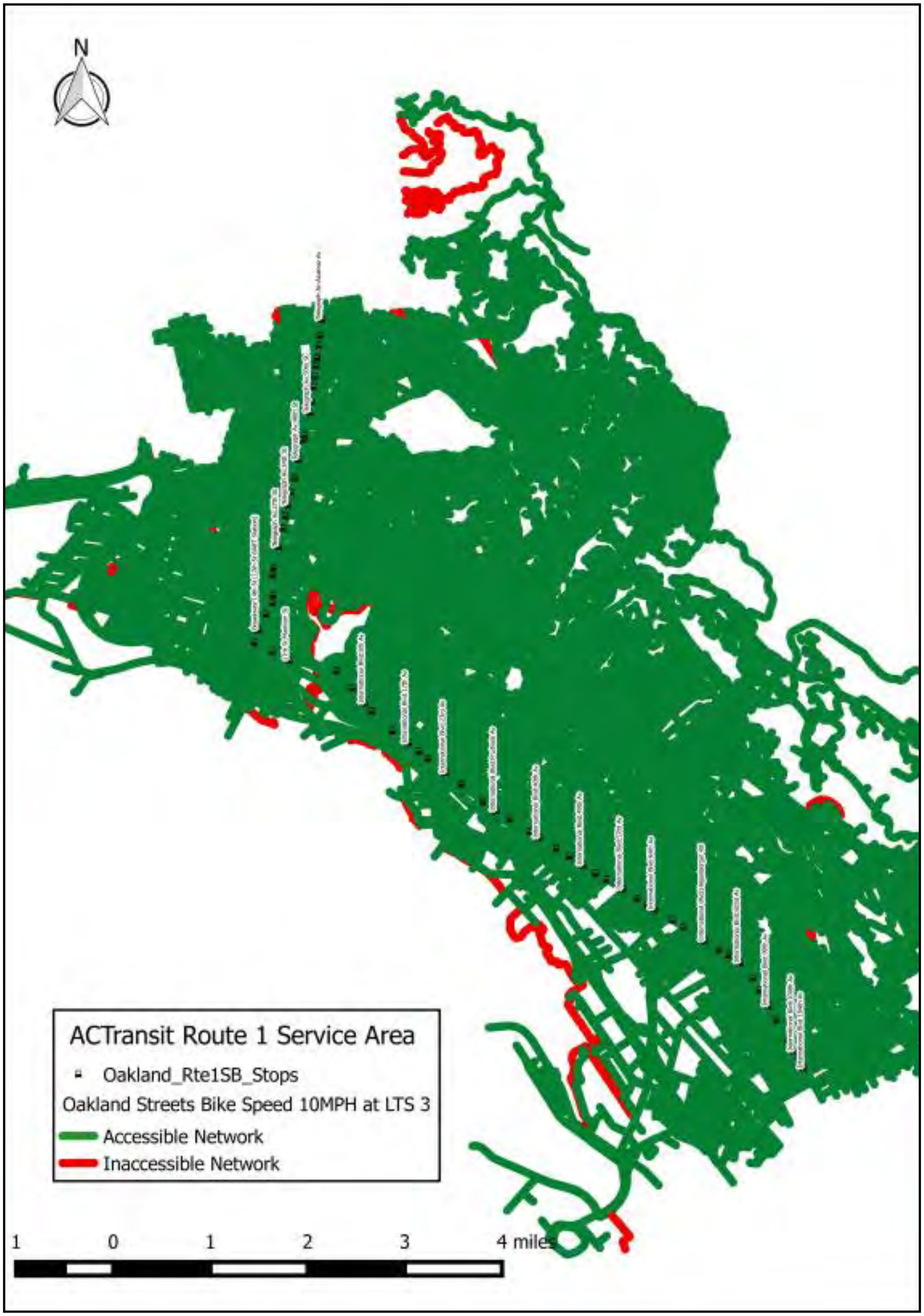

Figure 11. AC Transit Route 1 Stop Service Access Network at LTS 3

The accessible area is exactly the same for all speeds (walking or biking), yet there is variation on the travel times logged while getting to their destination. Table 8 provides aggregate total access travel times in minutes for the same demand and trip characteristics while varying the access speed and network LTS combination. The data is to be interpreted as the capability to travel from origin to the desired transit stop (the desired transit stop may be the last stop).

Table 8. Person Travel Times in Minutes by Walking or Biking for AC Transit Route 1 (65 Stops)

		LTS Measure		
Access Mode	**Speed (MPH)**	**2**	**3**	**4**
Walk	2	18,207	14,634	14,731
Bike	10	4,372	8,331	10,810
Bike	12	3,859	24,495	25,732
Bike	14	3,482	29,196	29,173

The accessibility measure of Table 8 highlights that a LTS 2 is the best network for transit access. The effect of the aggregate network travel times is different for walk and bicycle access primarily due to the speed differential between the two modes. The increase in LTS 2 or lower links in the overall network would improve transit access for walk and bicycle travel at the same time. The fact that the faster bicycle access speed has a lower accessibility measure is a reminder of the need to improve regular transit service. Bicyclists can be thought of as choice riders when it comes to short commutes. The transit patronage will likely improve even with the regular service, remembering that there is always a significant segment of the population that is averse to long-distance cycling (more than two miles of travel),[47] and also those who are disposed to a position of “no-way no-how” towards cycling. In summary, higher access speed together with a less stressful network garners the highest transit access rate as travel is made safe over the larger network, benefiting both transit and walking and bicycling at the same time.

A detailed look at the individual stop service areas are even more informative as to what is happening at the network level. Figures 12-15 show service area partitions for speeds 2 (walk) and 10, 12, and 14 mph (bike). The walking service area is distinct for each stop and partitions the network very well. As can be seen from the progression of the service area of the last stop, bike access (high-speed access) aggregates stop service areas and concentrates them around the vicinity of the stops very quickly, until at 14 mph all travel is very much focused towards the last stop.

One can draw conclusions as to the impact of improving the access network while at the same time improving transit operations. The analysis enables us to look into stop consolidation and service improvements with a view towards increasing transit patronage. The effect of LTS must be accounted as to the number of accessible stops at each level and the number of stops utilized based on travel time consideration considerations. The network fitness will determine how many of the transit stations are accessible, and what happens to the service area when the mode changes from strictly walk-only access to walk and bike access.

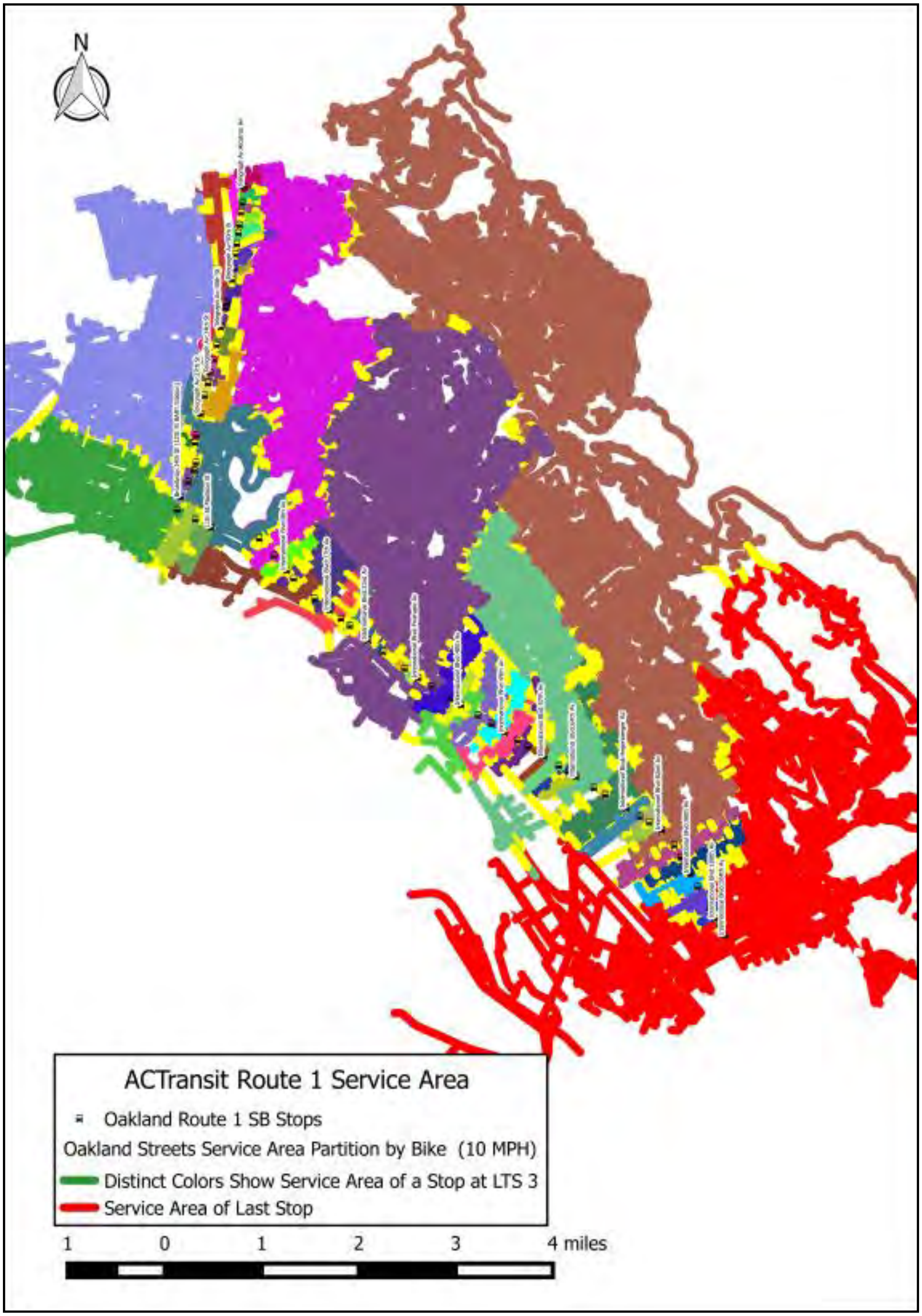

Figure 12. AC Transit Route 1 Bike Access Service at LTS 3 (10 mph)

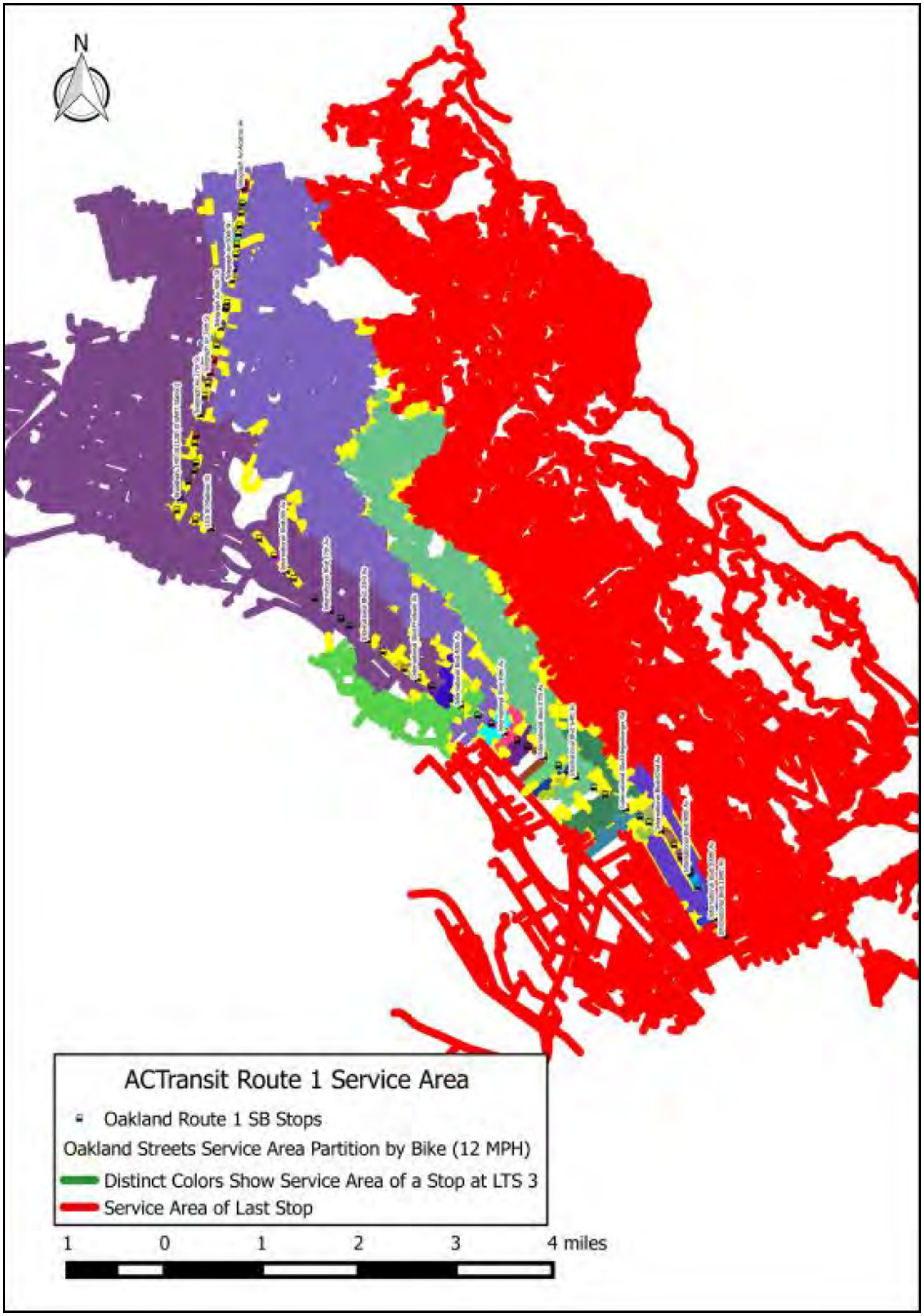

Figure 13. AC Transit Route 1 Walk Access Service at LTS 3 (12 mph)

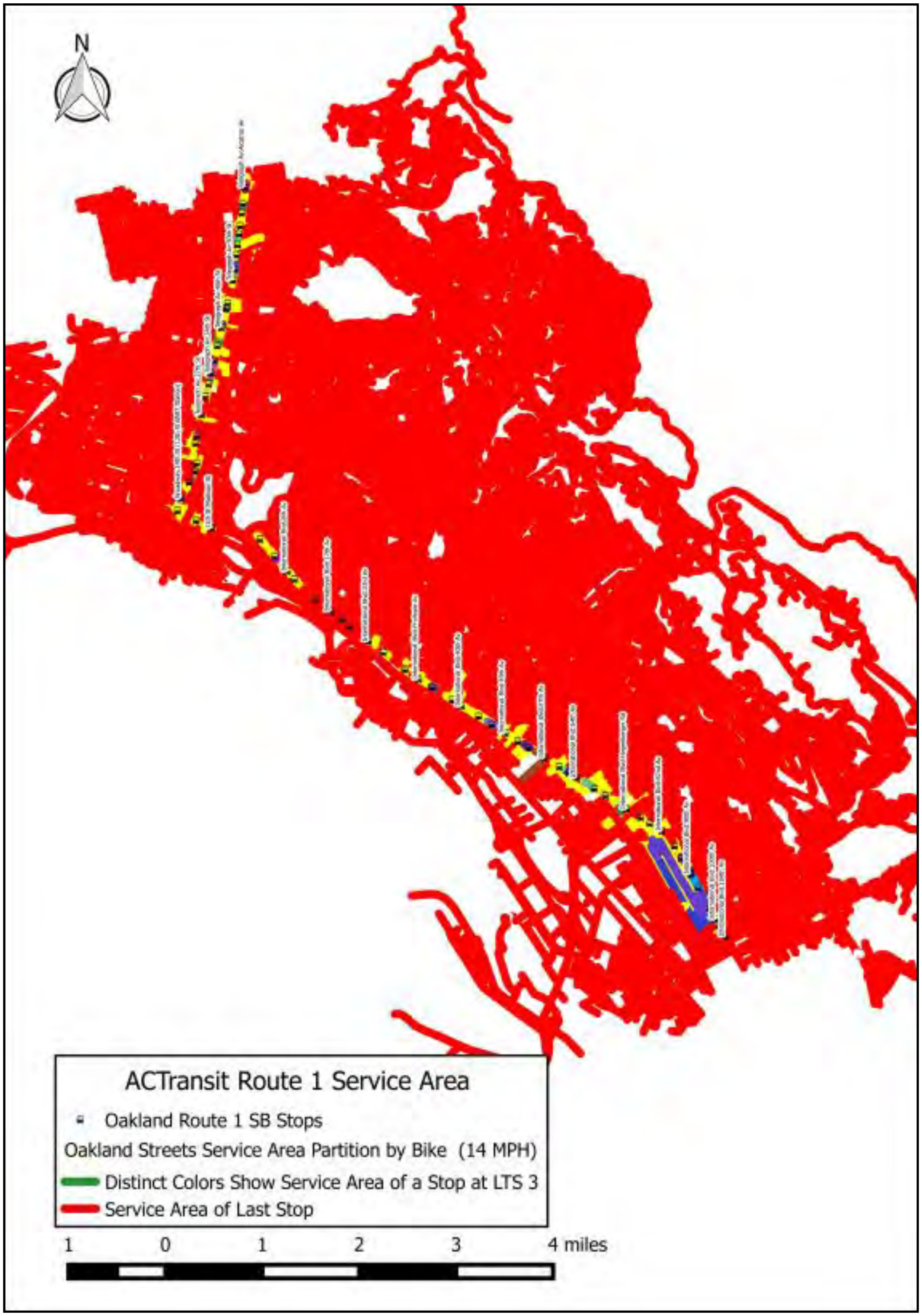

Figure 14. AC Transit Route 1 Walk Access Service at LTS 3 (14 mph)

Figure 15 shows the bicycle-access service area at LTS 3 (all the stops are accessible at this level) for the AC Transit Route 1 (southbound) travel. Yet some of the service areas are smaller than if all of the street network is available. There is very little difference between LTS 3 and 4 (the travel times and network service areas are practically the same), and can be ignored for the purpose of the analysis. For Route 1, the high-speed LTS links of I-880 are west of Route 1 (left side going north) and virtually divide its service area into two. The residential area where the majority of the demand for transit is derived comes from the right side of the high-speed roadway network. Access to coastal attractions, businesses, and the scenic bikeway is restricted by the presence of the freeway.

At LTS 3, the red areas on Figure 14 show that the cyclist would be arriving in a shorter time riding all the way to the end of the line anywhere outside a one-mile buffer from the transit route. Longer trip length (greater than 15 miles) would induce a reassessment of the one-mile catchment area. Access network fitness must also be considered at the same time. As we examine more, Figure 13 also shows that the bicycle service area for the majority of the route is about a mile in width (as the crow flies). Any origin beyond one mile away to the right (or left if the network was existent) of Route 1 is not in the stop service area for the entire route. All red links show that it is faster to ride all the way to the desired destination than to use the bus for the specific bus route travel time and network attributes. This ties in closely with what the TCQSM[48] suggests, with the potential bicycle service area being about one mile.

Figure 15 and Table 7 show that, at LTS 2, only 11 stops are accessible at that stress level. Comparison between LTS 3 and 4 shows that there is only a slightly lower access cost at LTS 4, as shorter walk and bike access is possible due to less circuitous routes being used. All of the 65 stops are available for use, but not all are useful for bike access. Since access using bicycles is dependent on LTS network level access and travel time to the closest stop, the usefulness of stops is dependent on the characteristics of the transit vehicle travel time and the LTS of the adjacent network. At both LTS 3 and 4, transit stops will be preferable only within a one-mile buffer area at a cycling speed of 12 mph or less. Any origins beyond that threshold might as well ride all the way to their desired destination instead of using the transit service. It is worth noting that in Geller,[49] the difference in potential user base between LTS 2 and LTS 3 is an order of magnitude higher (80% LTS 2 and 7% LTS 3). Therefore, it may pay off in terms of customer patronage if investment is made in improving the LTS 2 service area. Again, the red image shows the service area for all of the users who would be better off riding all the way to the desired destination (end of the line) instead of taking transit. Figure 14 illustrates that most of the routes are accessible only at stress levels greater or equal to LTS 3. Given this street network, less than 10% of potential riders will be likely to use bicycles to access transit.

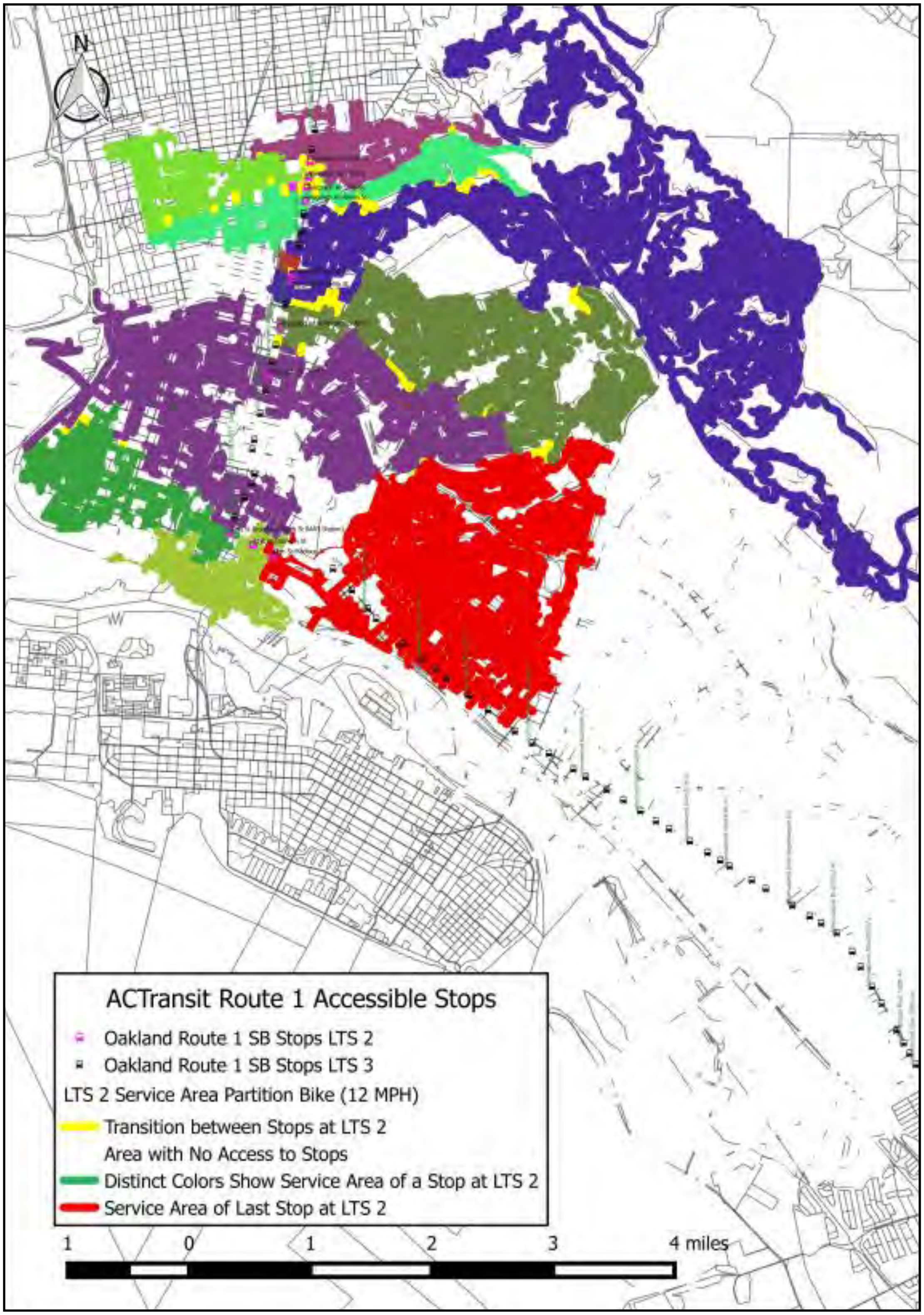

Figure 15. Oakland AC Transit Route 1 Bicycle Service Area at LTS 2

One of the takeaways from Figure 11 is that the bicycle transit service area may be limited to about one mile on either side of the route. As access distances increase (i.e., distance from the nearest transit stop is over a mile), bike travel all the way to the destination becomes attractive. The decision to travel by bike all the way is influenced by the availability of a safe street network and transit travel time. Service quality measures such as frequency (wait times), reliability, and availability of bicycle storage (onboard as well as parking) are other factors that contribute to the attractiveness of the transit mode.

V. CONCLUSION AND FUTURE WORK

As we have shown in this study, understanding the relative effectiveness of automobile alternatives (i.e., buses, bicycling, and walking) depends on how well streets are designed to work for these respective modes in terms of safety, comfort and cost, which can sometimes pit their relative effectiveness against each other. As we have explored herein, a street network that works well for high-speed vehicle traffic may work well for buses, but not for bicyclists and pedestrians. Until now, little research has been done looking at the relative quality of the street environment in terms of how it functions for the relative attractiveness of sustainable human-powered (bicyclists and pedestrian) and vehicle transport (bus transit). Building on previous research and the development of an innovative measure of traffic stress, this study reveals the often competing characteristics of safety and comfort against the speed and reliability that can drive the attractiveness of these modes.

FUTURE RESEARCH SUGGESTIONS: BICYCLE ACCESS SERVICE AREA ANALYSIS FOR RAPID TRANSIT SERVICES

While this research helps fill a key gap in our knowledge, we recognize more research is needed on the service area analysis for bicycle access to transit. Therefore, for faster and longer transit services, such as rapid transit and bus rapid transit, the service area is projected to increase by as much as two to three times.[50] Each service area is unique and must be modeled using local data, but nevertheless there is a general need to perform mode choice analysis. Our suggestion is to work with relevant travel survey data and build a utility model that incorporates details such as access network attributes (LTS classification); demographic and transit service levels (local, express, BRT, light rail, heavy rail); and station attributes such as presence of amenities (bicycle parking, onboard carrying capacity, bike share etc.). Such research can inform the enhancement and usefulness of the existing infrastructure.

CLOSING REMARKS

Understanding the relative attractiveness of alternatives to driving is vitally important toward lowering driving rates and, by extension, VMT, traffic congestion, GHG emissions, etc.

The key research findings and recommendations of this report are as follows:

- Higher LTS levels (LTS 3 and 4) in networks around transit routes are uncomfortable and unattractive for bicycling and walking—essentially, the traffic becomes a stressful barrier to non-motorized travel—thereby limiting the effective catchment area of the transit service. The recommendations from MTI Report 1005[51] to make sure connectivity is provided through the provision of safe crossings to destinations/attractors such as transit stations is again re-emphasized.

- For streets and networks with LTS level 2 or below, bus travel times are comparable to bike riding times to the point that they limit the effective attractiveness of bus transit service for bicyclists who use a bicycle/bus mode. This study suggests that the effective bus transit service catchment area can be constrained to within a one-mile network distance around the transit stops.

- Paradoxically, changes in network Level of Traffic Stress (LTS) can shift the relative attractiveness of once-complementary mode pairings (e.g., a bicycle/bus-transit mode choice) toward becoming directly competitive and substitutable with each other (e.g., a bicycle/transit versus a bicycle-only mode choice). For instance, at lower levels of traffic stress (LTS 1 or 2) the choice between a bicycling/bus transit and bicycle-only modes become equally attractive and substitutable, especially if you are a bicyclist outside the one-mile range of a regular service bus stop. In these cases, travel time between a bicycle/bus-transit trip and bicycling-only become more alike, and therefore the choice between the modes become interchangeable. Bicycling all the way to the destination becomes more attractive, especially considering transfer penalty, availability of safe parking, onboard accommodation, and cost, as well as the bicyclist's independence and self-determination regarding the characteristics of their trip (on-demand, route choice, trip chaining, opportunity to exercise, etc.).

- Improving transit mobility and the comfort and encouragement of pedestrians and bicyclists to access a larger service area than traditionally attributed to transit produces the highest livability and increases alternatives for the traveler. Therefore, we recommend that urban areas design and plan for LTS 2 levels, accompanied by enhancements to help transit operate more efficiently in conjunction with pedestrian and bicyclist comfort and safety improvements. Some measures to thoughtfully consider include transit-only lanes, transit priority lanes at the intersections, transit stop bulb-outs, and integrated networks of pedestrian and bicycle routes throughout the metropolitan area.

- Future research should also look to test which transit service improvement measures present the lowest impact to pedestrians' and bicyclists' comfort, while improving transit efficiency and effectiveness—an important balance toward encouraging the usefulness and livability of sustainable and active travel options.

ACRONYMS AND ABBREVIATIONS

AC	Alameda County
BART	Bay Area Rapid Transit
GHG	Greenhouse Gas
HPMS	Highway Performance Measurement System
LTS	Level of Traffic Stress
MTI	Mineta Transportation Institute
NHS	National Highway System
RTD	Regional Transit District
TCQSM	Transit Capacity and Quality of Service Manual
TCRP	Transit Cooperative Research Program
TTSAT	Time-Based Transit Service Area Tool
U.S.	United States
VMT	Vehicle Miles Traveled

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