FHWA GUIDEBOOK FOR

MEASURING MULTIMODAL NETWORK CONNECTIVITY

APPENDIX: CASE STUDIES

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All graphics by the associated case study agency.

Connectivity Measures to Support Livable Centers, Atlanta Regional Commission

Background

The Atlanta Regional Commission (ARC) is the regional planning agency for the 10-county Atlanta, GA metropolitan region. ARC collects detailed data on bicycle facilities and other factors related to bicycling, such as data on collisions and detailed land use data that ARC uses to model bicycle demand. Using this data to support decisionmaking can be challenging for ARC, however, because many key decisions about transportation investments are made by municipalities, not the regional commission. In addition, the region has many communities and activity centers spread over a large area that does not have strong street connectivity. Adopting a "one-size-fits-all" approach to bicycle planning is complicated by the fact that the land use and transportation factors that influence bicycling and walking vary widely between communities.

Case Study At-A-Glance

Focus:
Bicycle
Context of Study Area:
Urban/Suburban
Scale of Study Area:
Community
Tools & Models:
GIS
Application:
Planning

ARC's 2014 bicycle and pedestrian plan[1] identified coordination frameworks for ARC and local agencies to plan and promote better bicycling and walking networks, rather than focusing on specific projects. The plan includes guidelines and proposed policies on connectivity, such as a vision for a connected network of bicycle and pedestrian facilities serving key destinations with bikeways spaced a half-mile apart. Given the decentralized nature of decision making in the region, ARC's priority was to develop detailed connectivity standards or measures that could encourage local governments to adopt regionally consistent approaches to analyzing connectivity.

Technical assistance efforts for this case study focused on identifying local-scale connectivity measures to support ARC's Livable Centers Initiative (LCI).[2] LCI provides planning grants to help local governments create vibrant, walkable and bikeable community centers. The case study analysis drew on the data available to ARC and its stakeholders to pilot test different ways of measuring connectivity in a representative sample of LCI communities. The goal was to identify a best-practice connectivity measure that ARC could apply in its technical assistance to LCI communities to help identify new bicycle projects. This measure needed to be applicable to LCI communities across the region, which range from automobile-oriented suburban retail and employment centers to regional centers with extensive bicycle and pedestrian networks.

Because the LCI program focuses on increasing access to specific centers with relatively small planning areas, the pilot analysis targeted Access to Destination analysis methods and measures. These measures, which capture the number of people that can travel to each center via bicycle using safe and convenient facilities, are well suited for analyzing connectivity to specific destinations such as community centers. The process included identifying a sample of LCI communities, collecting data for each community, and analyzing travelsheds for each community. Travelsheds represent the area a bicyclist can reach in a typical trip via the bicycle network and are the basis for analyzing access. Two

[1] http://atlantaregional.org/plans-reports/bike-pedestrian-plan-walk-bike-thrive/
[2] http://atlantaregional.org/livable-centers-initiative/

different ways of defining the network for use in the travelshed were (1) a *facility-based* network consisting of designated bicycle facilities and a *low-stress* network comprised of low-traffic streets with no facilities, medium- or high-traffic streets with sufficient facilities to make cyclists feel safe and off-street paths and trails. These travelsheds were then reviewed and refined with ARC staff, a preferred network was selected, and access measures were calculated using that network.

Analysis and Results

Data Assembly

Several different datasets were used to calculate connectivity measures:

- The Metro Atlanta Bicycle Facility Inventory 2014 layer compiled by ARC and available through ARC's Open Data website[3] contains the location and type of current bicycle facilities.
- The Georgia 2010 Census Block layer compiled by ARC staff and made available through the Open Data site[4] contains fine-scale data on the location of people and housing units that were used to analyze household accessibility to destinations.
- ARC staff provided information on LCI planning areas, including a shapefile showing LCI study areas and shapefiles from the selected LCI study areas representing planned bicycle facilities.
- ARC staff also provided a shapefile with the results of a sketch-level, four-point level of traffic stress (LTS) analysis that they had previously conducted for all public roadways in the region. The ARC analysis rated LTS based on traffic volumes, roadway characteristics (e.g., width, number of lanes), and speeds.

The LTS analysis shapefile available through PeopleForBikes' Bike Network Analysis (BNA)[5] was also explored. BNA rates LTS using OpenStreetMap (OSM) data on traffic speeds, number of vehicle lanes, the presence of on-street parking, and the presence, type, and width of bicycle facilities. The ARC analysis, however, was chosen for three reasons. First, the BNA uses a two-point LTS scale (high stress/low stress), which is less detailed than the 4-point scale ARC uses. Second, BNA data is available only for the five largest cities in the ARC region and does not cover some of the suburban study areas that were desired for this analysis. Finally, the BNA LTS ratings consider bicycle facilities, whereas the ARC analysis does not. Although factoring in bicycle facilities when rating LTS is a best practice, it allows less flexibility to adjust future LTS levels based for streets with planned facilities. Conducting a sketch LTS analysis using OSM data also was considered, but the ARC analysis ultimately was chosen because it is based on more detailed and complete data.

The FACTYPE1 field of the Metro Atlanta Bicycle Facility Inventory layer captures the bicycle facilities listed below.[6] The analysis focused primarily on the seven facility types shown in italics at the top of the list, from shared use paths/ greenways to buffered bike lanes.

- *Shared Use Path or Greenway*
- *Shared Travel Lane*

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[3] http://opendata.atlantaregional.com
[4] http://opendata.atlantaregional.com/datasets/census-2010-blocks-georgia
[5] https://bna.peopleforbikes.org
[6] http://opendata.atlantaregional.com/datasets/metro-atlanta-bicycle-facility-inventory-2014?geometry=-88.504%2C32.988%2C-83.044%2C34.586&selectedAttribute=FACTYPE1

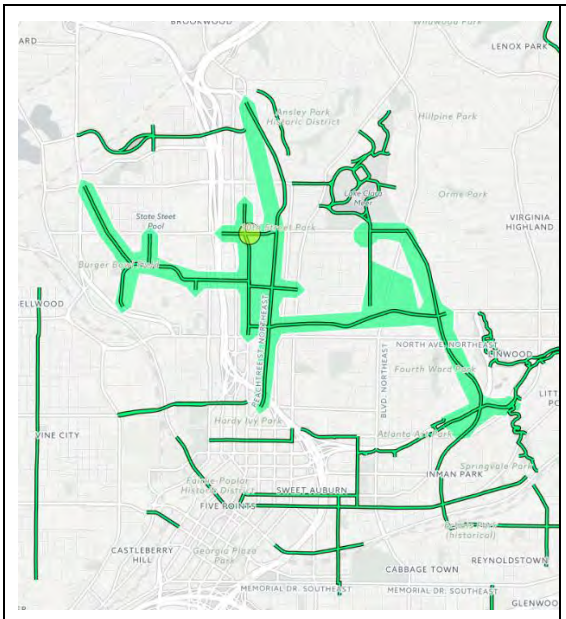
- *Side Path*
- *Conventional Bike Lane*
- *Protected Cycle Track*
- *Raised Cycle Track*
- *Buffered Bike Lane*
- Golf Cart Path
- Paved Shoulder
- Mountain Bike Trail
- Intersection
- Bike Box

Facilities intended primarily for recreational use (golf cart path, mountain bike trail) were not included because the agency does not consider them a high priority for improving connectivity. While recreational facilities in many regions often do double-duty as everyday commuter pathways, such as the greenway networks in Charlotte, NC and Washington, DC, the pathways in the Atlanta region tend to be separated from the key activity centers upon which this analysis was focused. Also excluded were facilities deemed inadequate by the agency, such as paved shoulders on arterials, because they were not considered safe and comfortable enough to support significant numbers of nonmotorized travelers. Intersections and bike boxes, which are not captured by the access metrics for the intended analysis, were also excluded. The Bicycle Facility Inventory also includes a FACTYPE2 field with a slightly different categorization of facility types; this field was not used because it provides no additional detail. The locally developed shapefiles of planned bike facilities that ARC compiled for the study reflected different ways of classifying bicycle facilities, as shown in Table 3.

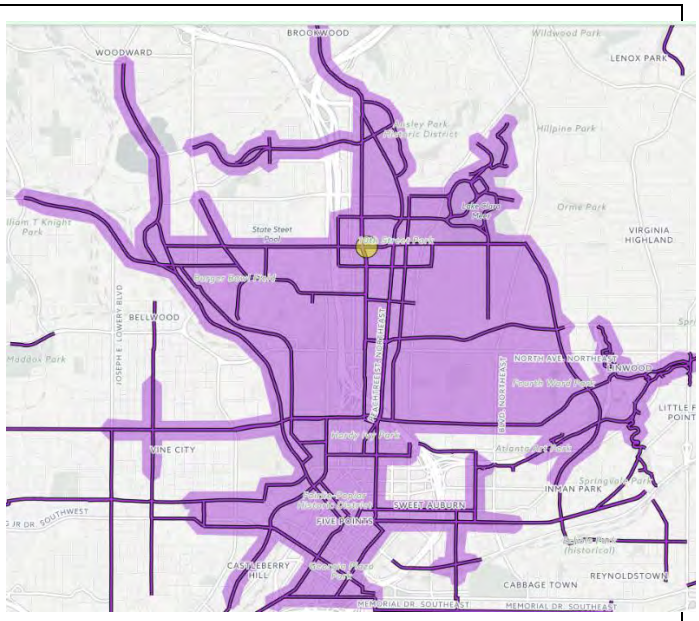
Results

The maps on the following pages (Figure 1 through Figure 5) show all five travelsheds for each of the five study areas. After review of these maps with ARC staff, the low-stress travelsheds were deemed better suited for analyzing connectivity in the Atlanta region than facility-based travelsheds for two reasons. First, low-stress travelshed analyses better capture existing conditions and improvements due to planned facilities in areas that currently lack facilities, such as Decatur, Perimeter, and many other suburban communities. A facility-based analysis of these types of suburban areas simply reveals that they lack facilities, whereas a low-stress analysis offers a more nuanced look at how well suited these areas are to bicycling and walking. Second, the low-stress travelshed analysis better captures the extent to which planned facilities are adequate for safe and comfortable travel. This is particularly evident in Perimeter, where the low-stress travelshed does not extend as far as the facility-based travelshed because the planned conventional bike lanes insufficiently address concerns about safety on the busy streets in the north of the study area. These types of issues are not uncommon across the Atlanta region, which has a disconnected street network. The streets that do connect different communities are often busy, automobile-oriented streets a separated facility is needed to help riders feel safe.

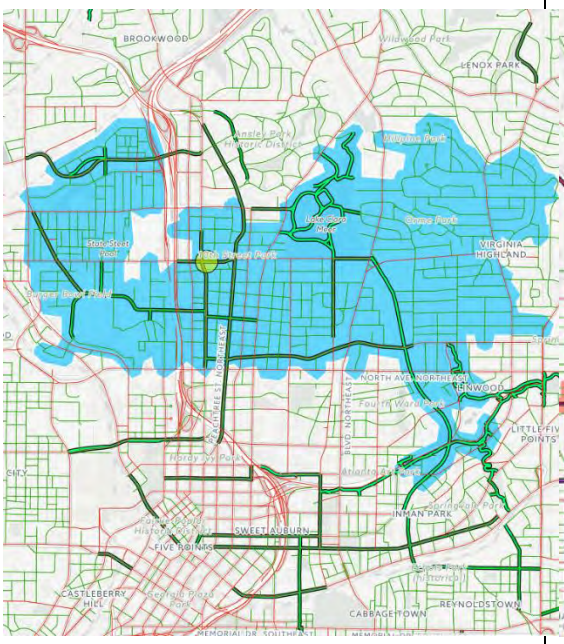
Figure 1: Midtown Study Area



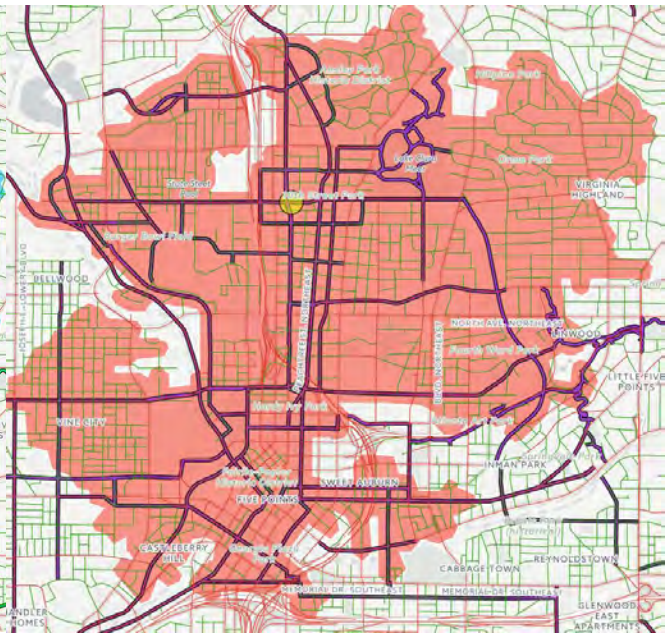
Current Facilities



Planned Facilities

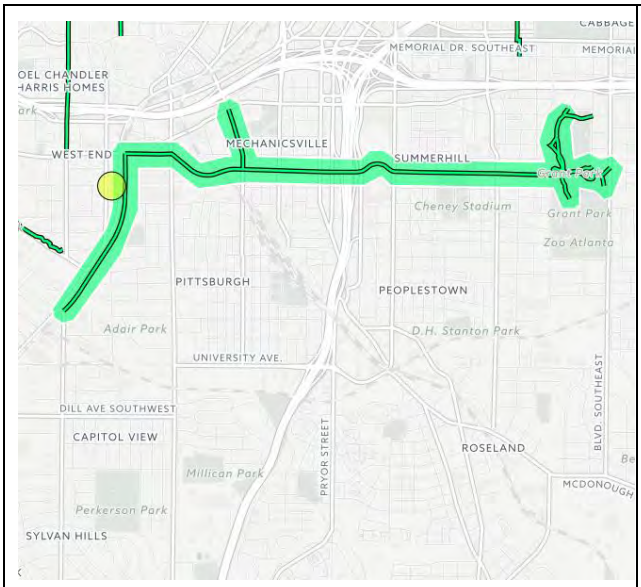


Current Low Travel Stress Network

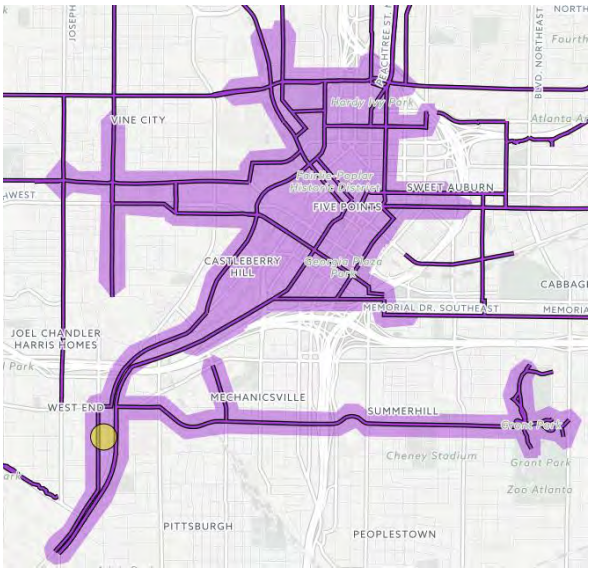


Planned Low Travel Stress Network

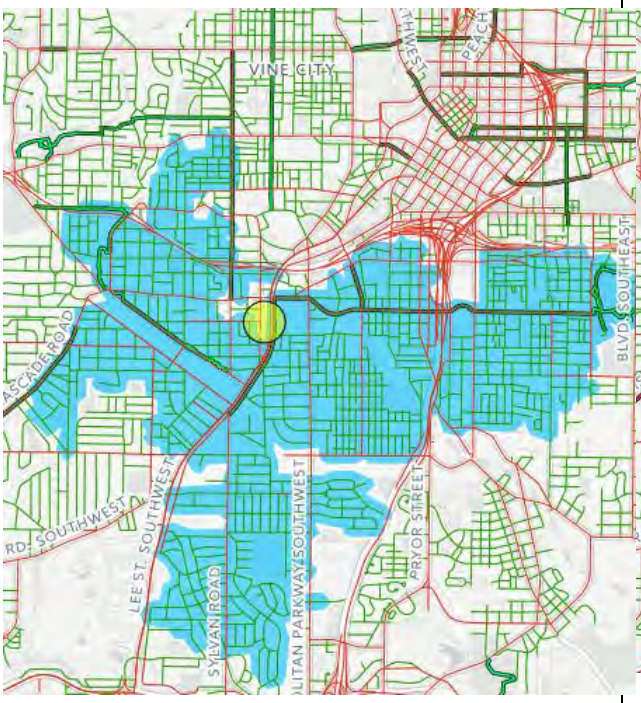
Figure 2: West End Study Area



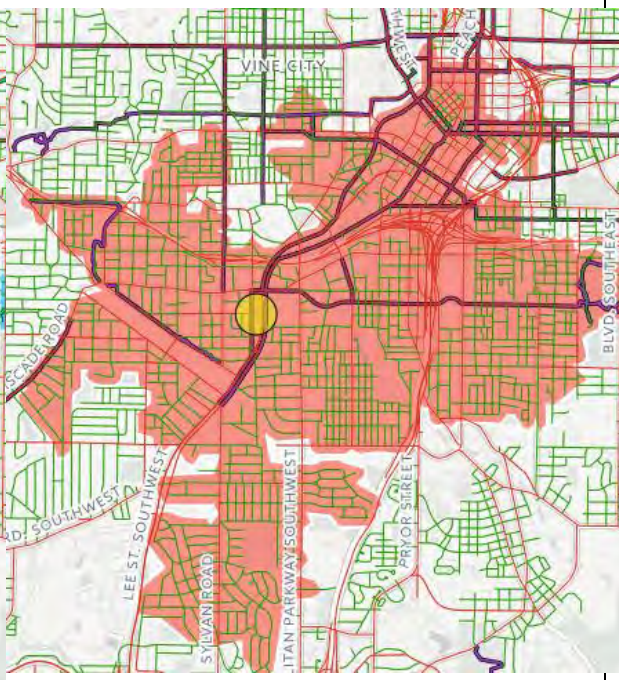
Current Facilities



Planned Facilities



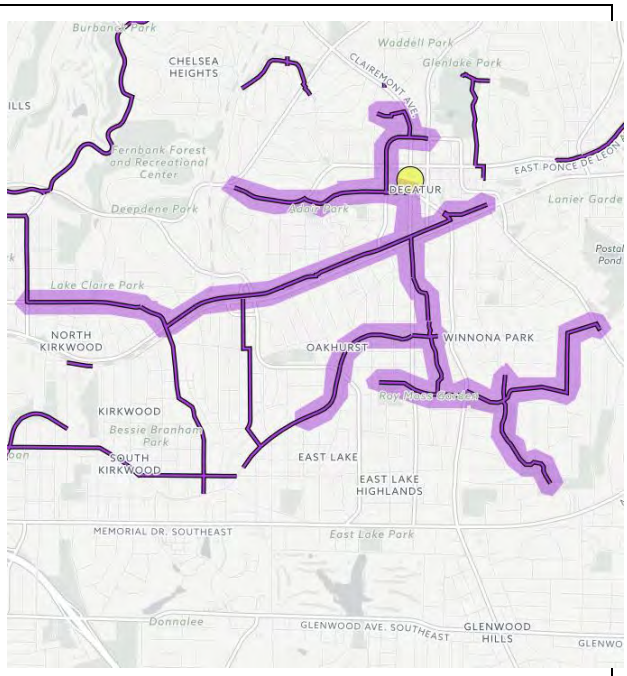
Current Low Travel Stress Network



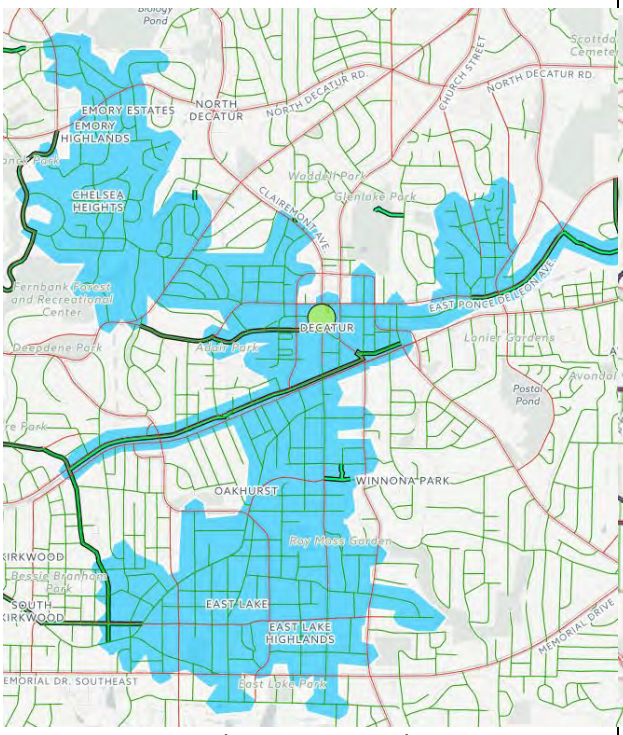
Planned Low Travel Stress Network

Figure 3: Decatur Study Area

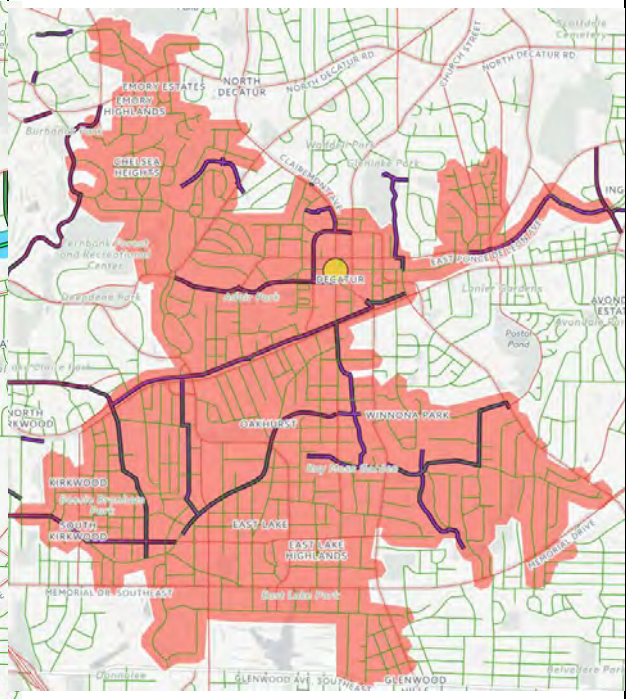
Current Facilities



Planned Facilities

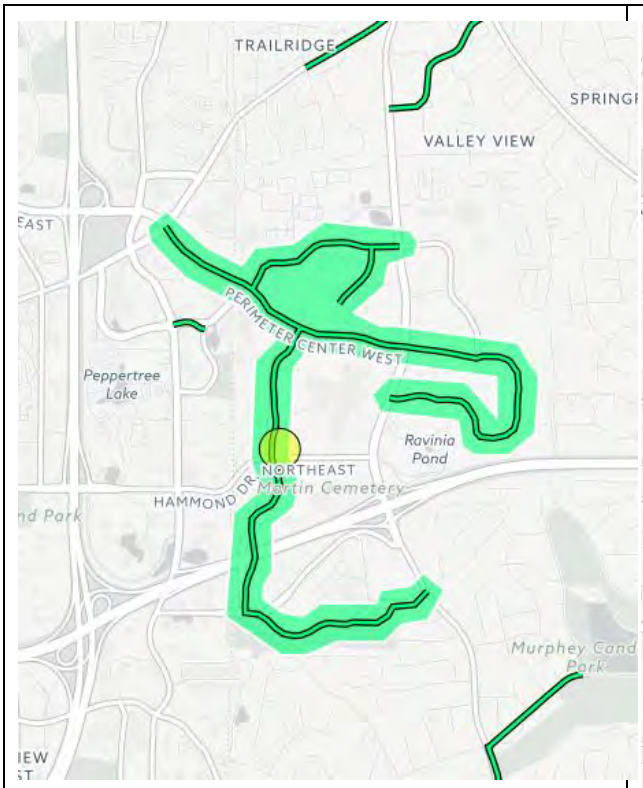


Current Low Travel Stress Network

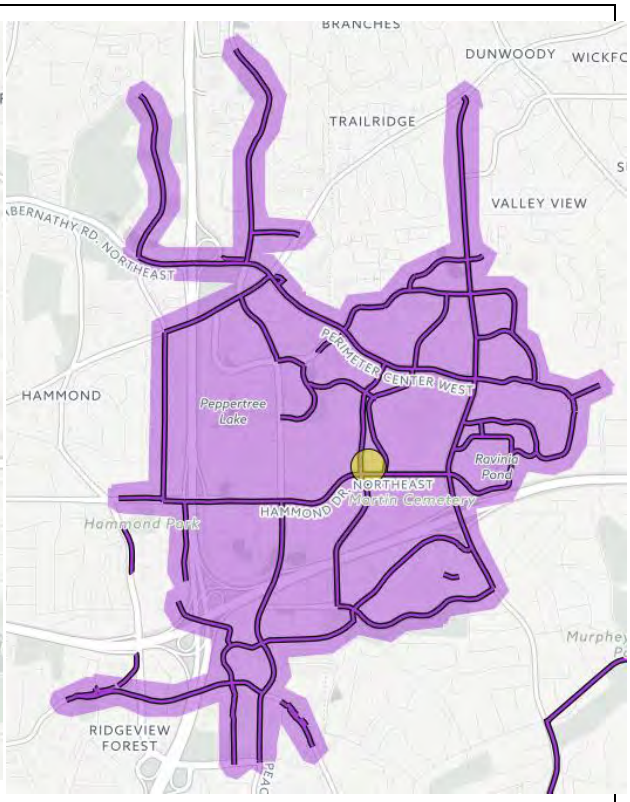


Planned Low Travel Stress Network

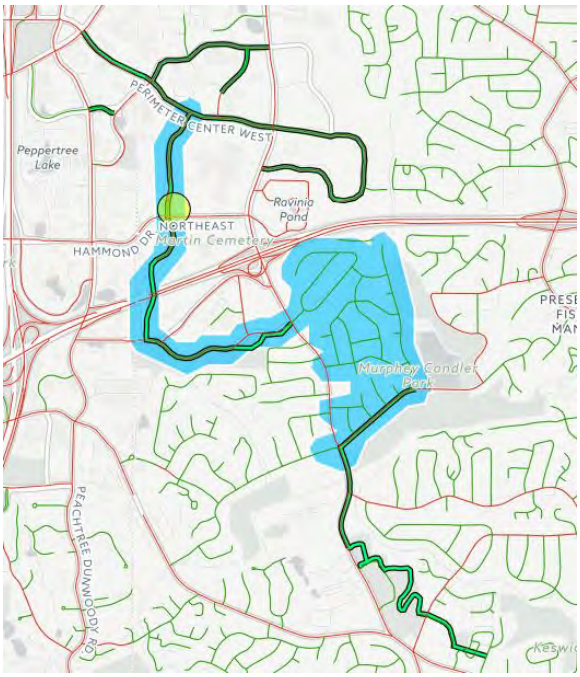
Figure 4: Perimeter Study Area



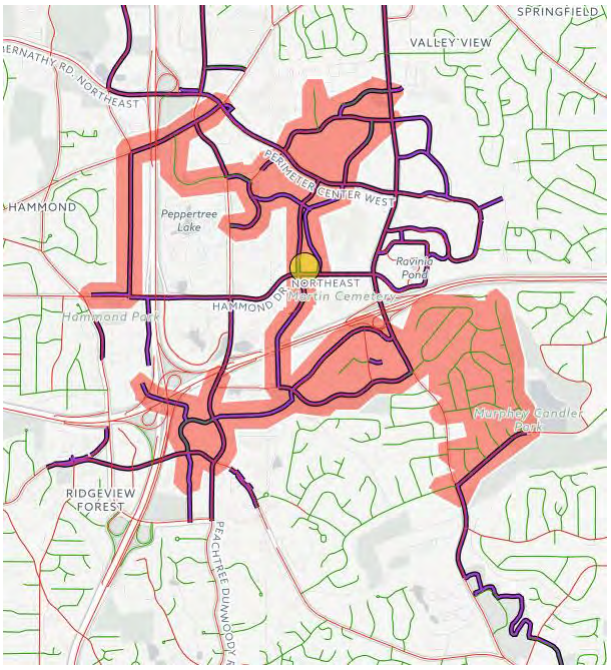
Current Facilities



Planned Facilities

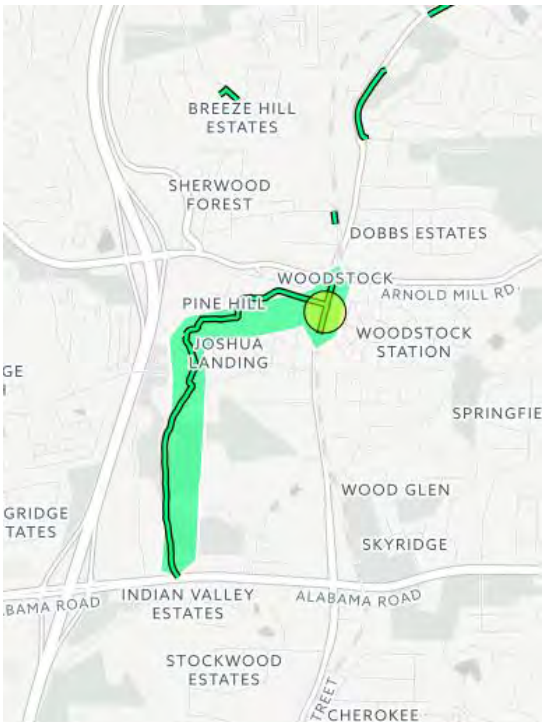


Current Low Travel Stress Network

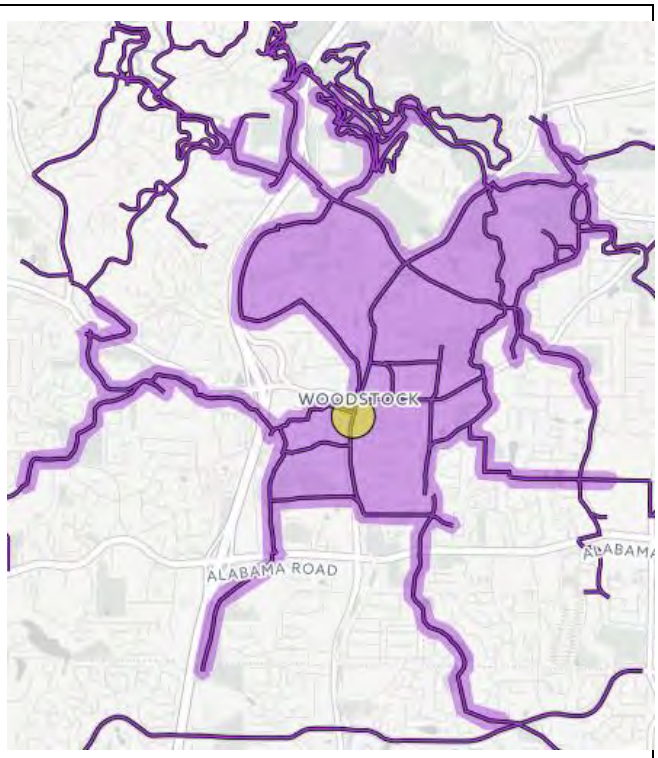


Planned Low Travel Stress Network

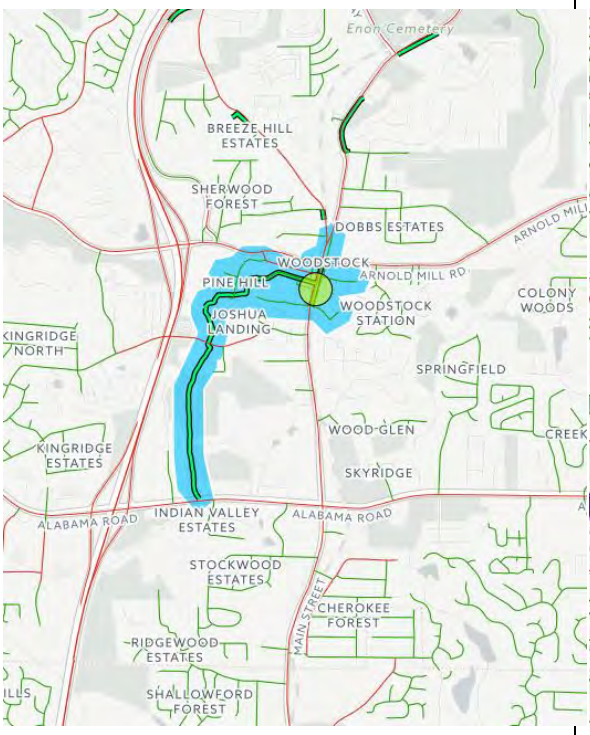
Figure 5: Woodstock Study Area



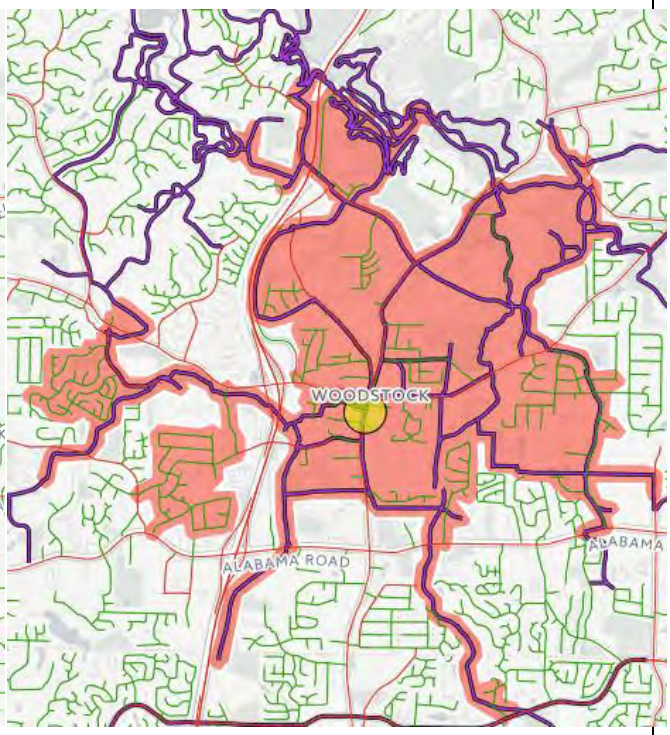
Current Facilities



Planned Facilities



Current Low Travel Stress Network



Planned Low Travel Stress Network

Table 1 shows the results for the number of homes accessible within a low-stress bicycle trip measure for each study area.

Table 1: Number of homes (and people) accessible to each study area within a low-stress bicycle trip

Measure	Current number of homes accessible near a low-stress bicycle trip	Future number of homes accessible near a low-stress bicycle trip
Midtown Atlanta	49,311 (84,650 people)	90,078 (148,879)
Decatur	21,152 (48,081 people)	33,657 (72,356)
Perimeter	4,147 (8,688 people)	14,028 (24,234)
Woodstock	3,672 (7,461 people)	21,383 (52,464)
West End Atlanta	26,828 (51,312 people)	39,189 (76,588)

Compared to these results, the travelsheds discussed above offer richer visual information about how well low-stress facilities connect to different parts of each study area, which provides a better basis for identifying where further improvements are needed. However, using a single number to quantify these measures makes interpreting results and comparing the benefits of different projects or planning scenarios easier. Furthermore, by considering household accessibility to destinations, the quantitative measure used effectively gives more weight to improvements that are more likely to see use than to those that are not. Using households as a basis for accessibility analysis might not adequately capture the benefits of bicycle projects in employment centers where fewer people live, such as Midtown Atlanta. Measuring job accessibility, or combined job and household accessibility, for these areas might be more informative.

Table 2 provides an estimate of jobs (and workers) within the low-stress sheds, but the accuracy of these numbers is limited because employment data were provided at the block group level, which can be much larger units than the population block data. For this analysis, job (and worker) numbers were apportioned based on the area within the shed, whereas for population all blocks touching a shed were counted. This approach might not accurately distribute the number of jobs (and workers) of the block group within the shed. Using more refined point-based job and employment data would help achieve a more accurate result.

Table 2: Number of jobs (and workers) accessible to each study area within a low-stress bicycle trip

Measure	Current number of jobs accessible within a low-stress bicycle trip	Future number of jobs accessible within a low-stress bicycle trip
Midtown Atlanta	46,764 (18,564 workers)	179,384 (31,456)
Decatur	15,560 (7,675 workers)	18,582 (12,877)
Perimeter	4,272 (782 workers)	19,707 (2,141)
Woodstock	487 (163 workers)	5,119 (5,932)
West End Atlanta	8,840 (11,603 workers)	73,530 (15,795)

Methodology

The final methodology (and key changes made during its development) for calculating connectivity measures is described below. The methodology was developed by reviewing data, consulting with ARC staff, and sharing preliminary results via an online mapping portal for ARC staff to review.

Preparing data

All layers listed above were loaded into a single GIS file. Centerpoints for each of the five LCI communities that ARC staff selected for the analysis were then identified:

- Midtown Atlanta: one of the region's main activity centers, Midtown currently has a variety of bicycle facility types, including cycle tracks, buffered lanes, and conventional bike lanes. Planned projects will create additional protected facilities along key routes.
- Decatur: a walkable town center that is planning several new bike facilities to better connect commercial areas to the many nearby regional trails.
- Perimeter: a suburban activity center north of Atlanta that includes a large mall and several big-box retail stores. Perimeter currently lacks bicycle facilities, but has several new lanes planned.
- Woodstock: a suburban city center in the region's northernmost county. Woodstock plans to expand its network of on-street and off-street bicycle paths significantly.
- West End Atlanta: a historic neighborhood to the west of downtown Atlanta that is one of the focal points of the City of Atlanta's latest bicycle planning efforts.

Center points for each community were manually created. Except for Woodstock, all points are centered on transit stations because connecting cyclists to the regional transit network is an ARC priority. For Woodstock, the center point was located at the statue of Bob the Turkey in the city center, a well-known landmark that is centrally located within the business district. In some cases during preliminary analysis, defining these centers as points created gaps in the network immediately surrounding stations, many of which are surrounded by plazas or parking lots that include no facilities. An eighth-mile buffer was added around each center to fill these gaps, assuming that cyclists would be willing to dismount and walk a short distance to the center if they encountered any gaps in the network.

Defining networks

Two networks were tested in the access analysis: a facility-based network and a low-stress network. Defining the facilities network was relatively straightforward. A new current bicycle facilities layer was created that included only the relevant facilities from the ARC Inventory, as discussed in the Data Inventory section. The shapefiles of planned bicycle facilities submitted by local governments contained only relevant facilities.

Defining the low-stress network was more complex, which began with the ARC LTS analysis shapefile that includes most roadways in the region but not off-street paths. The current and planned shapefiles were overlaid on the low-stress network to identify off-street facilities, which were assigned an LTS of 1. ARC's LTS ratings then were adjusted to account for current and planned on-street bicycle facilities, by attributing the facility types to the LTS geometry within 40 feet of a feature. Geometry mismatch between current/planned facilities and the LTS network presented some challenges, and in a few locations, features more than 40 feet from the LTS network needed to be manually attributed. These situations were not obvious until after the initial travelshed analyses were completed, requiring multiple rounds of the process to ensure accuracy.

The basic approach was to subtract one point from the LTS rating for unseparated facilities like conventional bike lanes and two points for separated facilities like buffered bike lanes or separated bike lanes. Table 3 summarizes how these LTS adjustments were applied to the facility type attributes contained in each shapefile used.

Table 3: LTS adjustments by facility type

Shapefile (and usage in case study analysis)	Separated on-street facilities (adjust LTS by -2)	Unseparated on-street facilities (adjust LTS by -1)	Off-street facilities (LTS = 1)	Excluded facilities (no LTS adjustment)
ARC Inventory (all current facilities)	• Buffered Bike Lane • Protected Cycle Track • Raised Cycle Track	• Conventional Bike Lane	• Greenway • Side Path	• Paved Shoulder • Shared Travel Lane • Golf Cart Path
Cycle Atlanta (planned facilities for Midtown and West End Atlanta)	• Buffered Bike Lane • Protected Bike Lane • Raised Bike Lane	• Bike Boulevard • Bike Lane	• Hard Surface Multi-Use Path	• Sharrows
Decatur (planned facilities)[7]	• Cycle Track • Greenway	• Neighborhood Greenway	• Sidepath • At-grade Trail	
Woodstock (planned facilities)	• Shared Use Path or Greenway • Side Path			• Mountain Bike Trail
Perimeter (planned facilities)		• All facilities[8]		

After applying these adjustments, all facilities with an LTS of two or less were selected. These facilities were included in the low-stress network.

Analyzing travelsheds

Three-mile travelsheds were then mapped out using the facilities and the low-stress network. Three miles, roughly a 15-minute trip, was chosen as the basis for the travelsheds because ARC typically assumes three miles to be the length of the average bicycle trip. For each study area, four travelsheds representing all combinations of both network types (facility-based and low-stress) and scenarios (current and future) were mapped. The travelsheds were created by following these steps using ArcGIS software:

1. Adjust line geometry to ensure connectivity. Small gaps in the dataset such as at intersections can limit the size of the travelshed.
2. Ensure that nodes are placed at intersecting lines. The ArcGIS Feature to Line tool will automatically add the nodes.
3. Create a new Network Dataset inside the geodatabase Feature Dataset containing the network geometry from Step 2. Use Length as the cost, allow for global turns, and build a service area index.
4. Within the Model Builder environment, use the Make Serve Area Layer tool, add the livable center points as locations (Add Locations) and then Solve. Use the Select Data tool to grab the service area geometry and then save as a new layer. Using the Model Builder environment

[7] Decatur's shapefile assigned multiple facility types to the same segment, making unclear how some on-street facilities were classified. If a segment was classified both as an unseparated and separated facility type, the more conservative -1 LTS adjustment was applied.

[8] Perimeter's shapefile included no information on facility types, and none of the facilities appeared to be off-street, so the more conservative -1 LTS adjustment was applied to all facilities.

speeds the process in the event that the initial travelsheds are inaccurate and changes need to be made to the network. Note that after any adjustments are made to the network, the Network Dataset (Step 3) will need to be rebuilt.

When reviewing the initial results, ARC staff noticed several gaps that constrained travelsheds. Some represented real gaps in the bike network, while others were a function of local shapefiles that were disconnected in the GIS file, or not completely aligned with the ARC facility inventory. To address this issue, travelsheds were allowed to bridge gaps of up to 250 feet for the purpose of the analysis. This allowed the analysis to move forward despite some misalignments or gaps in the shapefiles, although it meant a few actual gaps on the ground may have been missed in the results.

Calculating connectivity measures

ARC staff decided that low-stress travelsheds provided a better basis for analyzing connectivity (see the following section for discussion). The number of homes accessible to each study area within a low-stress bicycle trip were then calculated, as follows:

1. Overlay Census block-level data on housing units with low-stress travelsheds.
2. Include any block that overlaps with the low-stress travelsheds. Although these types of analyses can filter out some blocks by calculating the percentage of overlap (and accompanying percentage of housing units), the ARC analysis included blocks touching the shed for two reasons. First, cyclists living close to the three-mile shed could likely utilize the network in the shed. Second, ARC did not want to run the risk of excluding any housing units due to potential inaccuracies in the network geometry.
3. Sum the housing units from Step 2 across all blocks within each travelshed.

Lessons Learned and Noteworthy Practices

Key lessons learned from this case study include:

- **Regional agencies can promote consistent standards for all bicycle facility data**. Local governments use different attributes to describe bicycle facilities than ARC does and do not map facilities as accurately as ARC does, leading to gaps when merging current and planned network shapefiles. Ideally, spatial data for both current facilities and planned projects should use the same attributes and reference networks. Since ARC, like many regional agencies, relies upon partnerships with local agencies to develop and maintain network data and project shapefiles, the agency chose to promote bicycle facility data standards that local governments could adopt. This helps the localities to streamline and improve planning and analysis tasks that involve regional funds or plans, and it helps ARC to streamline data assembly and analysis for regional assessments. For example, upon completion of this analysis, the planned Beltline TCU Corridor was discovered to be missing from the planned facilities data. Such missing information about current or planned facilities can greatly limit the potential travelshed for a study area.
- **Defining a low-stress network allows for a more nuanced look at connectivity**. Many of the connectivity measures explored in this analysis are based on networks of facilities, not low-stress streets. Comparing low-stress and facility-based connectivity measures in this case study enabled comparisons of the merits of these two approaches. Low-stress travelsheds better accounted for what ARC staff considered on-the-ground bicycling conditions in the case study communities. They account for the fact that some facilities might not be adequate to make

riders feel safe on busy streets and that most cyclists feel comfortable traveling on a low-stress neighborhood street even if it lacks facilities.

- **Mapping travelsheds and quantifying connectivity measures can help paint a more comprehensive picture.** Travelsheds offer richer visual information about how well low-stress facilities connect to different parts of each study area, which provides a better basis for identifying where further improvements are needed. Quantitative measures interpreting results and comparing the benefits of different projects or planning scenarios easier.

Measuring Pedestrian Connectivity in a Dense Urban Area, Baltimore, Maryland

Background

The Baltimore City Department of Transportation (City DOT) is responsible for multimodal connectivity on hundreds of miles of roadways. The City DOT includes several divisions whose work impacts the quality and connectivity of pedestrian and bicycle networks, including Traffic, Transportation Engineering and Construction, Maintenance, Towing, Planning, Safety, Transit and Right of Way. The staff needed tools and metrics for nonmotorized travel analyses that could be used across divisions for a variety of purposes. This case study explored the development of a pedestrian assessment tool that could complement the City's Bicycle Level of Travel Stress (BLTS) analysis tool.

Case Study At-A-Glance

Focus:
Pedestrian
Context of Study Area:
Urban
Scale of Study Area:
Local
Tools & Models:
GIS
Application:
Planning/Programming/ Performance Measurement

The capacity to assess network quality was an important element of the desired tool. Because Baltimore is a well-established urban environment, its network of sidewalks and signalized crossings in the downtown area would portray 100 percent connectivity according to simple form-based assessments. The connectivity assessment could change considerably, however, when additional filters are applied that consider network quality and ease of travel for people with mobility impairments.

Development of a pedestrian measure that considers network quality and complements the BLTS can help improve ongoing and future planning processes within Baltimore. For example, the tool could enhance existing and proposed neighborhood multimodal plans to support the City's Complete Streets program. The pilot Complete Streets plan for the South Baltimore Gateway considered a range of elements including land use, roadway typology, bicycle facilities, sidewalk coverage, street trees, and community destinations. These data help provide an overview of the neighborhood's existing transportation network and key activity centers such as parks, employers, and transit stations.

Specific details about network quality, however, are not reflected in the existing plan sections. Pedestrian LTS measures that consider facility quality could contribute significantly to the development of a more comprehensive Complete Streets Plan for South Baltimore and for the proposed other neighborhood plans by identifying barriers to travel that are not evident from simpler analyses. The results of the Pedestrian LTS analysis could help the City DOT to identify gaps, propose improvements, and set priorities for investments in each neighborhood, and for other activities such as tracking progress over time or comparing network quality across neighborhoods for a citywide Multimodal Level of Service assessment.

Connectivity Measurement Experience

Data Assembly

The following datasets provided by the City GIS department formed the basis for calculating and informing the connectivity measures:

- Street Centerline
- Sidewalks: Feature includes width, quality, and location
- Ramp: Location of ramps that comply with disability accessibility laws and regulations
- Bicycle Facilities: Includes location and type
- Land Use
- Traffic Signal

Additional data was provided by the City of Baltimore or obtained through the City's open data portal. The study area for this case study was determined by the extent of current sidewalk data. This primarily includes the downtown area, covering 13 city-designated neighborhoods.

Data Limitations

Street centerline data did not include several fields necessary for analysis, such as posted speed, total number of lanes, and location of on-street parking. The project team collected this data for the study area using aerial imagery. Data was attributed to existing roadway centerline data, with the following detail:

- On-street parking was designated as being on one, both, or no sides of the street
- Total number of lanes is inclusive of turn lanes.

Methodology

Sidewalk Presence/Absence

The simplest metric was calculated based on the presence or absence of sidewalks in the study area. Representing a form-based measure that does not account for detailed data regarding sidewalk quality, this metric can provide a quick understanding of the level of sidewalk coverage in Baltimore. Calculations for this measure were based on the data prepared for a Pedestrian Level of Service analysis the City conducted. Results reveal the proportion of roadways with sidewalks on both sides of the road as compared to all other conditions (on only one side or no sidewalk). This measure does not consider sidewalk quality, width of sidewalk, or exposure to motor vehicles.

Pedestrian Space Analysis

The Pedestrian Space Analysis assesses perceived stress along each roadway segment. Based on research regarding the potential for pedestrian injury related to vehicle speeds,[9] the pedestrian space analysis considers the following factors:

- Sidewalk completeness (presence on zero, one, or two sides of roadway)
- Separation from motor vehicles
- Posted speed
- Number of travel lanes

[9] Tefft, B.C. Impact Speed and a Pedestrian's Risk of Severe Injury or Death. *Accident Analysis & Prevention* 50 (2013) 871-878.

Pedestrian Space Analysis does not consider detailed information about sidewalks, such as width or pavement quality, and the results are aggregated to the roadway centerline. This requires that all mapped attributes be tied to the street centerline.

The results are broken into five categories, with low-stress roadways scoring 1 or 2 and high-stress roadways scoring 4 or 5. The calculations do not consider the quality of sidewalk pavement, width of sidewalks, or presence of buffers.

Pedestrian Level of Traffic Stress

The methodology for calculating Pedestrian Level of Traffic Stress (PLTS) is adapted from the Oregon Department of Transportation's *Analysis Procedures Manual, Volume 2*. The methodology parallels the Bicycle Level of Traffic Stress methodology by assessing the quality of pedestrian space based on sidewalk width, compliance with disability laws, separation from motor vehicles, and traffic speed.

The following modifications were used to accommodate the data available:

- No buffer information was available, so Exhibits 14-17 and 14-18 in the ODOT methodology were omitted from the analysis.
- Due to a lack of data availability, ODOT Exhibit 14-22 was also omitted; however, the application of this table could significantly influence further differentiation of the PLTS scoring within Baltimore.
- Modifications were made to the crossing tables (ODOT Exhibits 14-20 and 14-21) to accommodate roadways wider than those identified in the ODOT methodology.

The ODOT scoring process is applied to the sidewalk centerline as follows:

- Score sidewalk segments based on width and pavement condition
- Score sidewalk based on buffer type and width (omitted in this application)
- Score unsignalized crossing locations
- Adjust crossings for crosswalk enhancements
- Calculate the final PLTS score based on the weakest link (i.e., highest score)

Pedestrian Level of Service (PLOS)

A 2004 report completed by the Baltimore Metropolitan Council assessed major roadways in the Baltimore region based on Pedestrian Level of Service criteria published in the *Transportation Research Record 1773 (2001)*.[10] The results of this report were intended to serve as a baseline measure that would be updated regularly as a way to assess the network and prioritize projects.

The measure aims to assess the perceived level of safety for pedestrians based on roadway and sidewalk conditions. Factors assessed include:

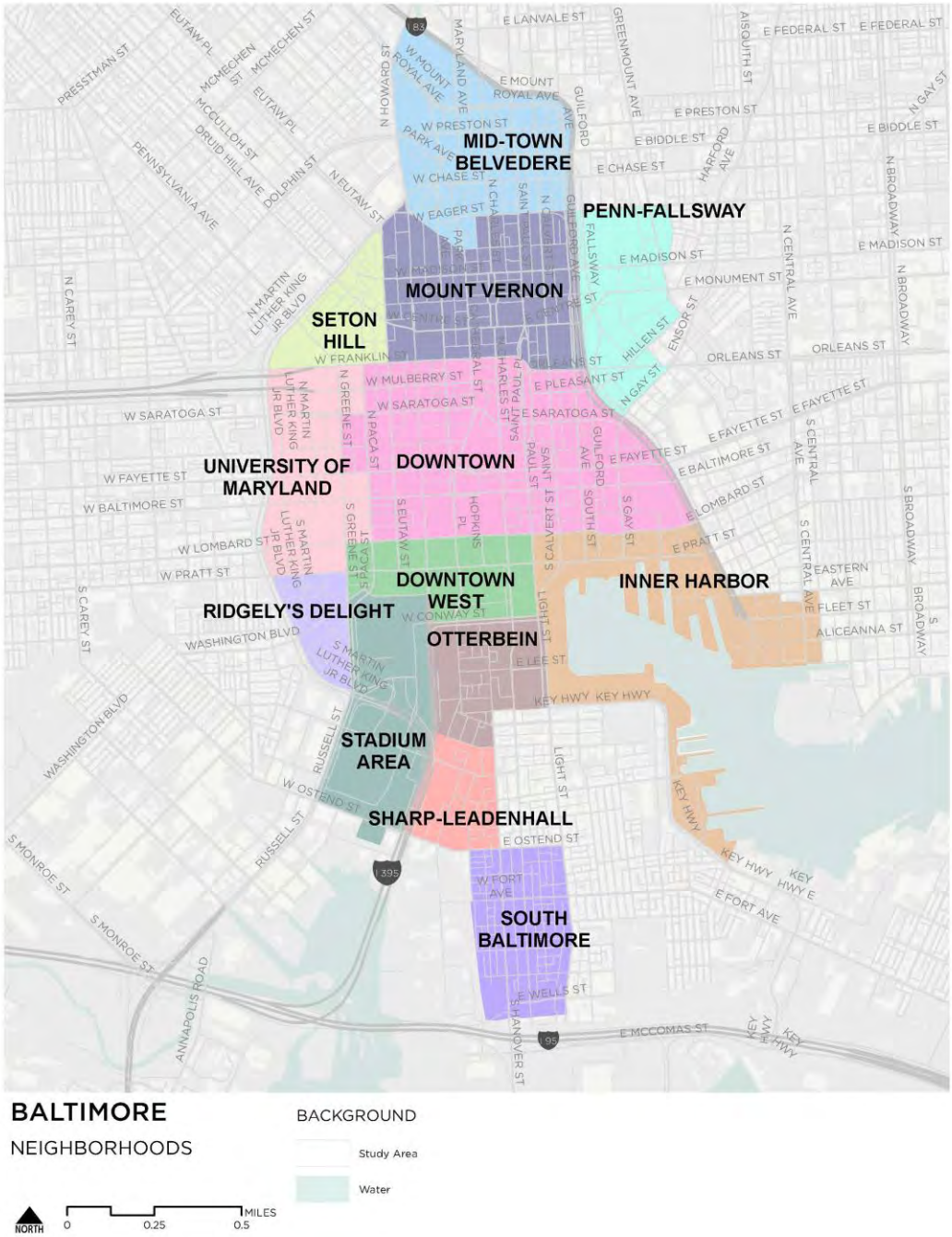
- Buffer area (including bike lanes, parking lanes, and distance between edge of pavement and sidewalk)
- Width of sidewalk

[10] Landis, B.W., V.R. Vattikuti, R. M. Ottenberg, D.S. McLeod, M. Guttenplan. "Modeling the Roadside Walking Environment: Pedestrian Level of Service," Transportation Research Record 1773, Transportation Research Board, National Academy of Sciences, 2001.

- Traffic volume
- Traffic speed

The results are analogous to the Level of Service used for motor vehicle travel, with scores ranging from A to F. While these results were already calculated in the 2004 report, the final scores (A-F) were coded into the roadway data to serve as a comparison for the updated measures included in this study.

Figure 6: Baltimore Neighborhood Map



Results

The following sections present the results of the four analyses. For each measure, as applicable, the results are summarized based on the overall condition, scores per roadway type, and conditions within each study area neighborhood. Results are displayed in Table 4 and Table 5, and Figure 7 shows the map.

Presence/Absence

As a dense urban center, Baltimore has extensive sidewalk coverage. Over 60 percent of roadways citywide have sidewalks on at least one side. Arterial and collector roadways are more likely to have sidewalks on both sides, with 82 percent of arterials and 89 percent of collectors meeting this standard. Roadways falling into the "Other" category, typically alleys and driveways, were the most likely to have no sidewalks present (47 percent).

Table 4: Sidewalk Presence by Roadway Functional Class

Roadway Functional Class	No Sidewalk	One Sidewalk	Two Sidewalks
Arterial	2.11%	15.44%	82.45%
Collector	0.39%	9.89%	89.72%
Local	4.21%	25.55%	70.24%
Other	47.35%	10.29%	42.36%

When assessed at the neighborhood level, only two neighborhoods have sidewalks on both sides of less than 50 percent of roadways. Roadways in some neighborhoods, such as Penn-Fallsway, are almost completely lined with sidewalks on both sides, whereas other neighborhoods, such as Stadium Area, have no sidewalks on over 70 percent of roadways.

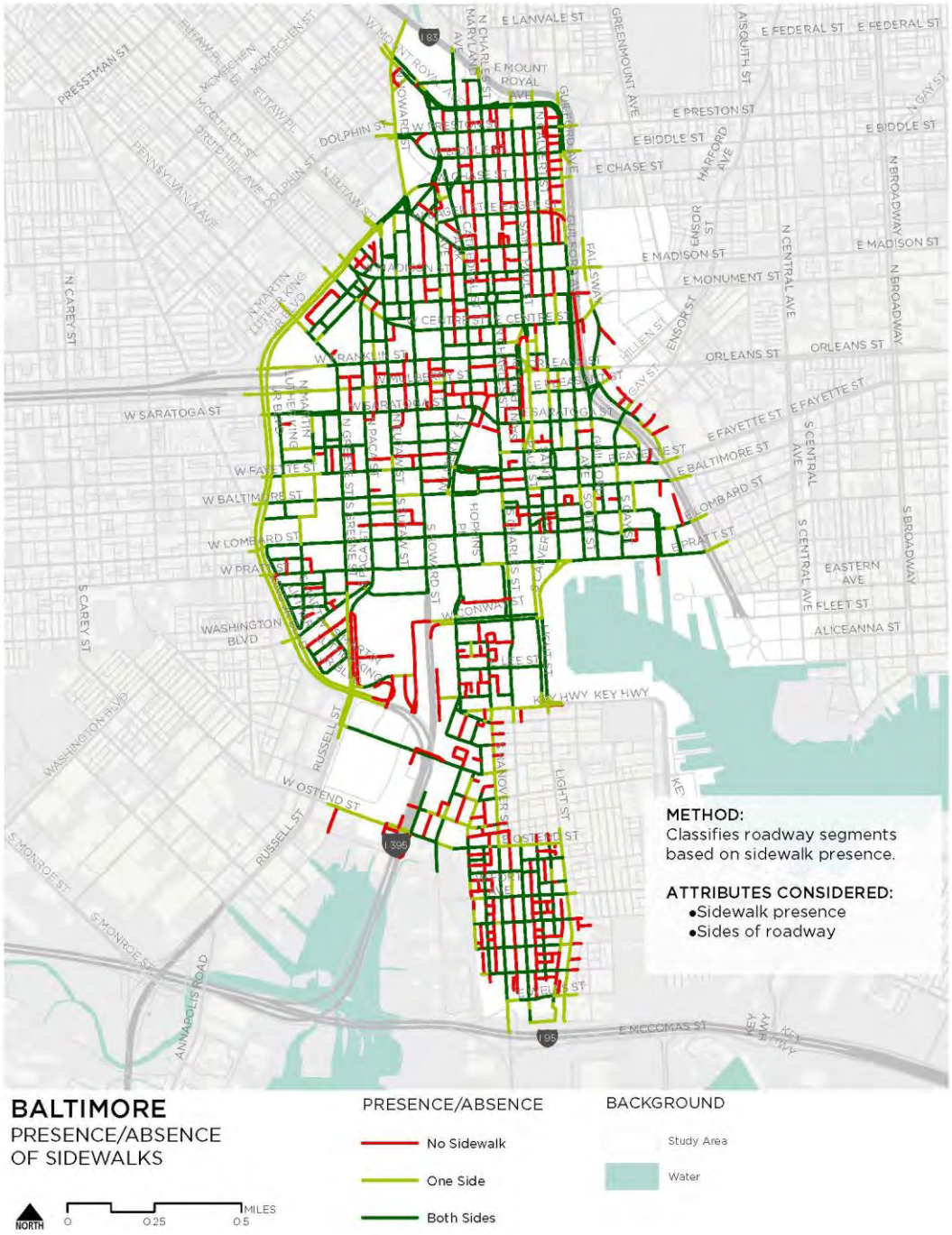
Table 5: Sidewalk Presence by Neighborhood

Neighborhood	Both Sides	One Side	No Sidewalk
Downtown	67.97%	10.95%	21.08%
Downtown West	88.44%	1.21%	10.36%
Inner Harbor	76.07%	13.38%	10.55%
Mid-Town Belvedere	66.17%	2.67%	31.16%
Mount Vernon	69.64%	6.45%	23.91%
Otterbein	61.80%	10.10%	28.10%
Penn-Fallsway	59.04%	40.96%	0.00%
Ridgely's Delight	78.02%	4.65%	17.33%
Seton Hill	67.39%	8.94%	23.67%
Sharp-Leadenhall	40.49%	38.87%	20.64%
South Baltimore	50.19%	13.18%	36.64%
Stadium Area	26.16%	1.64%	72.20%
University of Maryland	66.82%	23.91%	9.27%

Metric strengths: Data is easy to collect and interpret and easy to translate into form-based measures describing network composition and completeness.

Metric weaknesses: The data provides little information on network quality, safety, or accessibility. The data may show limited connectivity where sidewalks generally are not needed (e.g., alleyways).

Figure 7: Baltimore Sidewalk Presence



Pedestrian Space Analysis

Without detailed data regarding buffer presence, the accuracy of this measure is limited to the assessment of roadway posted speeds and widths. However, due to the low numbers of vehicle travel lanes and low posted speeds (30 mph or less) in much of Baltimore, more than 70 percent of roadways score 1 or 2 on a scale of 5. In some neighborhoods (Table 6 and Figure 8), more than 90 percent of streets score in the 1 to 2 range.

Table 6: Pedestrian Space Analysis by Neighborhood

Neighborhood	Percentage of Streets Scoring 1–2 on Pedestrian Space Analysis
Downtown	92%
Downtown West	89%
Inner Harbor	73%
Mid-Town Belvedere	94%
Mount Vernon	95%
Otterbein	74%
Penn-Fallsway	61%
Ridgely's Delight	98%
Seton Hill	99%
Sharp-Leadenhall	96%
South Baltimore	100%
Stadium Area	63%
University Of Maryland	86%

Metric strengths: Data are easy to collect and maintain; flexibility in the method allows consideration of buffers between pedestrians and traffic if the data is available. Intersection scoring tables are available. It is useful for providing an assessment of safety in terms of crash risk. Form-based metrics can be calculated with basic network quality information. Connectivity is assessed in terms of being able to travel between destinations with a degree of safety and comfort as an average adult.

Metric weaknesses: Data display can be difficult for the casual user to interpret. The five-point scale might be difficult to interpret without a carefully described key.

Pedestrian Level of Traffic Stress

The PLTS methodology emphasizes compliance with accessibility laws. Poor pavement quality and noncompliant ramps result in poor scores and were scrutinized carefully for this case study. With sidewalks present on most roadways, the results of the PLTS analysis provide insight into improvements needed to create a fully accessible network.

Sidewalks are generally present throughout downtown Baltimore; however, due to higher speeds on some roadways (greater than 30 mph), poor pavement quality, and lack of accessible ramps, most of the study area is rated 3 (high stress) on the Pedestrian Level of Traffic Stress (PLTS) scale.

Figure 8: Baltimore Pedestrian Space Analysis

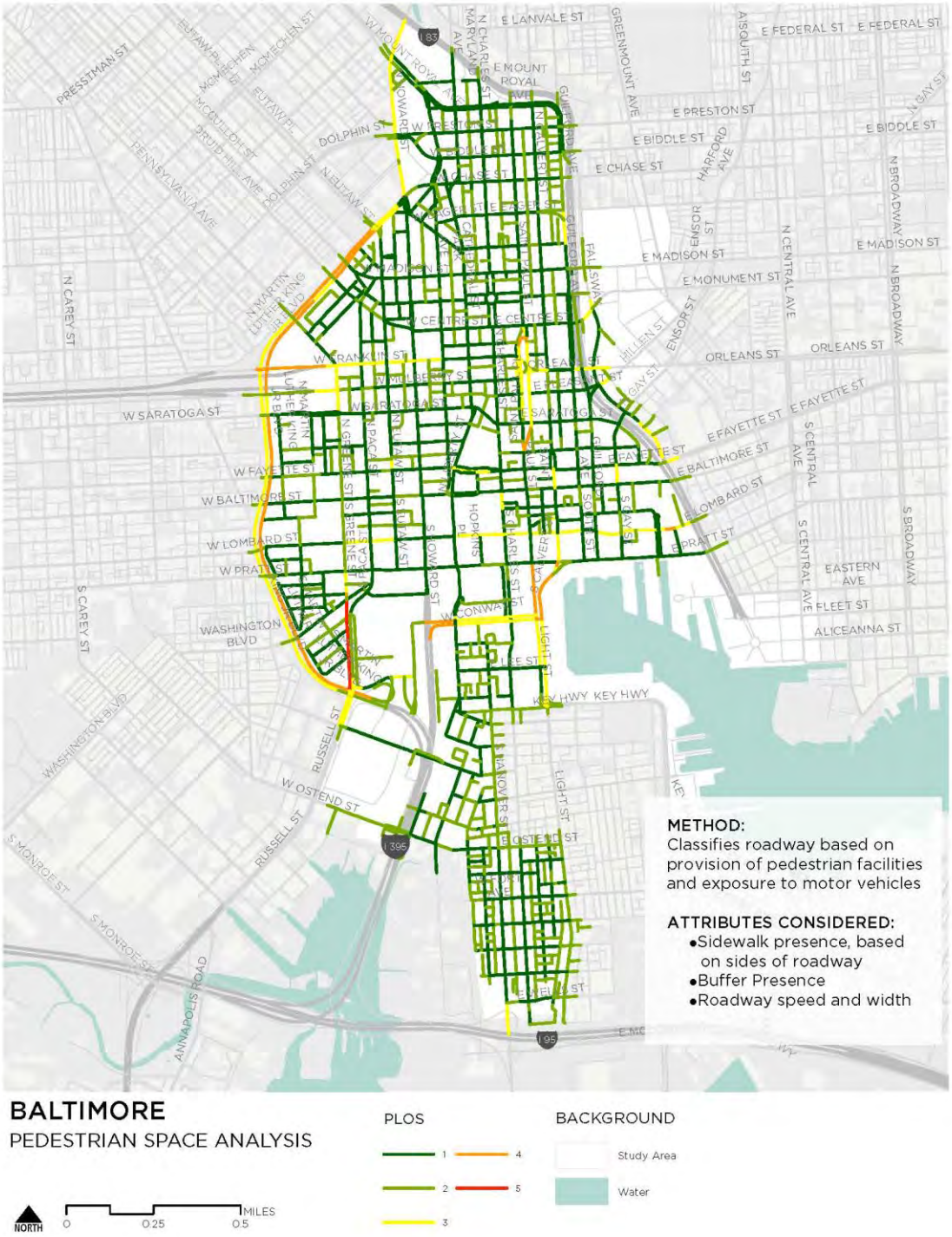


Table 7 shows the percentages of sidewalks within each neighborhood scored at PLTS levels 2, 3, and 4. In general, most sidewalks rated a PLTS 3, and very few sidewalks scored as low stress (2 or below). Figure 9 displays this information in map form.

Table 7: Baltimore Neighborhood Pedestrian Level of Traffic Stress Scores

Neighborhood	PLTS 2	PLTS 3	PLTS 4
Downtown	10.63%	83.72%	5.64%
Downtown West	33.04%	64.51%	2.45%
Inner Harbor	33.42%	63.71%	2.87%
Mid-Town Belvedere	8.60%	90.35%	1.05%
Mount Vernon	8.97%	87.97%	3.06%
Otterbein	10.33%	87.28%	2.39%
Penn-Fallsway	0.00%	87.61%	12.39%
Ridgely's Delight	0.57%	84.27%	15.16%
Seton Hill	0.91%	95.98%	3.11%
Sharp-Leadenhall	0.59%	95.09%	4.33%
South Baltimore	4.19%	94.37%	1.44%
Stadium Area	28.96%	47.70%	23.34%
University Of Maryland	6.66%	74.81%	18.54%

Metric strengths: The metric provides an objective picture of network quality, considering people with mobility impairments. It has clear intersection grading criteria. Data inputs and scoring are consistent with most elements of disability compliance transition plan and can be directly translated into proposed infrastructure improvements and form-based summary measures. Connectivity is assessed in terms of being able to travel between destinations as an adult with a mobility impairment.

Metric weaknesses: This metric is data intensive and relies on substantial field collection. Consistent data maintenance is required to maintain usefulness of data. Network results might be misinterpreted by a casual map user without a clear understanding of network intent. In addition, incomplete data can potentially skew the true picture. For example, more than 90 percent of Baltimore's sidewalks (by length) were documented as greater than 5 feet wide; however, the actual width of the sidewalk is unknown, so the benefit provided by the generally high widths was not calculated. The future addition of detailed data for buffer presence and sidewalk width could improve scores along many roadways.

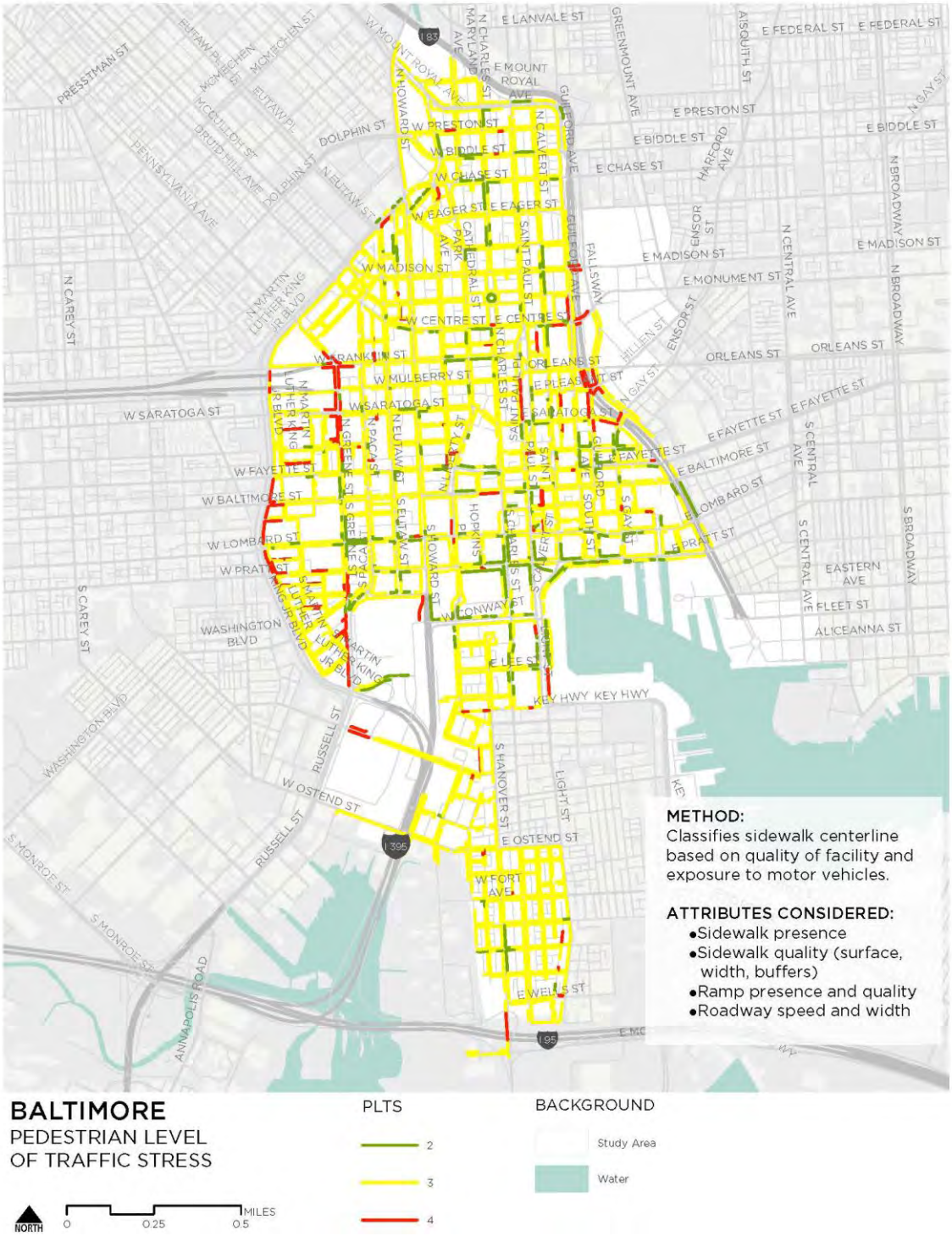
Pedestrian Level of Service

The PLOS scores generated prior to this case study categorized most major roadways within the study area as A through C, with a few segments scoring as D or F. The poorly performing segments are primarily along Martin Luther King Jr. Boulevard, a multilane corridor that carries high volumes of fast-moving vehicle traffic. This report does not include tables or maps of the Pedestrian LOS assessment.

Metric strengths: The metric is well known and accepted by transportation planners. The grading scale is consistent with the *Highway Capacity Manual.*

Metric weaknesses: The model is calculated through complicated formulas and the reason for a given score on a segment is not readily apparent.

Figure 9: Baltimore Pedestrian Level of Traffic Stress



Comparative Ratios of Low Stress Sidewalk Space to Roadway Space

Table 8 provides an example of the widely different results that can be generated by applying different pedestrian assessment measures to a given analysis. The ratio of total low-stress sidewalk space to total roadway travel lane space in each neighborhood was calculated for each of the three measures explored in this case study: Sidewalk Presence/ Absence, Pedestrian Space Analysis, and Pedestrian Level of Traffic Stress. Ideally, the ratio would be 2:1 (200 percent), indicating the length of low-stress sidewalk centerline is twice as long as the length of the roadway centerline.

Table 8: Ratio of Low-Stress Pedestrian Space to Roadway Travel Lane Space Ideal ratio is 200 percent (2:1 low-stress sidewalk area to roadway area)

Neighborhood	Ratio Based on Presence-Absence (Low-Stress = Presence on Both Sides)	Ratio Based on Pedestrian Space Analysis (Low-Stress = Score of 1-2)	Ratio Based on Pedestrian Level of Traffic Stress (Low-Stress = Score of 1-2)
Downtown	136%	93%	11%
Downtown West	177%	87%	53%
Inner Harbor	152%	75%	51%
Mid-Town Belvedere	132%	100%	8%
Mount Vernon	139%	97%	9%
Otterbein	124%	67%	8%
Penn-Fallsway	118%	85%	0%
Ridgely's Delight	156%	97%	0.8%
Seton Hill	135%	100%	2%
Sharp-Leadenhall	81%	100%	0.5%
South Baltimore	100%	100%	4%
Stadium Area	52%	79%	13%
University of Maryland	134%	88%	9%

This comparative demonstration highlights the different types and levels of scrutiny associated with each assessment method. The Presence/Absence measure exhibits the highest comparative ratios of low-stress sidewalk space to roadway space; many neighborhoods exceed 100 percent, with Downtown West scoring the highest having 1.77 more low-stress pedestrian space than roadway space. The Pedestrian Space analysis, however, reveals much lower ratios of low-stress sidewalk space to roadway space: the Downtown West ratio of low-stress pedestrian space to roadway space is a much more modest 87 percent, placing it in the middle of the range of scores. This demonstrates the different results generated by a method that relies solely on the presence of sidewalks versus one that takes into account qualifying factors such as roadway speeds and number of travel lanes. The Pedestrian Level of Traffic Stress-based ratio generates the lowest levels of low-stress sidewalk space compared to roadway space. The Downtown West neighborhood, according to the PLTS assessment, again scores the highest among all neighborhoods, but the amount of low-stress pedestrian space is only 53 percent greater than the amount of roadway space. The ratio for all of Baltimore's neighborhoods other than Downtown

West and the Inner Harbor area is less than 12 percent, with several indicating virtually no low-stress pedestrian space compared to roadway space.

PLTS differs importantly from the other two measures concerning the underlying assumption of total sidewalk area. For the Presence/Absence and Pedestrian Space ratios, the effective sidewalk length was determined by multiplying the roadway centerline length by the number of sidewalk sides. The PLTS measure of sidewalk space subtracts the area taken up by intersections and driveways. For this reason, the total length of sidewalk in the PLTS measure is a more accurate representation of pedestrian space than that of the other two measures, which rely upon a proxy for sidewalk length.

Lessons Learned

- **Determine the right level of detail for the analysis purpose.** Sidewalk networks are complex and often difficult to define. Collection of detailed information, especially for the first time, is highly time intensive. For this reason, broad categories are often easiest, as was the case, for example, in the width data for Baltimore's sidewalks. With width described in only three categories, the flexibility of this data is limited. However, broad categories can limit the level of scrutiny applied to a network. A clearly stated network vision and analysis goal can help planners determine the appropriate level of detail in data collection.
- **Select a measure appropriate for the study area context**. Because Baltimore is an established urban area with an extensive existing sidewalk network, the most useful measures are those that provide more detail and can account for user types. Simpler form-based measures are less informative with regard to network quality or connectivity.
- **Select a measure appropriate for the intended application.** The measure selected should reflect the intended application of the results. The existing Complete Streets framework assesses each neighborhood at a detailed level; additional bicycle and pedestrian metrics should provide an equally detailed level of analysis for other factors. By having an established application for the analysis results, Baltimore has the ability to select the measure that best fits the intended purpose.
- **View the picture from several perspectives.** Using several different connectivity analysis tools allows staff, decision makers and the public to interpret the pedestrian network through multiple lenses including safety and accessibility. It can mitigate the weaknesses of a single technique and lead to a more comprehensive understanding of conditions.

Resources

- Oregon Department of Transportation Analysis Procedures Manual version 2, 2016
- Baltimore Metropolitan Council. *Task Report 04-9: Bicycle Level of Service Evaluation Update & Pedestrian Level of Service Evaluation. 2004*. Retrieved from http://www.mdot.maryland.gov/newMDOT/Planning/Bike_Walk/Documents/Update_2017/BLOC_Analysis.pdf.
- City of Columbia, South Carolina. Walk Bike Columbia: Pedestrian and Bicycle Master Plan. 2015. Retrieved from http://www.walkbikecolumbia.org/documents.html

Bicycle Connectivity Across Highways, Caltrans District 4

Background

This case study examines opportunities to measure multimodal network connectivity at a large regional scale, with a focus on bicycle mobility around high-speed highway systems. Although some highways improve mobility by enabling motor vehicles to travel great distances at high speeds, they can also generate mobility barriers for other types of travelers, particularly pedestrians and bicyclists. Highways that prohibit nonmotorized travel are "hard barriers" of physically impassible space that require prohibited travelers to find routes around them. Highways that allow nonmotorized travelers to share travel lanes with fast-moving vehicles along the corridor or at designated crossings present "soft barriers." In these settings, bicyclists and pedestrians are not forced to find a way around the road, but they can experience high stress levels while traversing or crossing the corridor if the roadway is not designed to provide them with clearly designated, safe, and conveniently located paths.

Case Study at a Glance

Focus:
Bicycle
Context of Study Area:
Urban
Scale of Study Area:
Caltrans District 4
Tools & Models:
GIS, etc.
Application:
Planning/Programming/ Performance Measurement

As the operator of California's transportation network, Caltrans has jurisdiction over major highways throughout the state. In 2016–2017, Caltrans started developing its first district-level bicycle plan in District 4, which covers the San Francisco Bay Area. The plan, which is a pilot initiative intended for replication in the other Caltrans districts, focuses on improving bicycle mobility along and across the state transportation network throughout the nine-county region. Caltrans is identifying network needs by assessing and overlaying information about a variety of performance indicators, including the following:

- **Potential Bicycle Trip Demand on Existing Highway Networks.** The regional travel demand model produced by the San Francisco regional Metropolitan Transportation Commission (MTC) is used to identify trips that could be made via bicycle and that likely would require travel on or along the state network.
- **Supply and Quality of Bicycle Access to Existing Highway Networks.** A modified Level of Traffic Stress (LTS) measure is evaluated for travel along the state network where bicycles are allowed, including crossings at intersections or designated areas along access-controlled corridors.
- **Bicycle Safety on Existing Highway Networks.** Historic police reports of bicycle crashes are tabulated by severity level, using a moving-window aggregation along the network.
- **Perceived Barriers, Existing Travel Routes, and Desired Improvements on Existing Highway Networks.** Through a widely distributed online survey, residents throughout the region identified locations on the state network where they perceive barriers to bicycling, locations where they currently travel by bicycle, locations where they would like to travel by bicycle, and improved bicycle facilities that they would like to see constructed.

The goal of this case study is to expand on Caltrans' assessment of bicycle accessibility along and across state highways by evaluating the barrier effects of state highways within the context of local multimodal networks. While the focus of the case study is on highways, the methods developed here could also be applied to evaluating any linear barriers that reduce multimodal connectivity, such as arterial streets, railroad corridors or rivers. The case study examines local networks that are affected by the following four Caltrans highway corridors:

Table 9: State Highways Examined in Case Study

Corridor	County	Route	Milepost Range	Access Controls
1	Contra Costa	I-680	14.4–18.6	Freeway
2	Alameda	I-880	4.7–17	Freeway
3	Marin	US 101	10–22.9	Freeway
4	Napa	CA 121	4.47–11	Traffic signal

Connectivity Measurement Experience

Data Assembly

The primary data source for this evaluation is OpenStreetMap (OSM). OSM is an openly available crowdsourced map of the world with geospatial data on transportation networks and other map features. For this case study, OSM was accessed using the Python package OSMnx, which downloads a routable network for specified travel modes.[11] For example, a downloaded OSMnx "bikeable" network would include all streets and trails that allow bicycles, regardless of whether the routes are designated in a policy document, physically identified with signs or pavement markings, or otherwise acknowledged by local or state transportation agencies. The analysis also uses the Caltrans state highway network lines as a framework for sampling.

OSM has high quality geometric information, and the attributes associated with physical features are continuously updated by the public. The currently available OSM attribute data on California's state highways lacks some significant information about various roadway characteristics that were important for the District 4 Bicycle Plan. Accordingly, the OSM network for the plan and this case study were merged with Caltrans' Functional Roadway Classification data and with local bikeway data collected from the nine counties in the region.

Methodology

The analysis included determining the Level of Traffic Stress (LTS) for each segment and crossing of the state highway system. Because the LTS analysis framework is organized around roadway segments, a unique methodology was developed to evaluate LTS at highway crossings, including conventional, surface highway intersections and ramps to access-controlled facilities. The approach to defining LTS for

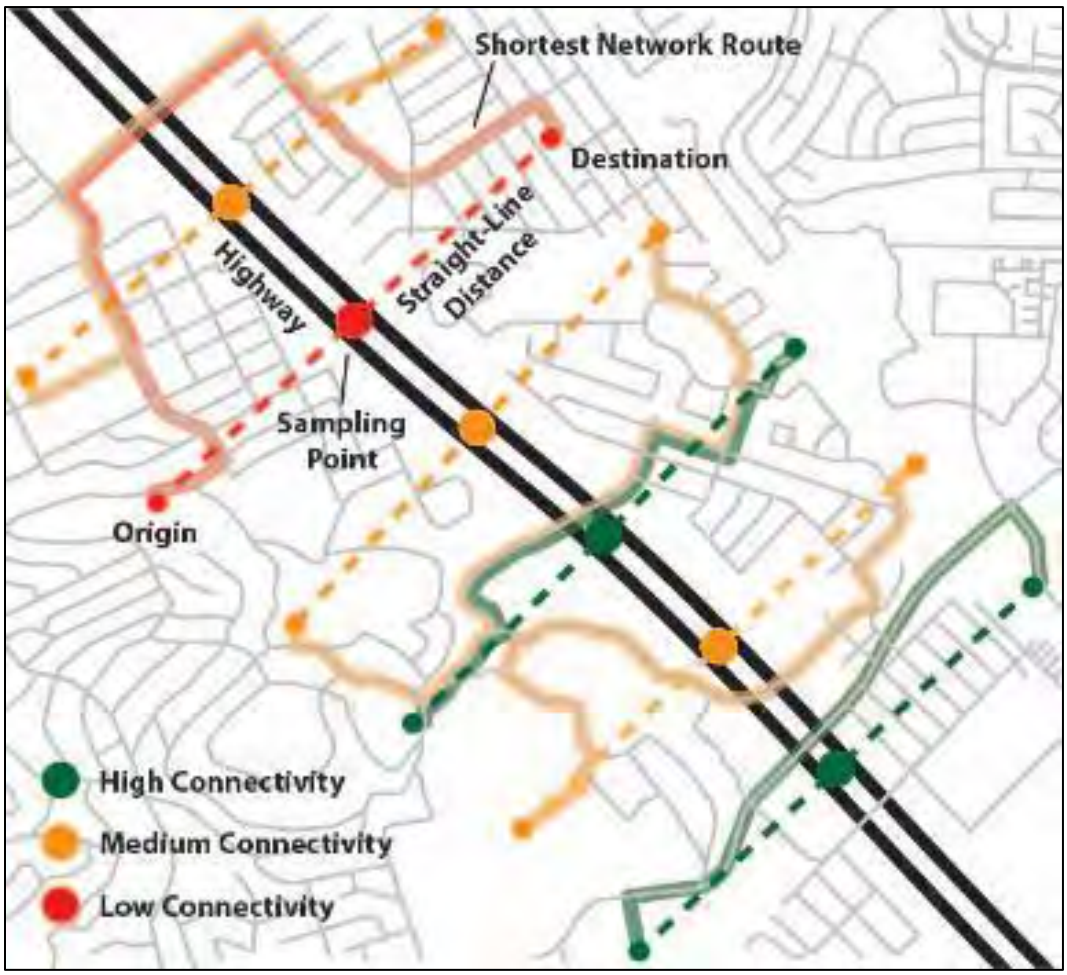
[11] Boeing, G. 2017. "OSMnx: New Methods for Acquiring, Constructing, Analyzing, and Visualizing Complex Street Networks." *Manuscript under review*. doi:10.2139/ssrn.2865501.

crossings is the same as that applied to roadway segments: the LTS score is linked to the type of user that would feel comfortable using the facility.[12]

The general approach for assessing connectivity across highways is to evaluate the directness with which a traveler may cross between points on either side. The Route Directness Index is calculated at numerous points along each highway corridor.

As illustrated in Figure 10, points for sampling route directness are placed at equal intervals along the highway. Origin and destination points are placed at equal distances to either side of the sampling points. Each origin-destination point is linked to the nearest point on the local road network. Straight-line distances are calculated between each origin-destination pair, representing the most theoretically direct route across the state highway.

Figure 10: Examples of Route Directness Indices along hypothetical highway corridor



To establish a comparative context for the theoretical straight-line distance assessment, a network analysis tool is used to calculate the shortest route across the state highway between each origin and destination along the actual road network. Currently, the network analysis assessment simply identifies

[12] Detailed LTS scoring methodology can be found in the District 4 Bicycle Plan Needs Analysis Technical Memorandum, *in progress.*

the shortest linear distance, but it could be refined to account for varying impedances along road segments. In addition, various subsets of the street network attribute data could be used to identify facilities suited for different modes or types of users; for example, low-volume streets and off-street paths could be identified to simulate a network available for children walking to school.

Based on the two sets of route directness assessments, the Route Directness Index is calculated as the ratio between straight-line theoretical distances and actual roadway network distances between origins and destinations on opposite sides of the state highway. Low-scoring routes are the most direct. Higher scores indicate the need for bicyclists to navigate substantially out of the most direct path to avoid a stressful or impassible area. Mapping the Route Directness Index scores along the highway provides a high-level indication of connectivity throughout the corridor.

The ratio between route distance and straight-line distance is unlikely to approach values of 1.0 in locations where the sampling point is not placed directly on a crossing. The sampling points are intentionally spaced evenly along the corridor at locations that might or might not have an actual roadway crossing. This helps ensure that the permeability of the highway is considered for all potential users, not just those who are traveling near an existing crossing.

Several parameters can affect the outcome of Route Directness Indices. The following parameters were assumed for this analysis:

1. Sampling points are placed every 500 feet along the highway, regardless of whether the location is a highway crossing.
2. For Corridors 1, 3, and 4, the origin and destination points are placed on either side of the highway 1/3 mile away from and perpendicular to the associated sampling points. For Corridor 2, variable distances between the origin destination points and the sampling point along the route were tested.
3. The local road network includes all publicly accessible roadways within 1.5 miles of the state highway that are available for use by bicyclists.

Results

Maps of Route Directness Indices for each corridor are shown on the following pages. Results for both the shortest path along the full network and for a “lower stress” network, excluding arterial streets, are presented. In the lower stress case, some sample points do not have observations because the origin or destination point fell into a “stress island,” meaning that no low stress route exists to cross the barrier from that location, for example areas of Walnut Creek (Figure 11).[13] These are a typical feature of road networks with strong arterial-collector-local hierarchies.

Assessing permeability using a Route Directness Index provides the added benefit of accounting for connectivity across the street network adjacent to a highway. A street network fragmented by loops and cul-de-sacs will restrict connectivity even if there are ample opportunities for highway crossing. In these cases, installing additional highway crossings without adding cut-throughs to improve access for bicyclists and pedestrians might not be worthwhile. A highly connected grid network, by contrast, might

[13] Mekuria, M.C., Furth, P.G., & Nixon, H. (2012). Low-stress bicycling and network connectivity.

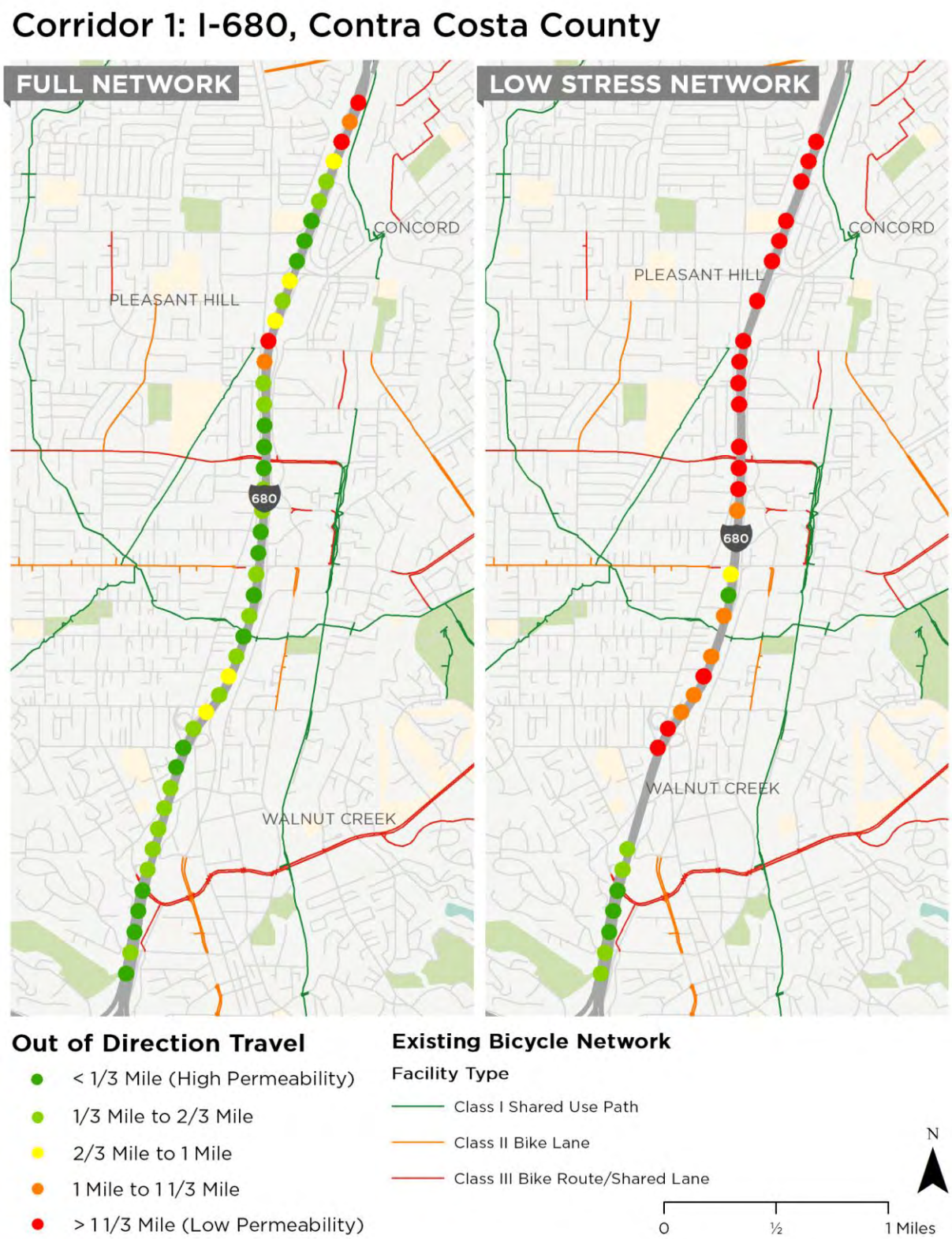
facilitate high connectivity across a highway with only moderately dense crossings. As such, Route Directness provides a contextual measure compared with more basic measures of crossing density.

Note that points on the following maps are not specific crossing locations. They are the sampling points used to represent the level of permeability between origin and destination on either side of the corridor.

Corridor #1:

The Route Directness analysis of potential crossings along Corridor 1 (I-680 through Walnut Creek) shows a high permeability along much of the corridor when considering all available bicycle routes (Figure 11, left panel). Much of the corridor has a Route Directness Index between 1 and 2, indicating that crossing the freeway requires users to travel out of their way by up to two times the straight-line distance between the two sides. Permeability is further reduced when routes are restricted to a “low stress network” that excludes arterial streets (Figure 11, right panel).

Figure 11: Comparison of State Highway Permeability in Contra Costa County



Although several permeable crossings are present along this corridor, most crossings require users to travel out of their way by distances two to four times longer than the straight-line distance between the two sides. As shown in **Error! Reference source not found.**, only 18 percent of crossings require less than 2/3 mile of out-of-distance travel.

Table 10: Corridor 1 Crossing Points Grouped By Low-Stress Permeability Level

Less than 1/3 mi out-of-direction travel	**1/3 mi to less than 2/3 mi out-of-direction travel**	**2/3 mi to less than 1 mi out-of-direction travel**	**1 mi to less than 4/3 mi out-of-direction travel**	**More than 4/3 mi out-of-direction travel**	**No Low-Stress Path**
9%	9%	2%	11%	39%	30%

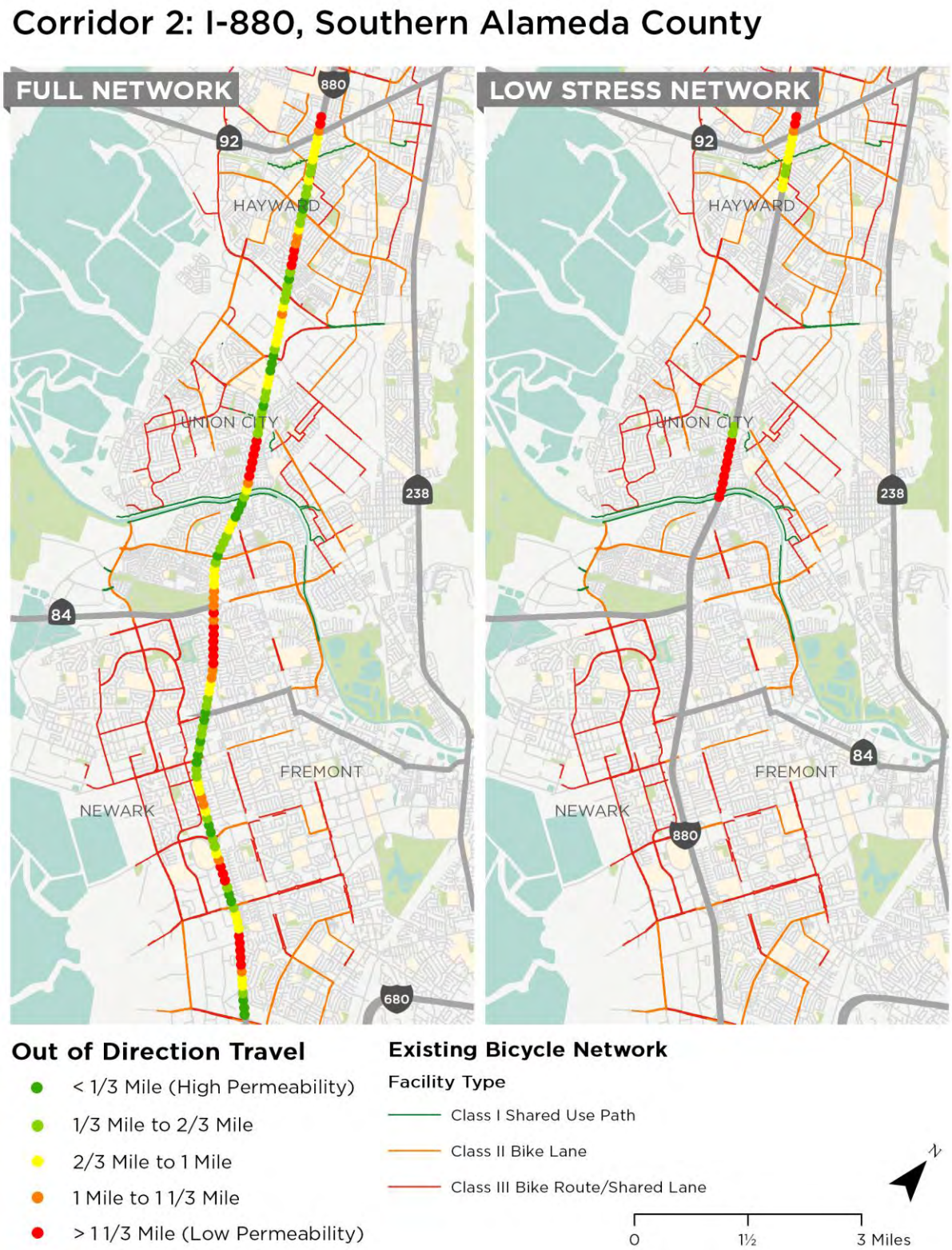
Note that here is a significant trail crossing along I-680 (near the center of the extent shown on the map). Using the OSM network, the sample point nearest this trail crossing appears to require a short distance of travel on an arterial to reach the trail (the sample point is in a development with direct access from an arterial). As a result, this point appears to be impossible in the Low Stress Only panel. More direct access points to this trail, which simply are not captured in OSM (and which might be informal infrastructure and not officially maintained by a jurisdiction), could exist. This issue highlights a particular challenge with conducting this permeability analysis, especially on the scale of a Caltrans District. Small gaps in connectivity within the data (i.e., cut-throughs that bicyclists can make) could substantially influence the measure of permeability.

Corridor #2:

The Route Directness analysis of potential crossings along Corridor 2 (I-880 in southern Alameda County) shows moderate permeability along much of the corridor when considering all available bicycle routes (Figure 12, left panel). Much of the corridor has a Route Directness Index between 2 and 4, indicating that crossing the freeway might require bicyclists to travel out of their way by distances two to four times the straight-line distance between the two sides. Places with low Route Directness Indices, represented by green dots on the map, represent the locations of overpasses, which provide ready access between the sides.

Permeability is dramatically reduced when routes for traversing the freeway are restricted to a “low stress network” that excludes arterial streets. Large portions of the freeway can be crossed only by traveling at least four times the straight-line distance between opposing points. Other areas, indicated by a lack of Index data, do not facilitate any crossing, as either the origin or destination point is in a “stress island,” an area of lower stress roadways, which cannot be exited without negotiating a high stress roadway. The difficulty of crossing the highway using this “low-stress network” more realistically simulates the difficulty faced by users who are uncomfortable cycling on a roadway with fast, high-volume traffic. Unfortunately, in areas with few highway crossings, those crossings that do exist are likely to be high volume to accommodate traffic needs, exacerbating the difficulty of crossing for vulnerable users.

Figure 12: Comparison of State Highway Permeability in Southern Alameda County



Error! Not a valid bookmark self-reference. presents a summary of permeability relative to the level of demand established by the bike plan. Most (83 percent) of the crossing points on this corridor are on stress islands—locations that connect only by high-stress corridor. Only four percent of observations require less than two-thirds of a mile of out-of-distance travel.

Table 11: Corridor 2 Crossing Points Grouped By Low-Stress Permeability Level

Less than 1/3 mi out-of-direction travel	**1/3 mi to less than 2/3 mi out-of-direction travel**	**2/3 mi to less than 1 mi out-of-direction travel**	**1 mi to less than 4/3 mi out-of-direction travel**	**More than 4/3 mi out-of-direction travel**	**No Low-Stress Path**
9%	0%	3%	5%	1%	83%

For Corridor 2, various distances from the corridor were used for measuring permeability. Because many of the facilities in this case study are access-controlled highways, the starting point for the permeability analysis could have significant impacts on its measurement. Figure 13 shows the distribution of the four scenarios (each point starting 1/3 mile farther from the highway). In general, the 1/3-mile scenario is the most evenly distributed, but the least out-of-direction travel comes from the 2/3-mile scenario (Table 11).

Figure 13: Distribution of Permeability by Analysis Scenario

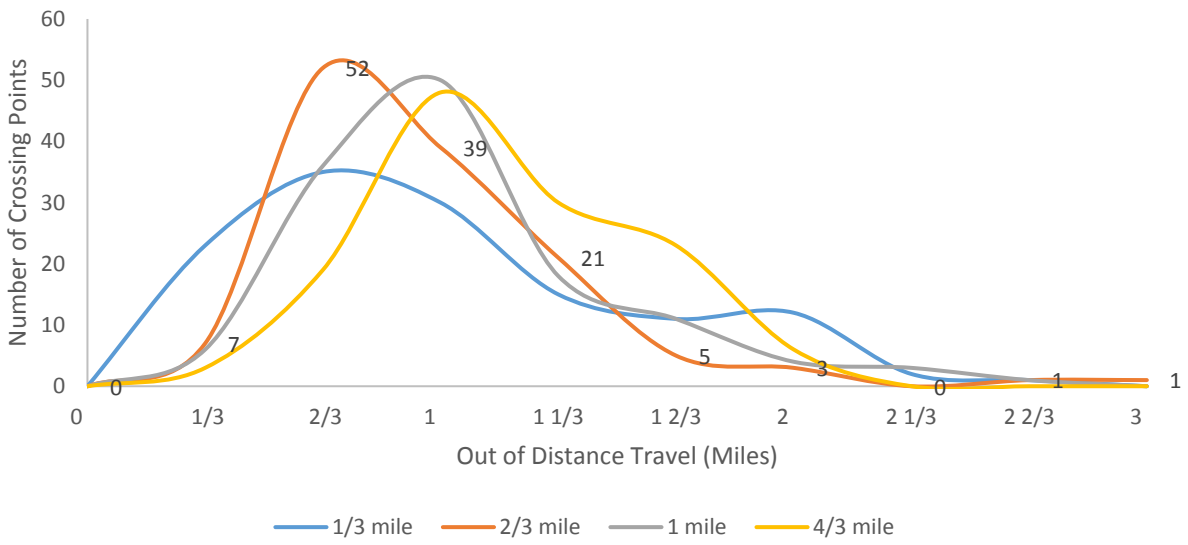


Table 12: Total Out-of-Direction Travel Per Scenario

Scenario	**Additional Out-of-Direction Travel (Miles)**	**Comparison to Previous Scenario (Miles)**
1/3 mile	109	n/a
2/3 mile	104	-5
1 mile	114	11
4/3 mile	131	17

Figure 14 presents these data on a map for the four scenarios. Relevant changes can be seen in several locations (highlighted on the map), including:

- **Near the State Route 92 and I-880 crossing (top of map).** As the distance increases from I-880, the crossing becomes significantly more challenging, requiring crossings of two access-controlled highways.
- **Near the Alameda Creek Trail (middle of the map).** As the sampling point distance increases, access to this creek trail from the adjacent neighborhoods might not be well captured in OSM. If the OSM data are correct, limited access points hamper the effectiveness of this trail for adjacent neighborhoods.
- **Near the Mowry Avenue interchange (bottom third of the map).** At this location, the 1/3-mile scenario has the greatest out-of-distance travel due to the lack of connectivity of the street network immediately adjacent to the highway.

Figure 14 State Highway Permeability By Proximity of Origin and Destination Points

The Route Directness analysis of potential crossings along Corridor 3 (US-101 in Marin County between San Rafael and Novato) shows moderate permeability along much of the corridor when considering all available bicycle routes (Figure 17, left panel). Similar to Corridor 2, much of the corridor has a Route Directness Index between 2 and 4, although clusters of high permeability are present in San Rafael. Permeability at the CA-37 interchange is dramatically lower due to the freeway-to-freeway connection and a street network that provides few bicycle and pedestrian crossing opportunities. Permeability along Corridor 3 is dramatically reduced when routes traversing the freeway are restricted to a low-stress network that excludes arterial streets (Figure 17, right panel). Large portions of the highway are not permeable when constrained to a low-stress network.

Figure 15: Comparison of State Highway Permeability in Marin County

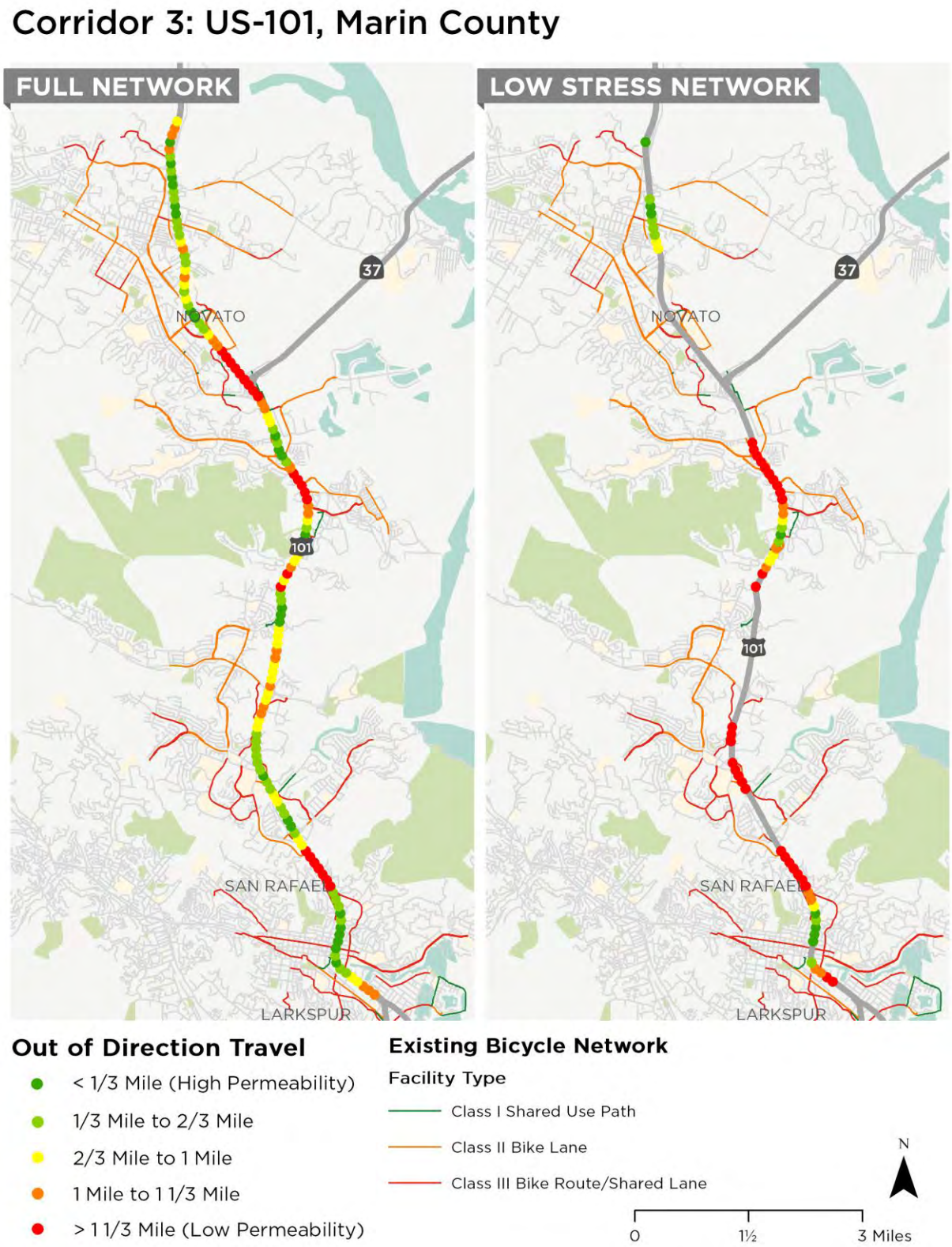


Table 13 relates the permeability measure to the level of demand estimated for the District 4 Bike Plan. Almost all crossing points showed mid-level demand, although relatively speaking, the crossings with no low-stress path are lower demand. Of the crossing points possible on a low-stress network, almost half require more than 4/3 miles of out-of-distance travel.

Table 13: Corridor 3 Crossing Points Grouped By Low-Stress Permeability Level

Less than 1/3 mi out-of-direction travel	**1/3 mi to less than 2/3 mi out-of-direction travel**	**2/3 mi to less than 1 mi out-of-direction travel**	**1 mi to less than 4/3 mi out-of-direction travel**	**More than 4/3 mi out-of-direction travel**	**No Low-Stress Path**
6%	6%	4%	6%	21%	56%

Corridor #4:

The Route Directness analysis of potential crossings along Corridor 4 (CA-121 through Napa) shows a high average permeability along the corridor when considering all available bicycle routes (Figure 18, left panel). Most crossings do not require users to travel farther than twice the straight-line distance. When routes for traversing Corridor 4 are restricted to a low-stress network that excludes arterial streets, permeability is constrained primarily to the CA-121 corridor between CA-221 and CA-29 (Figure 18, right panel). Permeability is dramatically reduced north of the CA-221 interchange.

Figure 16: Comparison of State Highway Permeability in Napa County

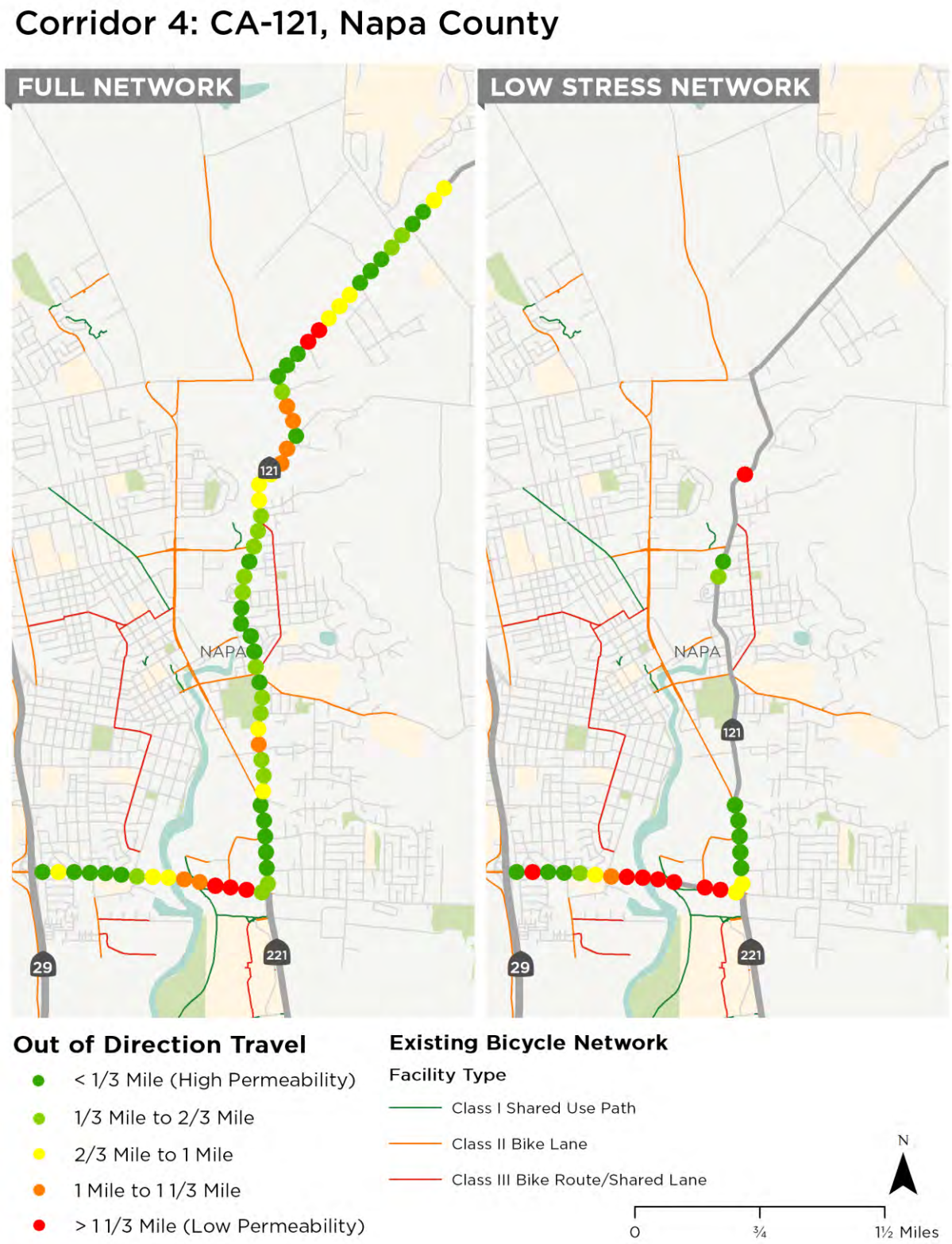


Table 14 indicates roughly 14 percent of the crossing points require less than 1/3 mile out-of-direction travel, while another 40 percent require more than 1 mile of out-of-direction travel.

Table 14: Corridor 3 Crossing Points Grouped By Low-Stress Permeability Level

Less than 1/3 mi out-of-direction travel	**1/3 mi to less than 2/3 mi out-of-direction travel**	**2/3 mi to less than 1 mi out-of-direction travel**	**1 mi to less than 4/3 mi out-of-direction travel**	**More than 4/3 mi out-of-direction travel**	**No Low-Stress Path**
14%	3%	5%	2%	12%	65%

Application to Decision Making

The permeability measure presented here provides an additional level of data analysis that Caltrans can use for its ongoing bicycle plan. The bicycle plan is identifying bicycle investment needs both along and across the state highway system. As that process identifies areas of high need, the permeability measure can be applied to help prioritize potential improvements.

The extra effort required to produce this measure makes producing it for the entire system challenging. Focusing on locations that are defined as high priority through the other metrics used in the plan—including demand, safety, LTS, and public input—will help Caltrans make use of this more sophisticated measure efficiently.

The documentation of this method created an opportunity for Caltrans to use this approach during the development of Transportation Concept Reports (TCR). TCRs are 20-year planning documents for each state highway that identify existing route conditions and future needs. Caltrans plans to add the bicycle permeability measure (and a similar measure for pedestrian permeability) would help identify multimodal needs in other congested corridors.

Connectivity measures will be presented alongside other measures as part of the project prioritization process. Maps and tables will be produced that show permeability alongside other metrics, following a similar format to the one presented in this case study.

Lessons Learned

- Level of effort required to measure permeability is challenging to produce for the entire system.
- The lack of 'real-world' pedestrian and bicycle network connections in OSM (e.g., between trails and local streets) reduces overall permeability.
- Out-of-distance travel varies depending on the distance between travel start and end points as discussed for Corridor 2.
- Excluding arterial streets to illustrate a low-stress network works as a proxy, but could be enhanced with more detailed network information.

Bicycle Network Assessment Comparison, Fort Collins Department of Transportation

Background

FC Bikes is a team within the FC Moves transportation planning department at the City of Fort Collins. FC Bikes aims to increase bicycling as a mode of transportation and promote a bicycle-friendly community through planning, programming, and advocacy activities. At the larger division scale, FC Moves encourages cooperation among departments as the City seeks to create a balanced transportation system.

FC Moves initiated the Transportation Master Plan (TMP) update during the summer of 2017. The effort expressed interest in developing multimodal benchmarks and level of services assessment tools that could be used not only to inform the TMP update, but also during all stages of the project lifecycle—beginning with long range planning and transitioning to project planning, alternatives analysis, design, and project implementation. Beyond applying to all stages of project and plan development, the measure also needed to have the following qualities:

Case Study At-A-Glance

Focus:
Bicycle
Context of Study Area:
Urban/Suburban
Scale of Study Area:
Local
Tools & Models:
GIS, etc.

Level of Traffic Stress, Low Stress network assessment
Application:

- **Easily updated and replicable:** As new network segments are implemented and Fort Collins continues to grow, the results need to reflect on-the-ground conditions.
- **Tracked over time:** The measure needs to serve as a benchmark for easy comparison across time using consistent methodology.
- **Easily communicated:** The results of the measure need to be easy to communicate to City officials and decision makers. Data creates a strong argument, but it must also be easily understood.

The focus of this case study is primarily on the bicycle network, as City staff focused on the pedestrian network are currently developing an assessment tool for existing sidewalk data. This pedestrian network assessment tool, although in its beginning stages, tracks information on network quality, compliance with disability laws, and equity implications and can inform project prioritization.

Despite an extensive network of bicycle lanes and trails, the City has not created a complementary assessment tool for the bicycle network. The 2014 Bicycle Plan included a modified Level of Traffic Stress analysis that has remained a point of interest for FC Bikes; however, this analysis has not proved repeatable over time due in part to vague documentation. As Fort Collins aims to improve their network and earn the Bicycle Friendly Community Diamond distinction, a metric is clearly needed that can be communicated among departments and with decision makers consistently over time.

Based on the identified goals and needs of Fort Collins, this case study compares two measures: Level of Traffic Stress and Low Stress Network Connectivity. These two methods are compared based on their

application to qualitative and quantitative analysis of the network and ultimately assessed on their relevance to the City's identified goals.

Connectivity Measurement Experience

Two methods were selected for assessing the Fort Collins bicycle network:

A Level of Traffic Stress (LTS) Network Analysis assesses the perceived stress level of roadway segments and intersections based on factors such as dedicated right of way for bicycles, speed of motor vehicle travel, number of travel lanes, and on-street parking. LTS scores range from 1 (least stressful) to 4 (most stressful). The methodology relies on the weakest link principle, which has two primary implications. First, the quality of a roadway segment or intersection is assessed based on the worst condition present. Second, the presence of a high-stress roadway segment or intersection will effectively prevent a trip from occurring; only those who are considered strong and fearless are likely to make these trips under higher stress conditions, while children or an average adult would not. [14]

A Low-Stress Network Analysis assesses perceived network stress based on similar criteria; however, instead of assigning a stress level based on the worst condition along a segment, segment stress levels are adjusted based on different criteria, resulting in variations of perceived length. For example, high posted motor vehicle speeds and more vehicle travel lanes will increase the perceived stress level by a certain percentage, whereas signalized intersections and separated bicycle facilities will reduce the perceived stress. This impact can be translated into the perceived distance traveled along a route. This means that higher stress segments will feel longer but will not necessarily prevent someone from making a trip.

The following sections describe the associated steps for data assembly, data clean up, and analysis for both measures.

Data Assembly

The analysis drew upon several different datasets to calculate and inform the connectivity measures:

- The existing Bicycle Facilities layer includes all Fort Collins roadways, travel lane widths, turn lane location and length, parking presence, bike facility type, posted speed, and the analysis results and recommendations from the 2014 Bicycle Master Plan.
- The Multi-Use Trails layers include all existing trails with details on surface type and bridge/underpass locations.
- Traffic Signals include the location of all signals within Fort Collins, including HAWK signals.
- Land Use data includes residential and commercial zoning throughout Fort Collins.

The City of Fort Collins GIS department provided the data. All bicycle facility types were included in the analysis with the exception of soft surface trails, which were omitted due to the recreational function of the trails within Fort Collins (hard surface trails were included in the data). The Land Use layer, which is maintained by the City, was obtained from the City's Open Data portal.

[14] Mekuria, Maaza C., Peter G. Furth, and Hilary Nixon. 2012. "Low-Stress Bicycling and Network Connectivity." http://transweb.sjsu.edu/project/1005.html

Data Limitations

Different departments are responsible for data maintenance and updates. This results in relevant data existing in multiple features datasets and data that is subject to varying policies and procedures regarding data completeness and data updates. Many of the attributes related to bike facilities were populated during the 2014 Bicycle Master Plan process, as these items were not historically tracked. Bicycle facility data is currently maintained by the FC Bikes department and is updated as projects are completed.

Despite efforts to maintain a complete bicycle network dataset, two additional challenges to data accuracy were found:

Speed: Along many segments, speed data was incomplete. Most often, these roadways were local or represented small segments in an otherwise-complete corridor. When one segment in a larger corridor was incomplete, the speed attribute was populated based on the speed of the corridor. For local roadways, the assumption of 25 mph was used, based on the guidance provided by City staff outlined below.

Future Roadways: Fort Collins is developing at a rapid pace, and the base network includes a series of future roadways with incomplete attribute information. In collaboration with City staff, these roadways were included, with the following assumptions:

- Speed limit was assigned based on Street Type
  - Arterial: 35 mph (average of arterial speed limits)
  - Collector: 30 mph
  - Local: 25 mph
- Number of lanes: Collectors and local roadways have only one motor vehicle lane in each direction.
- Bike Lanes
  - Present on Arterials and Collectors
  - Width ranges from 6.5 to 8 feet
  - No bike lanes on local roadway; assume shared use

Methodology

The following section outlines the methodology used in calculating the connectivity measures for the Fort Collins network and the data preparation steps. The methodology was developed based on existing data and consultation with City staff.

Preparing Data

The Bicycle Facilities layer did not include a total number of travel lanes attribute, nor were right turn lane lengths assigned to the corresponding intersections. Trails were also stored separately from the bicycle network. The following steps outline the creation of a complete routable network dataset for use in both analyses:

- Network segments were split to allow for assignment of intersection information, including right turn lane lengths, to the appropriate segment end.
- The Total Number of Lanes attribute was populated.
- Data layers of hard surface trails and bicycle facilities were merged.

- Network segmentation was edited to develop a topologically correct network analysis layer.

The resulting layer was used as the input analysis layer for both the Level of Traffic Stress analysis and the Low-Stress Network analysis.

Level of Traffic Stress Calculations

The LTS assessment was based on the standard four-point scale, with LTS 4 representing the highest stress roadways. Hard surface trails were included in this analysis to account for the vital role they play in the network and to allow for comparison to the Low Stress Connectivity analysis. Trails were assessed as a separated facility, receiving a baseline score of LTS 1. When the trail crossed a roadway, it was assigned a crossing score and graded using the relevant LTS tables.

All steps in the analysis were documented through the ArcGIS Model Builder to provide a documented, repeatable analysis tool. Following the initial data preparation, the analysis was completed using the following steps:

- Roadway segments were scored based on number of lanes, roadway speed, bicycle facility type and width, on-street parking presence and width, and land use context.
- Intersection approaches were scored based on right turn lane presence and length.
- Intersections were scored based on roadway crossings (number of lanes and speed); signalized intersections were omitted.
- A final score was calculated based on the highest LTS score present along a segment, approach, and intersection.
- The final score was assigned to the roadway segment.

Based on the final LTS score, segments scoring 1 or 2 were selected to create a low-stress network. These roadways and trails generally would be considered comfortable for children and average adults. This network was used for three additional steps in the analysis to explore the impact of the LTS results.

- **Low-Stress Connectivity Islands:** A visual display of the low-stress network that depicts groups of connected segments by color. As shown in Figure 19, connected segments are displayed as one color, and different colors represent areas not connected by low-stress segments. This analysis demonstrates barriers in the network, serves as a gap analysis, and provides a baseline understanding of where trips can be made within the City of Fort Collins.
- **Closest Facility Network Analysis:** Routes were determined between Census Block Centroids and Schools, as an example set of destinations. The length of the route between destination pairs was compared with the length of routes between destination pairs utilizing the full network (LTS 1–4). The comparison serves to demonstrate the amount of out-of-direction travel required to utilize the low-stress network. The closest facility network analysis builds on the Low-Stress Connectivity Islands; the assumption is based on research that people are willing to add up to 25 percent to the length of their trip to avoid stressful bicycling infrastructure. This means that, just because a low-stress trip can be made between point A and point B, the trip might not be made if it requires a long detour.
- **Link Centrality:** The number of times a link is used to reach a destination suggests the importance the segment plays in the network; this number can be used to determine project priority. The sum of times a segment was used in the routes found in the Closest Facility Network Analysis step was calculated to determine which segments are used most often. While

schools are used as the example set of destinations, ideally link centrality would be calculated based on a full range of destinations, including employment, recreation, transit, and medical locations, and others.

Low-Stress Network Analysis

Data Preparation

Additional data preparation was required to run the low-stress network analysis. The facility scalars and calculations are based on the methodology developed by Lowry, et al.[15] Steps included the following:

- Elevation data was applied to the analysis network to calculate percent slope. Average slope per segment was calculated by applying 3M NED data to the network and then calculation using the ET GeoWizard plug-in for ArcMap.
- Scalar values were assigned to roadway segments based on Lowry's methods.
- Delay scalars were assigned to turning movements. The scalars displayed in Figure 2 of Lowry's method were simplified to fit within the framework of ArcMap's Global Turn Delay Evaluator, which is used with the Network Analyst extension. Figure 2 was generalized to accommodate the limited number of turning measures that can be represented within the default format of the evaluator.
- A cumulative scalar value was calculated based on elevation impact, and bicycle facility type, roadway speed and number of lanes.
- The perceived length of a segment was calculated based on the cumulative scalar.
- The perceived distance was converted to travel time per link, assuming an urban travel speed of ten miles per hour to achieve compatibility with turning delay measurements.

The scalars represent the increase in stress level experienced based on bicycle facility type, roadway speed and number of lanes, and elevation changes and represent an increase in perceived travel distance. The assumption is that the perception of distance increases as conditions along network segments become less comfortable and turning movements become more stressful.

Calculations

As a first step of analysis, a visual comparison was completed between the Low-Stress Network Connectivity base network and the LTS results. Based on the methodology, the calculated scalar provides a proxy to LTS scores. Low-stress (LTS 1 and 2 equivalent) were selected from the Low-Stress Network Connectivity base network and a map of connectivity islands was created from this network.

Low-Stress Network Connectivity calculations rely on ArcGIS Network Analyst to determine the perceived travel time between locations using the scalars assigned during data preparation. For this example, block centroids and schools were the destination pairs. Utilizing the Closest Facility network function, routes between Census block centroids and schools were measured based on the actual distance traveled and the perceived distance traveled. The function searches for the shortest path to the school, taking into account the perceived stress scalar when calculating the perceived distance routes.

[15] Lowry, Michael B., Peter Future, Tracy Hadden-Loh. Prioritizing new bicycle facilities to improve low-stress network connectivity. 2016.

This provides two distinct route files from each block centroid to each school. Comparison of these two files provides two specific comparisons:

- **Increased distance due to perceived stress:** The comparison of the actual route length to the perceived route length allows connections to be identified that exceed 25 percent of the original trip length. This is the accepted threshold for when trips may no longer be made by bicycle.
- **Link centrality:** The number of times individual roadway segments are selected as part of a route can be calculated for both perceived distance and actual distance traveled. These counts, which identify segments vital to network connectivity, can be used to select areas for low-stress network improvements.

Results

LTS Connectivity Analysis Results

The results of the four-point LTS (analysis Figure 17) demonstrate that Fort Collins has a significant number of low-stress roadways. Within neighborhoods, LTS 1 roadways are common, while neighborhood collectors are often LTS 2. The downtown area, with its tightly gridded network, is primarily low stress, and the extensive trail system within Fort Collins provides additional low-stress segments.

Arterials serve as the primary barriers to travel within Fort Collins, with these roadways scoring as LTS 3 or 4. Representing a larger-scale grid network, these barriers are frequent and consistent across Fort Collins.

Figure 17: LTS Network Results (4-Point Scale)

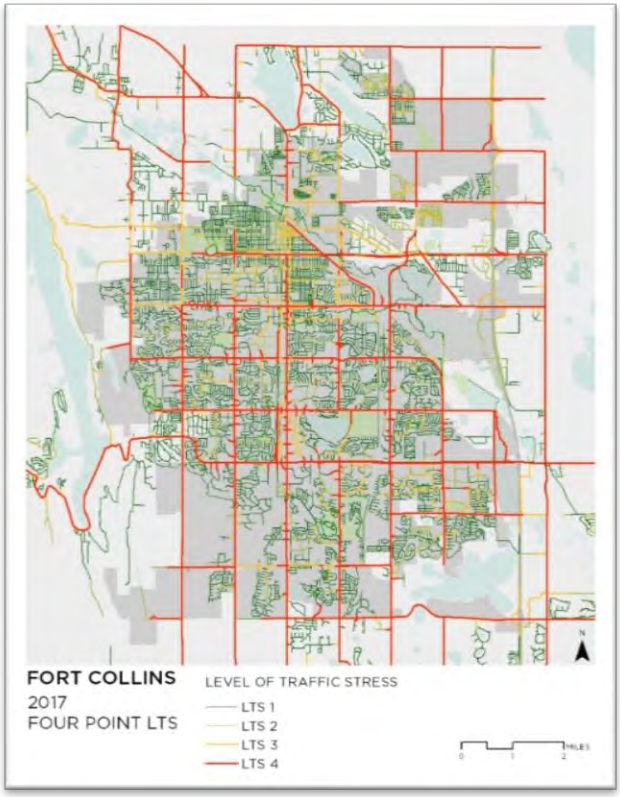
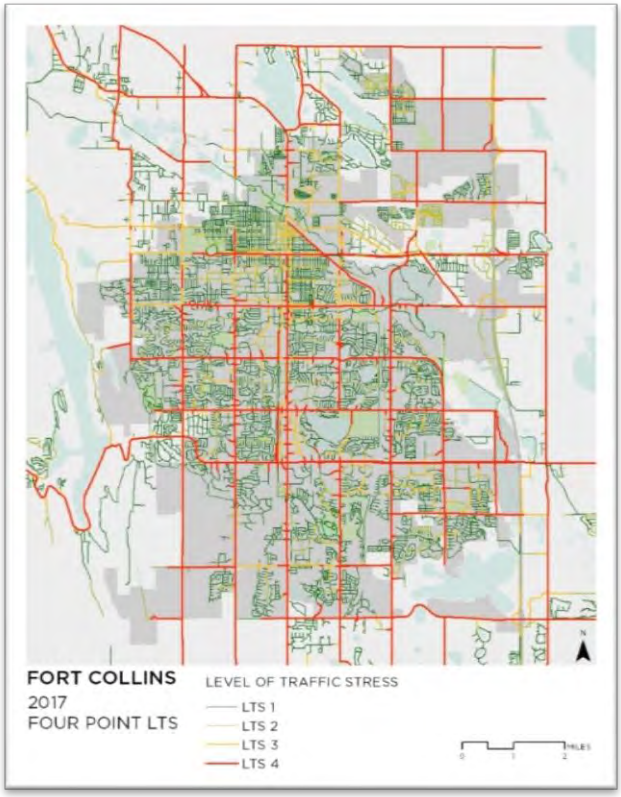


Figure 18: LTS Results from the 2014 Bicycle Plan (5 Point Scale)



Comparison to 2014 Five-Point LTS Analysis

The City's 2014 Bicycle Plan used a five-point LTS system (Figure 18), which considered additional characteristics such as traffic volumes and for arterial bike lanes wider than 7 feet. The 2014 assessment did not include trails in the analysis layer. When comparing the results of the four-point LTS to the five-point LTS, several differences are apparent:

- Local roadways more often score as an LTS 1 in the five-point system, likely because of their low traffic volumes.
- Minimal five-point LTS variation exists within the larger blocks created by arterials; minor roadways are more frequently rated low on the five point scale.
- Intersections do not appear to have significant impacts on five-point LTS scores; however, the extent to which they were evaluated is unclear.

Despite these differences, both of the analyses indicated that arterial roadways are highly stressful for nonmotorized travelers and serve as barriers to otherwise-connected, low-stress neighborhood networks.

Comparison to People for Bikes Bicycle Network Analysis Tool[16]

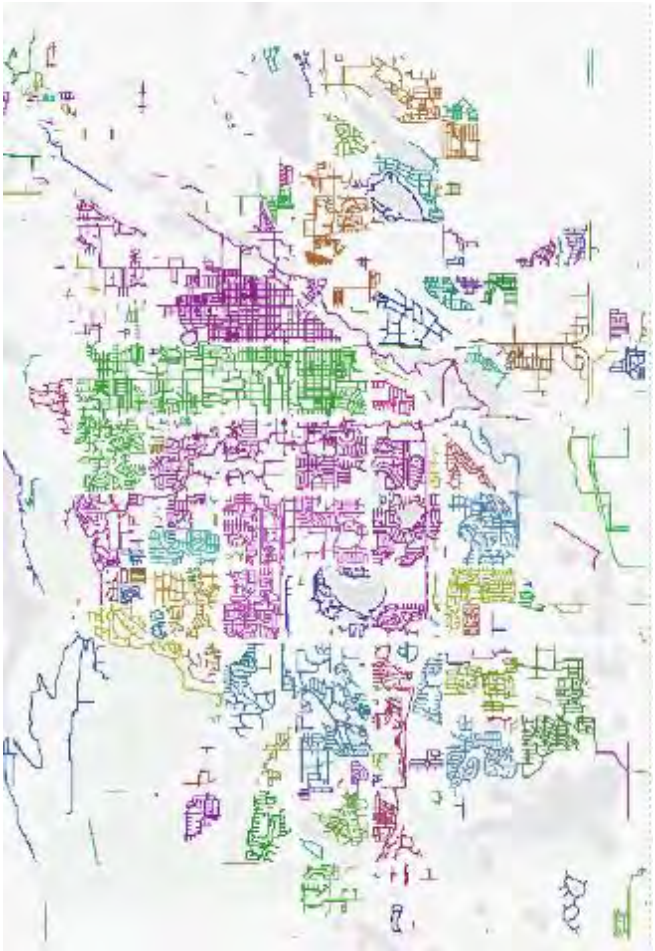
People for Bikes recently published an online analysis tool that scores low-stress connectivity in many cities across the United States, which represents a critical first step in providing methods to compare connectivity objectively between cities. Using Open Street Map data, scores are produced based on an adaptation of LTS methodology; further scores are developed based on the connectivity by bike to a variety of core services and recreational opportunities. The binary high-stress and low-stress results are similar to the results of the LTS analysis completed as part of this case study. Local roadways are typically considered low stress, while arterials are high stress. In this tool, unsignalized intersections are less prominent, however, and do not Impact network connectivity at locations where a local roadway intersects an arterial roadway.

LTS Low Stress Connectivity Islands

The presence of Low-Stress Connectivity Islands (Figure 19) revealed by the LTS analysis demonstrate clearly the impact that arterials have on a connected low-stress network. Throughout much of central Fort Collins, large areas are connected east-to west. However, Mulberry Street, Prospect Road, and Horesetooth Road create barriers for north-to-south travel. In the northern half of the city, trail segments connect east-to-west across major north-south arterials, which addresses the barrier these arterials would otherwise present.

[16] https://bna.peopleforbikes.org

Figure 19: LTS Analysis Results—Low-stress Connectivity Islands



Color denotes roadways that are connected by low-stress facilities. Color changes indicate a break in connectivity.

Connectivity islands further help demonstrate the differences development patterns create in connectivity. As shown in Figure 19, the area surrounding Old Town is a tight grid pattern; with most of these roadways scoring as low stress, this area serves as a highly connected low-stress network. Farther south in Fort Collins and farther from the center, the connected series of curved roadways within neighborhoods generally lack connectivity across major roadways, effectively isolating these low-stress networks.

Network Connectivity

As expected, when comparing routes between block centroids and schools from the full network to that of only low-stress segments, the low-stress network results in greater use of neighborhood connections across Fort Collins. With a 3-mile limit on trip distance, however, far fewer potential routes exist. Fewer than 50 percent of the routes found in the full network analysis are available for the low-stress network. This is due to the disconnected network links or longer trip distances that exceed the 3-mile threshold established for this example.

Link centrality, which examines the frequency of use of each network segment, reveals that approximately 9 percent of all network links are used more frequently in the low-stress network. When isolated to just those links present in both the high-stress and low-stress networks, this percentage approaches 45 percent. These high-use links are found primarily in the central area of Fort Collins, where the road network is most dense and neighborhood roadways provide a low-stress alternative to arterials or collectors.

High-use network links within the high-stress network are dispersed across the city, reaching areas farther from the center that the low-stress network does not cover. Comparing high-stress segment use to low-stress segment use can help identify areas where infrastructure investment could be needed to increase the viability of bicycling. This example provides insight into routes to school. Ultimately, however, link centrality would be calculated over a range of destinations as a method for identifying which roadway segments will provide the most benefit for a range of trip types.

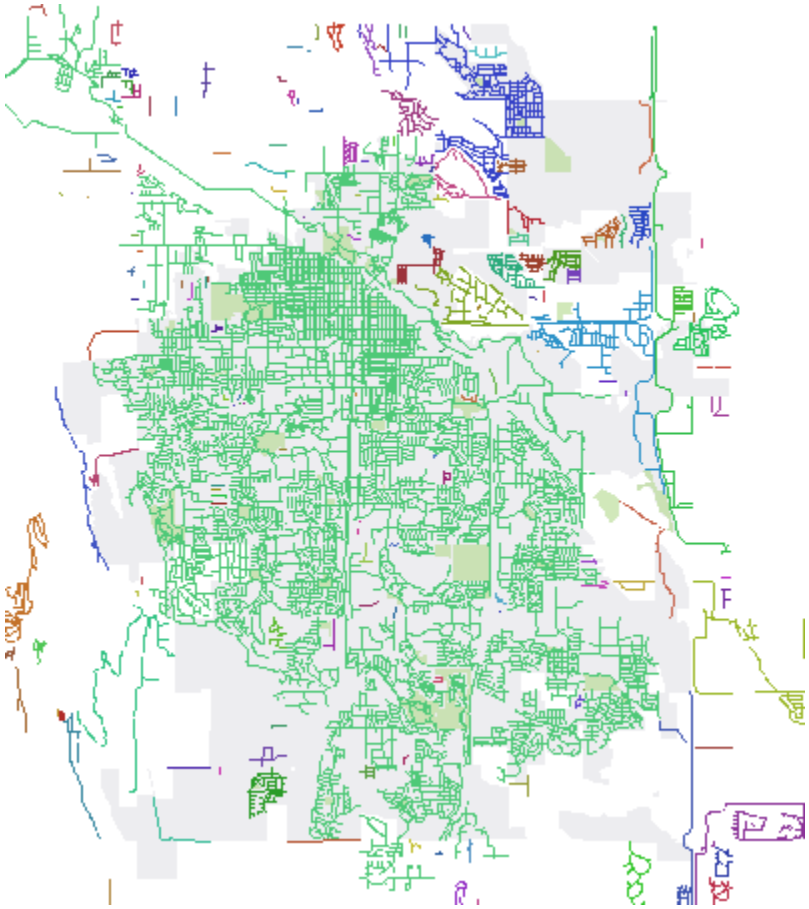
Out-of-direction travel was calculated by comparing route length between destination pairs for both the high-stress and low-stress networks. Trips requiring 25 percent greater total distance than the shortest path represent trips that likely will not be made. Of the possible trips made between destinations pairs in both the high-stress and low-stress networks, approximately 23 percent of these trips would not be made if relying on the low-stress network alone. These route pairs influence potential routes across the entire city and are not isolated to a particular area. Those trips that represent the greatest out-of-direction travel are those where the full network provides a short connection along an arterial or major collector, whereas use of a low-stress network requires the bicyclists to travel through neighborhood connections to reach their destination eventually.

Low Stress Network Connectivity Analysis Results

Low Stress Analysis Connectivity Islands

Comparing the connectivity islands revealed by the LTS analysis (Figure 19) to those illuminated by the Low-Stress analysis (Figure 20), the latter assessment depicts greater low-stress network coverage. The entire central area of the city is connected, despite high-stress arterials, due to the omission of intersections in the Low-Stress analysis. The larger areas of connected network in the Low-Stress analysis result in less out-of-direction travel, as compared to the results of the LTS analysis.

Figure 20: Low-Stress Network Analysis Results—Low-Stress Islands



Color denotes roadways that are connected by low-stress facilities. Color changes indicate a break in connectivity.

Network Connectivity

The network routing presents a much different result, however. When comparing possible routes, limited to 3 miles in length, the perceived distance results in minimal coverage across the city. While low stress connections exist, many routes will require travel along a high-stress route or experience significant delay due to high-stress turning movements and other intersection conditions. In fact, approximately 3 percent of segment links are actually utilized more in the low-stress network, with 97 percent of possible links being used less. The primary area of increased segment use is located in and around downtown, where a tightly gridded network provides significant opportunity to use parallel, low-stress streets and benefit from signals and lower stress turning movements. This is consistent with the finding of the LTS connectivity islands, where more of the downtown area is connected through low-stress network links.

The perceived travel time along routes was then compared to the actual travel time to determine the perceived out-of-direction travel that route stress causes. The mean perceived out-of-direction travel was 40 percent greater than the actual trip length; 25 percent is commonly accepted as the threshold at

which one will no longer make a trip. Important to note is that no route's perceived length was less than actual length; however, some routes did approach this, with the least impact being a 9-second increase.

The most significant increased perceived travel times were found in the outer areas of the city and often in close proximity to school locations. This indicates that although the route might be relatively short in distance, even small segments along high-stress arterials can significantly influence the perceived stress and length of the trip.

Application to Decision Making

Based on the review of the results of both analyses and considering the goals established by the City of Fort Collins, the Level of Traffic Stress analysis is recommended as most applicable for several reasons:

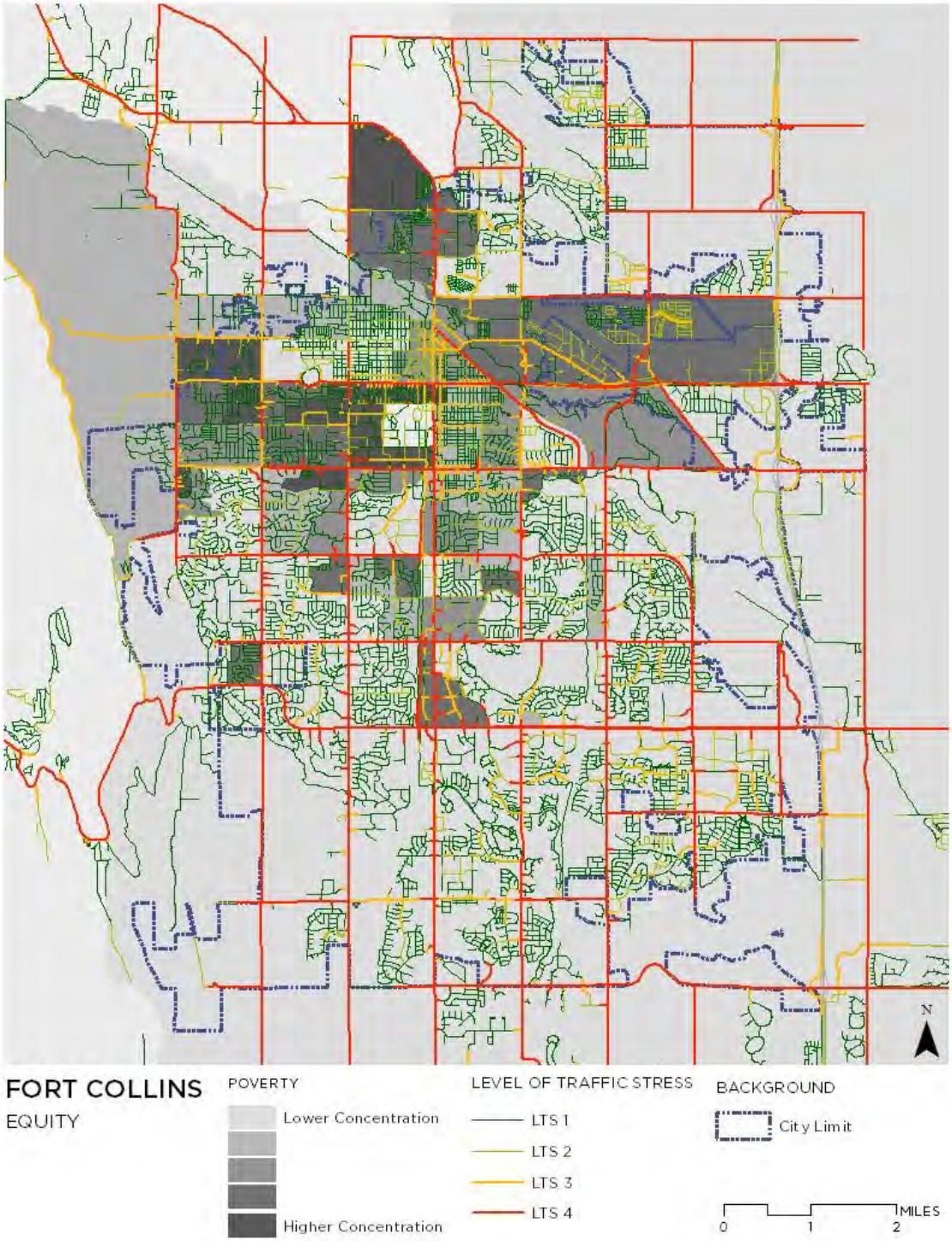
- The development of a toolbox makes the calculation repeatable over time as data is updated.
- The data required is readily available within the city. Existing data limitations can be addressed through updated data storage procedures.
- The results can be viewed in several different ways (connectivity islands and LTS scores) and used as inputs into more complex analyses.
- LTS is increasingly being used at the corridor scale to provide an objective framework for the conceptual design process and alternatives assessment.
- The results can be tracked over time to assess improvement in network comfort.
- The simplicity of the LTS score and the accompanying tables allows for clear communication with decision makers.

The LTS results provide planers with a clear understanding about the existing comfort level of the bicycle network, and can be used to develop specific recommendations to improve the comfort level and connectivity of the network over time. LTS also can be used with form-based measures to draw comparisons between the motor vehicle and bicycle networks, or as a comparative assessment between two cities. LTS can also serve to inform safety assessments. For example, a comparison of collision data to an LTS analysis can help planners to identify the most important high-stress roadways or intersections to improve.

LTS analyses do not address issues of accessibility to destinations or equity, but LTS results can be overlaid with this data for a clearer picture of network deficiencies. Overlaying the LTS results with equity data can help planners to identify locations with the greatest need for connectivity investments. For example, Figure 21 displays census blocks groups based on the concentration of individuals at or below 200 percent of the federal poverty level. Block groups located in the northwestern area of the city, between Mulberry and Prospect and west of Taft Hill, exhibit a high concentration of individuals experiencing poverty. The LTS results indicate these neighborhoods have low-stress streets, but are surrounded by high-stress roadways that limit residents' access to services and jobs outside their communities.

Related information such as calculations of routes to different destinations and determinations of link centrality can help planners to set priorities for a variety of proposed facility improvements. The identification of vital links in the network can provide an important level of context when considering the potential impacts of transportation projects. The LTS results will also inform the inclusion of bicycle travel in the City's multimodal level of service traffic model.

Figure 21: Overlay of LTS with poverty data based on 2010-2015 ACS data.



Lessons Learned

- **Data storage:** The most significant obstacle to completing either the LTS or Low-Stress analysis was the storage of data attributes. In general, Fort Collins maintains detailed data on their bicycle network. However, the required attributes are stored in multiple feature classes, and the attribute structure requires additional processing to apply either analysis. This processing not only requires additional time, which reduces the ease of replicating the tool, but the additional steps introduce the potential for error and inconsistencies among results. With the purpose of using the results of the analysis as a benchmarking tool, data should be stored in a manner that is consistent with the needs of the analysis to improve the replicability of the tool.
- **Data maintenance procedures:** The quality of information provided by these analyses depends on the quality and accuracy of data in the original datasets. That all datasets are up to date and reflect real-world conditions is essential. Policies and procedures should be in place to ensure that data is maintained with similar frequency and levels of accuracy among departments. These policies can better define who is responsible for data maintenance and the frequency with which they are updated.
- **Picking the right tool:** The complexities of measuring connectivity can be lessened by clearly defining the questions at hand, and by articulating how the results will be used. The criteria outlined by FC Bikes pointed clearly to LTS as a strong contender for adoption and future use.
- **Tool adaptability:** To compare results over time, assessment methods must be consistent. This is demonstrated by the subtle differences between the 4-point and 5-point LTS methods. While both are viable assessment frameworks, a decision to adopt a more detailed scale in a given year precludes an apples-to-apples review of changes in connectivity over time. Picking a method that supports long-term comparative assessments is a challenge given the continuing potential for tool refinements enabled by research and by improved data availability.
- **Weakest link vs. cumulative stress measurement results:** The weakest link assumption that underlies the LTS method restricts travel to low stress streets, while the cumulative stress assumption that underlies the low-stress analysis method allows for the possibility of completing portions of trips on higher stress facilities. The LTS network connectivity analysis assumes a trip will not be made at all if high stress segments are present and no other route exists, whereas the low-stress network connectivity analysis assumes the trip will be made but at a higher cost to the user. Additional research and validation might be required to determine which method best represents user behavior, or if a hybrid profile is appropriate.

Resources

- Mekuria, Maaza C., Peter G. Furth, and Hilary Nixon. Low-Stress Bicycling and Network Connectivity. 2012. http://transweb.sjsu.edu/project/1005.html Lowry, Michael B., Peter Future, Tracy Hadden-Loh. *Prioritizing new bicycle facilities to improve low-stress network connectivity.* 2016.
- Fort Collins. *2016 Bicycle Plan.* Accessed May 16, 2017. http://www.fcgov.com/bicycling/pdf/2014BicycleMasterPlan_adopted_final.pdf

Regional Connectivity Measures, Portland Metro

Background

Metro is the regional planning agency for the Portland, OR, metropolitan region. Metro's goal for this case study was to refine the bicycle and pedestrian connectivity measures to be used in its 2018 regional transportation plan (RTP) update.

In prior RTPs, Metro focused on measuring the completeness of the bicycle and pedestrian networks, as indicated by the percentage of planned miles of bicycle facilities, trails, and sidewalks completed. This measure was problematic, however, for measuring the region's progress in improving connectivity over time because pedestrian and bicycle plans are continuously updated in the Portland region. It also obscured the picture of progress toward complete connectivity because some local governments are more proactive than others in planning and building bicycle and pedestrian facilities.

Case Study At-A-Glance

Focus:
Bicycle and Pedestrian
Context of Study Area:
Urban/Suburban
Scale of Study Area:
Region
Tools & Models:
GIS
Application:
Planning

For this RTP, Metro developed a group of connectivity measures that capture the physical qualities of the bicycle network to take a more objective look at where new facilities are needed and to assess how well the bicycle and pedestrian projects in the RTP would fill these gaps. Metro worked with a stakeholder group to identify seven measures, each of which would be calculated for the base year and future-year investment packages at three levels of geography: 1) within the MPA boundary, 2) in historically marginalized communities, and 3) in agency-designated historically marginalized communities that were of particular concern to the region ("focused" communities).

The first draft measures included the following elements, some of which were refined as part of the technical assistance process:

- **Street density:** the number of linear miles of streets per Census tract; a higher number indicates higher street density.
- **Street connectivity:** the ratio of intersections (three-way or more) to total linear miles of streets per Census tract; a higher ratio indicates higher street connectivity.
- **Sidewalk density:** the number of linear miles of street segments with more than 50 percent of sidewalks completed per Census tract; a higher number indicates higher sidewalk density.
- **Sidewalk connectivity:** the ratio of sidewalk density (miles of street segments with more than 50 percent of sidewalks completed) to total linear miles of streets per Census tract; a higher ratio indicates higher sidewalk connectivity.
- **Bikeway density:** the number of linear miles of street segments with bikeways completed per Census tract; a higher number indicates higher bikeway density.
- **Bikeway connectivity:** the ratio of bikeway density (miles of street segments with bikeways completed) to total miles of streets per Census tract; a higher ratio indicates higher bikeway connectivity.

- **Trail density:** the number of miles of trails completed per Census tract; a higher number indicates higher density.[17]

The technical assistance process was devoted to pilot testing these measures and helping Metro refine them for application in the RTP. The objectives were as follows:

- Ensure that the measures capture the information Metro intended to study. Each measure was mapped for the entire region to determine if areas that performed well aligned with the areas that Metro staff felt were better suited for bicycling and walking.
- Determine whether the measures adequately reflect change due to planned projects. Metro had not developed a complete shapefile of active transportation projects for the RTP, so these measures were tested for the current network and for future projects contained in the 10-year investment package of Metro's Regional Active Transportation Plan (ATP).[18]
- Refine the definitions of measures and the process for calculating them. The first draft definitions listed above were not detailed. The process for calculating each measure was documented to streamline Metro's future work with these measures.
- Identify opportunities to simplify measures. Using seven measures that capture two aspects (density and connectivity) of four different facility types (streets, bike facilities, sidewalks, and trails) could make interpreting results challenging for staff and decision makers. This approach included opportunities for aggregating results and eliminating redundant measures.

Analysis and Results

Data Assembly

Several different Metro datasets were used to calculate connectivity measures:

- Metro staff provided a shapefile of the Regional ATP 10-year investment scenario projects that were used to define a set of potential future bicycle and pedestrian projects for analysis (Figure 22). The shapefile included lines representing new bike lanes, sidewalks, paths, and trails, and shapes or points representing areas targeted for general improvements, such as intersection upgrades and projects to enhance or fill gaps in bike lanes and sidewalks. Only the lines were included in the analysis because Metro's performance measures focus on linear features such as the length of bicycle facilities, sidewalks, and trails. Only new facilities could be measured and included in calculations because improvements to existing facilities result in no more linear miles. Planned ATP projects do not include all local projects in this analysis.
- The Bike Routes layer of Metro's Regional Land Information System (RLIS)[19] contains information on current bicycle facilities, such as some regional trails. This shapefile includes all streets deemed eligible candidates for bicycling facilities, eliminating grade-separated freeways and on-ramps (see Figure 23).
- The RLIS Sidewalks layer[20] contains information on current sidewalk coverage (see Figure 23).

[17] Metro, RTP System Evaluation Measures Methodology, Access to Travel Options – System Connectivity and Completeness, Updated Draft March 2017. Edited for readability.

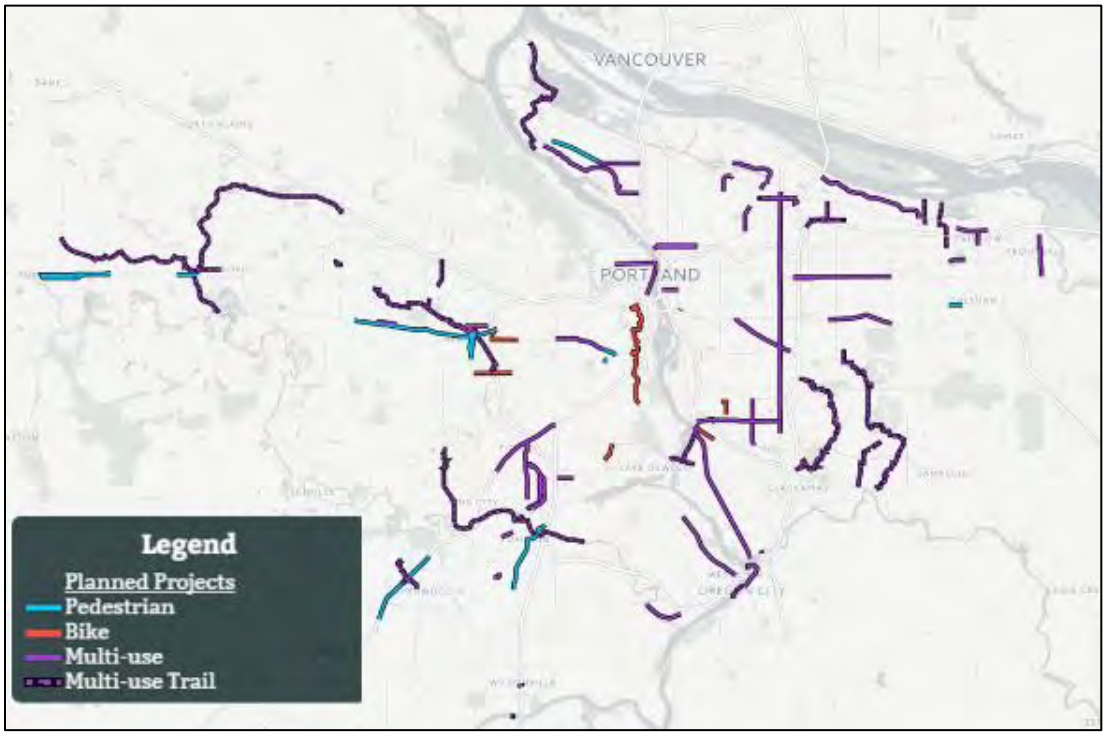
[18] http://www.oregonmetro.gov/sites/default/files/2014_regional_active_transportation_plan_0.pdf

[19] http://rlisdiscovery.oregonmetro.gov/?action=viewDetail&layerID=3312#

[20] http://rlisdiscovery.oregonmetro.gov/?action=viewDetail&layerID=2851

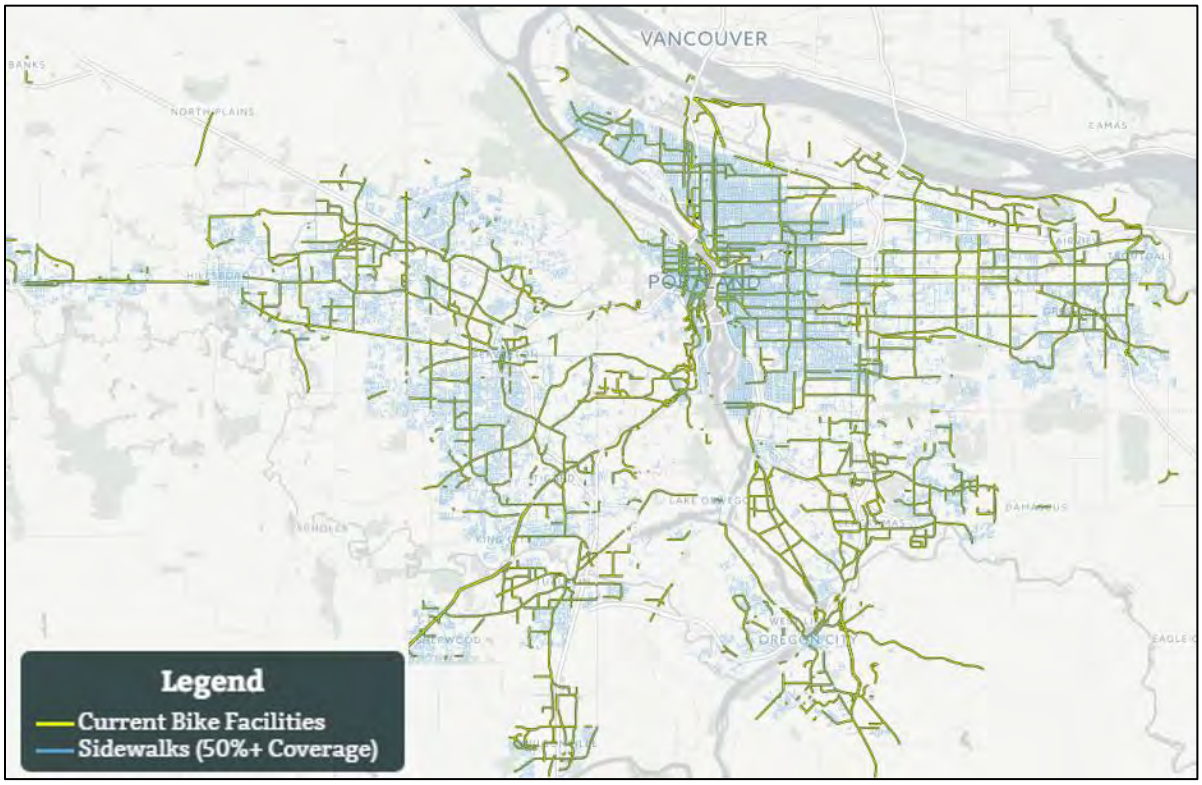
- The RLIS Trails layer[21] describes the current regional trail network. Many of these trails are included in the Bike Routes layer described above.
- Metro staff provided a shapefile of transportation analysis zones (TAZs), the smallest scale of analysis used in the regional travel model. Because the travel model will be used to assess many other RTP performance measures, TAZs were used as the basic geographic unit of analysis instead of Census tracts.

Figure 22: Active Transportation Plan (ATP) projects used in the case study



[21] http://rlisdiscovery.oregonmetro.gov/?action=viewDetail&layerID=2404

Figure 23: Current bicycle facilities and streets with adequate sidewalk coverage in the region



The BIKETYP field of the Bike Routes layer uses the following attributes to characterize bicycle facilities:[22]

- BKE-BLVD: Bike Boulevard. Also known as a neighborhood greenway. These are shared sections of low traffic and low speed roadways.
- BKE-LANE: Bike Lane. Indicates that either side of a roadway has a painted lane for bicycle use.
- BKE-BUFF: Buffered Bike Lane. A bike lane separated from the automobile traffic lane by a painted buffer.
- BKE-TRAK: Cycle Track. A bicycle facility separated from auto traffic by a physical barrier.
- BKE-SHRD: Shared Roadway or Marked Bicycle Route. A section of roadway marked by a sharrow or a clearly marked shared-use sign.
- PTH-LOMU: Local Multiuse Path.
- PTH-REMU: Regional Multiuse Path
- OTH-CONN: Shared Roadway Gap Connector. A section of roadway used to connect one or more existing bicycle facilities.
- OTH-XING: Pedestrian or Bicycle overpass or underpass
- OTH-SWLK: Sidewalk that allows bicycle travel.
- SHL-WIDE: Wide Shoulder. A section of roadway with a shoulder at least 4 feet wide.

For this analysis, facilities designated as OTH-SWLK or SHL-WIDE were excluded because Metro staff consider these facilities inadequate to support safe and convenient travel. Additionally, this particular analysis examined on-street bicycle facilities only. PTH-LOMU and PTH-REMU features were included in

[22] http://rlisdiscovery.oregonmetro.gov/metadataviewer/display.cfm?meta_layer_id=3312

the trail analysis. Future analyses might consider including multiuse paths as bicycle facilities if they serve the function of providing access to destinations as well as recreation.

Five fields in the Sidewalks layer were used to identify streets with adequate sidewalk coverage:

- LS: Left side sidewalk presence (0 = no data, 1 = no sidewalk, 2 = sidewalk exists, 99 = sidewalk exists but exact location is not known)
- LPCT: Left side sidewalk percentage coverage (value from 10 to 100)
- RS: Right side sidewalk presence (0 = no data, 1 = no sidewalk, 2 = sidewalk exists, 99 = sidewalk exists but exact location is not known)
- RPCT: Right side sidewalk percentage coverage (value from 10 to 100)

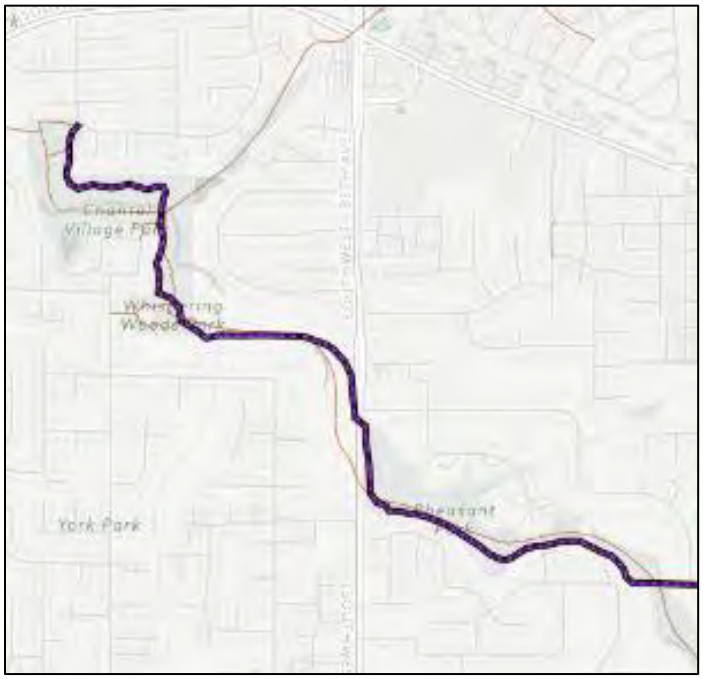
Figure 23 provides a snapshot of the current bicycle facilities and streets with adequate sidewalk coverage used in the analyses.

Three key challenges were encountered during the data assembly process: (1) a lack of data on planned facilities, (2) inconsistencies between current and future data fields for reference networks, and (3) a lack of clarity about facility characteristics in the base network. These challenges are described below.

Lack of data on planned facility types: Ideally, the ATP shapefile would use the same fields and attributes to describe planned bicycle facilities and sidewalks as the RLIS layers that describe current facilities; this would enable a consistent approach to identifying current and future facilities. This was not the case. The ATP shapefile contained only descriptive names of planned facilities. For this analysis, Metro staff created and manually entered two new fields in the database: MODE (bike/ped/both) and TRAIL (yes/no).

Inconsistent reference networks in data on current and future facilities: Facilities in the RLIS bicycle facility and sidewalk layers are referenced to the street and trail network used by Metro throughout the RLIS shapefiles, whereas the ATP shapefile only showed the approximate location of many facilities. The facilities in the ATP shapefile were manually aligned with the base network used in the RLIS shapefiles, but it was challenging in some cases to distinguish proposed new trails from current ones (see Figure 24).

Figure 24: Metro RLIS Existing and Planned Trails



Current trails from the Metro RLIS Trails shapefile are shown in brown; planned future trails from the ATP shapefile are shown in purple. In several places, the current and future trails overlap, but do not align exactly. It is difficult to determine whether the lines in these places indicate proposed new segments that parallel the existing trail or a misalignment of the existing segment in the GIS file.

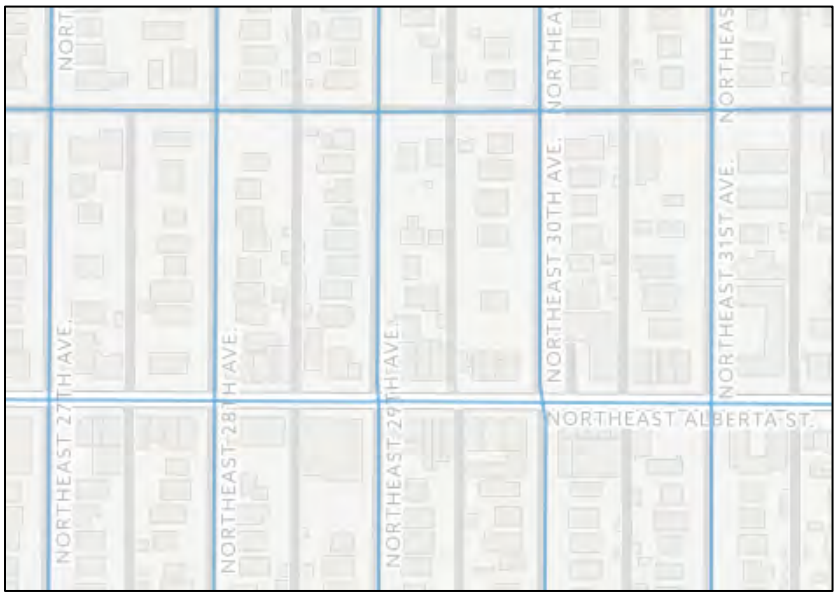
Lack of clarity and data on the base street network: The bikeway and sidewalk connectivity measures capture the percentage of streets with bicycle facilities or sidewalks. Implicit in this definition is that "streets" should only include streets that are eligible candidates for these facilities, and should exclude grade-separated freeways, on-ramps and other segments that prohibit bicycling and walking. Metro, however, had not created such a layer. The available street network shapefiles were reviewed and then the base network in the RLIS Bike Routes layer was selected; this layer excludes facilities that are not eligible candidates for bicycle facilities. These same facilities were assumed ineligible candidates for sidewalks, and the base network was assumed to remain unchanged in the future, because a comparable shapefile for the planned street network was lacking. Additionally, the layer selected as the base street network currently includes alleyways. These segments are likely not candidates for future facility projects, and removing them from the analysis might provide a more accurate measure. Current inclusion could significantly decrease the percentage of completeness measures for some TAZs (Figure 25).

Methodology

Each of the seven draft measures was reviewed and results posted to an online mapping portal for Metro staff to review. An interactive Web map was selected as the best way to deliver complex results for the seven measures—many of which contain future scenarios and change metrics—across small TAZ units for a large regional area. All figures from this report were captured from the Web map, which can be viewed in detail using the tool (hosted through at least 2018). The methodology for certain measures

was then revised based on Metro's feedback. Below is a description of the final methodology for calculating each measure, which show maps of regional results and highlights key discussion points that arose during Metro staff's initial review. The following section summarizes the results.

Figure 25: Example of High-Density Alleyways



This northeastern Portland neighborhood has many alleyways. Although sidewalk coverage is high in this area, the level of completeness score appears relatively low because alleyways are included in the total street network.

Street connectivity (intersection density): This metric was calculated using the following methodology:

1. In the base street network for the RLIS Bike Routes layer, count all of the intersections with at least three legs.[23] This count was completed by converting the line layer to vertices (ends only), creating a field of concatenated coordinates, and then counting the number of duplicate concatenated coordinate fields. Those with three or more end vertices at a single location were included as an intersection.
2. Calculate the area (in square miles) of each TAZ.
3. For each TAZ, divide the result of Step 1 by the result of Step 2. Figure 26 shows the result for the current scenario.
4. Future street connectivity was not calculated for this measure because data on planned streets was not available.

During the review, Metro staff noticed high results for some suburban communities they did not consider Figure 27 particularly walkable, such as King City (the area shaded dark purple southwest of Tigard in Figure 26). This result appears to be due to the measure's capturing of short, dead-end stubs in this area as intersections (Figure 28). These stubs do not contribute to connectivity, because they do not allow pedestrians and bicyclists routes of travel that are more direct. Redefining this

[23] Because of the way this layer is mapped, right-angle turns on a single street can be coded as two-legged intersections. Setting the threshold at three legs removed these segments, which are not functional intersections.

measure to capture only four-way intersections would discount some of these "intersections," but not all of them.

Figure 26: Current Intersection Density

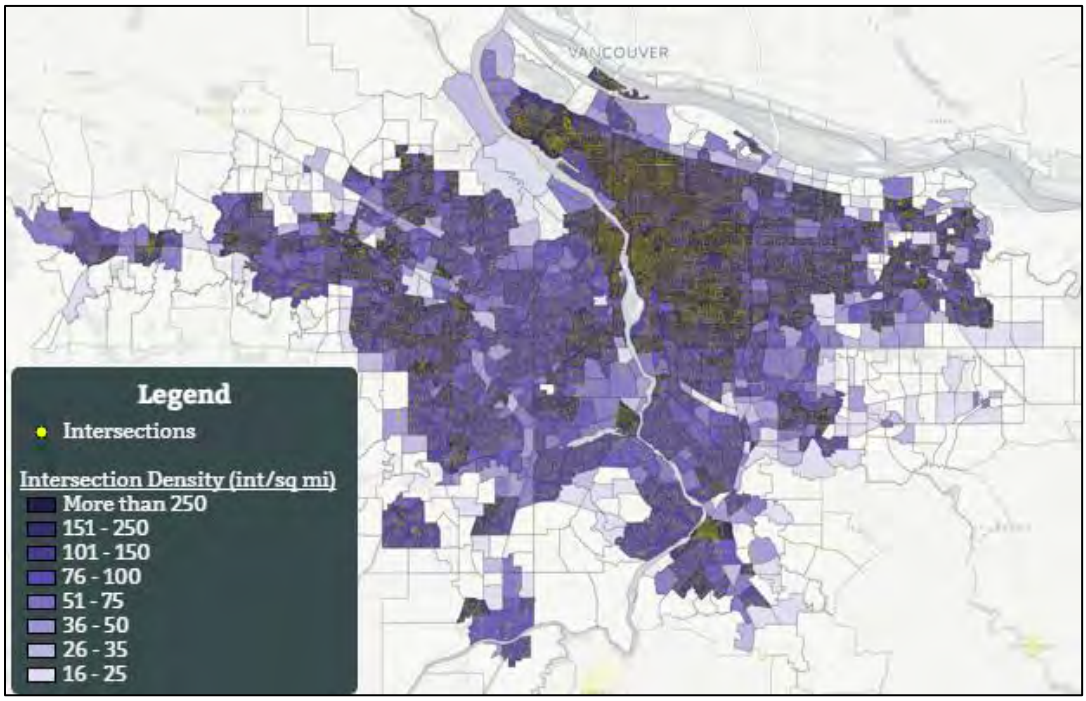
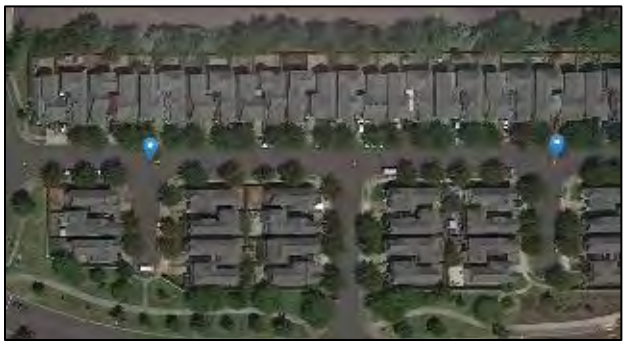


Figure 27: Satellite View of Three-way Intersections



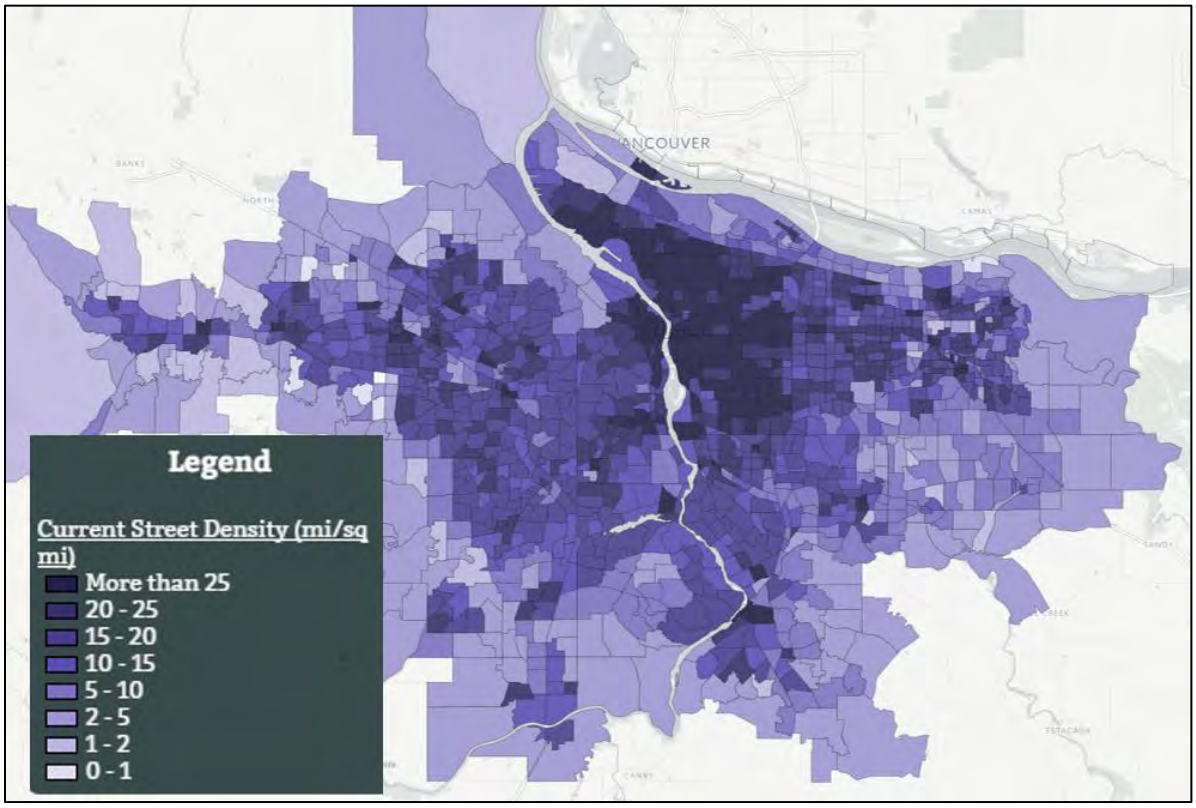
Blue markers indicate intersections that do not contribute to connectivity

Street density: The following methodology was used to calculate this metric:

1. Calculate the area (in square miles) of each TAZ.
2. Intersect the TAZ layer with the street network layer, and calculate the total street miles for each TAZ
3. For each TAZ, divide the result of Step 2 by the result of Step 1. This is the result for the current scenario.

Figure 28 shows the assessment results for current street density. Future street density was not calculated for this measure because data on planned streets was not available.

Figure 28: Current Street Density



Sidewalk completeness (named "connectivity" in the initial draft list): The following methodology was used to calculate this metric:

1. In the RLIS Sidewalk layer, select all street segments with sidewalk coverage greater than 50 percent. The following formula was used: (LPCT + RPCT) / 200. A new field was created to indicate segments with at least 50-percent coverage.
2. Intersect the result of Step 1 with the TAZ layer, and calculate the total length in miles of streets with at least 50-percent coverage for each TAZ.
3. Intersect the base street network with the TAZ layer and calculate the total length of streets in miles for each TAZ.
4. Divide the result of Step 2 by Step 3 to obtain the result for the current scenario.
5. Merge new sidewalk segments in the ATP layer (MODE = ped or both, TRAIL = no) with the layer created in Step 1, ensuring that duplicate segments are accounted for. Repeat Steps 2–4, which yields the result for the future scenario.

Figure 29 shows current sidewalk completion based on this assessment. Figure 30 shows future *change* in sidewalk completion based on planned investments; the map of changes makes identifying TAZs with significant levels of improvement due to new ATP projects easy.

Figure 29: Current Sidewalk Completeness

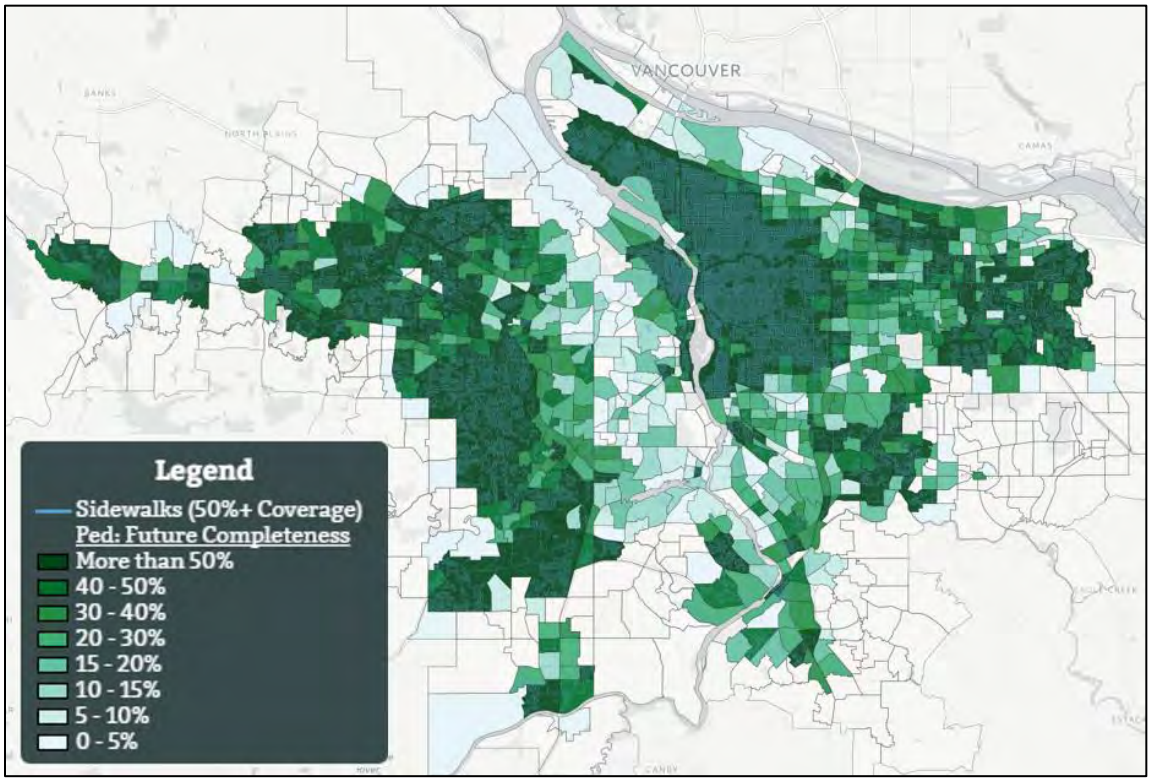
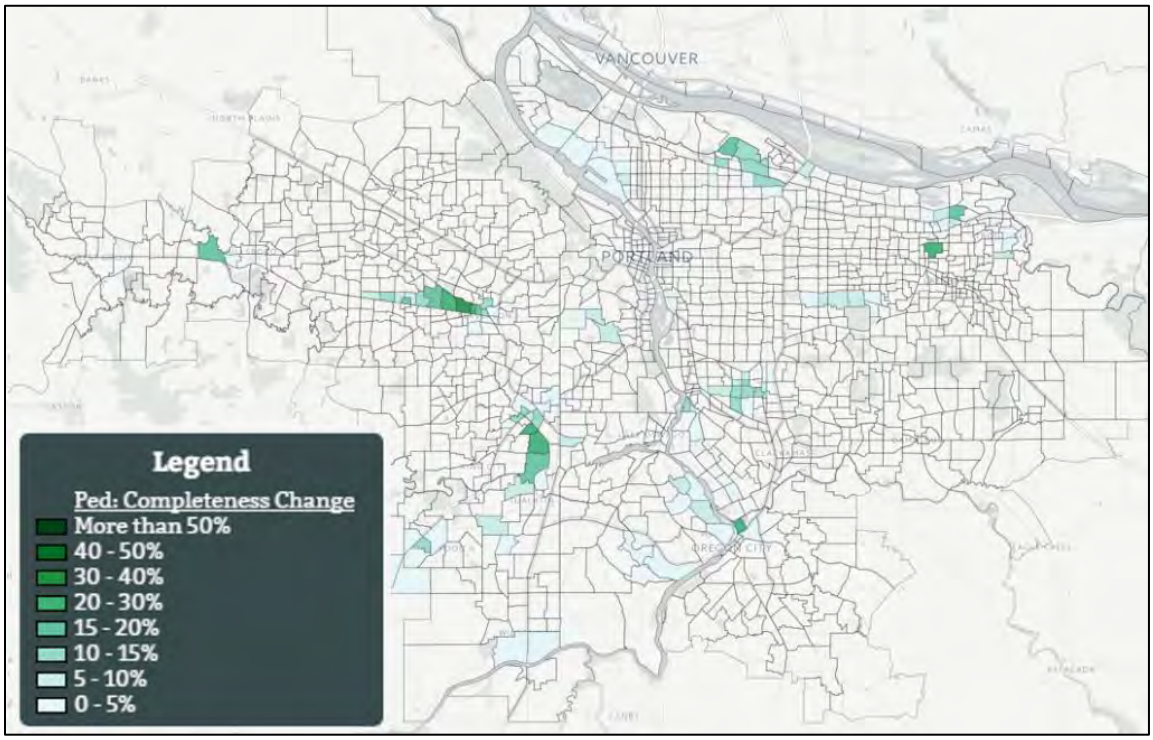


Figure 30: Planned Change in Sidewalk Coverage



Sidewalk density: The following methodology was used to calculate this metric:

1. In the RLIS Sidewalk layer, select all street segments with sidewalk coverage greater than 50 percent. The following formula was used: (LPCT + RPCT) / 200. A new field was created to indicate segments with at least 50-percent coverage.
2. Intersect the result of Step 1 with the TAZ layer and calculate the total length in miles of streets with at least 50-percent coverage for each TAZ.
3. Divide the result of Step 2 by the area in square miles for each TAZ to obtain the result for the current scenario.
4. Merge new sidewalk segments in the ATP layer (MODE = ped or both, TRAIL = no) with the layer created in Step 1 ensuring that duplicate segments are accounted for. Repeat Steps 2–4, which yields the result for the future scenario.

Figure 31 shows current results, and Figure 32 shows future *change* results. The map of changes makes identifying TAZs with significant levels of improvement due to new ATP projects easy.

Figure 31: Current Sidewalk Density

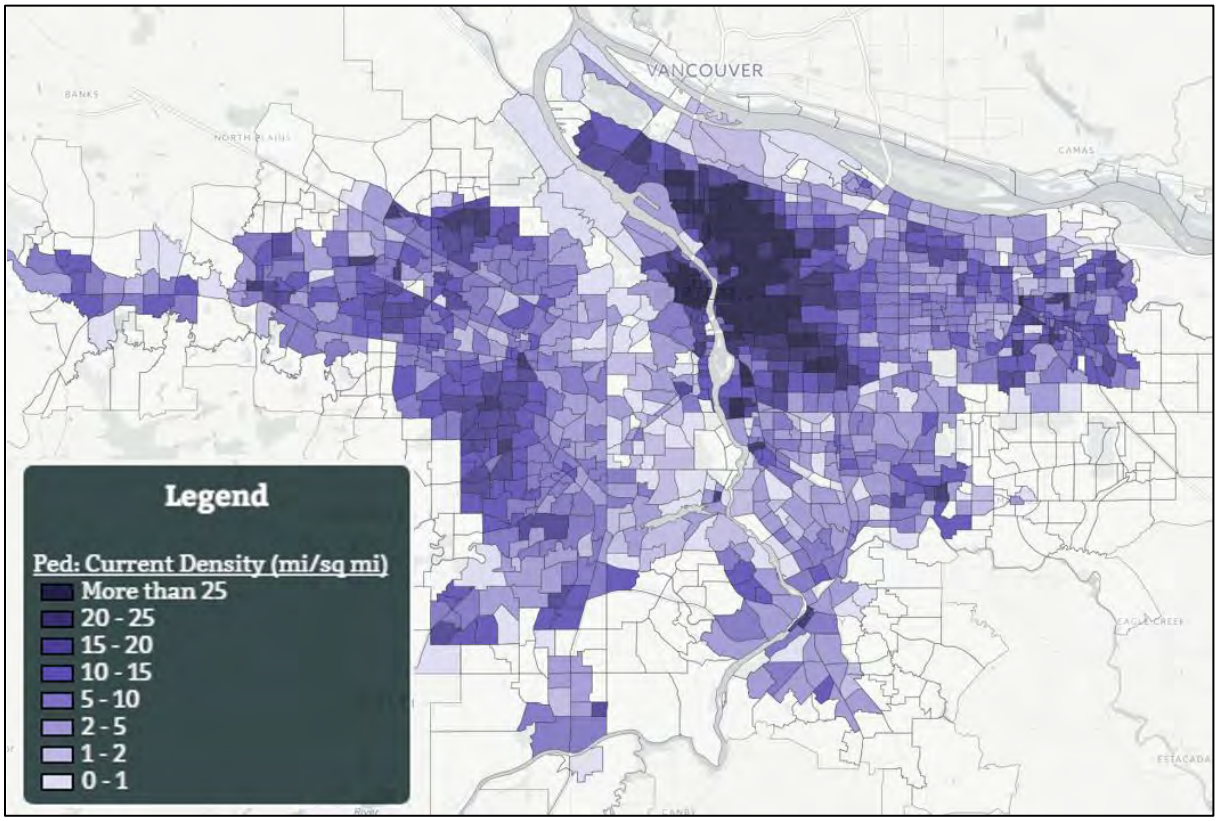
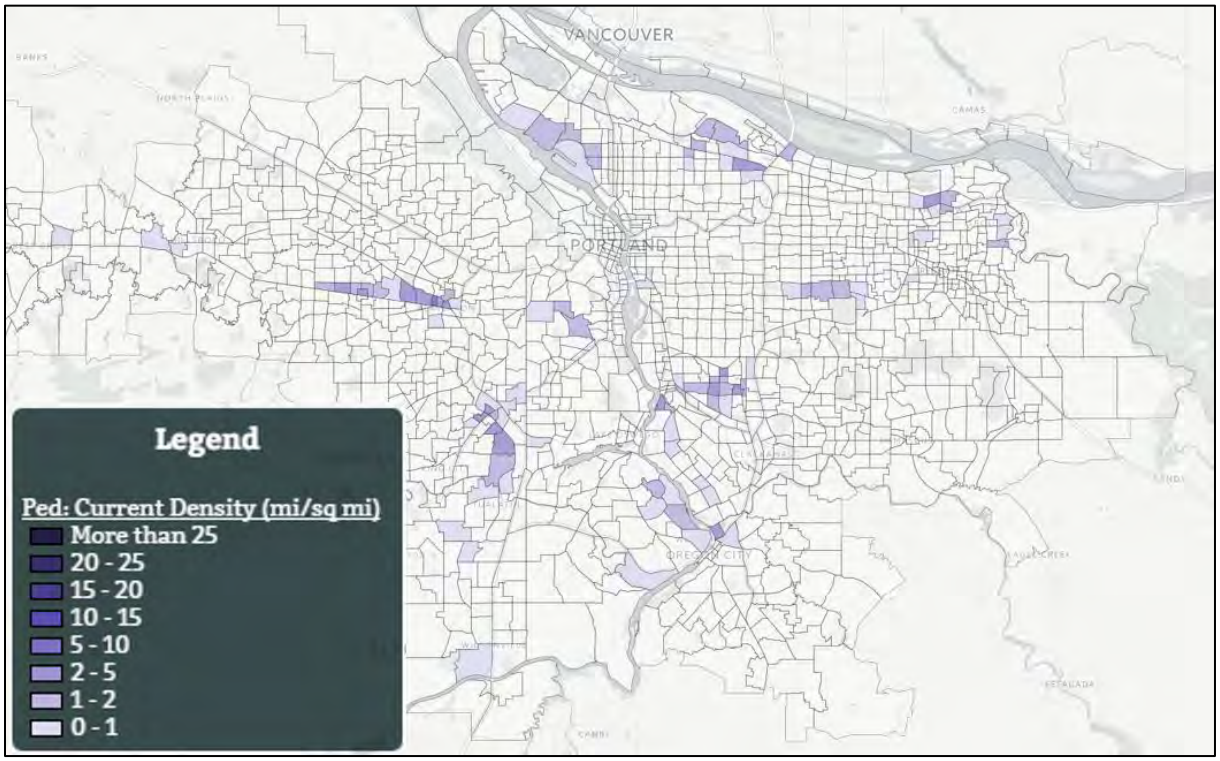


Figure 32: Planned Change in Sidewalk Density



Bikeway completeness (named "connectivity" in the initial draft list): The following methodology was used to calculate this metric:

1. In the RLIS Bike Routes layer, select all on-street bicycle facilities (BIKETYP contains a value other than PTH-LOMU, PTH-REMU, OTH-SWLK, or SHL-WIDE), and export these streets to a separate shapefile. This shapefile represents all street segments with on-street bicycle facilities.
2. Intersect the result of Step 1 with the TAZ layer, and calculate the length (in miles) of all streets with on-street bicycle facilities within each TAZ.
3. Calculate the length (in miles) of all street segments in the RLIS Bike Routes base network within each TAZ.
4. Divide the result of Step 2 by Step 3 to obtain the result for the current scenario.
5. Merge new on-street bicycle facilities in the ATP layer (MODE = bike or both, TRAIL = no) with the layer created under Step 2. Repeat Steps 2–4 to obtain the result for the future scenario.

This metric originally was calculated to include both on-street facilities and paths and trails for consistency with the bikeway density measure described below and because trails can provide alternative paths of travel when parallel roadways lack facilities. Metro staff, however, felt this calculation did not reflect the intent of this measure, which was to capture the percentage of streets with on-street facilities. Additionally, the calculation might over represent the value of trails that are assessed in other measures. The methodology therefore was revised to count only on-street facilities in the metric. Future analyses might consider the inclusion of trails when they serve as reasonable

alternatives to on-street travel and omit the trail specific measures. Figure 33 shows current results, and Figure 34 shows future *change* results.

Figure 33: Current Bikeway Completeness

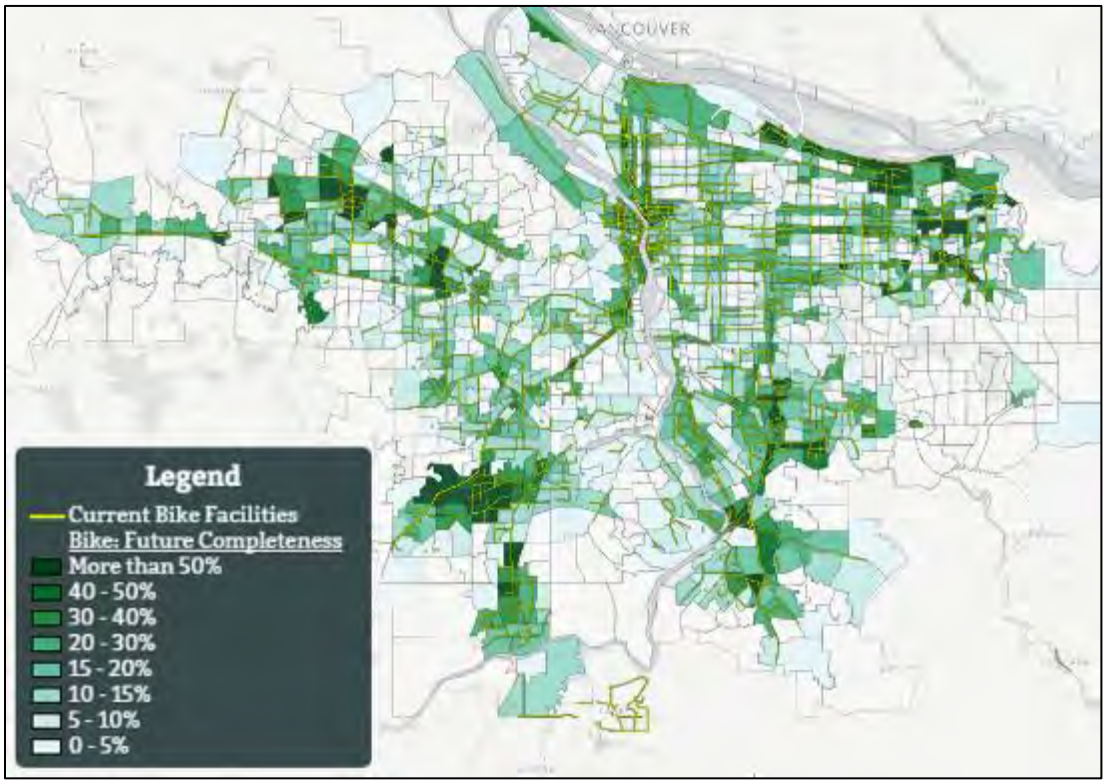


Figure 34: Planned Change in Bikeway Completeness

Bikeway density: The following methodology was used to calculate this metric:

1. Overlay the RLIS Bike Routes shapefile with the TAZ shapefile. Use a spatial join to assign each segment to a TAZ.
2. In the RLIS Bike Routes layer, select all sufficient bicycle facilities (BIKETYP contains a value other than OTH-SWLK or SHL-WIDE) and export these streets to a separate shapefile.
3. Calculate the length (in miles) of all sufficient bicycle facilities within each TAZ.
4. Calculate the area (in square miles) of each TAZ.
5. Divide the result of Step 3 by Step 4 to obtain the result for the current scenario.
6. Merge new bicycle facilities in the ATP layer (MODE = bike or both, TRAIL = yes or no) with the layer created under Step 2. Repeat Steps 3–5, which yields the result for the future scenario.

Figure 35 shows current results, and Figure 36 shows future *change* results.

Figure 35: Current Bikeway Density

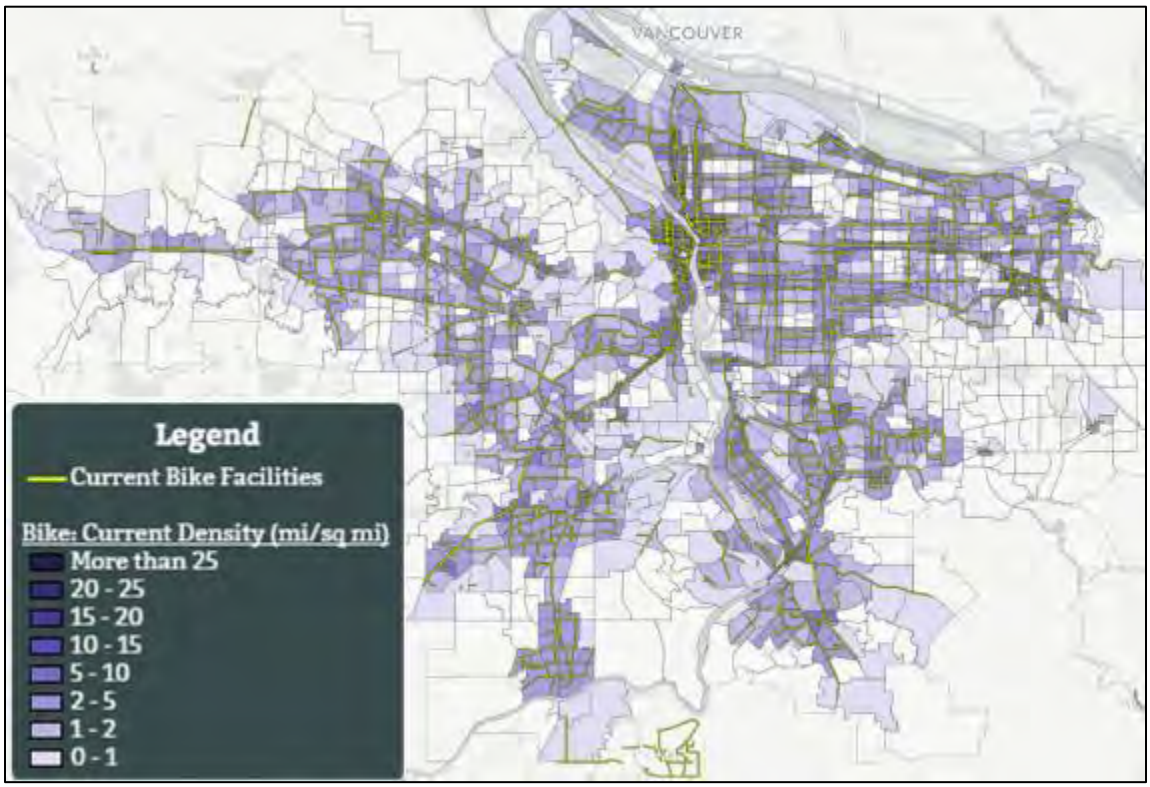


Figure 36: Planned Change in Bikeway Density

Trail density: The following methodology was used to calculate this metric:

1. Intersect trails with TAZ layer and calculate the length (in miles) of all trails within each TAZ
2. Calculate the area (in square miles) of each TAZ.
3. Divide the result of Step 1 by Step 2 to obtain the result for the current scenario.
4. Merge new trails in the ATP layer (TRAIL = yes) with the layer created under Step 2. Repeat Steps 1–3, which yields the result for the future scenario.

Figure 37 shows current trail-density assessment results, and Figure 38 shows future *change* results.

Figure 37: Current Trail Density

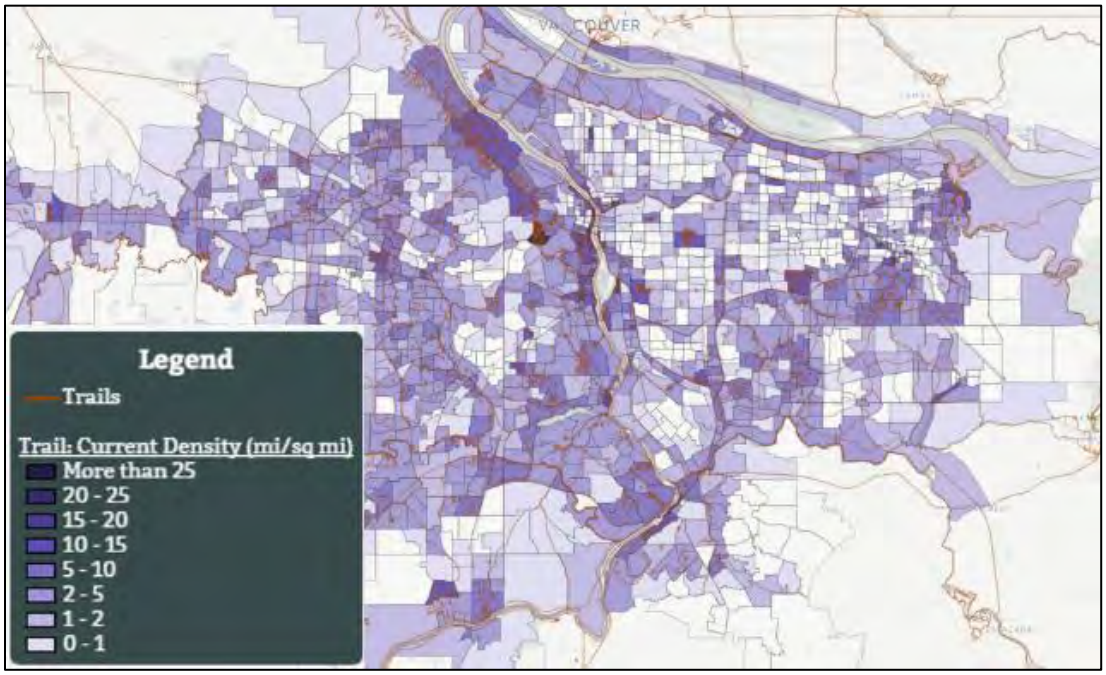
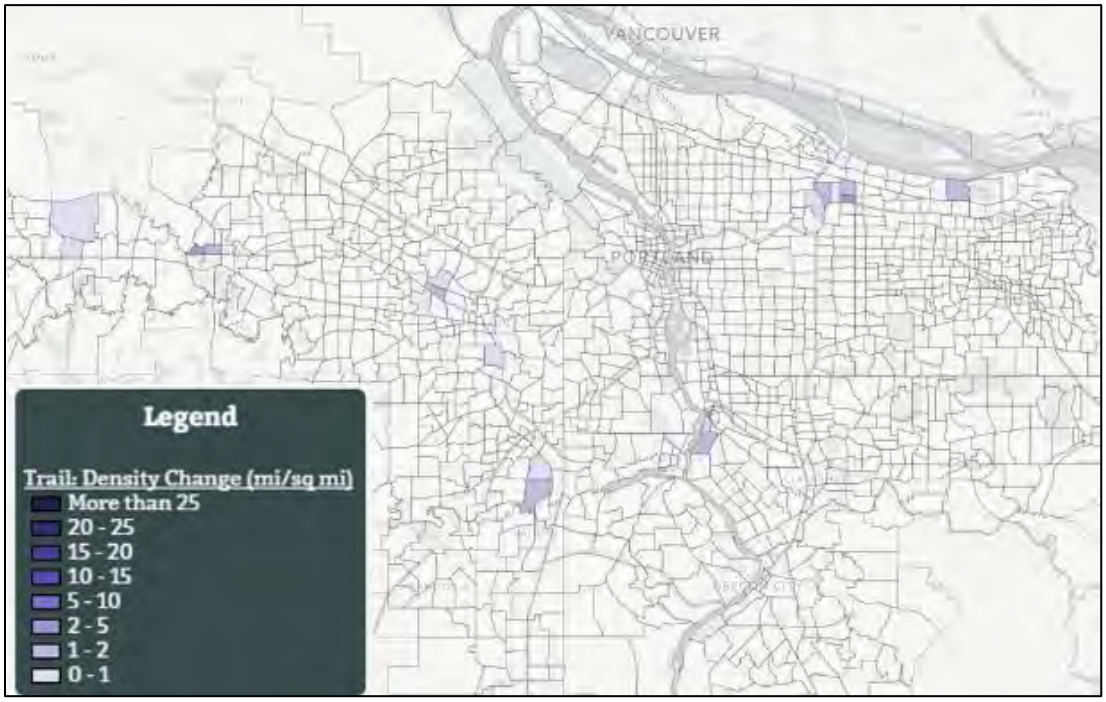


Figure 38: Planned Change in Trail Density



Assessment Results

Table 15 summarizes the results for all seven connectivity measures tested for the Metro planning region as a whole and for the region's Focused Historically Marginalized Communities, which are key to Metro's equity analysis. Most of the changes measured appear to be quite small when quantified at the

regional scale. The small changes makes interpreting results challenging and could lead to the impression that the investments made little difference. Big changes, however, could be happening at a neighborhood level. An alternative approach might be to classify the data in a way that reveals relative differences in local contexts. For example, Metro could define a threshold for "good" levels of completion or density and map TAZs according to the percentage of change in "good" networks.

Table 15: Current and future results for Metro connectivity measures, regional total and total for FHMCs

Measure	Current	Future	Regional Change	Current FHMC	Future FHMC	FHMC Change	Current HMC	Future HMC	HMC Change
Street Connectivity	84.29	–	–	105.87	–	–	141.1	–	–
Street Density	12.57	–	–	14.74	–	–	18.2	–	–
Sidewalk Completeness	42.8%	43.4%	0.5%	47.9%	48.8%	0.9%	53.6%	54.2%	0.6%
Sidewalk Density	5.39	5.45	0.07	7.07	7.20	0.13	9.7	9.9	0.11
Bikeway Completeness	11.4%	12.0%	0.7%	14%	15%	1%	12.8%	13.8%	1.0%
Bikeway Density	1.43	1.51	0.09	2.10	2.28	0.18	2.3	2.5	0.18
Trail Density	0.351	0.353	0.002	0.356	0.361	0.005	0.472	0.476	0.004

Assessment Methodology Issues

During the joint review of the draft and final results, Metro staff and the technical assistance team noted several issues with the data and methodology that could be improved in future assessments:

The measures do not capture many high-priority bicycle and pedestrian projects. Most measures that Metro has chosen are based on the length of bicycle and pedestrian facilities, so the level of network improvements associated with future projects captures only new segments of sidewalks, bicycle facilities, and trails. The bicycle and pedestrian networks in many areas of the Portland region, however, are already built out. In these areas, Metro often prioritizes projects that fill gaps or improve the quality of existing facilities. Because these projects do not increase the length of the network, they are not reflected in the performance measures, which creates two issues. First, although Metro's ATP investments include a significant number of projects in the region's inner areas, the greatest overall improvement appears in suburban areas where connectivity is currently poor and new facilities are planned (see Figure 35 for an example). Second, the overall results do not reveal the full picture of active transportation investments because many projects are not captured. Some data preparation steps that Metro could take to address these issues are mapping district-level projects (which typically focus on filling gaps and improving facilities in regional centers) as collections of linear projects rather than as shapes or points. These projects then would count toward measures of linear mileage. Over the longer term, however, a more effective approach would be to develop measures that capture projects that do not increase network mileage but that do fill gaps or improve existing facilities.

Many local projects are not included in the regional ATP. The Gateway neighborhood in Portland plans to add several new bike facilities not reflected in Metro's ATP data. Capturing more locally planned and funded projects could influence the regional assessments of changes in network completeness and connectivity. This creates a planning disconnect between agency levels that could result in inefficient project selection (e.g., a regional route parallel to a local one of equal or better quality).

The measures do not adequately capture how trails improve connectivity. Several trails in the Portland region, such as the Springwater Corridor and the I-205 Multi-Use Path, provide bicyclists and pedestrians with high-quality connections along routes that otherwise would be unsafe. Several issues with how Metro's connectivity data and measures capture these trails, however, are apparent. First, as discussed in the Data Assembly section, inconsistencies in how Metro maps current and future active transportation projects make identifying new trail segments challenging. Second, while the data fields distinguish local from regional trails, Metro's measure does not distinguish between trails that improve regional connectivity and those within the dense networks of recreational trails that crisscross many small city parks. Many measures show connectivity "hot spots" that exaggerate connectivity in areas within these parks.

Some bicycle and pedestrian "connectivity" measures actually measure completeness. The current connectivity measures largely reflect the presence of bicycle and pedestrian facilities. An area with a disconnected street network that has bicycle facilities and sidewalks on every street will score highly on bicycle and pedestrian connectivity, even though the network does not actually provide cyclists and pedestrians direct, convenient travel paths to key destinations. Defining these as measures of "completeness" rather than "connectivity" would be more accurate.

Some measures appear to be redundant. The density and connectivity measures are designed to capture different aspects of connectivity. Before they were applied, different results were expected; the density measures favor urban areas where bicycle and pedestrian networks are denser and TAZs are smaller, and the connectivity measures favor suburban areas where street networks are less dense, meaning fewer facilities need to be in place for an area to score highly. The density and connectivity results, however, show similar trends for both sidewalks and bikeways. Metro might be able to eliminate some connectivity measures to focus stakeholders and decision makers on those that are most informative. A basic factor analysis determined which measures were driving the results. As expected, many measures were redundant (completeness vs. density), and a few scored low (such as trails). The results indicate that the seven measures could be condensed into two, with the bicycle measures scoring higher on one and sidewalk measures scoring higher on the other. Figure 39 and Figure 40 show how these look visually, but a more robust analysis is required before any conclusions can be drawn. Results are provided as standard deviations from the mean, which provide a way to normalize scores into measures that are more intuitive: below average (orange) and above (purple).

Figure 39: Consolidated Measure 1—Emphasis on Bicycle Measures

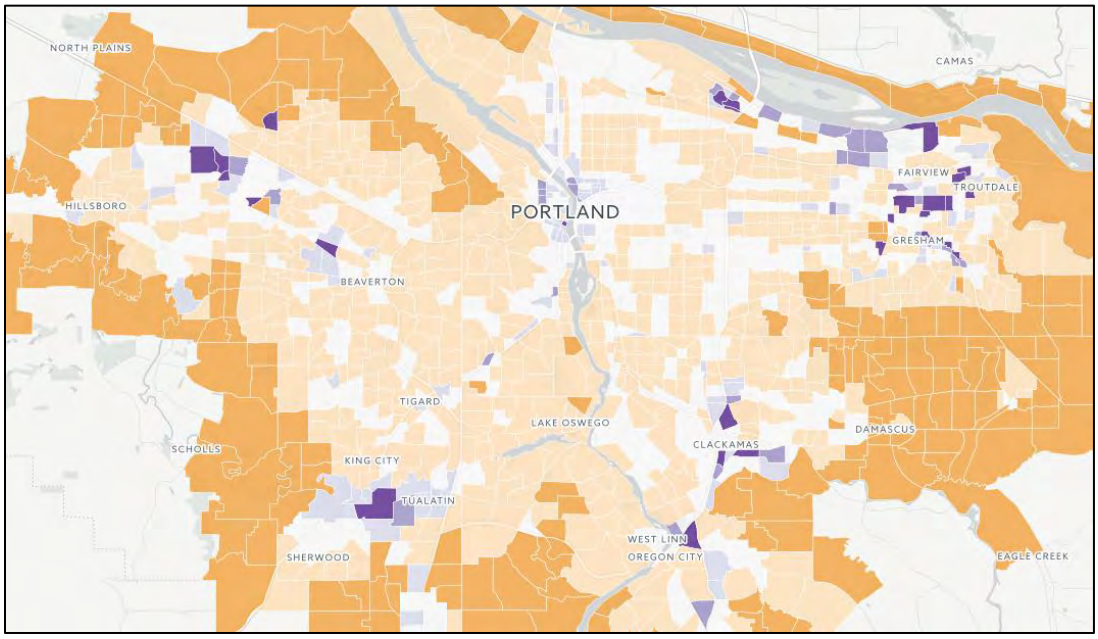
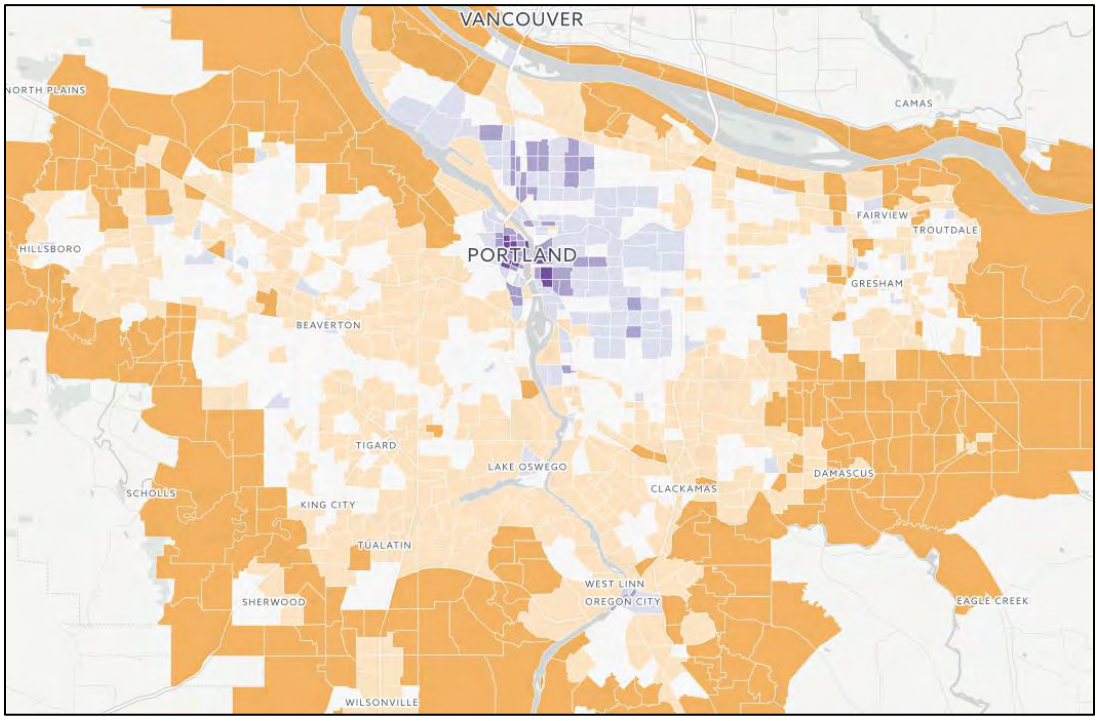


Figure 40: Consolidated Measure 2—Emphasis on sidewalk measures



Legend for Figures 39 and 40

Purple: Above average combined connectivity/ density score

Orange: Below average combined connectivity/ density score

Because of the limited time for technical assistance and the focus on testing measures that Metro had already approved, the alternative connectivity measure was not explored. The following potential long-term changes, however, were discussed with Metro as part of the case study process:

- Create a single definition of bicycle facilities and pedestrian facilities rather than separating trails from bikeways and sidewalks to better reflect how bicyclists and pedestrians actually travel.
- Strengthen data sharing between Metro's modeling group and the planning group. The modeling team has developed some sophisticated connectivity and accessibility measures that could be adapted by the planning group for other analyses.
- Analyze level of traffic stress (LTS) and identify a low-stress network. One way to approach the change discussed above would be to map a network for low-stress bicycle and pedestrian routes, which could include low-traffic streets with no facilities, medium- or high-stress streets with adequate facilities, and dedicated trails. Measuring LTS would be more data and labor intensive but would allow Metro to capture the many projects in the region focused on improving existing facilities, because these projects could be incorporated as a reduction in LTS. PeopleForBikes has measured LTS for the three largest cities in the Portland region,[24] which could serve as a template for Metro's efforts.
- Measure bicycle and pedestrian accessibility rather than density or completeness. Accessibility measures quantify the number of destinations that a bicyclist or pedestrian can reach in a typical trip via dedicated facilities or low-stress routes. These measures are well suited for capturing the benefits of projects that close gaps, because they account for the connectivity of the entire network instead of focusing on the length of newly built facilities. Accessibility measures are more complex than the measures that Metro uses but, because they provide richer information, a single accessibility measure might be able to substitute for the multiple measures that Metro currently uses.

Lessons Learned

Key lessons learned from this case study include the following:

- **Agencies should use consistent standards for all bicycle and pedestrian data.** Shapefiles for both current facilities and planned projects should use the same attributes and reference networks. For regional agencies to standardize data can be challenging because they often rely on local agencies to submit project shapefiles. Promoting data standards for use by local governments up front can streamline assembly of bicycle and pedestrian data.
- **Communities with mature bicycle and pedestrian networks need to use more sophisticated connectivity measures to capture the full impact of planned projects.** The bicycle and pedestrian network in many areas of the Portland region is largely built out. Metro often prioritizes filling gaps and improving existing facilities in these areas rather than building new facilities. Simpler measures capture only newly built facilities; measures that are more complex such as low-stress access would reflect improvements to the existing network.
- **Test connectivity measures before committing to them.** This technical assistance provided an opportunity to test measures developed via a stakeholder committee that provided input on what performance measures should capture in theory, but did not have a chance to test these

[24] https://bna.peopleforbikes.org

measures in practice. Testing these measures provided a valuable opportunity to refine the methodology, check whether the measures capture what Metro intended to measure, and think about how to communicate results.

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