FHWA GUIDEBOOK FOR

MEASURING MULTIMODAL NETWORK CONNECTIVITY

U.S. Department of Transportation
Federal Highway Administration

FEBRUARY 2018

1.	REPORT NO. FHWA-HEP-18-032	2.	GOVERNMENT ACCESSION NO. N/A	3.	RECIPIENT'S CATALOG NO. N/A
4.	TITLE AND SUBTITLE Guidebook for Measuring Multimodal Network Connectivity			5.	REPORT DATE February 2018
				6.	PERFORMING ORGANIZATION CODE N/A
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9.	PERFORMING ORGANIZATION NAME AND ADDRESS ICF, 9300 Lee Highway, Fairfax, VA 22031 Portland State University (PSU) PO Box 751, Portland, OR 97207 Alta Planning + Design (Alta) 711 SE Grand Ave, Portland, OR 97214			10.	WORK UNIT NO. (TRAIS) N/A
				11.	CONTRACT OR GRANT NO. DTFH61-ll-D-00033 6801-1-6084
9.	SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Planning, Environment, and Realty Federal Highway Administration 1200 New Jersey Avenue, SE, Washington DC 20590			13.	TYPE OF REPORT AND PERIOD COVERED Research Result and Conclusion
				14.	SPONSORING AGENCY CODE FHWA/HEPH-10
15.	SUPPLEMENTARY NOTES N/A				
16.	ABSTRACT *The Guidebook for Measuring Multimodal Network Connectivity* is a guide for transportation planners and analysts on the application of analysis methods and measures to support transportation planning and programming decisions. It describes a five-step analysis process and numerous methods and measures to support a variety of planning decisions. It includes references and illustrations of current practices, including materials from five case studies conducted as part of the research process.				
17.	KEY WORDS Network, connectivity, measure, analysis, data, bicycle, pedestrian, multimodal, planning			18.	DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161
19.	SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20.	SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 76	22. PRICE $0

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This report discusses general research associated with performance measures and elements of a performance management framework. This report was not intended to address the specific requirements associated with the FHWA rule that established national measures for system performance and other associated requirements, including specific target setting, data collection/reporting, and other general reporting requirements. That final rule ["National Performance Management Measures; Assessing Performance of the National Highway System, Freight Movement on the Interstate System, and Congestion Mitigation and Air Quality Improvement Program": Docket No. FHWA–2013–0054, RIN 2125–AF54, Federal Register - Vol. 82, No. 11, Pg. 5970 - January 18, 2017] can be found at: https://www.gpo.gov/fdsys/pkg/FR-2017-01-18/pdf/2017-00681.pdf. Within this final rule a measure to track the percentage of travel occurring in non-single occupancy vehicles (non-SOV) was established to reflect multimodal transportation use. The FHWA acknowledged in the rulemaking that the approaches to effectively track multimodal performance will improve with time, and, for this reason, noted that the required non-SOV measure will serve as a starting point. The FHWA further discussed its intent to revisit this measure in the future, as research projects underway to evaluate multimodal performance reach their completion. This report is an example of a research project that will help inform transportation decision makers in how they can effectively measure and improve multimodal performance. Complimentary efforts that are underway both within and outside of FHWA will be used as well to evaluate how and when required multimodal performance measures can be improved.

ACKNOWLEDGEMENTS

TABLE OF

CONTENTS

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01

INTRODUCTION

INTRODUCTION

ABOUT THIS GUIDEBOOK

In 2016 the United States Department of Transportation (USDOT) Federal Highway Administration (FHWA) published a *Guidebook for Developing Pedestrian and Bicycle Performance Measures* that presents methods for measuring walking and bicycling performance and activities and embedding them into the transportation planning and decisionmaking process (U.S. Department of Transportation 2016). Building on the 2016 guidebook, this resource focuses on pedestrian and bicycle network connectivity and provides information on incorporating connectivity measures into state, metropolitan, and local transportation planning processes. Connectivity measures can help transportation practitioners identify high priority network gaps, implement cost-effective solutions that address multiple needs, optimize potential co-benefits, and measure the long-term impacts of strategic pedestrian and bicycle investments on goals such as improving safety, system efficiency, network performance, and access to key destinations. Toward that end, this resource should be used in conjunction with self-evaluation and transition plans to evaluate needs for pedestrians with disabilities.

WHAT IS MULTIMODAL NETWORK CONNECTIVITY?

Connectivity is one of several concepts commonly used in transportation performance measurement to describe the ease with which people can travel across the transportation system. At its simplest level, network **connectivity** addresses the question, "Can I get where I want to go easily and safely?" **Multimodal** network connectivity adds the dimension of travel choices to the picture: "Can I get where I want to go easily and safely in whatever way I choose—for example, walking, bicycling, using transit, or driving?" A connected multimodal network allows people to travel by whatever mode they choose, including people who do not drive or do not have access to a motor vehicle.

Key Components of Pedestrian and Bicycle Network Connectivity

This guidebook outlines five core components of multimodal network connectivity, as listed below, with a focus on pedestrians and bicyclists. While these components are all related, the distinctions between them provide a framework for selecting connectivity measures that address specific questions. The guidebook describes analysis methods and supporting measures associated with each of these components.

- **Network completeness** – How much of the transportation network is available to bicyclists and pedestrians?

- **Network density** – How dense are the available links and nodes of the bicycle and pedestrian network?

- **Route directness** – How far out of their way do users have to travel to find a facility they can or want to use?

- **Access to destinations** – What destinations can be reached using the transportation network?

- **Network quality** – How does the network support users of varying levels of experience, ages, abilities, and comfort with bicycling or walking?

These analysis methods involve assessments of one or more types of performance measures, such as average trip lengths and the numbers of jobs accessible within a given distance of a multimodal route. The FHWA *Guidebook for Developing Pedestrian and Bicycle Performance Measures* (2016) provides detailed discussions of these and many other measures. It is a useful companion to this guidebook, which focuses on connectivity analyses, by providing technical information on computing a broad range of bicycle and pedestrian performance measurements.

HOW CAN MULTIMODAL NETWORK CONNECTIVITY ANALYSES SUPPORT TRANSPORTATION DECISIONS?

Although connectivity analysis methods and measures are still evolving, a growing body of research points to the key role of high-quality, connected networks in making bicycling and walking safer, more convenient, and more prevalent (Buehler and Dill 2016; Tal and Handy 2012). Since connectivity has a strong influence on the likelihood of achieving these types of outcomes, planners can use ongoing connectivity assessments as leading indicators of the potential for the outcomes to ultimately occur, even though actual changes in travel behavior or safety impacts may take time to become fully evident.

The outputs generated by connectivity analyses enhance accountability by helping decisionmakers weigh the potential outcomes of planned multimodal connectivity investments. Connectivity assessments can help transportation agencies and stakeholders examine questions such as: If we make it easier for pedestrians and bicyclists to cross busy streets, will the roadways be safer for all users? Or if we make sure every neighborhood has bike paths to schools and jobs, would more people bike to these destinations? Multimodal connectivity measurement can inform the iterative, comprehensive process of planning and implementing complete multimodal networks shown in Figure 1. Table 1 identifies relevant questions that connectivity analyses can inform at each step of the planning process.

WHO CAN USE THIS GUIDE?

While this guide can be informative for people involved in all aspects of transportation decisionmaking, the
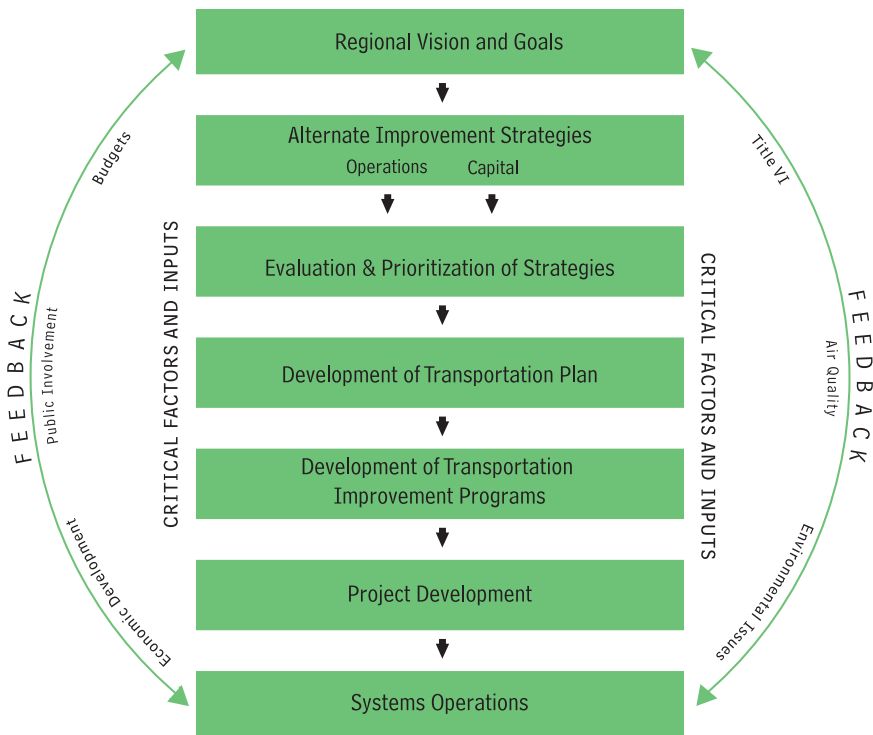
Figure 1. *Transportation Planning, Decisionmaking and Implementation. Source: U.S. Department of Transportation. 2016. "The Transportation Planning Process Briefing Book." https://www.fhwa.dot.gov/planning/publications/briefing_book*

MEASURING MULTIMODAL NETWORK CONNECTIVITY POSITIONS A TRANSPORTATION AGENCY TO:

- Enhance access to jobs, training, schools, and economic centers

- Accelerate project delivery by capturing efficiencies in economies of scale, project sequencing, construction phasing, financing, and community involvement

- Increase accountability of efforts to increase mobility options and system efficiency

- Prioritize infrastructure investments that fill gaps and address barriers in the transportation network, and that increase safety for all users

- Partner with the private sector to provide innovative multimodal transportation services and capture opportunities relating to shared-use mobility and automated and connected technology

material is targeted to planners and analysts who conduct the analyses that support the decisionmaking process. For those who desire a broad understanding of the concepts and methods involved in assessing connectivity, Chapter 1 offers a high-level overview of the analysis process. Readers are introduced to concepts of bicycle and pedestrian networks common to all measures of connectivity.

For those who want a deeper understanding of the technical process, Chapter 2 provides a step-by-step approach for conducting a connectivity analysis, supplemented in Chapter 3 by a series of fact sheets on analysis methods and measures. Chapter 4 summarizes lessons learned from practitioners in case study communities, and the Appendix provides descriptions of five case study assessments conducted as part of the research to develop this guide. Referenced throughout the report, these case studies highlight opportunities, challenges, and notable practices as well as illustrations of different ways of implementing the connectivity analysis steps.

WHAT IS ACCESSIBILITY?

The word "accessibility" can take on different meanings depending upon the context in which it is used. Broadly, it is about the ability to reach destinations safely and conveniently. It has long been associated with the usability of facilities by individuals with disabilities, but is also often used by transportation planners as a synonym for general pedestrian, bicycle, and transit connectivity. This guide uses the moniker "Access to Destinations" when referring to analysis methods and measures for examining pedestrian and bicycle connections between origins and destinations.

Table 1: *Assessing Multimodal Connectivity Throughout the Planning Process*

PLANNING PROCESS STEP	RELEVANT PLANNING TASKS	QUESTIONS INFORMED BY CONNECTIVITY ANALYSIS
Vision and Goals	Monitoring and Benchmarking	• What are the needs, priorities, and desires of community members and stakeholders? How and where do they want to see connections that will support their everyday needs and their bigger-picture goals, such as economic revitalization and job growth? • How has multimodal network connectivity changed over time? • How does connectivity in one area compare to other similar communities, regions, or states?
Alternate Improvement Strategies	Gap Identification Needs Assessment	• Where are missing or low-quality connections in existing facilities? Where are fixes needed?
Evaluation and Prioritization of Strategies	Scenario Analysis Project Prioritization	• How do different projects or strategies compare when it comes to improving the connectivity of the network? • What small but important improvements, such as connecting a bike route bisected by a highway intersection or fixing broken sidewalks, could make a big difference in achieving local goals for access to jobs, training, and essential services for all users?
Development of Transportation Plan	Scenario Analysis Gap Identification Needs Assessment Project Prioritization	• What destinations can people reach by biking and walking? • Which neighborhoods have higher or lower accessibility to the network or to specific destinations? • How does multimodal connectivity relate to other planning issues such as safety, system use, job growth, and equity?
Development of Transportation Improvement Programs	Project Prioritization	• How can the most cost-effective connectivity improvement be achieved while still advancing other high-priority needs? • How can funding be leveraged to best improve connectivity and achieve multiple agency goals for economic revitalization and job growth?
Project Development and System Operations	Feedback Loop to Inform Iterative Plan Updates	• How can multimodal connectivity be maintained or improved during project construction? • How can multimodal connectivity be preserved and enhanced during routine system maintenance and operation?

02

CONNECTIVITY ANALYSIS PROCESS

STEP 1

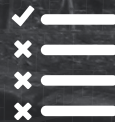*Identify the planning context*

STEP 2

Define the analysis method

STEP 3

Assemble the data

STEP 4

Compute metrics

STEP 5

Package results

Figure 2. *Steps of the Connectivity Analysis Process*

STEP 1

Identify the planning context

Clarify the purpose of the analysis, the decision(s) it will support, and the planning processes it will inform

STEP 2

Define the analysis method

Decide which method(s) and measures are best suited to the purpose of the analysis, and will make productive use of available resources

STEP 3

Assemble the data

Define the base network and assemble facility attribute and other relevant data

STEP 4

Compute metrics

Run the analysis to calculate connectivity for selected links, routes, and areas

STEP 5

Package Results

Develop overlays, visualizations, and other presentation materials to support the decisionmaking process

CONNECTIVITY ANALYSIS PROCESS

This guide provides a step-by-step framework for selecting and applying connectivity measures to help make decisions that are grounded in a comprehensive vision, supported by clearly defined goals and measurable objectives. Organized around the five steps shown in Figure 2, this chapter describes the terminology and procedures, while highlighting practical examples in each step.

In many real-world applications, the steps above will require an iterative process; for example, initial connectivity calculations might highlight errors or other deficiencies in underlying data that need to be corrected. As part of the development of this guidebook, five communities participated in case study applications of the analysis tools and measures discussed (Table 2). References to the case study results appear illustratively throughout the guidebook and are summarized in the Appendix.

Table 2: *Connectivity Analyses in Case Study Communities*

	ATLANTA	BALTIMORE	CALIFORNIA	FORT COLLINS	PORTLAND
STEP 1 *Identify the planning context*	Identify potential bicycle projects that would improve access to local centers in urban and suburban locations, using a regionally consistent approach that can inform regional funding decisions	Develop more sensitive pedestrian network connectivity measure for citywide planning, benchmarking, and accessibility to destinations	Measure bicycle mobility across high speed state highway corridors for project planning, prioritization, funding, and benchmarking	Analyze bicycle network quality and connectivity, repeatable over time for citywide planning and benchmarking	Identify bike/walk connectivity gaps and evaluate how well Regional Transportation Plan (RTP) projects address the gaps
STEP 2 *Define the analysis method*	Access to destinations (centers) via bicycle networks: a) Facility-based b) Quality-weighted (level of stress)	Network completeness: a) Facility-based (sidewalks) b) Quality-weighted (level of stress)	Directness of routes crossing the highway that use facilities that meet a minimum quality	Network completeness and access to destinations via low-stress network	Selected facility-based measures developed as part of RTP update, as well as two statistically consolidated measures
STEP 3 *Assemble the data*	Planned and existing routable networks, designated bicycle facilities, level of traffic stress segment ratings, population, community centers/boundaries	Centerline network, posted speed, number of lanes, sidewalks, curb ramps, bicycle facilities, land use, traffic signals, number of lanes, parking	Routable network open to bikes, roadway functional class, state highway corridor centerlines	Routable network, bicycle facilities, lane widths, turn lanes, parking, posted speeds, trails, traffic signals, topography, and land use	Existing and planned bicycle and pedestrian facilities, on-street and trail, transportation and equity planning areas
STEP 4 *Compute metrics*	3-mile travelsheds along low-stress networks calculated in GIS	Sidewalk presence and two quality-weighted scores for each network link	Level of traffic stress rating for each segment, and shortest paths along lower-stress network at regular intervals	Level of traffic stress, route directness from Census blocks to schools on low-stress network, and link centrality	Seven form-based metrics computed at traffic analysis zone (TAZ) level; two consolidated measures derived from factor analysis
STEP 5 *Package results*	Travelshed maps, population within travelshed by area	Network link maps and tabular result summaries aggregated to neighborhood	Route directness ratings along corridors, and tabular summaries by corridor	Connectivity island (network gap) maps, and equity overlays	Current and percent change maps by TAZ; overall change by metric and equity-focus area

IDENTIFY THE PLANNING CONTEXT

As an initial step, agencies need to identify the planning context and specific steps or questions that a network connectivity analysis will inform. Analysis performed without this context in mind is unlikely to provide the right information. Further, many connectivity measures are technically complex, and results can be challenging to understand and communicate in isolation. The analysis goal should be to provide answers to questions posed by specific planning tasks, while acknowledging and coordinating with the broader agency planning and policy context where possible.

Once defined, the specific analysis purpose will guide the rest of the connectivity analysis. As the case study examples in Table 2 illustrate, some key parameters to consider when defining the planning context include mode (bikes, pedestrians, or both); analysis scale (local areas, corridors, or regionwide); and the role of the agency (local or state network ownership/ operation, regional planning and technical assistance). Specifically, the questions discussed below will help define the analysis context.

WHAT ARE THE KEY QUESTIONS, PROBLEMS, OR DECISIONS TO BE INFORMED BY THIS ANALYSIS?

The specific planning context will, to a large extent, define connectivity analysis parameters, including the mode focus (pedestrian, bicycle, or both), scale, and key outputs. The Atlanta Regional Commission (ARC) case study, for example, focused on local analysis of bicycle network gaps around specific locations, while the Portland Metro case study sought to inform region-wide connectivity for pedestrians and bicyclists without specific destinations in mind. Measures, data, and summarization techniques will naturally vary between such different cases.

WHAT RELATED PLANS AND POLICIES MIGHT INFORM OR BE INFORMED BY THIS ANALYSIS?

In addition to the specific analysis context, an agency's broader planning context can provide useful input into the design of connectivity analyses and the selection of specific methods. Aligning measures with existing plans and policies can help decisionmakers interpret results or allow agencies to substitute simpler measures that more efficiently capture the implementation of current plans and policies. For example, the Portland Metro case study connectivity analysis borrowed aggregation areas and equity definitions from their broader regional planning context. This helped to align

connectivity findings with related regional plan data and policies. The City of Lincoln (Nebraska) developed an interactive network gap analysis tool that could be used to support specific planning tasks throughout their broader Complete Streets program (Lincoln/Lancaster County Planning Department 2015). The tool is updated and used regularly by staff and can be pulled up in any agency planning meeting to provide connectivity information.

Relevant plans and policies to consider in identifying connections to broader policy or planning context include the following:
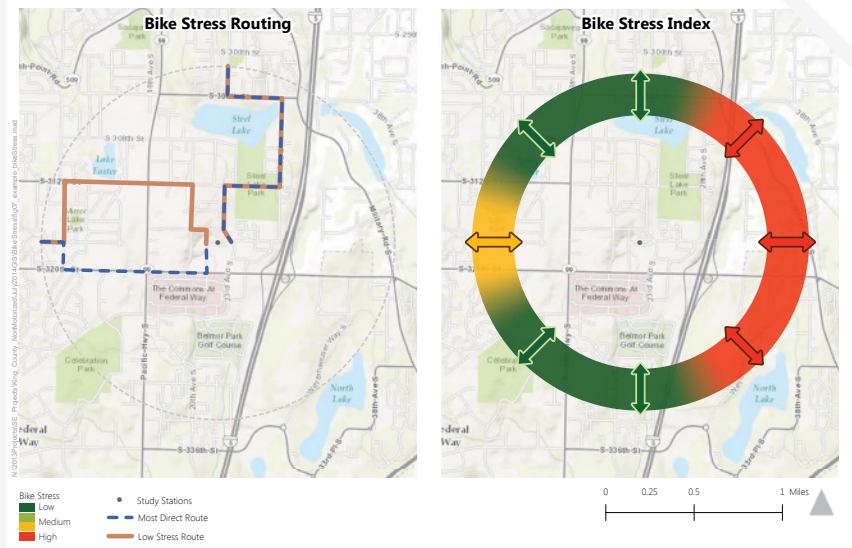
- **Current bicycle and pedestrian plans:** One simple way to analyze connectivity is to measure the percentage of planned facilities that have been built. This approach can be meaningful when a community has developed a detailed, consensus-based bicycle and/or pedestrian plan, but it is less meaningful if the plan is dated or has only received limited stakeholder feedback or approval. It also doesn't account for the fact that some projects will have a relatively more important impact on the overall network than others and that this isn't necessarily determined by the size of the project.

- **Other transportation policies:** Connectivity measures can also capture the extent to which other transportation policies are being implemented. For example, in communities that have adopted complete streets standards, it may be useful to measure the

Source: King County Metro and Sound Transit. 2014. "Non-Motorized Connectivity Study." http://metro.kingcounty.gov/programs-projects/nmcs/pdf/nmcs-report-091214.pdf

percentage of street-miles with bicycle and pedestrian facilities. Some communities have minimum street spacing standards that could serve as a basis for assessing the density of the bicycle and pedestrian network.

- **Precedent:** In communities that have previously conducted a connectivity analysis, it may be useful to be consistent with the measures used before for benchmarking purposes.

❓ WHAT ARE THE RELEVANT EXISTING AND/OR PLANNED NETWORKS?

Since connectivity analyses are inherently tied to bicycle and pedestrian networks, identifying the relevant network or networks is a necessary part of identifying the planning context. For example, in the California case study analysis, Caltrans was interested only in network connectivity across specific highway corridors. This informed method selection in subsequent steps; for instance, a method meant to summarize connectivity across an entire network or within areas (e.g. on either side of the highway) would not have been suitable. In the Portland Metro case study example, all bicycle and pedestrian facilities were included as attributes of the base year network, but planned projects included only those identified in the

HOW TRANSIT AGENCIES HAVE USED CONNECTIVITY ANALYSIS

Transit agencies typically do not have jurisdiction over pedestrian and bicycle facilities beyond their station sites, and funding for improvements is limited outside of major capital projects. TriMet (Oregon) and King County Metro (Washington) each developed pedestrian and bicycle connectivity tools and analyses that helped local jurisdictions make more informed decisions about improving access to transit (TriMet 2011; King County Metro and Sound Transit 2014; TriMet 2016). Both

10-year regional Active Transportation Plan (ATP). The ATP was the primary process the connectivity analysis was meant to inform. Method selection then focused on measures of system completeness and density to capture the impact of ATP projects on the bicycle and walking networks. More detailed discussion of defining analysis networks is provided under Step 3.

agencies noted that, in addition to prioritizing planned projects, the connectivity analyses and tools had been useful for writing grant applications, and at least one jurisdiction (City of Beaverton, Oregon) had used the resulting methodology in updating its Active Transportation Plan (City of Beaverton 2017). The agencies suggested that it was important to work with localities early in the analysis process to get "buy in" on design and data standards, further noting the key intermediary role of the regional MPO.

❓ WHAT IS THE AGENCY'S ROLE IN ADVANCING MULTIMODAL CONNECTIVITY?

The agency conducting the connectivity analysis does not always own or have primary planning responsibility for the network. And, even for those that do have planning or jurisdictional authority, connectivity assessments that consider only the roadways and facilities within an agency's control will often not be as useful as ones that

consider the function of those facilities within the larger network.

Agencies without direct control over network facilities may still wish to provide technical support, help to secure funding to network owners for project implementation, or simply consider how their own facilities interface with others. For example, metropolitan planning organizations (MPOs) and transit agencies may provide connectivity analysis data or tools to local jurisdictions. In the Atlanta case study example, one goal of the MPO was to further development of a standardized, repeatable bicycle network connectivity analysis that could be conducted by local jurisdictions for grant funding applications. The California case study analysis recognized that the state highway system posed barriers to bicycle and pedestrian connectivity, so Caltrans focused their analysis on assessing directness of nonmotorized routes that crossed their facilities. The text box on the previous page provides further examples from transit agencies that produced tools or analysis for use by owners of bicycle and pedestrian networks that provided access to transit facilities.

❓ WHAT IS THE APPROPRIATE SCALE FOR THIS ANALYSIS?

The scale of analysis is affected by the specific purpose and context of the analysis. Is the planning need a high-level sketch of the network as a whole, with limited details on the characteristics and quality of individual links? Should connectivity be summarized to specific areas? For example, will the study overlay with supporting data to measure progress toward equity goals? Or does the planning context require more

Source: Atlanta Regional Commission. 2014.
"Bicycle Pedestrian Plan – Walk. Bike. Thrive!"
http://atlantaregional.org/plans-reports/bike-pedestrian-plan-walk-bike-thrive

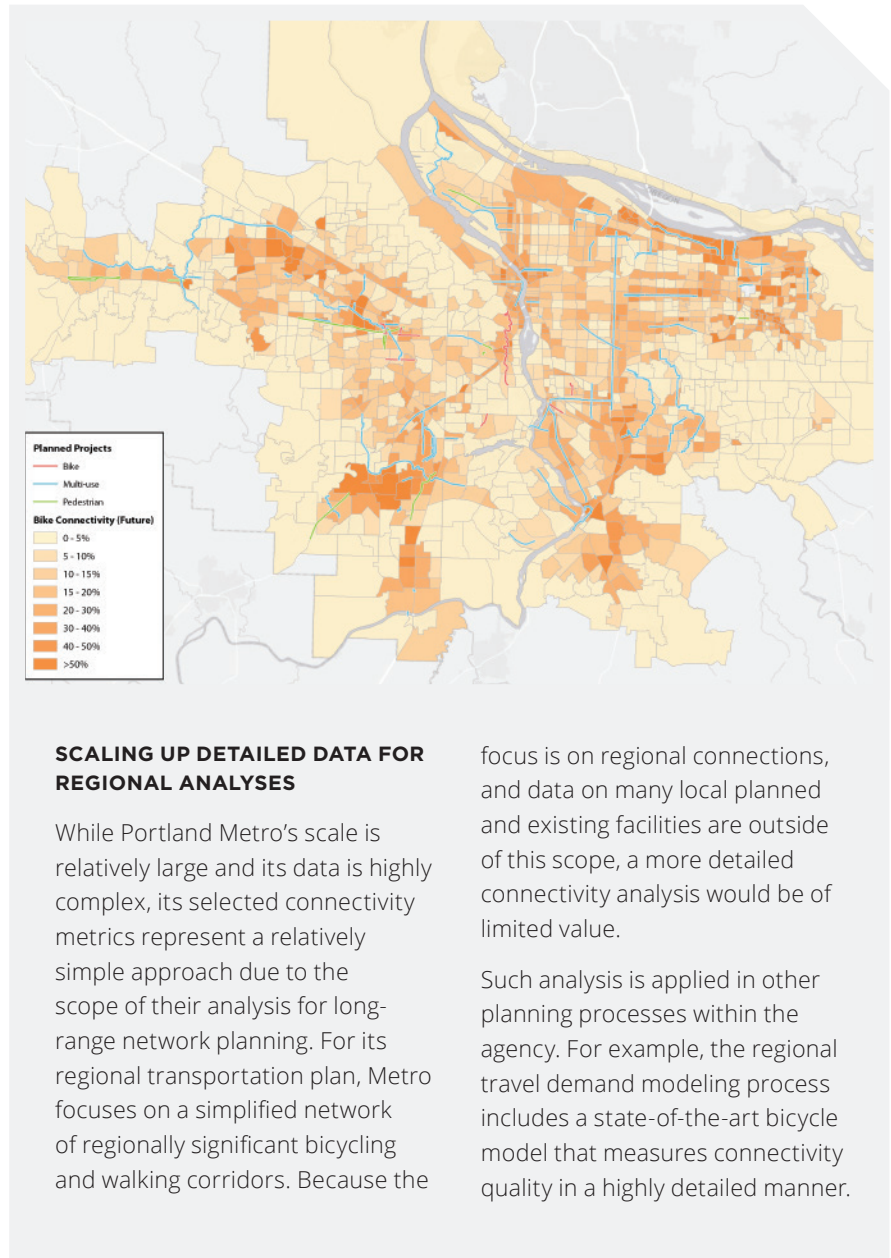### PROMOTING LOCAL CONNECTIVITY FROM A REGIONAL PERSPECTIVE

MPOs conduct regional analyses but also serve an important role in assisting and promoting consistency and innovation in local planning. The Atlanta Regional Commission (ARC) is the regional planning agency for the ten-county Atlanta (GA) metropolitan region. In its 2007 bicycle and pedestrian plan, ARC identified bicycle improvements along key regional corridors based on a detailed analysis of bicycle level of service, but found it difficult to coordinate implementation among the many local transportation agencies that had jurisdiction over segments of these corridors. The agency tried a different approach in its 2014 bicycle and pedestrian plan by identifying frameworks for ARC and local agencies to plan better together rather than identifying specific regional projects (Atlanta Regional Commission 2014). The plan includes some detailed guidelines on connectivity, such as connected network serving key destinations with bikeways spaced a half-mile apart, but focuses primarily on connectivity standards and measures that promote a coordinated but customized approach among localities.

in-depth descriptions of the quality of routes that connect specific origins and destinations?

Data availability is another consideration when determining the scale of an analysis. Some agencies find that required data is hosted in various departments or across different jurisdictions, all with different standards and maintenance procedures. Data can be maintained at varying levels of detail and one department or agency's database may omit specific attributes that another department needs. In other instances, data may not be readily available and will need to be collected or purchased to conduct the analysis.

When analysis is based on facility quality (e.g. level of service or perceived stress/attractiveness) or specific destinations, it is possible to collect more detailed data and conduct a more sophisticated analysis than larger-scale assessments with limited data availability. Typically, larger-scale analyses and tools have relied on simpler measures due to limited data availability. However, larger scale does not necessitate simpler measures. If data are available, large-scale measures can be more fine-grained and facilitate reuse for smaller-scale assessment as part of the planning process. For example, the Atlanta case study was able to reuse region-wide network link quality scores for a new analysis of local access to specific local centers. Had the regional analysis been done with simpler or coarser measures, the old analysis would not have been useful at the new, smaller analysis scale. With these tradeoffs in mind, the scale—and complexity—of the analysis is ultimately driven by both the specific planning

Planned Projects
— Bike
— Multi-use
— Pedestrian

Bike Connectivity (Future)
0 - 5%
5 - 10%
10 - 15%
15 - 20%
20 - 30%
30 - 40%
40 - 50%
>50%

SCALING UP DETAILED DATA FOR REGIONAL ANALYSES

While Portland Metro's scale is relatively large and its data is highly complex, its selected connectivity metrics represent a relatively simple approach due to the scope of their analysis for long-range network planning. For its regional transportation plan, Metro focuses on a simplified network of regionally significant bicycling and walking corridors. Because the

focus is on regional connections, and data on many local planned and existing facilities are outside of this scope, a more detailed connectivity analysis would be of limited value.

Such analysis is applied in other planning processes within the agency. For example, the regional travel demand modeling process includes a state-of-the-art bicycle model that measures connectivity quality in a highly detailed manner.

context as well as the resources available for data collection, agency and jurisdiction coordination, GIS and related analysis, and data maintenance.

Chapter 3 of this guidebook provides brief fact sheets about analysis types and specific metrics and tools that can

be used to assess connectivity at a variety of scales and at varying levels of complexity. The fact sheets in Chapter 3 identify potential scales of application and key questions each analysis type might help an agency to answer.

DEFINE THE ANALYSIS METHOD(S) AND MEASURES

After establishing the planning context and analysis goals in Step 1, the next step is to define an appropriate analysis method, including the specific measures to be used and the data required. Often, there will be many ways to answer the planning questions at hand. A connectivity analysis might include multiple measures that are aggregated or summarized in a variety of ways in order to visualize the information comprehensively. Complex analyses and measures can provide more nuanced results, but this must be balanced against increasing data and resource requirements.

CONNECTIVITY ANALYSIS METHODS

This guide focuses on five fundamental connectivity analysis methods, as listed below, summarized in Table 3, and illustrated in Figure 3.

- Network completeness
- Network density
- Route directness
- Access to destinations
- Network quality

Three of the methods—completeness, density, and directness—focus on the efficacy of the network's design. There is considerable overlap among the three categories, and recent work has shown that systematically combining measures from each may provide a more complete view of network connectivity (Schoner and Levinson
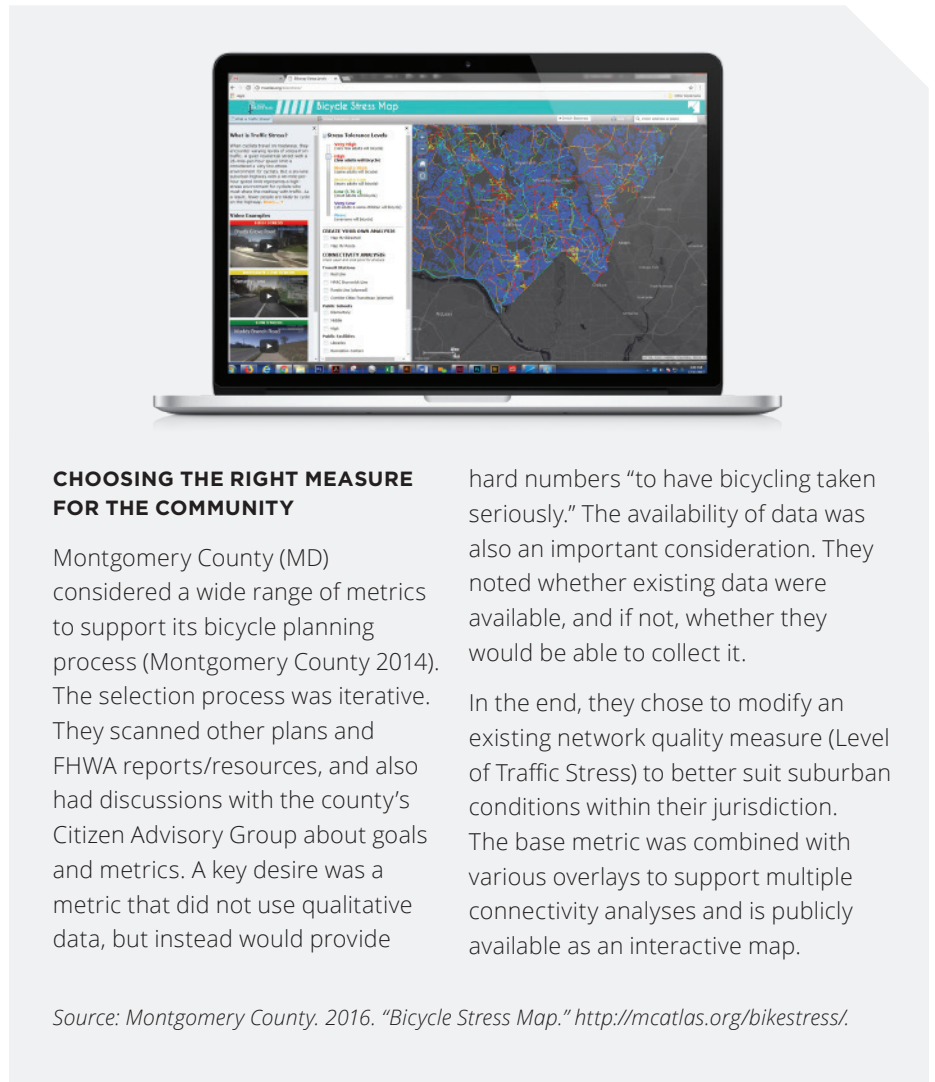
CHOOSING THE RIGHT MEASURE FOR THE COMMUNITY

Montgomery County (MD) considered a wide range of metrics to support its bicycle planning process (Montgomery County 2014). The selection process was iterative. They scanned other plans and FHWA reports/resources, and also had discussions with the county's Citizen Advisory Group about goals and metrics. A key desire was a metric that did not use qualitative data, but instead would provide hard numbers "to have bicycling taken seriously." The availability of data was also an important consideration. They noted whether existing data were available, and if not, whether they would be able to collect it.

In the end, they chose to modify an existing network quality measure (Level of Traffic Stress) to better suit suburban conditions within their jurisdiction. The base metric was combined with various overlays to support multiple connectivity analyses and is publicly available as an interactive map.

Source: Montgomery County. 2016. "Bicycle Stress Map." http://mcatlas.org/bikestress/.

2014). The fourth method, access to destinations, incorporates the land use context in order to illustrate the level to which the network facilitates movement to, from, and between important origins and destinations. Finally, network quality analyses enable planners to consider the experiences of nonmotorized network users, such as safety, convenience, and comfort, which can make a critical difference in the overall usefulness and performance of the system.

Table 3: *Multimodal Connectivity Analysis Methods and Measures*

ANALYSIS METHOD	KEY QUESTION	EXAMPLE MEASURES	SCALE	PLANNING TASK
Network Completeness	How complete is the planned bicycle and pedestrian network?	• Percent of planned nonmotorized facility-miles that are complete • Miles of planned nonmotorized facilities that have been built	• Small area • Large area	Monitoring and Benchmarking
	What portion of streets contain nonmotorized facilities?	• Percent of street-miles with nonmotorized facilities • Percent of street-miles that meet level of service or low-stress thresholds	• Small area • Large area	Needs Assessment, Scenario Analysis
Network Density	Does the street network allow for travel between destinations via a number of routes?	• Intersection density • Connected node ratio • Block length • Network density (street-miles per square mile)	• Route • Small area • Large area	Needs Assessment; Scenario Analysis
	Do designated bicycle and pedestrian facilities allow people to travel between destinations via a number of routes?	• Network density of nonmotorized facilities (lane miles per square mile) • Intersection density of nonmotorized facilities	• Small area • Large area	Scenario Analysis, Project Prioritization
Route Directness	Do nonmotorized facilities allow users to travel throughout a community via direct routes?	• Out of direction travel as a percentage of shortest path route • Network permeability	• Corridor • Small area • Large area	Scenario Analysis, Gap Identification, Project Prioritization, Benchmarking
Access to Destinations	How well do bicycle facilities connect to key destinations?	• Nonmotorized travelshed size • Number of homes/jobs accessible by bike/foot • Accessibility indices (e.g. Walk Opportunity Index) • Number of homes/jobs accessible by bike/foot using a certain level of network quality	• Corridor • Small area • Large area	Needs Assessment, Gap Identification, Project Prioritization
Network Quality	What is the objective quality of connectivity provided by an existing or planned network?	• Percent or area of network with high ratings for nonmotorized Level of Service, Bicycle Route Quality, or Pedestrian Index of Environment • Percent or area of network with low ratings for Level of Traffic Stress	• Link • Route • Small area • Large area	Needs Assessment, Gap Identification, Scenario Analysis

CONNECTIVITY ANALYSIS MEASURES

Analysis methods can be supported by a number of different measures, each of which presents specific data requirements, advantages, and disadvantages. In general, the connectivity assessment methods for density and completeness have the lowest data and computation needs. Data can often be assembled from existing sources, either within an agency or via U.S. Census or other public network data. Route directness and destination access typically will require network path analysis with routable network data (i.e. with defined connections) and place data that may be more difficult to assemble. Network quality-based analyses generally require more detailed data describing on- and off-street facilities, such as street configurations, traffic volumes and/or speeds, and more specific bicycle and pedestrian facility details. Table 3 provides an overview of the connectivity analysis methods and methods described in this guidebook. Chapter 3 includes fact sheets with more information about the five analysis methods and a selected array of measures.

THE IMPORTANCE OF DEFINING THE ANALYSIS NETWORK

A fundamental element of conducting a multimodal network connectivity analysis is determining the types and characteristics of transportation facilities to be included in the base network. This decision has a strong bearing on the metrics and conclusions that can be drawn from the analysis. The types of networks that are typically assessed include all roadways (and perhaps trails), roadways and trails that have designated bicycle and pedestrian facilities, or roadways and trails that have specific combinations of attributes (especially adequate separation from motor vehicle traffic). Often, the latter classification is based on thresholds meant to be comfortable for all users. Incorporating network quality into the definition of bicycle and pedestrian network connectivity is consistent with assessing other types of modal connectivity. For example, unimproved roadways or alleyways may be removed from assessment of many motor vehicle networks, and the available clearance afforded by overpass height is incorporated into the assessment of freight route connectivity.
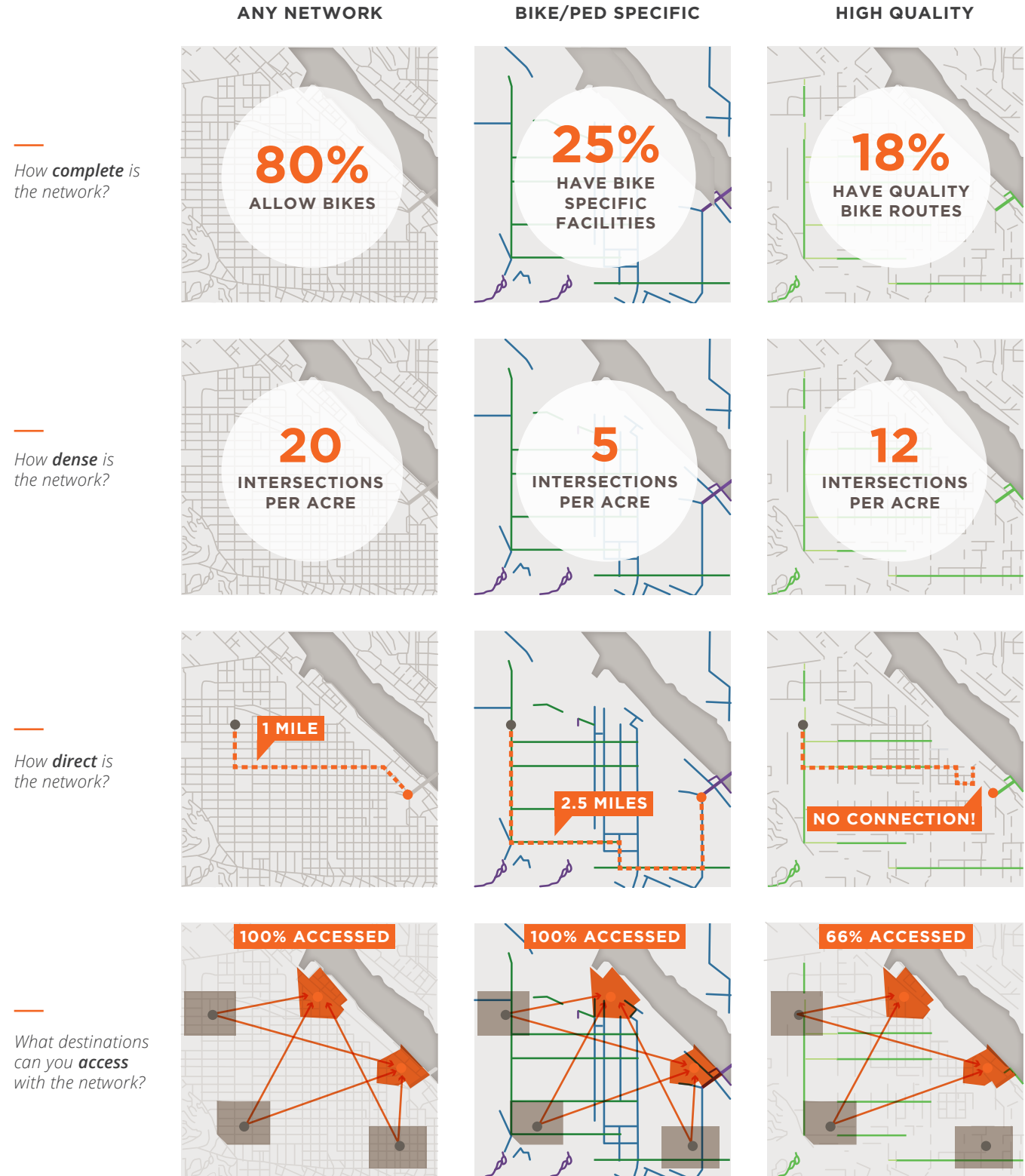
In the Baltimore case study, pedestrian network completeness was initially measured based on whether each link had sidewalks or not. This initial result was then compared with a completeness measure based on a quality rating metric that took into account a variety of attributes related to perceptions of stress. Many links that appeared "complete" in the initial analysis did not meet quality thresholds for low-stress connectivity, and area scores by each metric varied greatly.

In addition to the binary approach of including or removing links based on quality thresholds as portrayed in Figure 3, recent preference-based weighting techniques include all available links but assign relative quality weights based on the characteristics of each link. However applied, including elements of network quality as an assessment method produces a more robust and nuanced understanding of the physical network. Both facility-based and quality-weighted networks and supporting data are discussed more fully in Step 3.
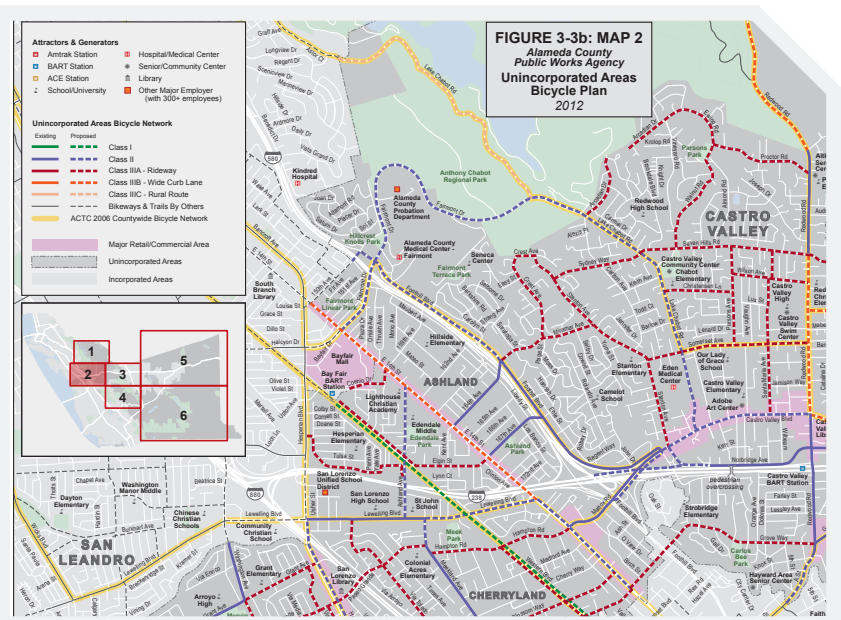
Figure 3. *Connectivity Analysis Methods*

This graphic depicts differences that can result from selecting different base networks for a connectivity analysis. The rows depict four of the five analysis methods (excluding the Network Quality method). The columns represent connectivity analyses conducted for three different base networks: 1) All streets; 2) Designated pedestrian and bicycle facilities; and 3) High-quality facilities identified through a Network Quality assessment.

	ANY NETWORK	BIKE/PED SPECIFIC	HIGH QUALITY
How **complete** is the network?	**80%** ALLOW BIKES	**25%** HAVE BIKE SPECIFIC FACILITIES	**18%** HAVE QUALITY BIKE ROUTES
How **dense** is the network?	**20** INTERSECTIONS PER ACRE	**5** INTERSECTIONS PER ACRE	**12** INTERSECTIONS PER ACRE
How **direct** is the network?	1 MILE	2.5 MILES	NO CONNECTION!
What destinations can you **access** with the network?	100% ACCESSED	100% ACCESSED	66% ACCESSED

Source: Alameda County Transportation Commission. 2012.
"Alameda County Bicycle and Pedestrian Plan for Unincorporated Areas."
https://www.acpwa.org/s/Bike-Ped-Plan-for-Unincorporated-Final.pdf.

ADAPTING EXISTING MEASURES TO LOCAL CONTEXTS AND DATA

Agencies sometimes find that existing measures or data definitions do not fit the local context. In other cases, an agency may determine that specific data requirements cannot be met nor can the agency find a suitable alternative measure. In such cases, existing measures have sometimes been modified, or, less commonly, agencies have developed a new measure. There are significant downsides to these approaches, most notably in weakening links to research support and validation, comparability to other applications, and the often-significant development and testing time required to modify or create new metrics. In some cases, the benefits of a localized measure may outweigh the costs. Examples of measure (Montgomery County, MD) and data (Alameda County, CA) adaptations are provided in this chapter. The case study applications for Baltimore, Atlanta, Portland Metro, and California each involved adapting data or methods to suit local planning needs, data availability, and local context.

ADAPTING CONNECTIVITY MEASURES TO FIT LOCAL DATA AND GOALS

The Alameda County (CA) Bicycle and Pedestrian Plan for Unincorporated Areas (2012) recognized the need to modify existing bicycle facility definitions to survey existing conditions and support planning outside of urban areas. Taking the California Department of Transportation Bikeway Categories as a starting point (Class I: Paved Bike Path, Class II: Bike Lane, Class III: Bike Route), four additional categories were created and coded in the bicycle network: Class IA: Unpaved Trail Bikes Allowed, Class IIIA: Low/Slow Traffic Bike Route (Rideway), Class IIIB: Bike Route with Wide Curb Lanes, and Class IIIC: Rural Bike Route

with Wide Shoulders. These classifications were used, among other things, to identify segments where low-cost spot improvements could connect existing facilities. Total miles of each facility type (current and proposed) were also calculated as a basic measure of aggregate network connectivity.

The Kansas City (KS) Walkability Plan (2003) adapted Pedestrian Level of Service (PLOS) to summarize existing pedestrian environments across the city. Links were scored on an A to F rating scale, mapped, and manually grouped into areas of similar walking quality. The overview was used to target more detailed analyses, including public input, in areas where improvements to increase the Pedestrian Level of Service (PLOS) might be needed.

STEP 3

ASSEMBLE THE DATA

Once the purpose of the analysis is clarified and the method is selected, it is time to assemble data, which includes spatial definitions of the bicycle and pedestrian network(s) as well as the data required to rate the components of the network using one or more measures (Step 4), and then to aggregate, summarize, and visualize the results (Step 5), potentially overlaying other data, in order to inform the key planning questions and analysis goals (Step 5).

The process illustrated in Figure 4 and in the following discussion represents a simplified, linear version of Steps 3 to 5. In practice, the process will be iterative, and multiple metrics may be applied in the same analysis. The Fort Collins case study example started with a broad network of all links open to bicycling, measured connectivity at the link level using a measure of traffic stress, and then used the results to narrow the analysis network to only those segments meeting a minimum quality threshold. The reduced network was then used in three additional steps to identify gaps (via map visualization), access to schools (via route directness scores), and link importance (via a link centrality metric). The Fort Collins example highlights the way that a single metric (level of traffic stress) can be summarized and overlaid in different ways to address planning questions in a larger connectivity analysis framework.

NETWORK DATA

Central to every connectivity analysis is the mapping of the network. The output of this step is a defined network consisting of a set of links and nodes as well as data on the attributes required by the selected technique. The building blocks of connectivity are the links (street or trail segments) and nodes (intersections or junctions) that define the bicycle and pedestrian network, as well as attributes that describe the facilities on and characteristics of each link and node.

Key considerations when defining the network include the following:

- Results are only informative to the extent that they measure the "right" network—the one that bicyclists and pedestrians are likely to use in real life

- Defining the network can be challenging because agencies often have only limited data on bicycle and pedestrian facilities. Developing the necessary data is a key step to defining the network.

- Often, this will be an iterative process, and either analysis goals, network definitions, or methods may need to be modified to fit available data and resources

The choice of which links, nodes, and attributes to include is jointly determined by a selected measure's requirements and the planning question or application at hand. In some cases, an agency might choose to include only links within its jurisdiction or planning process (e.g. only state-owned roadways for a state DOT, or bicycle facilities in the Regional Transportation Plan); however, depending on the question, other facilities may need to be considered where they interact with the selected system. For example, an analysis of state highways might consider where local bikeways and walkways interact with state highways. Similarly, a local analysis might consider where state-owned highways present barriers to connectivity. In the Portland Metro

SMALL CONNECTORS CAN MAKE A BIG DIFFERENCE

Networks based on designated facility types might seem simple on paper, but complications arise in practice. For example, different ways of classifying certain facilities can make a difference in the final assessment of connectivity. Portland Metro evaluated questions such as the following when deciding which facilities to include in its base network for the connectivity analysis conducted as part of the research for this guidebook:

- Should some or all off-street trails be included when calculating network completeness or density metrics?

- What about unimproved alleyways that add many miles of network but are unlikely to have designated bicycle or pedestrian facilities?
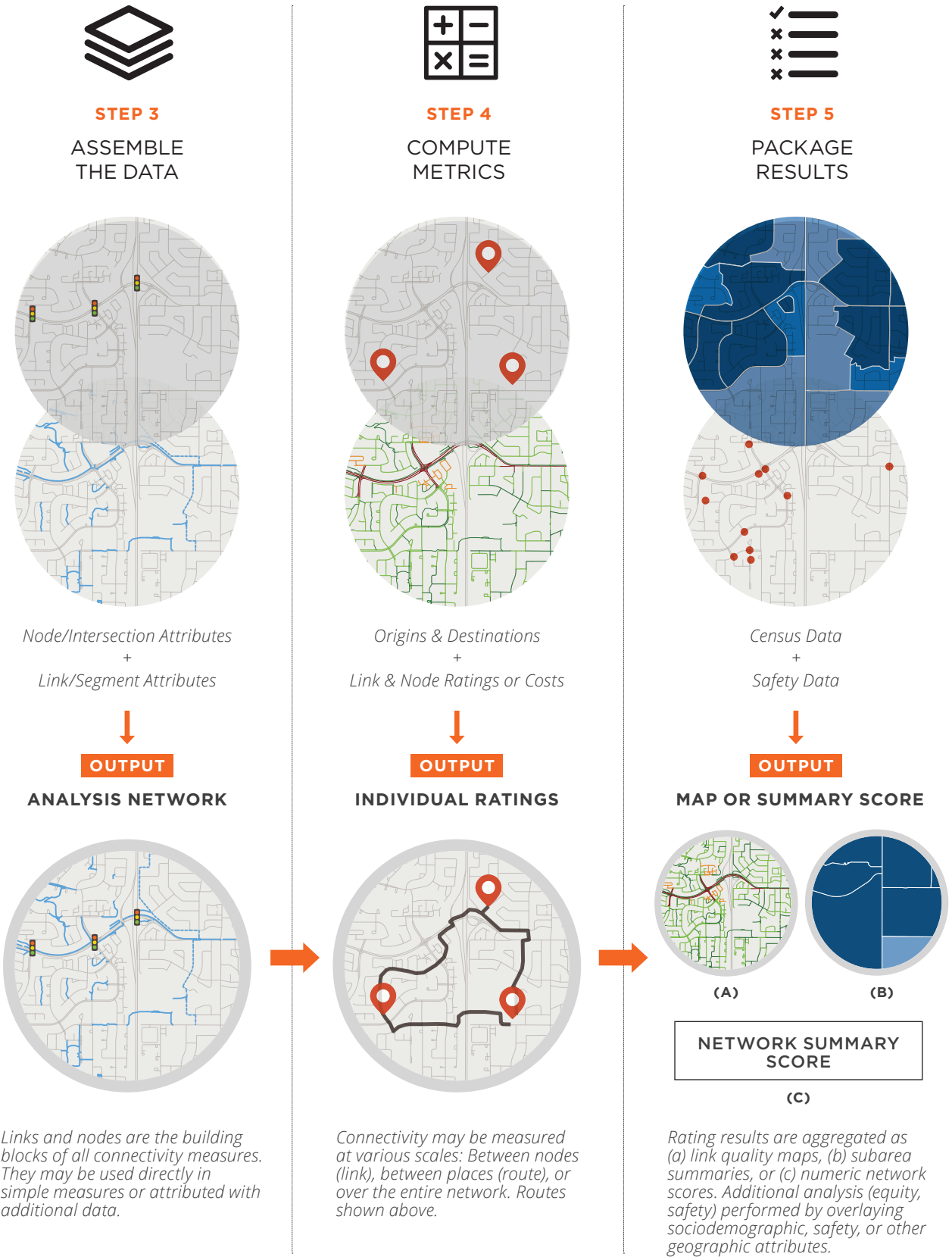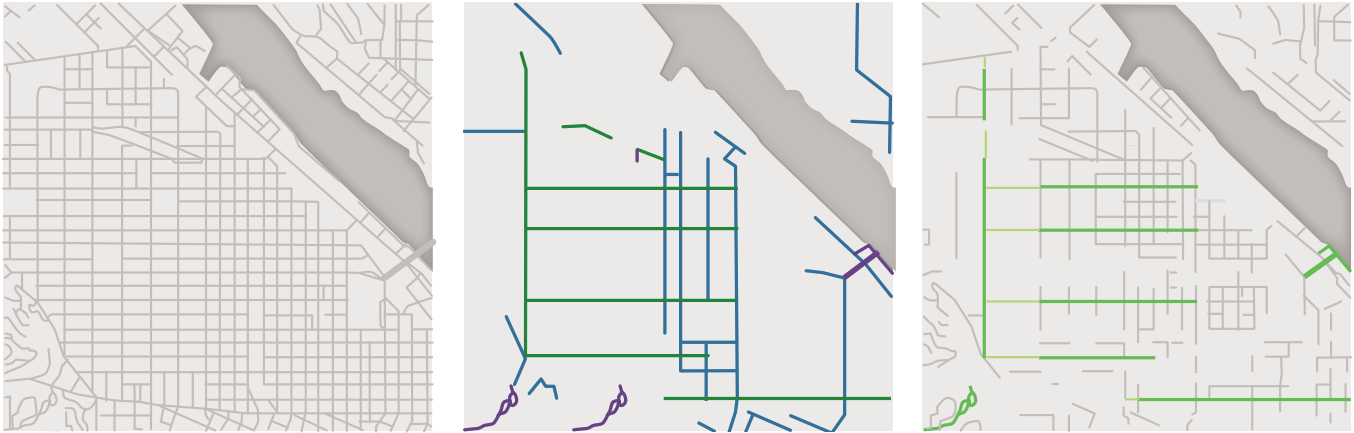
19

STEP 3

ASSEMBLE THE DATA

Node/Intersection Attributes
+
Link/Segment Attributes

OUTPUT

ANALYSIS NETWORK

Links and nodes are the building blocks of all connectivity measures. They may be used directly in simple measures or attributed with additional data.

STEP 4

COMPUTE METRICS

Origins & Destinations
+
Link & Node Ratings or Costs

OUTPUT

INDIVIDUAL RATINGS

Connectivity may be measured at various scales: Between nodes (link), between places (route), or over the entire network. Routes shown above.

STEP 5

PACKAGE RESULTS

Census Data
+
Safety Data

OUTPUT

MAP OR SUMMARY SCORE

(A) **(B)**

NETWORK SUMMARY SCORE

(C)

Rating results are aggregated as (a) link quality maps, (b) subarea summaries, or (c) numeric network scores. Additional analysis (equity, safety) performed by overlaying sociodemographic, safety, or other geographic attributes.

Figure 4. *Illustration of Steps 3-5*

Figure 5. *Network Representation*

From left to right: All streets network; Facility-based (line color showing different facility designations); Quality-weighted (line color showing different quality levels for links meeting some minimum quality/maximum stress threshold)

case study example, the lack of future local facilities that were not in the RTP network was identified as a limitation of the resulting analysis. Ideally, the analysis network will closely match the one actually considered by pedestrians and bicyclists.

Some measures are only defined or suited for a specific subset of links, such as arterial streets (e.g. Bicycle Level of Service), links with sidewalks (e.g. Sidewalk Density or Completeness), links with designated bicycle facilities (Bicycle Network Density or Completeness), or links where walking or cycling is permitted (Route Directness Index). Other measures, particularly simple, form-based measures such as intersection or link density, connected node ratio, or similar, can be applied to all streets. While it is unreasonable to assume that all streets are equally suitable for bicycle and pedestrian travel, it is also important to note that cyclists and pedestrians are not limited to streets with designated facilities. Fifty to ninety percent of cycling in the U.S. has been found to take place on streets without separate space for cycling; that is, in mixed traffic (Buehler and Dill 2016). Priority or low-stress networks often include both links with facilities and

links with low traffic or slower vehicle speeds.

To date, node (intersection) attributes have been applied less frequently to bicycle and pedestrian network analyses, but their importance to connectivity is increasingly recognized (Buehler and Dill 2016). An otherwise high-quality bicycle or walking facility will be of limited use if there is a major barrier along the route, such as an unsignalized crossing of a high traffic volume street.

As noted in the call-out box on network data sources on the following page, some information, such as crowdsourced data or commercially produced inventories, change rapidly, so practitioners should check them frequently for updated content and availability.

NETWORK TYPES

Analysis networks are typically defined as either facility-based or quality-weighted networks:

- **Facility-based networks** are defined as networks that typically consist of designated bicycle and pedestrian facilities but may sometimes include all streets open to walking and bicycling. These may be separated facilities for nonmotorized users, or shared

facilities that have been designed to accommodate pedestrians and/or bicyclist as well as other users.

- **Quality-weighted networks** are defined using an objective rating system for links and nodes that accounts for the quality of the facility. After scoring, the rated network can be used in further analysis, or a minimum rating threshold can be applied to create a restricted network for analysis. For example, a low-stress network might include only segments assumed to be safe and comfortable for bicyclists of a certain ability level or age, based on a maximum Level of Traffic Stress (LTS) rating or similar.

Figure 5 illustrates three representations of the same underlying network: an all-streets network that only omits facilities where walking and cycling are prohibited; a facility-based network of designated multimodal systems; and a quality-based network of facilities that exhibit certain desired characteristics such as low Level of Traffic Stress ratings. The connectivity within a given study area appears quite different depending on the decision of which networks to include in the assessment.

NETWORK DATA SOURCES

Publicly available data: Most of the data required for bicycle facilities analysis must be collected by transportation agencies. However, the following data sources can be used to supplement agency data, subject to coverage and availability:

- **OpenStreetMap (OSM):** A crowd-sourced map that includes some information on bicycle facilities and street characteristics. Coverage may be limited, and most attributes are not required. Data completeness and quality will depend to a large degree on the extent to which local agencies and community members provide data and updates.

- **Census TIGER/Line:** Generally, the most complete publicly-available source of street network data.

- **Highway Performance Monitoring System/All Roads Network of Linear Referenced Data (HPMS/ARNOLD):** Supported by state DOTs, FHWA maintains geographic databases of all state and federally owned roads (HPMS) and is developing a standard submission and update process for all public roads (ARNOLD). HPMS data includes traffic volume and number of lanes, among other items.

- **State DOT data:** In addition to submissions to ARNOLD,

	OSM	TIGER/LINE
Nonmotorized facility location and type	(✓)	
Basic street network centerlines	✓	✓
Roadway functional classification	✓	✓
Traffic speeds	(✓)	
Number of lanes	(✓)	
Shared Use Paths	✓	
Intersection attributes	(✓)	

(✓) *Indicates attributes that are not required or less likely to be available*

most states maintain additional attributes on roads within their jurisdiction and sometimes local roads as well.

- **Privately developed data from proprietary sources (e.g. HERE/ TomTom, NAVTEQ):** Can provide additional data on roadway characteristics such as number of lanes, traffic volumes, and speeds, but proprietary algorithms and rapidly evolving data and practices can make it challenging to know what data can support analysis.

The table above summarizes the data that may be included in two of the sources with greatest coverage and availability. As noted above, attributes from state DOT databases may help to enrich the national data sets. Data from all of these sources typically require additional processing to support network routing.

DATA STANDARDIZATION

To allow for application of connectivity measures, agencies should use consistent standards for all bicycle and pedestrian network data, including:

- Consistent facility types and attributes

- Consistent reference geographies

Agencies do not always use the same detailed standards to map and classify planned bicycle and pedestrian facilities that they use when mapping the current network, because projects may not be planned to a high level of detail. Promoting consistent standards can be especially challenging for regional and state agencies, which often rely on local agencies to supply data on planned bicycle and pedestrian projects.

Facility-based Networks

Defining networks by facility type is a common approach. For some simple, form-based measures, it may be appropriate to include all parts of a network that allow bicycling and walking. Distinguishing facility types in more detail gives agencies the ability to exclude inadequate facilities from their networks and conduct more meaningful connectivity analyses. For example, shared lane markings or even conventional bike lanes on higher speed or higher volume streets may be considered inadequate for most bicyclists. Table 4 provides a list of facility types and definitions that can be used to help define network elements and characteristics.

Quality-Weighted Networks

Quality-weighted network definitions, such as Level of Service (LOS) or Level of Traffic Stress (LTS), rate or quantify the quality of links and intersections based on separation from motor vehicle traffic and other attributes by applying standardized weighting schemes.

- **Level of Service models** have been developed primarily from stated preferences for different facility configurations (Landis, Vattikuti, and Brannick 1997; Landis et al. 2001; Petritsch et al. 2008; Foster et al. 2015). Mirroring motor vehicle LOS ratings, bicycle and pedestrian LOS ratings generally apply to major streets (arterials and above) and rate

Table 4: Bicycle and Pedestrian Network Facility Types

FACILITY TYPE	DEFINITION
Sidewalk	That portion of a street or highway right-of-way, beyond the curb or edge of roadway pavement, which is intended for use by pedestrians*
Sidepath	A shared use path located immediately adjacent and parallel to a roadway*
Shared Use Path	A bikeway physically separated from motor vehicle traffic by an open space or barrier and either within the highway right-of-way or within an independent right-of-way*
Bike Lane	A portion of roadway that has been designated for preferential or exclusive use by bicyclists by pavement markings and, if used, signs*
Buffered Bike Lane	Conventional bicycle lanes paired with a buffer space designated by markings that separates the bicycle lane from the adjacent motor vehicle travel lane and/or parking lane
One-Way Separated Bike Lane / One-Way Protected Bike Lane / One-Way Cycle Track	An exclusive one-way facility for bicyclists that is located within or directly adjacent to the roadway and that is physically separated from motor vehicle traffic with a vertical element
Contraflow Bike Lane	A portion of the roadway that has been designated to allow for bicyclists to travel in the opposite direction from traffic on a roadway that allows traffic to travel in only one direction
Contraflow Buffered Bike Lane	A buffered bike lane that has been designated to allow for bicyclists to travel in the opposite direction from traffic on a roadway that allows traffic to travel in only one direction
Contraflow Separated Bike Lane / Protected Bike Lane / Cycle Track	A separated bike lane that has been designated to allow for bicyclists to travel in the opposite direction from traffic on a roadway that allows traffic to travel in only one direction
Two-Way Separated Bike Lane / Two-Way Protected Bike Lane / Two-Way Cycle Track	An exclusive two-way facility for bicyclists that is located within or directly adjacent to the roadway and that is physically separated from motor vehicle traffic with a vertical element
Bike Boulevard / Neighborhood Greenway	A street segment, or series of contiguous street segments, that has been modified to accommodate through bicycle traffic and minimize through motor vehicle traffic*
Paved Shoulder	The portion of the roadway contiguous with the traveled way that accommodates stopped vehicles, emergency use, and lateral support of subbase, base, and surface courses. Shoulders, where paved, are often used by bicyclists*

American Association of State Highway and Transportation Officials, 2012, Guide for the Development of Bicycle Facilities, 4th ed.

at the segment level without regard to intersection or midblock crossing features.

- **Level of Traffic Stress ratings** are subjective scales based on different classes of potential users. Lower stress categories represent facilities that would be comfortable for a wider range of users, including less experienced users, children, and older adults. While numerous versions and adaptations have been applied in planning and research settings, all draw from original work on bicycling by Mekuria, Furth, and Nixon (2012). Subsequent work has

expanded the original model to apply to walking, including accessibility attributes (e.g. Baltimore case study).

- **Preference models** developed from observed behavior have mainly been used in academic research applications to date. Their direct link to observed behavior is potentially useful. MPOs including Portland Metro (Oregon), San Francisco County Transportation Authority (California), Los Angeles County Metropolitan Transportation Authority (California), Lane Council of Governments (Oregon), and Puget Sound Regional Council (Washington) have either

applied or are working toward applying these more complex connectivity models within their planning processes. Models of bicyclist route choice in Portland and San Francisco have served as the basis for most of these efforts (Broach, Dill, and Gliebe 2012; Hood, Sall, and Charlton 2011). Route choice findings have been further validated against bicycle use data (Broach and Dill 2016; Broach and Dill 2017).

Defining a quality-weighted network is considerably more data-intensive than defining a facility-based network.

Table 5: *Examples of Network Quality Analysis Methods and Associated Data*

	LEVEL OF SERVICE MODELS	TRAFFIC STRESS RATINGS	PREFERENCE MODELS
Bicycle and pedestrian facility data			
Bike lanes	✓	✓	✓
Shared-use paths	✓	✓	✓
Bicycle boulevards			(✓)
Sidewalks	✓		✓
Signed routes		(✓)	(✓)
Intersection features	✓	✓	✓
Slope		(✓)	✓
Supporting data			
Number of lanes	✓	✓	
Traffic volume	✓	✓	(✓)
Traffic speed	✓	✓	
Functional class			(✓)
Street / lane widths	✓	✓	✓
Presence of on-street parking	✓	✓	
Heavy vehicle traffic	✓		
Potential obstacles (driveways, blockages, right turn lanes, bridge crossings)		✓	

(✓) *For each type of quality rating scheme, a number of specific measures have been developed. Parentheses around a data item indicate that a particular attribute is not required by all measures in a class. In other words, agencies lacking such data might still find a measure of this type that can be applied.*

In addition to data on the location and type of bicycle facilities, such methods may require additional facility attributes (e.g. width/position of facilities and frequency of blockage) and data on other roadway characteristics that may affect bicyclists' and pedestrians' perceptions of safety or facility attractiveness (e.g. traffic volume, traffic speed, road slope, or intersection controls).

Quality Data Challenges

Agencies often lack the data needed to analyze network quality according to research-based methods. In some cases, agencies customize these rating systems to the data that are available. Table 5 provides a snapshot of typical pedestrian and bicycle network facility data that support the most common types of network quality assessments.

DATA ON ACCESS TO DESTINATIONS

Connectivity is ultimately about enabling travel between places, not just around a network, and adding place data to network scoring metrics can add valuable information to an analysis. Place data can be as simple as calculating population (see Atlanta case study) or employment within areas scored differently by a connectivity metric (e.g. all those within a certain [weighted] distance of a destination, or all those within an area in a given connectivity score range).

Quality-weighted network measures lend themselves to route scoring, or estimating the relative connection quality between sets of origin-destination pairs. Route scoring is explained in more detail in subsequent sections. This additional analysis can provide a better idea of the effectiveness of network connections. Table 6 provides examples of place data that have been used to measure network connectivity between sets of locations.

Table 6: *Connectivity Measures and Data Sources for Analyzing Access to Destinations*

ANALYSIS PURPOSE	PRIMARY MEASURE	ORIGIN DATA (PEOPLE)	DESTINATION DATA (PLACES)
Assessing community-wide bikeability*	Community-wide access to destinations	Census Blocks	Census/LEHD: Population, employment
			OpenStreetMap: Education, health/medical, recreation/community, retail, transit
Assessing community wide bikeability (M. Lowry et al. 2012)	Community-wide access to destinations	Regularly spaced points representing residential origins	Commercial parcels (weighted by square footage and distance from origin)
Predicting bicycle commuting patterns (Broach and Dill 2017)	Connectivity to employment	Census Block Group centroids (weighted by population)	Census Block centroids (weighted by number of jobs)
Identifying low-stress streets (Mekuria, Furth, and Nixon 2012)	Overall connectivity	Census Block vertices	Census Block vertices
Prioritizing bicycle network improvements (M. B. Lowry, Furth, and Hadden-Loh 2016)	Home-based access to destinations	Residential parcels	Selected groups or "baskets" of important and/or desirable types of destinations (21 types)
Quantifying local access to destinations (Kuzmyak, Baber, and Savory 2007)	Home-based access to destinations	Traffic Analysis Zones (TAZs, weighted by number of households)	TAZs (weighted by jobs and distance)
Assessing bicycle access to regional centers**	Home-based access to destinations	Census Blocks	Centers designated by the community, such as Livable Centers Initiative communities in the Atlanta region
Assessing bicycle access to local K-12 schools ***	Home-based school access	Census Block centroids	K-12 Schools

* https://bna.peopleforbikes.org/#/methodology
** Atlanta case study
*** Ft. Collins case study

Figure 6. Links, nodes, and networks
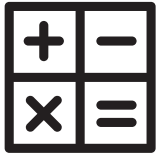
STEP 4

COMPUTE THE METRICS

Once the network is defined and links and nodes are assigned attributes, connectivity is scored at one (or more) of three scales: link, route, or area/network, as shown in Figure 6.

LINK

The smallest unit of analysis is the connection between two nodes along a single link. The quality of the connection provided by a link is defined by attributes of the link, and, possibly, the approach to the end node or intersection. A numeric score or derived rating is assigned to the link by weighting the attributes relative to one another or by applying a classification scheme. In this case, the output is a single score for each link in the analysis network (sometimes a score for each direction of travel).

Common examples of metrics that score at link-level are Bicycle/Pedestrian Level of Service (BLOS/PLOS) and Level of Traffic Stress (LTS).

ROUTE

Measures can also be computed at the route or corridor level, defined as the set of available routes connecting two places along a series of links connecting locations of interest. There are typically multiple routes of travel in a given corridor. The highest quality or least-cost connection can be defined using available data, but for bicycle and pedestrian networks it may be more appropriate to consider a range of routes, given varying user behavior. Different people may take different routes in the same general corridor due to slight variations in origins and destinations, variability in comfort at using different facilities, knowledge of available bicycle and pedestrian facilities, and random chance. Route-based scores reflect both the quality of individual links and how those links fit together. Output in this case is a score or rating representing the quality of connection for each pair of places

LINKS, NODES, AND NETWORKS
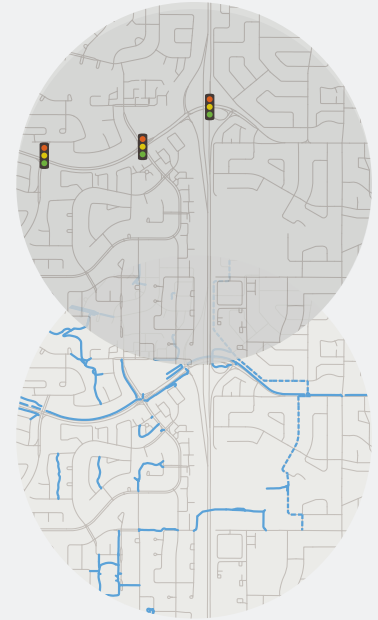
Node/Intersection Attributes
+
Link/Segment Attributes

OUTPUT

ANALYSIS NETWORK
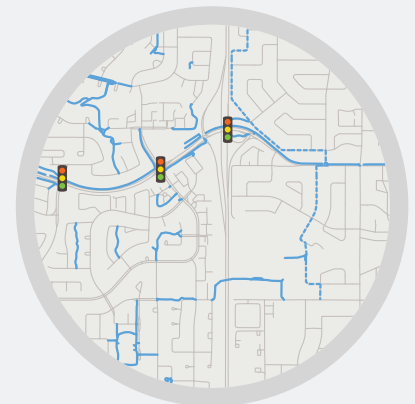
along the "best" route provided by the current or planned network. Any link-based metric can be applied at the route scale as long as routes can be identified.
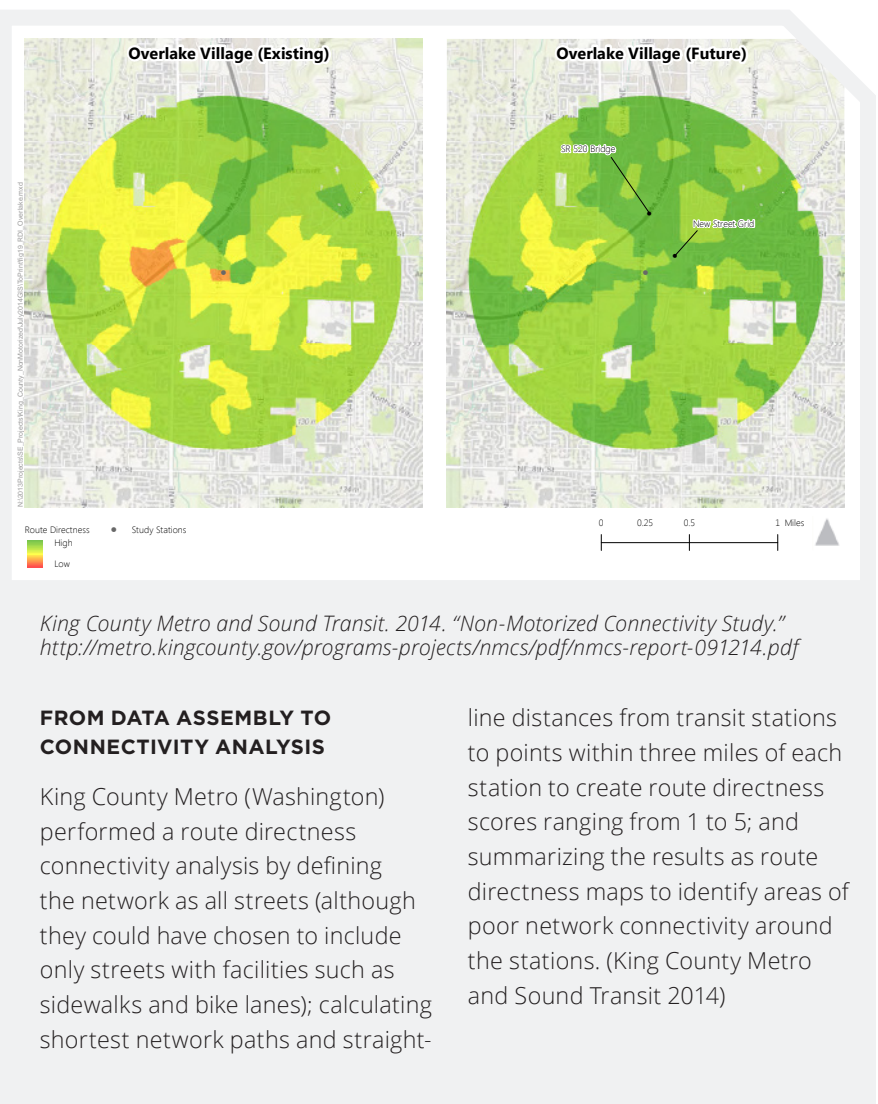
Measuring quality along the immediate path of a given route is valuable, as it reflects the end goal of connecting people and places. To measure the full connectivity of the area served by the route, however, an analyst needs to identify specific origins and destinations associated with the route. For specific planning applications, such as access to transit stops or schools, it may be enough to specify all points within a reasonable distance of the given destinations (sometimes referred to as travelshed analysis). In other cases, a more varied sample of origins and destinations is required. Table 6 in the previous section provides examples of place data that have been used for route-level connectivity analysis.

AREA/NETWORK

Form-based metrics such as Block Length Analysis, Connected Node Ratio, Sidewalk Density, and Route Directness typically work only at the scale of entire networks or areas. Links and nodes or attributes of interest are counted, or techniques are applied to calculate general measures such as density, directness, or fragmentation of the network. The output in this case is a single area or network-wide score. Subareas or subnetworks can be defined and scored for different areas within the same planning region or locale.

Source: FHWA

King County Metro and Sound Transit. 2014. "Non-Motorized Connectivity Study." http://metro.kingcounty.gov/programs-projects/nmcs/pdf/nmcs-report-091214.pdf

FROM DATA ASSEMBLY TO CONNECTIVITY ANALYSIS

King County Metro (Washington) performed a route directness connectivity analysis by defining the network as all streets (although they could have chosen to include only streets with facilities such as sidewalks and bike lanes); calculating shortest network paths and straight-line distances from transit stations to points within three miles of each station to create route directness scores ranging from 1 to 5; and summarizing the results as route directness maps to identify areas of poor network connectivity around the stations. (King County Metro and Sound Transit 2014)

PACKAGE THE RESULTS

The final step in the process is to relate the results of the analysis to the planning context that was articulated in Step 1. If the purpose of the analysis is to inform regional or subarea plans or project prioritization, for example, data on thousands of individual links and routes must be aggregated into map(s), charts, and other visualization tools that help decisionmakers to understand the results at the scale relevant to their needs. The aggregation process would ideally occur as a result of scaling the analysis to suit the planning context, but planners must often do some post-processing in order to create

maps and graphics that summarize the information in an understandable way. In these cases, analysts and planners need to work carefully in order to avoid "burying" essential details or otherwise distorting the results of the analysis.

Overlaying the aggregated results with other maps and data on topics such as equity, safety, or economic growth will help planners and stakeholders prioritize the projects that are going to produce the greatest benefit for bicyclists and pedestrians and help to achieve additional community goals. Again, it is important for planners and analysts to work together in order to

ensure that the messages conveyed by overlays help to enrich, rather than skew or obscure, the key points identified in the connectivity analysis.

AGGREGATE

The simplest way to aggregate link scores is to display them on a map, representing quality with colors or symbols to help stakeholders visualize routes of interest, gaps, barriers, and relative connectivity across areas. Figure 7 shows an example of a weighted link/node quality measure displayed as a connectivity map. The map visualizes routes and areas with
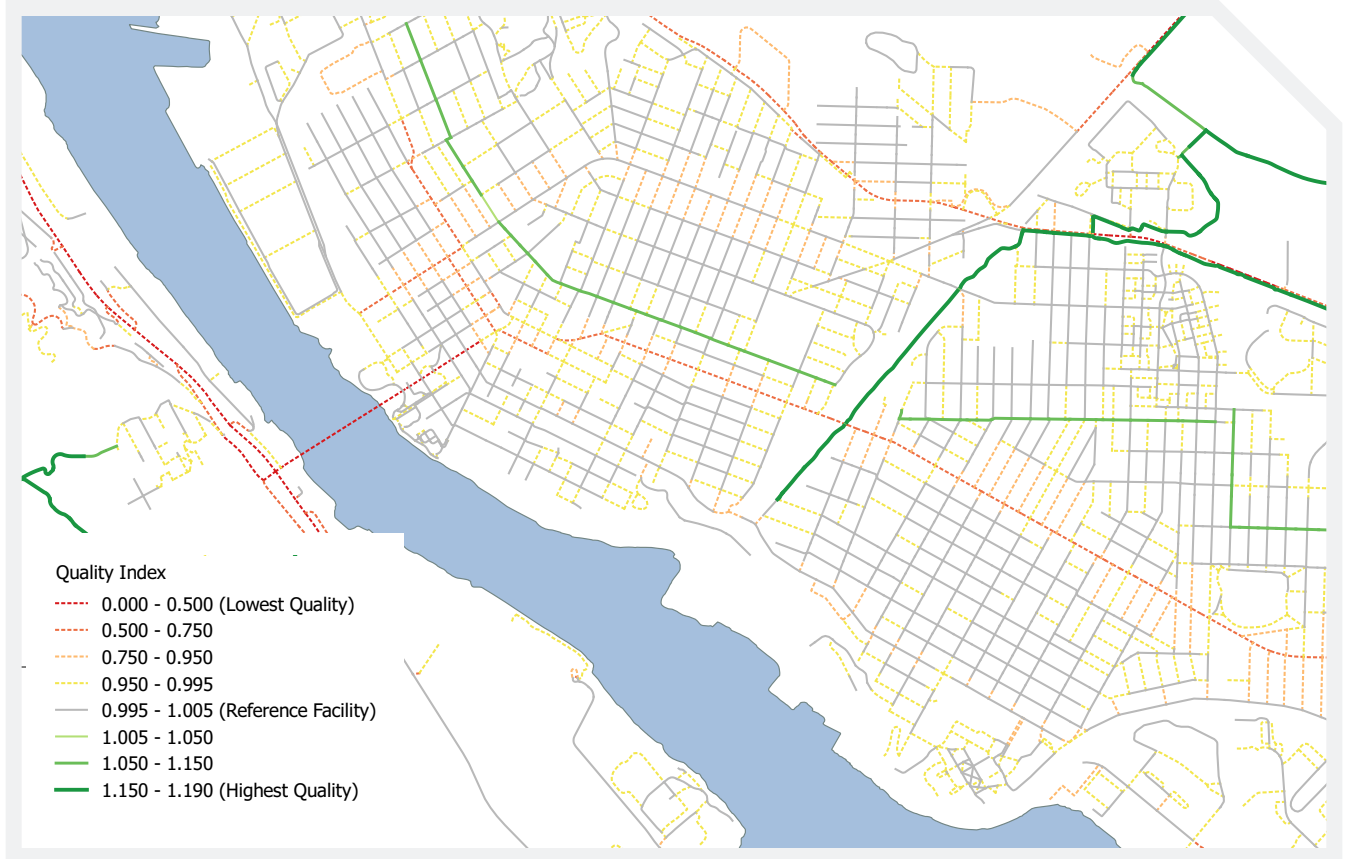
Figure 7. *Link-level Connectivity Map*

In this connectivity map, individual links are weighted by a preference-based model that includes multiple factors. Darker/thicker lines represent better (solid green) or worse (dotted red) connectivity.

higher or lower connectivity, as well as apparent gaps and barriers.

With route-scale outputs, the average route quality score for all origins or destinations in the subarea might be calculated (perhaps weighted by population, jobs, or some other measure of importance). Typically, the aggregate route-based scores take the form of an index, percentage, average, or some other relative indicator. For example, Bicycle Level of Traffic Stress is often summarized as the percent of origin-destination pairs connected at a reference traffic stress level or better (Mekuria, Furth, and Nixon

18.97%

23.08%

23.08%

21.03% 12.

14.36%

35.38%

13.85%

42.05%

7.18%

21.03%

26.15%

31.79%

15.9%

25.13%

22.56%

36.41%

22.05%

13.33%

8.72%

22.56%

13.33%

22.05%

24.1%
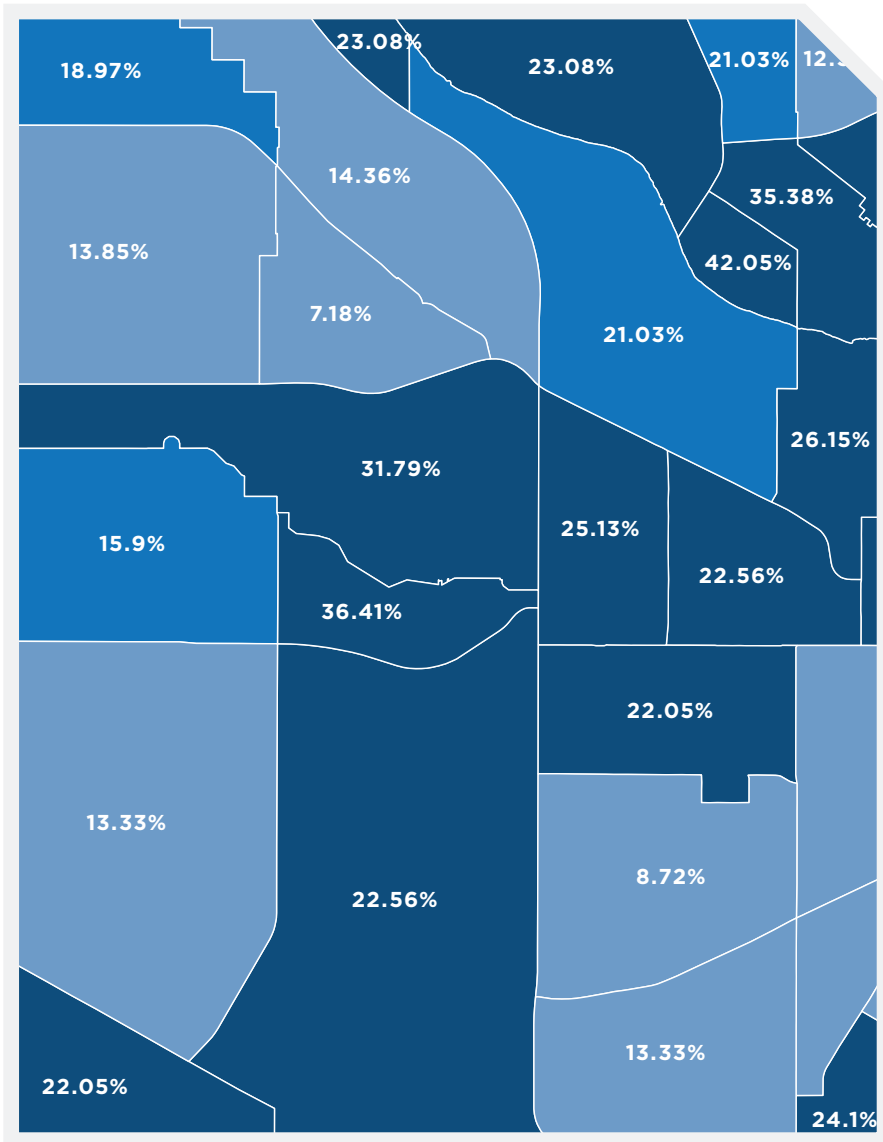
Figure 8. *Connectivity Measures Aggregated to Small Areas*

In this map of sidewalk connectivity analysis results, darker colors show Traffic Analysis Zones (TAZs) with greater sidewalk coverage.

2012). In another example, Bicycle Route Quality Index (RQI) can be normalized by equivalent distance on an "adequate" or "average" facility such as an on-street bike lane (Broach and Dill 2017). These ratings can then be compared with one another to assess the relative level of need in different subareas or measure changes in connectivity over time. As a final example, the PeopleForBikes' Bicycle

Network Analysis (BNA) tool is a new connectivity measure based on Bicycle Level of Traffic Stress. It has been applied in a number of cities and small towns throughout the U.S. The BNA score ranges from 0 to 100, based on access to a destination basket along bicycling routes meeting a specific quality and distance threshold.[1] Each of these measures is described in more detail in Chapter 3.

Connectivity ratings can also be aggregated to an entire community, or to subareas within the larger community, using measures such as the average quality of all links or the percentage of links of a given quality. Figure 8 provides an example of a connectivity measure (sidewalk completeness) measured at the link level and aggregated to small areas.

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1 *https://bna.peopleforbikes.org/#/methodology*
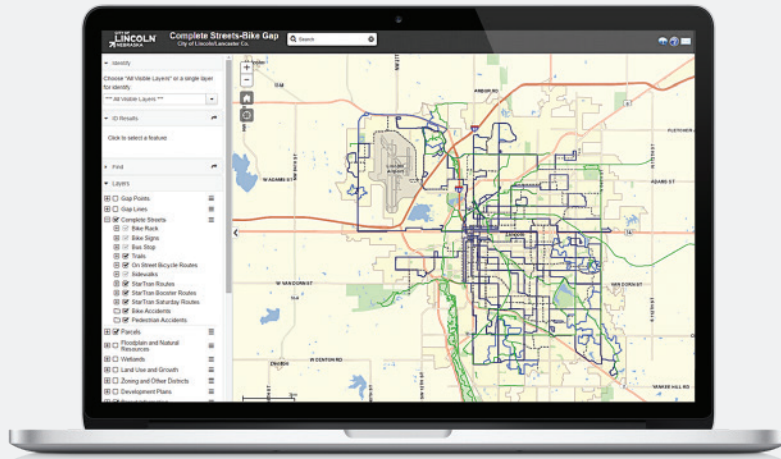
Source: Lincoln/Lancaster County Planning Department. 2015. "Complete Streets Gap Analysis and Prioritization Strategy." https://lincoln.ne.gov/city/plan/reports/GapAnalysis.pdf.

ADDING VALUE WITH DATA OVERLAYS

The City of Lincoln (NE) developed an interactive Gap Analysis Tool to support their Complete Streets program (Lincoln/Lancaster County Planning Department 2015). The interactive tool has helped to identify and prioritize projects to receive annual funding. Initial data collection across agencies was aided by Lincoln's Open Data policy. Collaboration with the Public Health Department produced pedestrian/bicycle crash data that can be overlaid with identified connectivity gaps. The system was designed to be relatively easy for staff to update, and features continue to be added over time in response to planning needs.

OVERLAY

Overlaying is an optional step that involves combining connectivity results with data that represent complementary policy goals. Connectivity results are overlaid or joined with other geographic data to support analysis on topics such as equity, safety, and system usage.

Safety analyses can be overlaid with connectivity results. Crash data can be overlaid on connectivity scores to help planners understand the relationship between high-crash locations and poor connectivity. This could be done by area or for specific locations. An area, segment, or node with a low connectivity score and high crash rate might reflect an important gap with high demand and few alternative options. Critical network gaps can be prioritized.

Motor vehicle volume data could be joined to connectivity scores, especially for future scenarios, where bicyclists or pedestrians are likely to come into conflict with other road users. This could help identify areas for proactive treatments to reduce crash risks in those locations.

Equity analyses can be performed to determine how network connectivity is distributed across different parts of a planning region and across different socioeconomic groups. As an example, overlaying income or race/ethnicity data on a connectivity map could be used to identify disadvantaged communities in low connectivity parts of the network and to prioritize projects that will improve conditions for people that may be more likely to rely on bicycling and walking for transportation. In the Portland Metro case study example, connectivity results were overlaid with areas meeting targeted equity criteria in the regional plan to better understand how planned projects were contributing to equity goals.

System usage relationships have been validated for a few connectivity measures. Overlaying land-use data with connectivity scores can support prediction of rates or changes in the rate of bicycling and walking. For example, the impact of a new connection or a series of quality improvements could be related to expected increases in use. The overall change could help inform project selection and determine whether existing plans are sufficient to meet targets for walking and cycling.

PACKAGE FOR PRESENTATION

Connectivity maps or scores can help planners and stakeholders identify priorities for projects or further study in a variety of ways. Perhaps most importantly, connectivity analysis brings a fresh set of objective information "to the table." For example, during an analysis of bicycle connectivity, transit agency TriMet (Portland, Oregon) realized that prioritizing bicycle access in low-density areas served by transit might be effective because the walk distance to transit stops was too far for many residents. This was challenging to communicate to stakeholders but an important result that guided future planning.

Communicating connectivity effectively involves not only presenting the analysis methods clearly, but also responding to concerns that come up during the planning process. In Seattle, Washington, advocates felt that connectivity was not effectively evident or prioritized in the city's bicycle plan update, partly because evaluation metrics were mileage weighted. Mileage weighting pushed the discussion toward the strategy of adding mileage in outlying locations, where it was cheaper, even if the goal of connectivity might be better served by filling gaps in urban areas.

It is important to not lose sight of the specific analysis purpose defined in Step 1. Results should be summarized at a scale, level of detail, and with overlays appropriate for answering the key questions that drove the connectivity analysis in the first place.

Existing Streets with Bicycle Level of Comfort 1-2
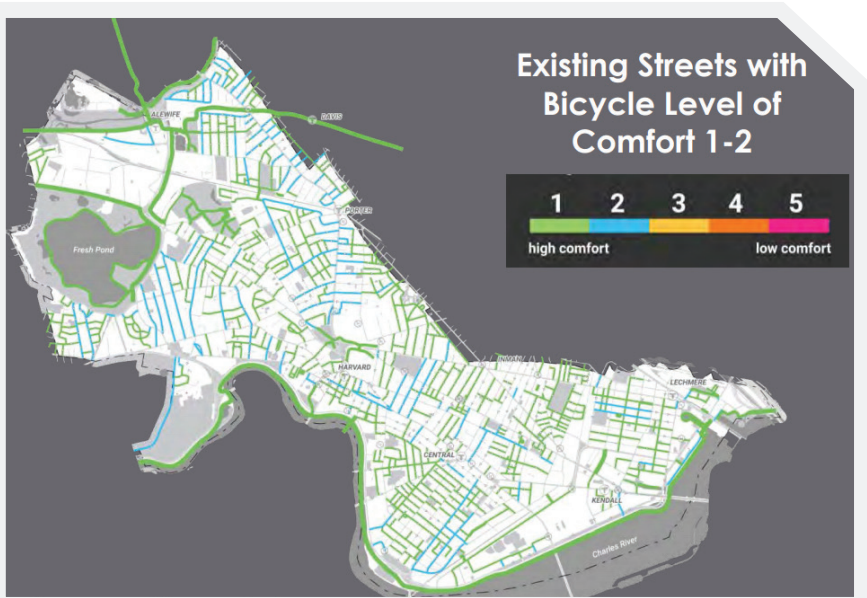
Source: City of Cambridge. 2015. "Cambridge Bicycle Plan." http://www.cambridgema.gov/CDD/Transportation/bikesincambridge/bicyclenetworkplan.

LOCALIZING CONNECTIVITY MEASURES TO IDENTIFY PRIORITY PROJECTS

The **Cambridge (MA) Bicycle Plan** (2015) mapped existing conditions using a 1 to 5 Bicycle Comfort Level (BCL) rating. The initial GIS-based ratings of individual segments were refined through public comment, including online map comments. The resulting database and maps were used to prioritize projects and maintenance strategies in the broader plan. Projects that closed gaps in the existing low-stress (BCL 1 or 2) network were ranked highest, followed by individual projects that would shift a street to BCL level 1 or 2. The lowest priority projects improved conditions but resulted in a facility at BCL 3 or worse.

The **Minneapolis, MN Pedestrian Plan** (2009) identified a preferred block size and analyzed block length relative to the preferred size. Areas where larger block sizes indicated lower walk connectivity were mapped and used to identify priority locations for midblock crossings and other improvements.

MAKING DATA-DRIVEN CONNECTIVITY INVESTMENT DECISIONS

The City of Fort Collins wanted to select a bicycle connectivity measure for implementation into its Transportation Master Plan Update. In their experience with previous programs, they found data-supported arguments and the ability to track program impact increased support by elected officials. They focused on metrics that both demonstrate the need for bicycle facilities and that can be easily communicated to city officials and decisionmakers when tracking progress over time.

In the case study example, they selected several measures based on low-stress network analysis.

33

03

FACT SHEETS ON CONNECTIVITY ANALYSIS METHODS AND MEASURES

Source: FHWA

FACT SHEETS ON CONNECTIVITY ANALYSIS METHODS AND MEASURES

Chapters 1 and 2 defined multimodal connectivity analysis, described its importance in general terms and outlined a process for measurement. This chapter provides summaries of technical information about commonly applied connectivity analysis methods and measures, with references to more materials that can help practitioners to assemble data and calculate results. Detailed descriptions of many of the methods and measures presented here, along with other analysis measures and tools, can be found in the *FHWA Guidebook for Developing Bicycle and Pedestrian Performance Measures* (2016).

CONNECTIVITY ANALYSIS METHODS

The first part of this chapter consists of a set of fact sheets about each of the five types of analysis methods described in Chapters 1 and 2, as follows:

- Network completeness
- Network density
- Route directness
- Access to destinations
- Network quality

Each fact sheet describes the following information:

- **Key Question(s):** Which specific question(s) is the analysis method best suited to answer?

- **Description:** What core concept is measured and what are some key characteristics of this type of analysis?

- **Example Planning Application(s):** What types of policies or decisions can this analysis inform?

- **Example Measures:** What are some specific metrics associated with this type of analysis? Footnotes in these sections provide references to guidebooks and articles on how to compute key measures.

- **Typical Data:** What types of data are typically required to support this analysis method?

- **Advantages:** What makes this analysis method useful and/or relatively easy to conduct?

- **Considerations:** What are some important things to be aware of when conducting this type of analysis?

- **Peer Applications:** Where has this type of analysis been applied? The fact sheets provide a few selected examples from agencies that have conducted the analysis method.

CONNECTIVITY MEASURES

The second part of this chapter consists of a set of fact sheets about the following measures that can inform one or more of the connectivity analysis methods listed above:

- Bicycle Level of Service
- Bicycle Level of Traffic Stress
- Bicycle Low Stress Connectivity
- Bicycle Route Quality Index
- Pedestrian Index of the Environment
- Pedestrian Level of Service
- Pedestrian Level of Traffic Stress

All of the selected measures described in the fact sheets are fundamental to network quality assessments. The other types of connectivity analyses (network density, completeness, route directness, and access to destinations) can be conducted by assessing existing or planned network conditions without developing the quality-related measures presented in these fact sheets. The data collected and analyzed for these measures can, however, significantly enrich an agency's ability to make fully informed transportation investment decisions.

The connectivity measure fact sheets are organized similarly to the connectivity analysis method fact sheets, with slight variations to incorporate more in-depth discussions of elements such as inputs, outputs, and relevant research. Topics addressed in each fact sheet include the following:

- **Key Question(s):** Which specific question(s) does this measure address?
- **Description:** What are some key characteristics of this measure?
- **Example Planning Application(s):** What types of planning exercises and scales are best suited to this measure?
- **Typical Data:** What types of data are typically required to develop this measure?
- **Advantages:** What makes this measure useful and/or relatively easy to conduct?
- **Considerations:** What are some important things to be aware of when developing and applying this measure to an analysis?
- **Peer Applications:** Where has this measure been applied? The fact sheets provide a few selected examples from the array of agencies that have computed the measure.

CONNECTIVITY ANALYSIS METHOD

NETWORK COMPLETENESS

How complete is the planned bicycle and pedestrian network?

DESCRIPTION

A network completeness analysis reveals either the proportion of the network with designated bicycle or pedestrian facilities, or the extent to which the planned bicycle or pedestrian network has been built out. In the first case, it captures the availability of the street network for bicycling and walking. Completeness may be usefully compared between stages of build out. When measuring only the percent of a planned network that is built, this method assumes that the design of the planned network is built on robust community and stakeholder input and analyses of existing conditions.

EXAMPLE MEASURES

- Percent of planned nonmotorized facility-miles that are complete
- Percent of street-miles with designated nonmotorized facilities
- Percent of street-miles that meet level of service, low-stress, or accessibility thresholds

EXAMPLE PLANNING APPLICATION(S)

- A planned nonmotorized network designed with a high level of consensus-building and rigorous analysis. These measures are most meaningful when they are tracking the completion of a system that represents all stakeholders' vision and closes key gaps in connectivity.

- Details on what type of facilities are planned in each location (and the data to track whether those facilities are being built). It is best if agencies track not only whether they are building facilities in planned locations, but also whether these facilities meet the standards in the plan. This helps avoid questions such as "does it count if we put shared lane markings in a location where the plan calls for a separated bike lane?"

TYPICAL DATA

- Shapefile of planned nonmotorized facilities
- Shapefile of current nonmotorized facilities
- Centerline street network

➕ ADVANTAGES

- The data are relatively available or easy to collect
- The metrics are easy to communicate
- Tracking metrics over time can illustrate progress towards a goal

❓ CONSIDERATIONS

- The value of the analysis for identifying gaps increases as network completion approaches 100 percent; results may not be as meaningful for sparse networks that have more gaps than facilities

- The apparent level of network completeness may decrease if the definition of "network" changes or if the analysis compares current conditions to a newly expanded planned network

- Network completeness is not easily comparable from one area to the next, as there is no standard definition of a bicycle or pedestrian network

Legend (left map):
- No Sidewalks
- Sidewalks One Side
- Sidewalks Both Sides

Legend (right map):
- PLTS 2
- PLTS 3
- PLTS 4

PRESENCE/ABSENCE

PEDESTRIAN LEVEL
OF TRAFFIC STRESS

0   0.25   0.5 MILES
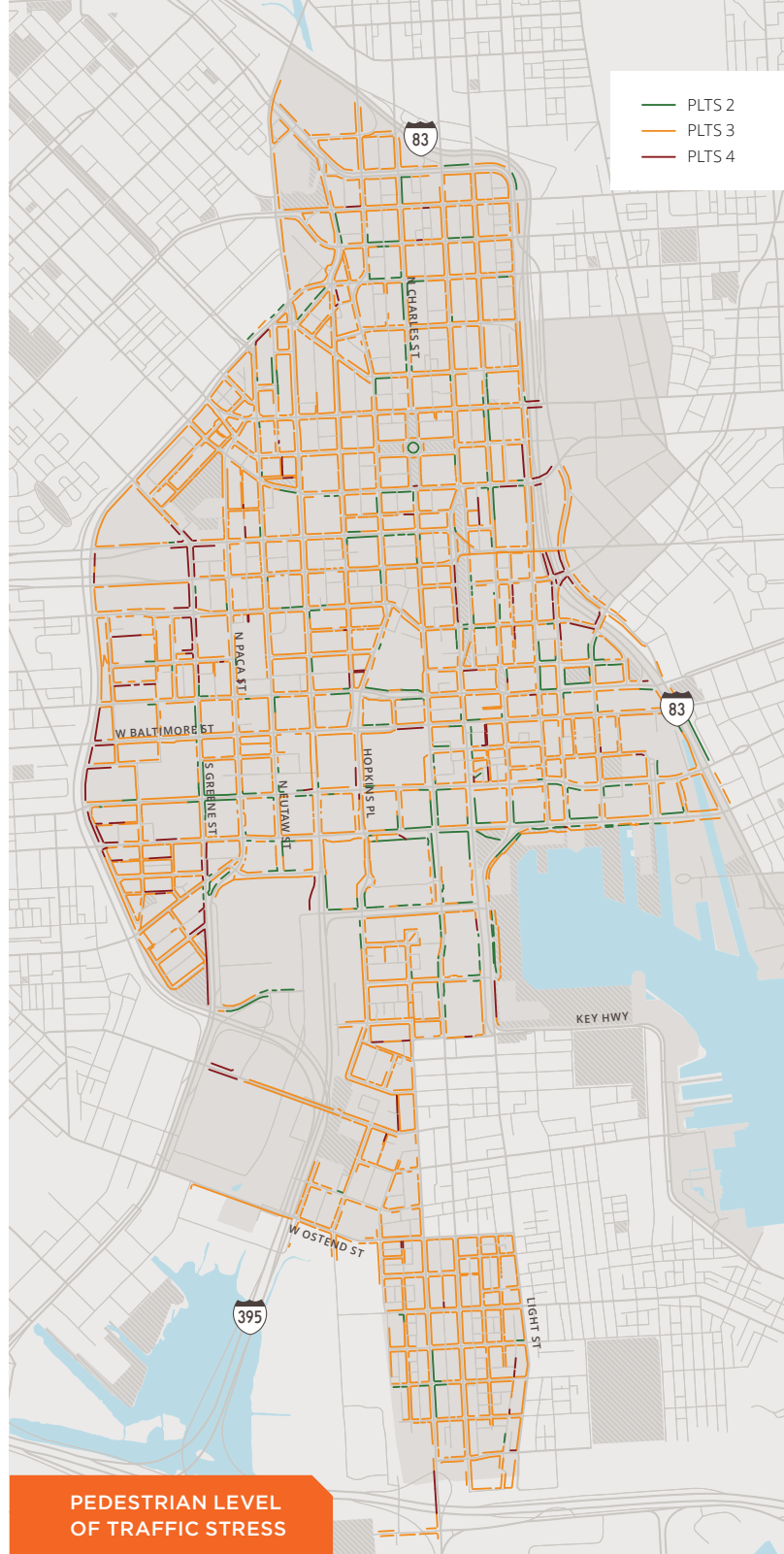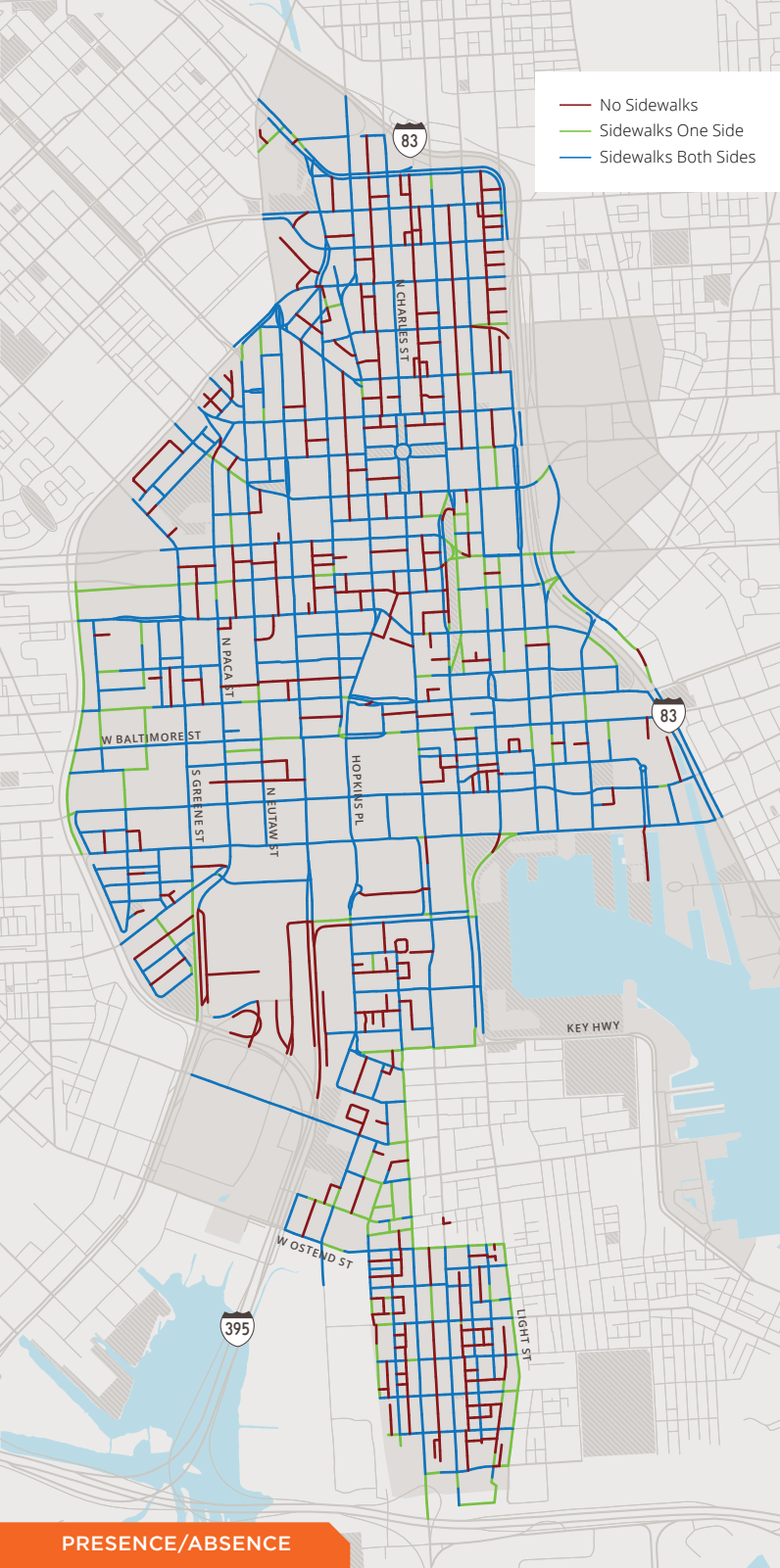
PEER
APPLICATION:
BALTIMORE, MD

The Baltimore case study assessed the level of
completeness for sidewalks within the downtown area
based on several different metrics. The analysis first
considers presence or absence of sidewalks, regardless
of quality, based on neighborhoods and roadway type.
However, in areas with built-out networks, completeness
can be measured instead based on the completeness of
high-quality (or low-stress) facilities.

NETWORK DENSITY

Does the multimodal network provide a variety of direct route options for those who travel by bike or on foot?

DESCRIPTION

Network density measures assess whether the street grid provides options for travel between locations for people who walk and bike. Research shows that areas with high street density have higher rates of walking and lower rates of driving. More dense networks are also more resilient – a closure of one street will be less likely to inhibit travel.

EXAMPLE MEASURES [1]

- Intersection density
- Connected node ratio
- Block length
- Network density (street-miles per square mile)

---

1 *https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/performance_measures_guidebook/*

EXAMPLE PLANNING APPLICATION(S)

- To evaluate minimum intersection density standards for new development
- To consider access management standards for spacing of local streets or limitations on cul-de-sacs

TYPICAL DATA

- Centerline street network

ADVANTAGES

- The data required to measure network density can be simple and can consider presence or absence of facilities
- Network density is widely applied in research to measure how the built environment supports bicycling and walking
- This method is particularly appropriate to walking. Agencies are less likely to have detailed data on the pedestrian network than on the bicycle network, and pedestrian trips are shorter than bicycle trips and more likely to make use of all streets as opposed to streets with designated facilities.
- Density is a useful measure of the potential of the street network to support biking and walking

CONSIDERATIONS

- If network quality is not considered, the density metrics reported assume that all network links are of adequate and equal quality, which can produce false assumptions about how well people that walk and bike are accommodated
- Using a density method without other metrics can report in resulting of false need. For example, parks may be reported as areas of high potential demand and low network density.

BICYCLE AND PEDESTRIAN NETWORK DENSITY

Another way to calculate this measure is to examine only the available bicycle and pedestrian network. This requires some additional data on the bicycle and pedestrian network, but shares the same features as the broader street density measure.

One additional advantage of this measure is the ability to compare the density of bicycle and pedestrian facilities to the broader street network (e.g. for comparison across travel modes) and to examine how the network varies over space (i.e. do some areas have more network available than others).
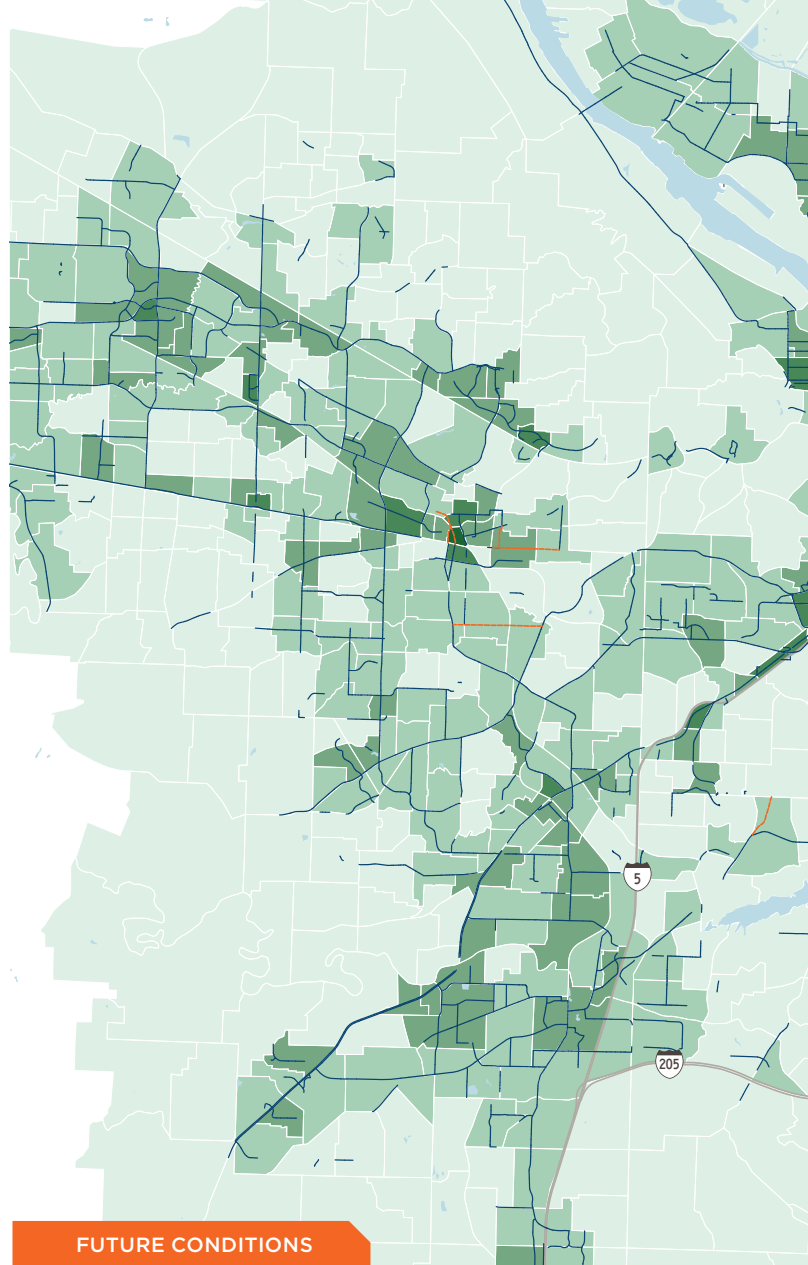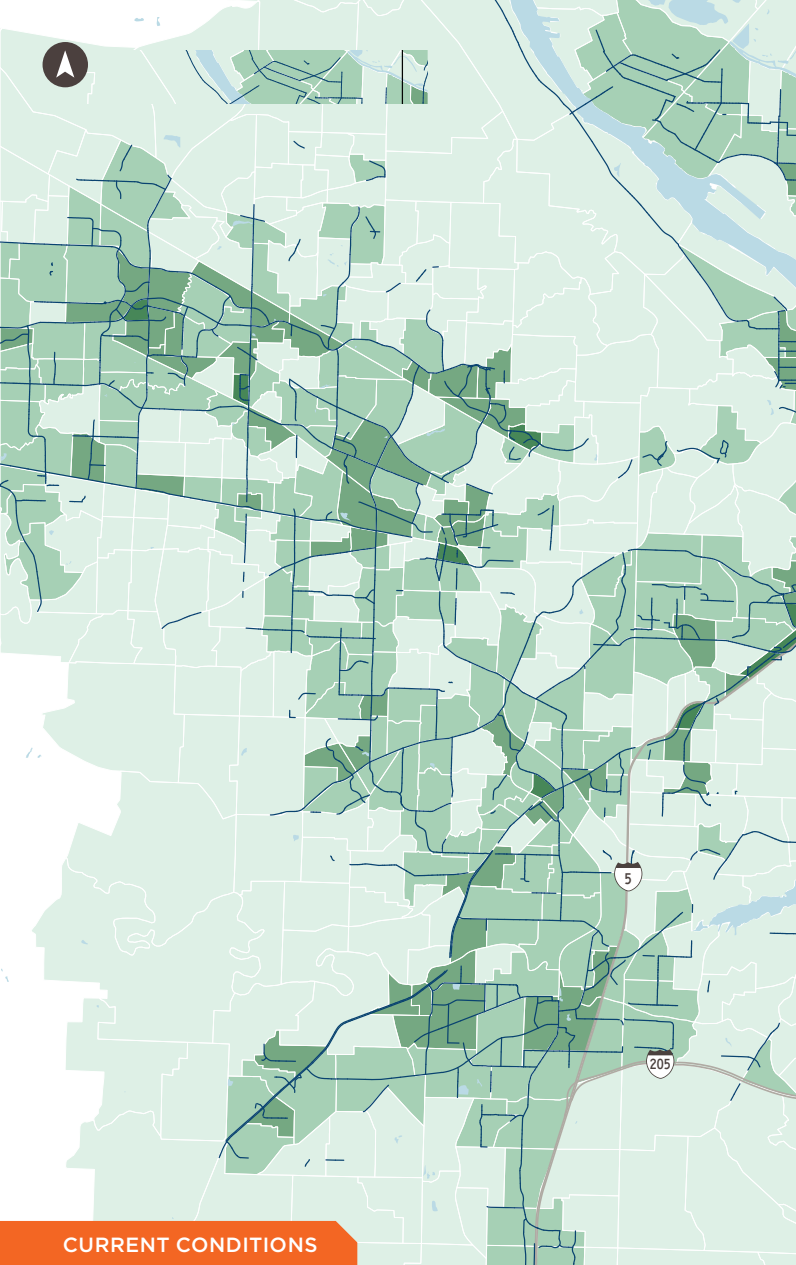
PEER
APPLICATION:
PORTLAND METRO

The Portland Metro case study assessed system density for sidewalk, bicycle, and trail networks. This application considered the difference in density between the current network and the future network based on the current ATP for both the regional scale and Historically Marginalized Communities. This assessment found that at the regional level, the impact of projects appears to be minimal, while at a more focused neighborhood level, this metric reveals greater changes.

— Current Bike Facilities
--- Planned Bike Facilities

Greater Bike Density

Less Bike Density

CONNECTIVITY ANALYSIS METHOD

ROUTE DIRECTNESS

Do bicycle and pedestrian facilities allow users to travel throughout a community via direct routes?

—

DESCRIPTION

Route directness considers the variation in trip distance between the route a bicyclist or pedestrian will actually travel versus the shortest available path. Directness may be used to characterize the network in terms of obstacles impeding direct travel. This method is often used for specific destinations but can be used on a network level by computing an average score across a set of generalized origins and destinations.

—

EXAMPLE PLANNING APPLICATION(S)

- To develop standards for network spacing that reduce required out of direction travel

EXAMPLE MEASURES

- Out of direction travel required as a percentage of shortest path route

- Crossing opportunities[1]

TYPICAL DATA

- Shapefile of current/planned nonmotorized facilities, including a roadway network suitable for routing (i.e. topologically correct)

- Origins and destinations, including schools, residential dwellings, employment centers, recreation destinations, health facilities, and others

- Detailed network data, if stress or quality metrics are used

———

1   *https://www.fhwa.dot.gov/environment/bicycle_
pedestrian/publications/performance_measures_
guidebook/*

➕ ADVANTAGES

- Route directness provides a more detailed analysis of connectivity for areas with more advanced bicycle and pedestrian networks

- Results can demonstrate the level of connectivity among destinations

- Results can be communicated in terms of time or distance

❓ CONSIDERATIONS

- Network analysis may require significant data preparation and can be labor intensive, especially when completed at a large scale
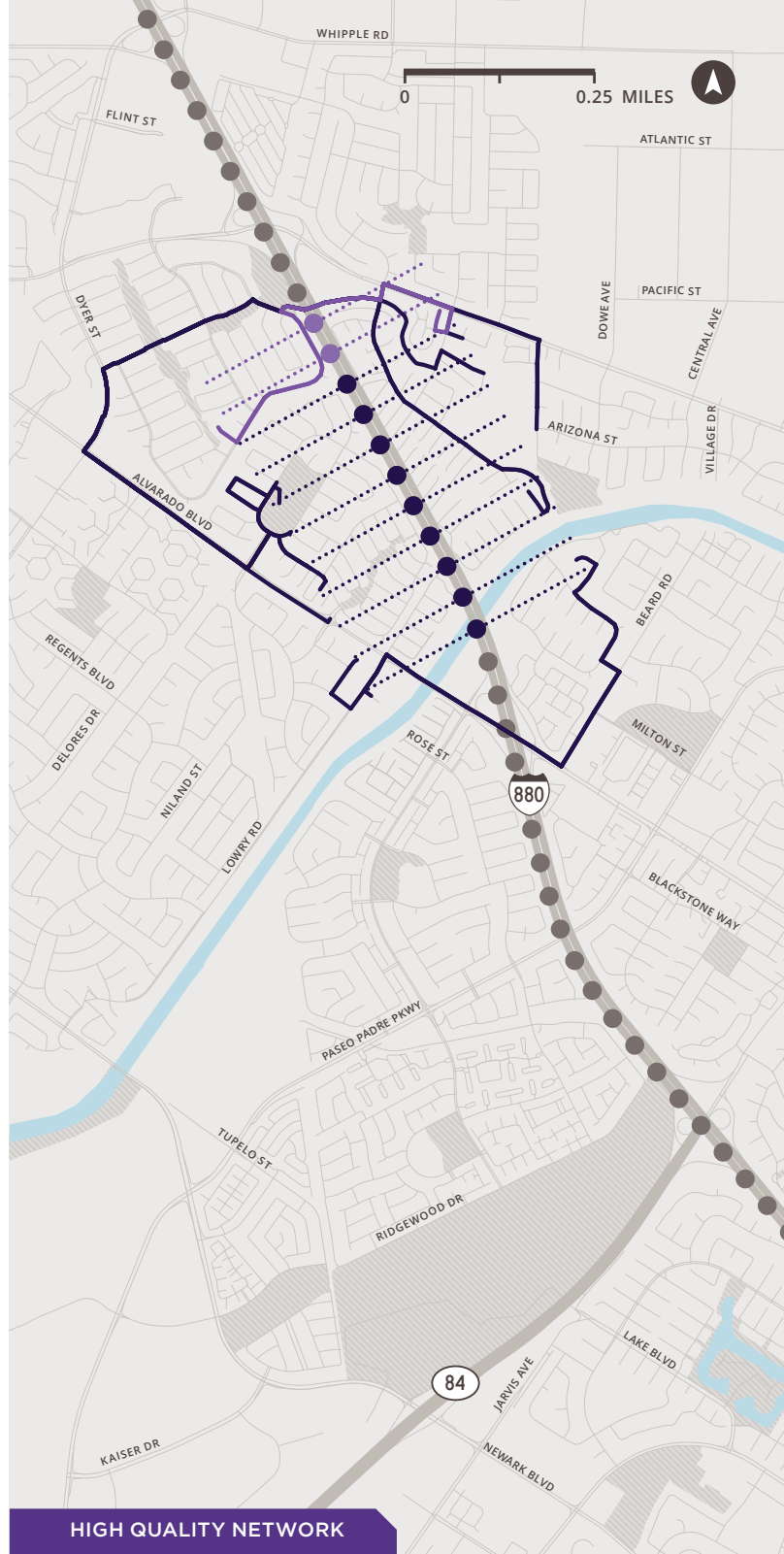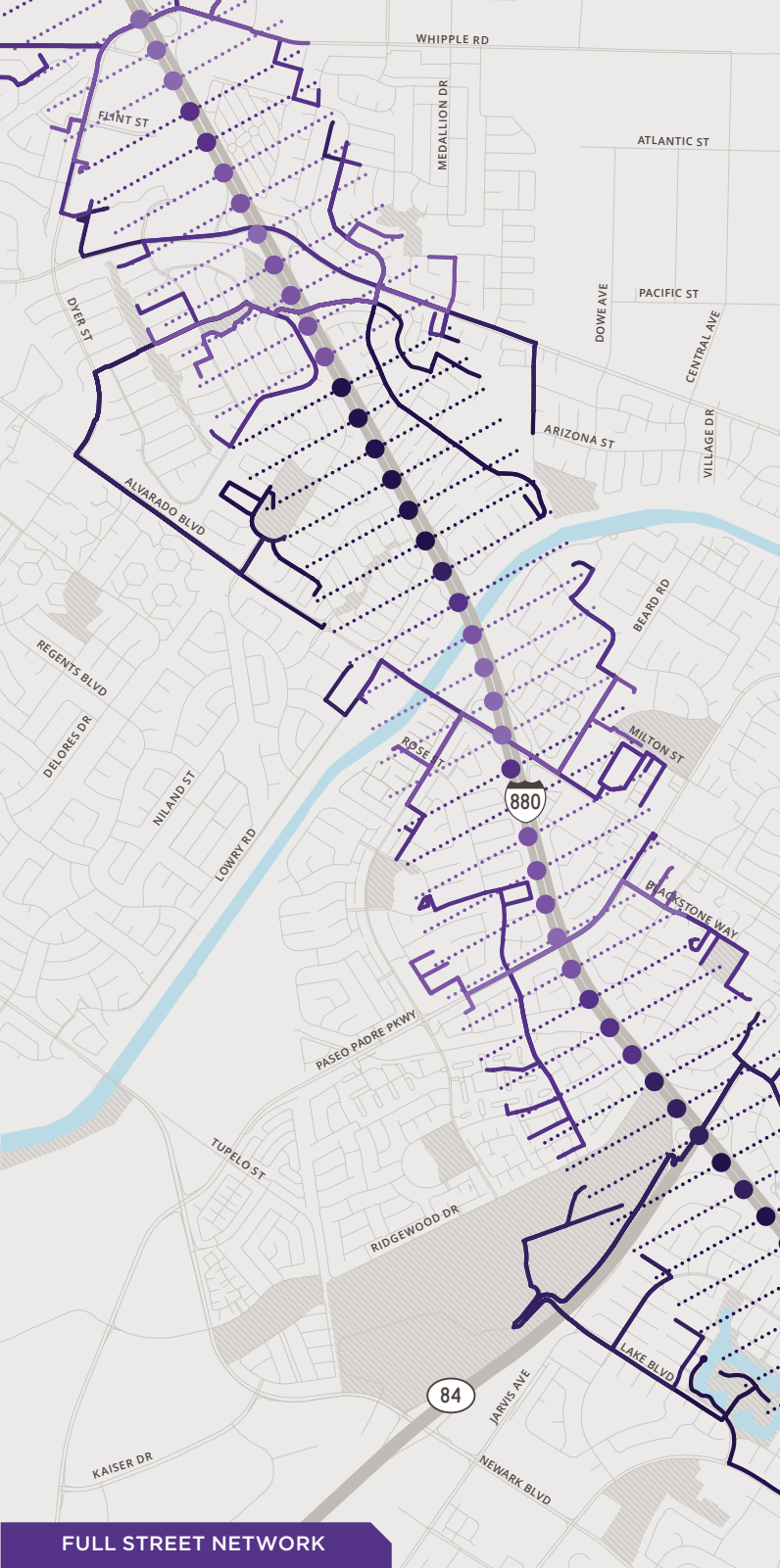
FULL STREET NETWORK

HIGH QUALITY NETWORK

············· Straight Line Distance

⬤ ── High Connectivity

⬤ ──

⬤ ── Medium Connectivity

⬤ ──

⬤ ── Low Connectivity

⬤ *Crossing not accessible without
using low quality network*

The Caltrans District 4 Case Study assesses network permeability along state highways to understand the barrier that major highways may create. Permeability was assessed considering both the entire roadway network and only a low-stress network (determined by LTS) to determine the level of out-of-direction travel required to cross the highway via low-stress crossings.

43

CONNECTIVITY ANALYSIS METHOD

ACCESS TO DESTINATIONS

Do bicycle and pedestrian facilities connect people to key destinations?

DESCRIPTION

This measure addresses whether people can use the bicycle and pedestrian network to reach important destinations like jobs, training, shopping, or transit stations.

EXAMPLE PLANNING APPLICATION(S)

- To inform plans or policies calling for bikeable/walkable development around designated centers or transit stations. For example, the City of Portland has a policy calling for 20-minute neighborhoods in which residents can walk to grocery stores and other commercial services via high-quality pedestrian facilities. Some transit agencies have policies to prioritize bicycle and pedestrian projects within a certain distance of stations.

EXAMPLE MEASURES

- Area around specific point that nonmotorized users can access (travelshed)
- Number or percent of jobs accessible by bike/foot
- Access to community destinations[1]

TYPICAL DATA

- Shapefile of current/planned nonmotorized facilities or of high-quality routes
- Fine-scale land use data such as points, parcels, or Census blocks

➕ ADVANTAGES

- Access to destination measures are particularly well-suited for identifying and prioritizing projects that connect to important destinations such as transit stations, because they can capture the benefits of connectivity projects at a fine scale
- While other connectivity measures focus solely on the characteristics of the network, access-related measures capture whether the network connects people to the places that they want to travel. Projects that are useful to people walking or bicycling for transportation are likely to have a greater impact on mode shift than those likely to be used only for recreation.
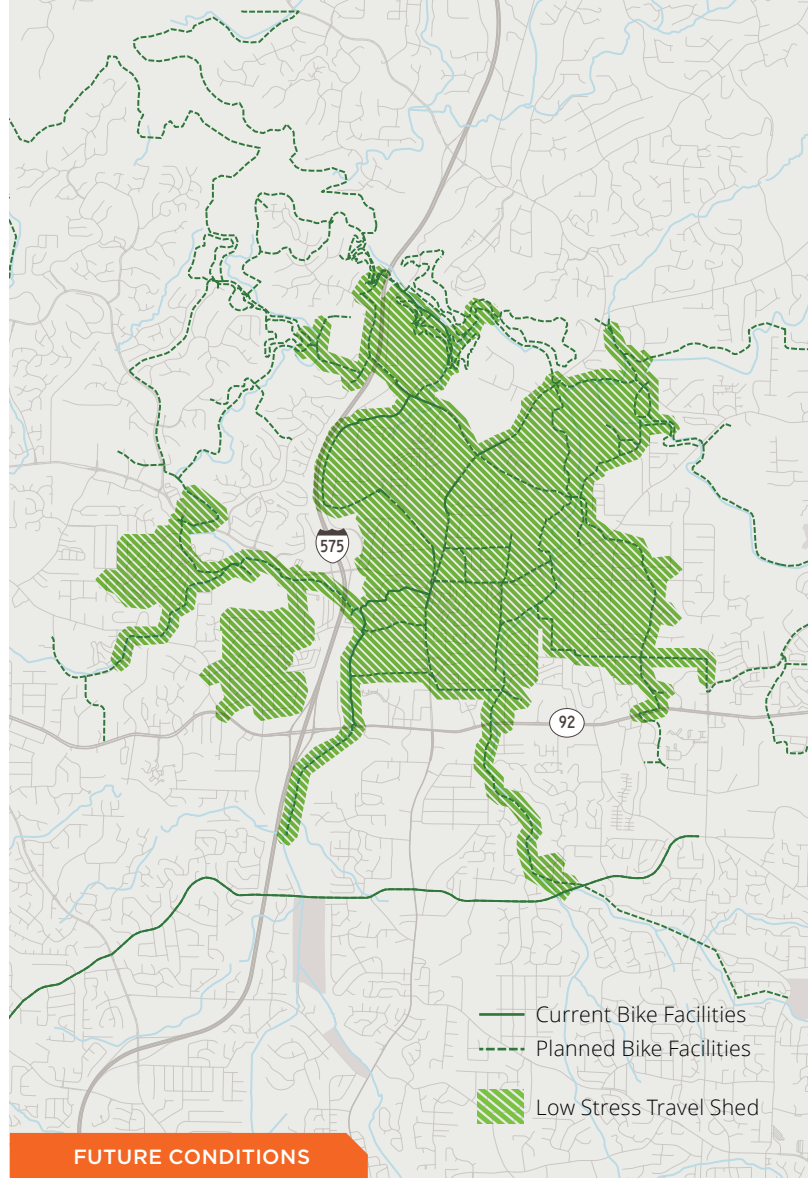
❓ CONSIDERATIONS

- Access to destination measures are data- and labor-intensive, requiring fine-scale land use data and sophisticated network analysis
- Careful thought must be given to the type of destinations in order to create impactful metrics
- Summarizing origins is equally important and can be just as challenging as destinations. Due to shorter average trip lengths, understanding the location and demographics of the target population is critical.
- Results can be hard for transportation agencies to interpret and act upon. There is little research on how many destinations should be accessible by bike or on foot, and relatively few examples of agencies that have conducted detailed access analyses or set access-related policies that can help agencies benchmark results. Furthermore, land use patterns have a significant impact on destination access, which tends to be higher in more compact neighborhoods with diverse uses, but transportation agencies often do not have authority over land-use decisions.

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1   *https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/performance_measures_guidebook/*

Current Bike Facilities
Planned Bike Facilities
Low Stress Travel Shed

CURRENT CONDITIONS

Current Bike Facilities
Planned Bike Facilities
Low Stress Travel Shed
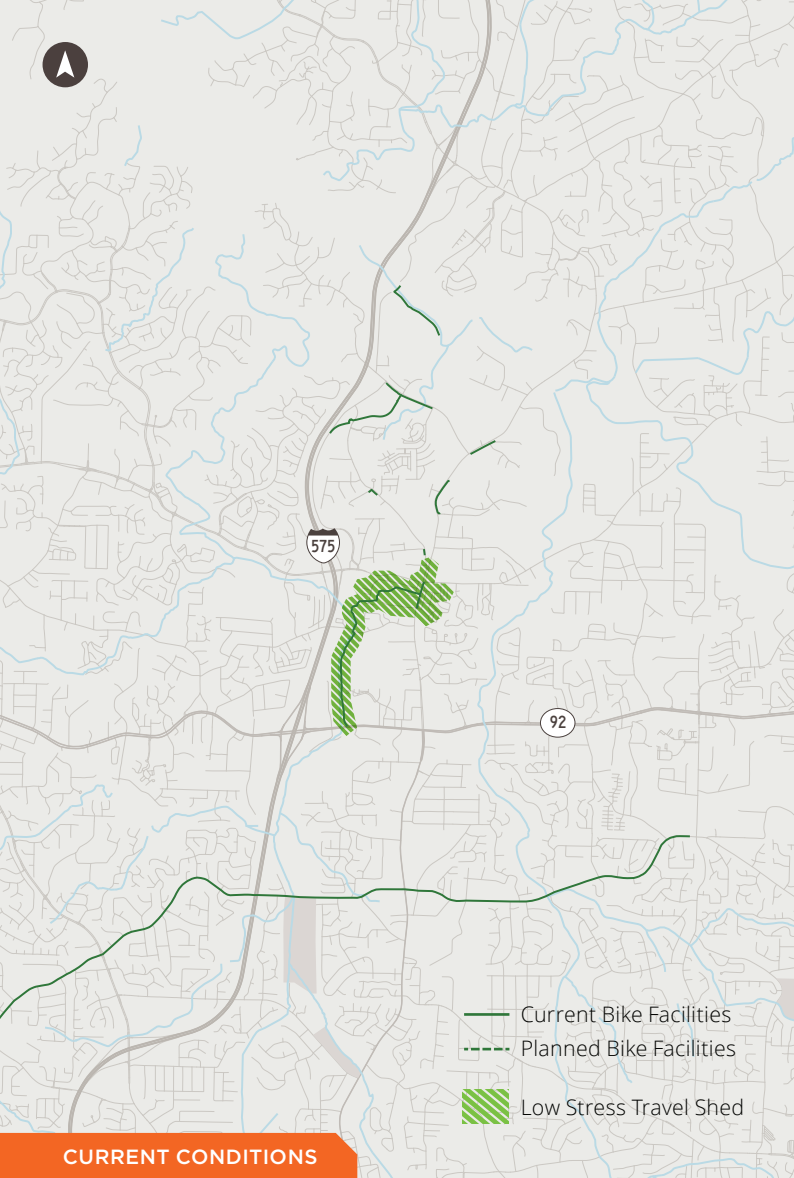
FUTURE CONDITIONS

PEER
APPLICATION:
ATLANTA

The Atlanta Regional Council (ARC) case study assesses access to destinations by calculating the number of homes and jobs accessible near existing and planned low-stress networks. Travelsheds were created for each network scenario using a three-mile distance threshold and overlaid with Census Data to calculate the number of households and jobs within the travelshed.
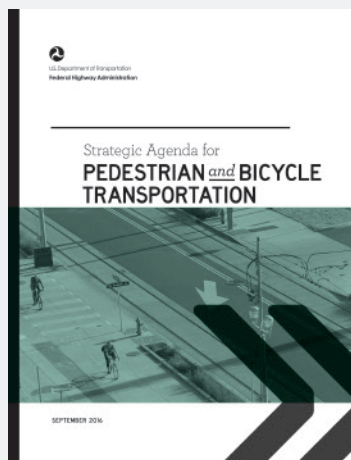
U.S. Department of Transportation. 2016. "Strategic Agenda for Pedestrian and Bicycle Transportation." https://www.fhwa.dot.gov/environment/ bicycle_pedestrian/publications/ strategic_agenda/fhwahep16086.pdf.

FOCUSING MULTIMODAL ANALYSES AND STRATEGIES ON THE FIRST-AND-LAST MILE

In September 2016, FHWA released the *Strategic Agenda for Pedestrian and Bicycle Transportation*. The plan sets an aspirational goal of "increasing the percentage of short trips represented by bicycling and walking to 30 percent by 2025." A short trip is defined as one mile on foot and five miles by bike. Focusing analyses and investments on the quality, density, and completeness of walking and bicycling infrastructure within walking or cycling distance of destinations can help communities achieve this goal.

CONNECTIVITY ANALYSIS METHOD

NETWORK QUALITY

What is the quality of the users' experience provided by an existing or planned network?

DESCRIPTION

Research shows that people walking or biking are more sensitive to the physical attributes of a facility than a person driving a motor vehicle. Assessing the physical qualities of bicycle and pedestrian facilities and providing a score for each roadway and intersection (or route) can provide robust information about the user experience provided and capture the types of users that feel comfortable on specific facility types.

EXAMPLE PLANNING APPLICATION(S)

- To inform project selection by assessing the impact of different alignments, facility types, and network phasing on the experience of nonmotorized travelers

EXAMPLE MEASURES

- Level of Traffic Stress[1]
- Level of Service[2]
- Preference-based route utility or quality[3]

TYPICAL DATA

- Shapefile of existing/planned nonmotorized facilities
- Detailed roadway network data, including attributes such as number of lanes, posted speed, traffic volume, heavy vehicle use, on-street parking, intersection features, facility type, facility width, slope, pavement quality

⊕ ADVANTAGES

- Quality analyses can help to identify routes that may be particularly attractive to pedestrians and bicyclists for whom network qualities are particularly important, such as children or average-skill riders
- Developing a consistent, periodically updated measure of the quality of the network allows municipalities to better understand the impact of planned or implemented improvements
- Findings from quality analyses can be easily applied to facility design and improvement strategies
- Some measures are available that are supported by use and behavior data
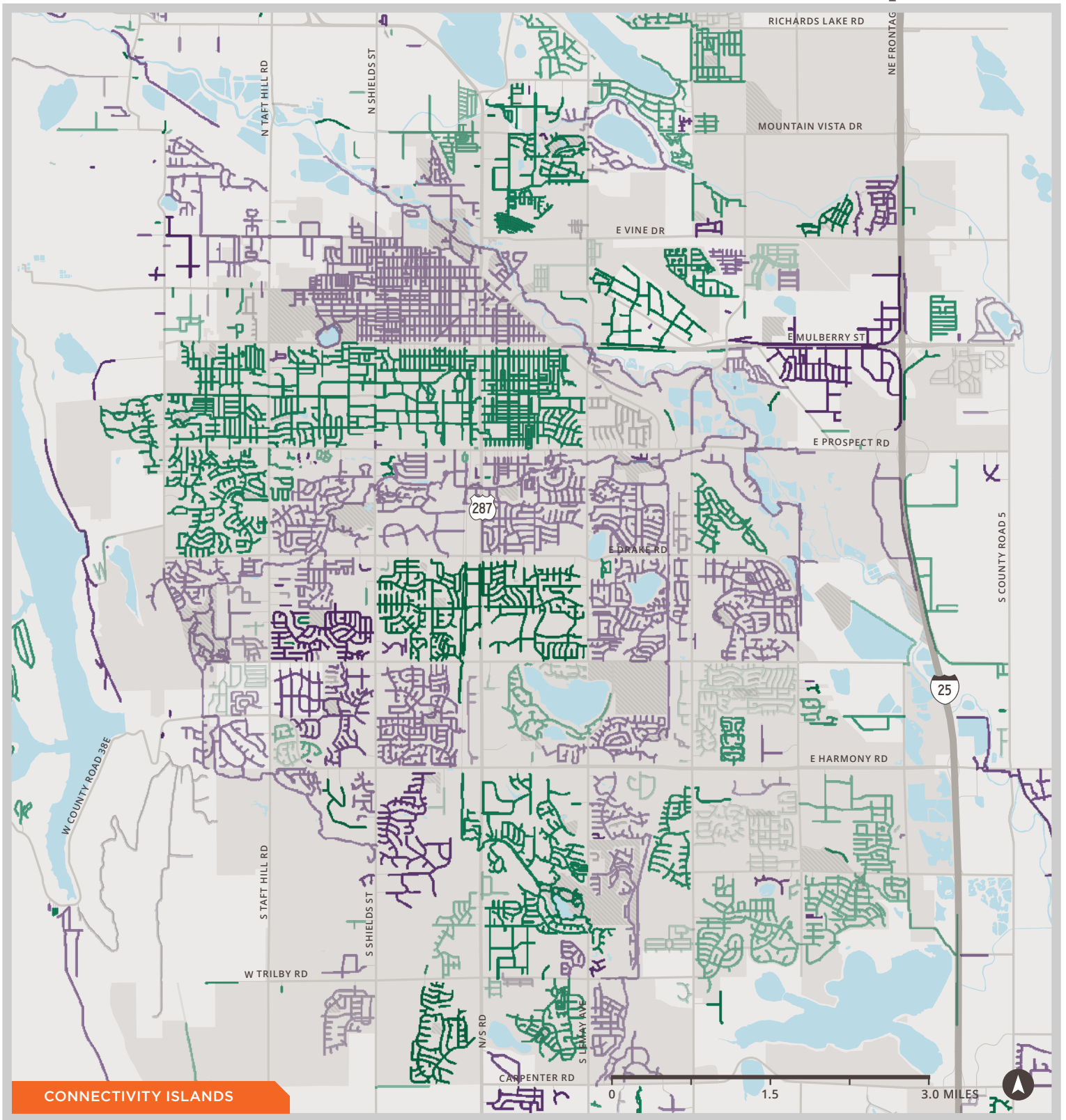
? CONSIDERATIONS

- Quality analyses tend to be data intensive. Advanced applications that use measures such as low-stress network ratings are also often labor-intensive.
- Quality analyses are most useful in urban settings where networks are fairly complete and mature; assessments of sparse networks in suburban or rural areas produce less coherent information
- There are questions about the transferability of existing quality measures to different contexts. Quality measures have been developed mainly in urban settings where networks are fairly dense and mature.
- Due to data and technical challenges, quality measures are often modified to adapt to a given analysis context and available resources. While such adapted measures may still be useful, comparability and connections to supporting research will be reduced.

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1 Mekuria, Furth, and Nixon (2012); M. B. Lowry, Furth, and Hadden-Loh (2016)

2 Landis, Vattikuti, and Brannick (1997); Landis et al. (2001); Petritsch et al. (2008); M. Lowry et al. 2012; Foster et al. (2015)

3 Broach and Dill (2016); Broach and Dill (2017)

Map labels (as shown on the map):

- RICHARDS LAKE RD
- NE FRONTAGE RD
- N TAFT HILL RD
- N SHIELDS ST
- MOUNTAIN VISTA DR
- E VINE DR
- E MULBERRY ST
- E PROSPECT RD
- S COUNTY ROAD 5
- 287
- E DRAKE RD
- 25
- E HARMONY RD
- W COUNTY ROAD 38E
- S TAFT HILL RD
- S SHIELDS ST
- W TRILBY RD
- N/S RD
- S LEMAY AVE
- CARPENTER RD
- 0   1.5   3.0 MILES

CONNECTIVITY ISLANDS

PEER
APPLICATION:
FORT COLLINS

Note: The colors on this map are intended to convey geographic distinctions between various connectivity islands; however, the colors do not have a relative value associated with them.

The Fort Collins case study considers network quality based on both Level of Traffic Stress and Low-Stress Network Connectivity. These measures were then used to define low-stress networks for input in subsequent measures, including route directness considerations. Display methods were also explored to identify gaps in the existing low-stress network.

NATIONAL PRACTICE

The PeopleForBikes Initiative to Measure Bicycle Network Connectivity Nationwide

Table 7: *BNA Data Sources*

DATA	SOURCES
Network	OpenStreetMaps
Population	US Census
Employment	US Census LEHD
Destinations	OpenStreetMaps

Figure 9. *Example BNA Results*

OVERVIEW

In 2016, PeopleForBikes launched a national effort to measure bicycle network connectivity as part of their PlacesForBikes city ratings. At the core of their approach is a measure of bicycle network quality based on level of traffic stress (Mekuria, Furth, and Nixon 2012). Their Bicycle Network Analysis (BNA) tool applies the stress network to a basket of destinations meant to cover most everyday travel needs. Origins and destinations are considered connected if they are within about 10 minutes by bicycle (one and two-thirds miles) via a low-stress connection requiring at most a 25% detour.[1] The maximum stress level chosen is meant to appeal to a broad range of typical adults.

Based on the number of destinations reachable in different categories, scores from 0 to 100 are assigned to each census block origin. The scores have also been aggregated to city level (on the same 0 to 100 scale) by weighting each block score by population. Figure 9 shows examples of network, block, and city level scoring. Scores were initially tabulated for nearly 300 cities.[2] The source code is publicly available.[3]

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1 *https://bna.peopleforbikes.org/#/methodology*

2   *http://peopleforbikes.org/blog/we-scored-the-bike-networks-in-299-u-s-cities-heres-what-we-found/*

3   *https://github.com/azavea/pfb-network-connectivity*

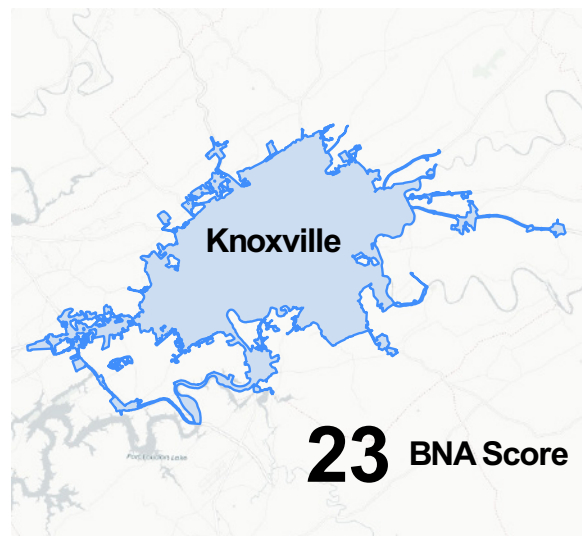## DATA

The BNA tool relies on network, population, and destination data from OpenStreetMaps (OSM) and the US Census Bureau (Table 7). Specific network data used to calculate stress level include the following attributes:

- Functional class
- Speed limit
- One-way traffic (car and bike)
- Roadway width
- Bike infrastructure (width, direction)
- Number of lanes (by direction)
- Number of intersection crossing lanes (by direction)
- Street parking (by direction)
- Center turn lane presence
- Intersection treatments such as median islands and traffic signals
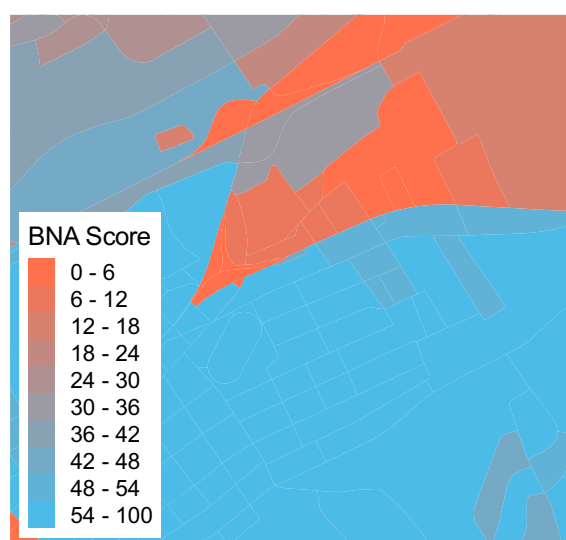
From left: Network Segments, Census Block, and Citywide

Destinations are measured across six major categories comprised of 16 sub-categories, including indicators such as the following:

- People (population)
- Opportunity (jobs, education)
- Core services (health/medical, grocery)
- Recreation
- Retail
- Transit

Destination access is scored based on both the number of destinations that can be reached in each subcategory, as well as the ratio of places reachable along low- versus high-stress routes.

As shown in Table 7, much of the data comes from OSM, a crowd-sourced, public database of street network and place data. Data quality and coverage varies by location, and PeopleForBikes has encouraged cities to update and improve local data by providing an OSM editing toolbox for commonly used ArcMap GIS software.

RELEVANCE TO THIS GUIDEBOOK

PeopleForBikes' BNA tool represents an important effort to make connectivity analysis available to a wide audience and to simplify and standardize data and measurement. Although PeopleForBikes cautions that the scores and methodology are preliminary and subject to errors and future modifications, the tool is an exciting new option in the connectivity landscape.

This guidebook explains how a measure such as BNA is chosen, constructed, and applied, while situating it within the broader spectrum of techniques available to measure pedestrian and bicycle networks.

CONNECTIVITY MEASURE

BICYCLE LEVEL OF SERVICE (BLOS)

How well does network infrastructure support bicycle travel, including interaction with other modes, based on perceived bicyclist comfort levels?

MODE	METHOD	OUTPUTS	CONNECTIVITY ANALYSIS METHODS	ACCESSIBILITY	USE IN PRACTICE	LEVEL OF EFFORT
	Inputs entered into weighted formula; GIS tool available to make calculations easier	Numeric scores converted by formula to a six-point scale (A through F)	Quality	Explicit consideration of accessibility for people with disabilities: **No**	Common among agencies with strong interests in multimodal planning	LOW

DESCRIPTION

Bicycle LOS (BLOS) indicates the overall quality of the network in terms of bicyclist comfort levels. BLOS is an adaptation of a standard measure of motorized road quality. The initial research was supported by a stated preference study of a broad range of facility attributes (Landis, Vattikuti, and Brannick 1997), with additional stated preference data incorporated into an updated version (Petritsch et al. 2008). Additional research has extended BLOS to include separated (protected) bike lanes (Foster et al. 2015). The original link quality measure has been extended into a measure of connectivity by using BLOS as a link weight in order to solve routes between sets of origins and destinations (Lowry et al. 2012). Bicycle LOS is also referenced in the Highway Capacity Manual (HCM).

EXAMPLE PLANNING APPLICATION(S)

· Can be used to assess the potential impacts of changes such as building or removing a major facility on an area-wide network

· Not generally useful for subarea analyses of specific links or corridors such as local streets, paths, trails, or protected bike lanes, nor for individual project development plans

TYPICAL DATA

· Roadway centerline and characteristics, including number of lanes, shoulder width, outside lane width, posted speeds, pavement condition, presence of curb, on-street parking (including percent occupied)

· Motorized traffic data, including speed, volume, percent heavy vehicles

· Bicycle lanes, including width

· Defined set of destinations or origin/destination zones
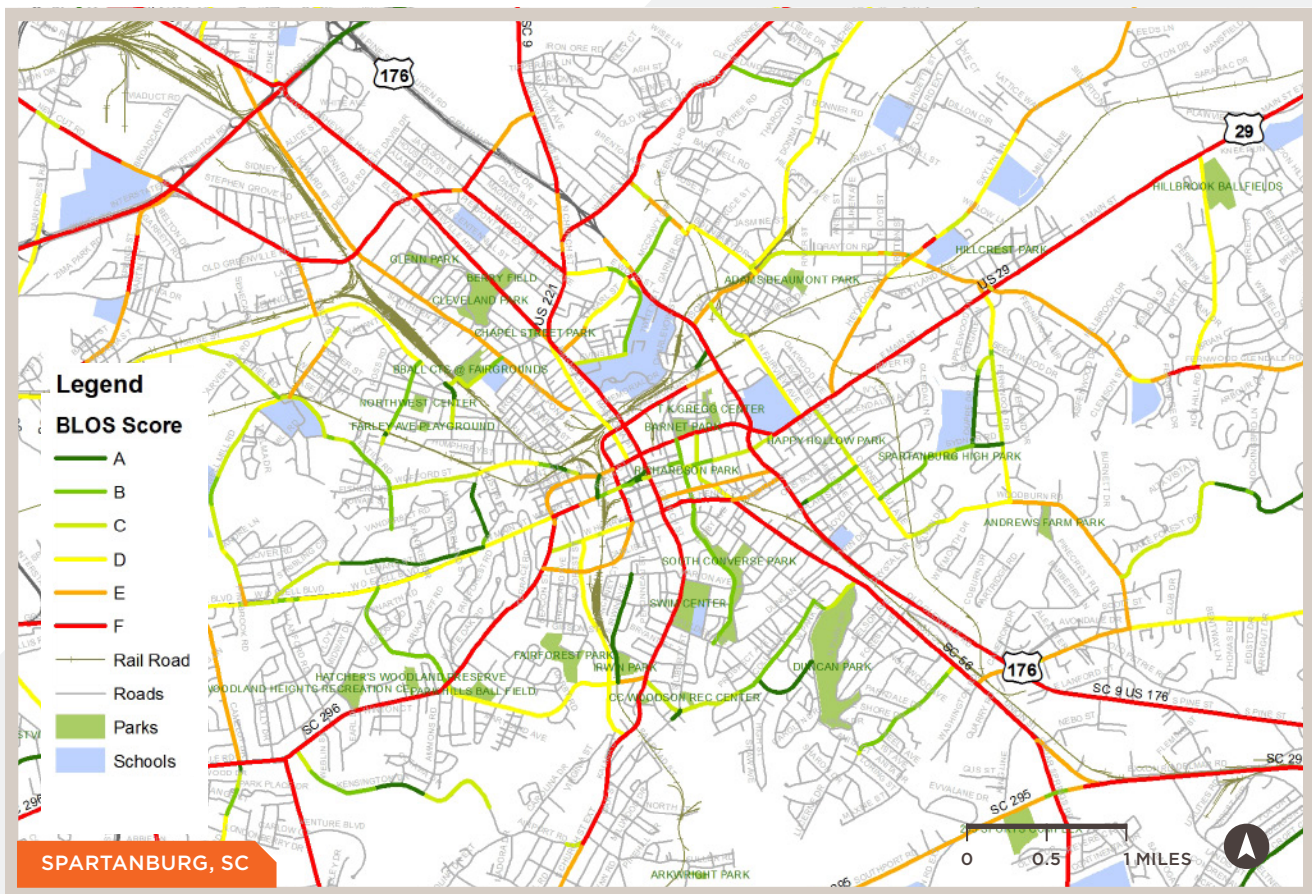
Source: City of Spartanburg. 2009. "Spartanburg Bicycle & Pedestrian Master Plan."
http://www.cityofspartanburg.org/planning-zoning/bicycle-ped-plan/.

PEER APPLICATION

- Florida Department of Transportation: LOS standards are used in the review of actions that directly impact the State Highway System for all planning and permitting processes; methods are outlined in the Quality/Level of Service Handbook (2013)

- Spartanburg, SC: The City Bicycle & Pedestrian Master Plan (2009) utilizes a Bicycle Level of Service measure to help identify the bicycle network updates

- A variety of large and mid-size agencies assess BLOS, including the Memphis MPO, Community Planning Association of Southern Idaho (COMPASS), City of Winston-Salem, NC, and Omaha-Council Bluffs Metropolitan Area Planning Agency (MAPA)

ADVANTAGES

- The outputs are similar to vehicle LOS, which is widely used and understood

- The tools are endorsed by the Highway Capacity Manual (HCM)

- It captures the quality of facilities, with a strong focus on the extent to which vehicle traffic and parking makes cyclists feel unsafe

- Despite relatively high data requirements, BLOS has been a popular measure in planning practice. It is supported by the original stated preference data and a version has been included in the HCM. A number of versions (many simplified) have been developed across a range of planning applications, mostly related to documenting existing conditions, identifying connectivity gaps, and evaluating network-wide quality.
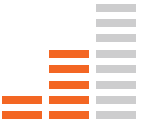
CONSIDERATIONS

- The tool is data-intensive

- Trails, pathways and separated bike lanes are not assessed

- The standard version of the tool is not designed to be used at corridor-scale

- The letter-grade scale has not been validated with user or behavior data

- Intersection conditions are not evaluated

BICYCLE LEVEL OF TRAFFIC STRESS (BICYCLE LTS)

What is the extent to which bicyclists feel safe and comfortable using the network, particularly on streets where they share space with motorized traffic?

MODE	METHOD	OUTPUTS	CONNECTIVITY ANALYSIS METHODS	ACCESSIBILITY	USE IN PRACTICE	LEVEL OF EFFORT
	Classify roadway links by type by highest stress attribute	Traffic stress rating of 1 through 4 for street segments and intersection	Completeness, Density, Directness, Accessibility to Destination, Quality	Explicit consideration of accessibility for people with disabilities: **No**	Common	MODERATE

DESCRIPTION

Measures and rates traffic stress for street segments and intersections, based on different types of cyclists' presumed comfort level near motor vehicle traffic. The components of the network are scored on a four-point scale relating to user types and confidence levels. Links and intersections are classified based on their most stressful feature, and routes are classified by the most stressful link or intersection between a given origin and destination.

Bicycle Level of Traffic Stress (Bicycle LTS) is based on the concept of the maximum level of traffic stress that will be tolerated by specific groups of existing and potential cyclists (Mekuria, Furth, and Nixon 2012). The classification scheme is loosely based on both the Types of Cyclist (not interested, interested but concerned, enthused and confident, and strong and fearless) line of research from Portland, Oregon (Dill and McNeil 2013), and also on Dutch age-group based bicycle facility planning standards. Most analysis has focused on LTS 2, a level thought to be acceptable to many interested adult cyclists. The Bicycle LTS measure is extended to capture connectivity through route selection and maximum detours using approximations from empirical studies of cyclist route choice.

EXAMPLE PLANNING APPLICATION(S)

- To identify problems and develop strategies to improve the users' perceived and actual experience, particularly in situations where multiple modes share a common facility
- To compare the availability and directness of low-stress routes to all possible routes on the street network

TYPICAL DATA

- Roadway centerline, including number of lanes and posted speed
- Bicycle infrastructure, including type and width
- On-street parking presence, including width
- Signalized intersections
- Turn lane locations and length
- Not recommended for locations with limited, incomplete, or inconsistent data
- Planners should consider adjusting the user type definitions in an LTS model to reflect the demographics of riders relevant to a specific planning context
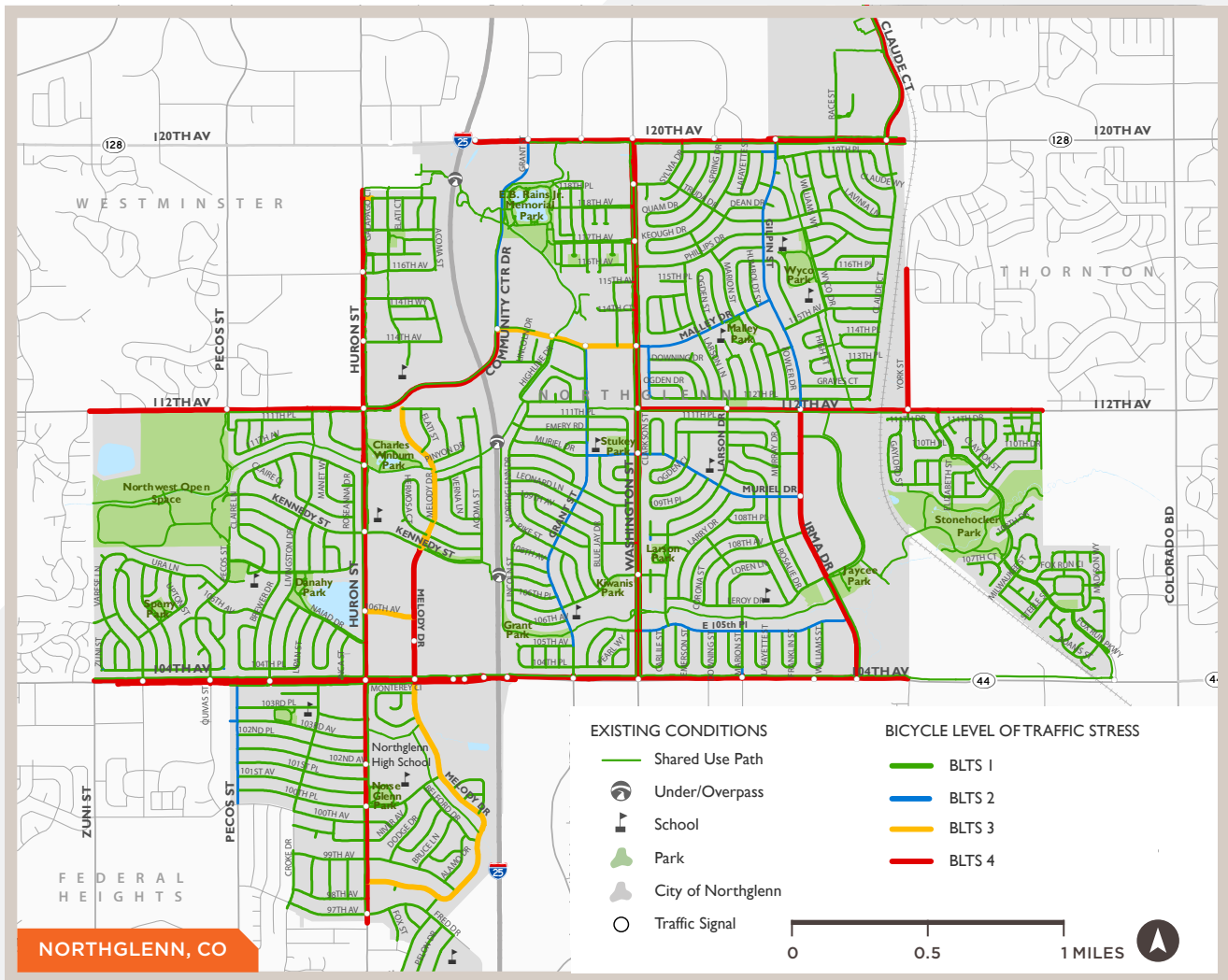
Source: City of Northglenn Department of Transportation. 2017. "Connect Northglenn: Bicycle and Pedestrian Master Plan."

PEER APPLICATION

- In Oregon, the Department of Transportation calls for Bicycle LTS as the preferred measure for Regional Transportation Plans and Transportation System Plans. It can also be used on a screening-level basis for project development and development review. The methodology is outlined in the state's most recent update of its Analysis Procedures Manual, which includes strategies for rural applications that consider shoulder width as well as traffic volumes and speeds.[1]

_____

1 http://www.oregon.gov/ODOT/Planning/Pages/APM.aspx

ADVANTAGES

- Specifically considers user (and potential user) differences

- Simple interpretation, making it suitable for use in a variety of contexts

- Captures the quality of a wide range of facilities and crossings, with a strong focus on the extent to which motor vehicle traffic makes cyclists feel unsafe

- For a complex measure, it has been widely applied and the framework is familiar to many practitioners

- Can be applied at route level for broader range of applications

CONSIDERATIONS

- Data-intensive and assumptions can impact the usefulness of the results

- Classification scheme is not strongly supported by preference data

- "All or nothing" classification, sensitive only to "weakest link" improvements

- Methods are not yet validated against behavior/use data

CONNECTIVITY MEASURE

BICYCLE LOW-STRESS CONNECTIVITY

What is the quality of bicycle connections between origins and destinations?

MODE	METHOD	OUTPUTS	CONNECTIVITY ANALYSIS METHODS	ACCESSIBILITY	USE IN PRACTICE	LEVEL OF EFFORT
🚴	Assess routes among types ("basket") of destinations based on link and attribute weighting; aggregate connectivity at range of scale	Centrality by link or project; percent of destinations reached; impedance	Directness, Accessibility, Quality	Explicit consideration of accessibility for people with disabilities: **No**	Emerging	HIGH

DESCRIPTION

Bicycle low-stress connectivity measures help planners to assess access to key destinations and to identify the importance of specific network links. Low-stress Bicycle Connectivity was designed specifically to prioritize and evaluate bicycle infrastructure projects. The measure combines elements of Level of Traffic Stress (LTS) and Route Quality Index (RQI) in a new way to gauge the quality of routes connecting origins and destinations. A key element is a defined "basket" of destinations. Positive points are awarded if destinations can be reached using routes of acceptable stress levels (accounting for traffic stress and terrain). Outputs include parcel-level accessibility scores and a measure of each planned project's "centrality," a measure of importance related to the expected number of cycling trips that would use links related to the project.

EXAMPLE PLANNING APPLICATION(S)

- To identify segments and routes that are most likely to be utilized by bicyclists

- To consider strategies for improving the quality of connections and/or the range of available destinations that bicyclists can access comfortably and safely

- To compare quality of connectivity within subareas or across regions (not suited to assessments of a single link)

TYPICAL DATA

- Roadway centerline, including number of lanes and posted speed

- Bicycle infrastructure, including type and width

- Intersection attributes (e.g. signals) and bicycle accommodation

- Potential destinations
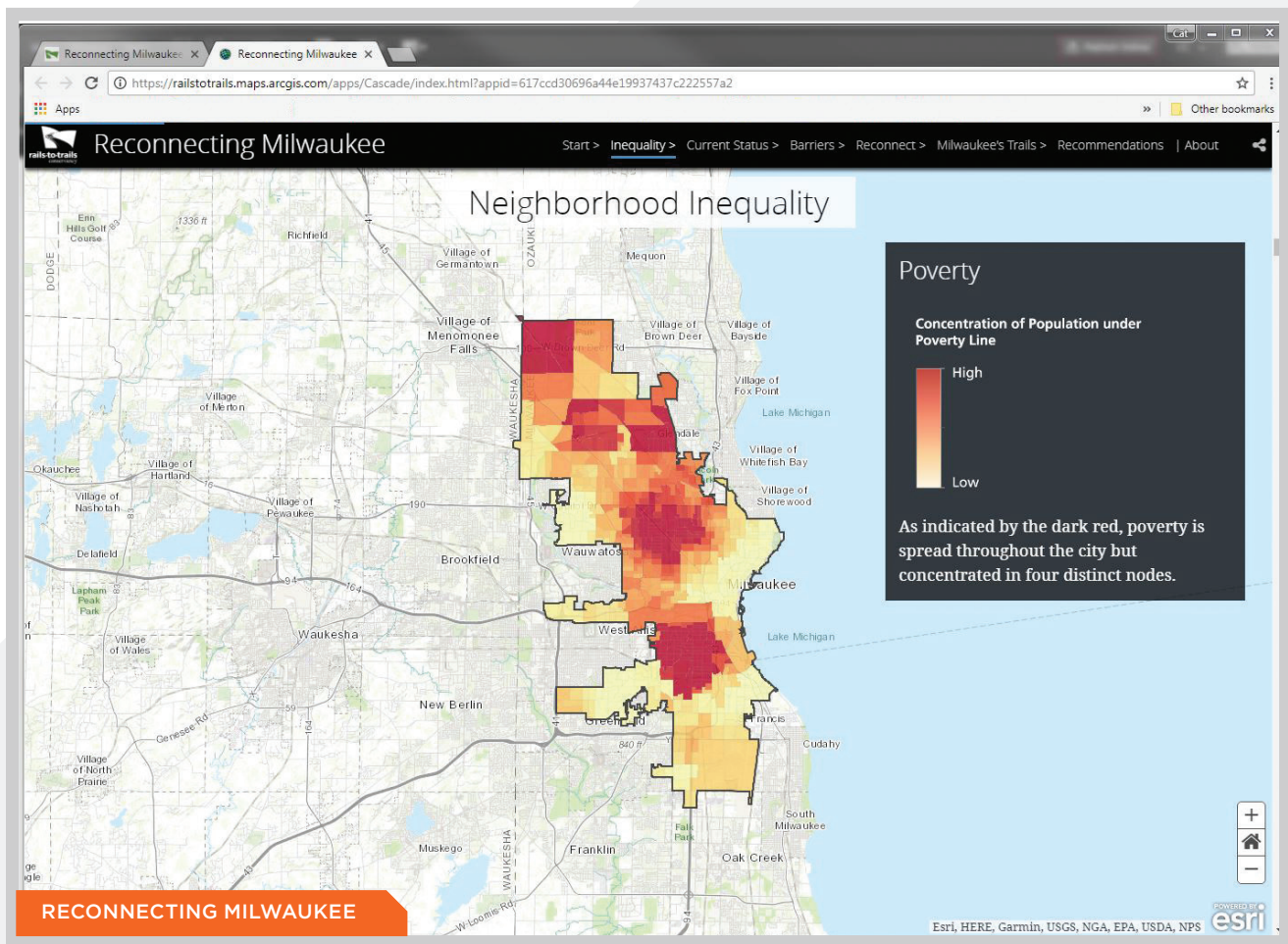
Source: Rails to Trails Conservency. 2017. "Reconnecting Milwaukee."
https://railstotrails.maps.arcgis.com/apps/Cascade/index.html?appid=617ccd30696a44e19937437c222557a2.

PEER APPLICATION

- Test scenarios have been run by researchers in Seattle, Washington and by the Rails with Trails Organization in Milwaukee, Wisconsin. PeopleForBikes Bicycle Network Analysis Tool, described in more detail elsewhere in this document, has been applied to a range of cities and small towns around the U.S.

ADVANTAGES

- The tool is specifically designed to test scenarios
- The tool can produce corridor-level results for a broader range of applications
- A default set of origins and destinations are defined, though these can be modified
- The tool captures the quality of facilities, with a strong focus on the extent to which vehicle traffic makes cyclists feel unsafe
- Intersections and crossings are considered

CONSIDERATIONS

- The tool is data intensive
- Computation of the scores is time- and effort-intensive
- The classification scheme blends existing measures in an ad hoc way
- The results are not yet validated against behavior/use data
- Transferability to rural contexts is not well understood, and rural facilities may not easily fit within the existing urban-oriented scoring framework

CONNECTIVITY MEASURE

BICYCLE ROUTE QUALITY INDEX (RQI)

Where are the best bicycle available routes between given origins and destinations, considering elements such as directness, trip purpose, and supporting infrastructure?

MODE	METHOD	OUTPUTS	CONNECTIVITY ANALYSIS METHODS	ACCESSIBILITY	USE IN PRACTICE	LEVEL OF EFFORT
	Link and intersection attributes are scored by weighted formula; routes are solved between a defined set of destinations. Route scores are indexed and aggregated to origin points/areas.	RQI measure for a route (relative to distance) or facility (for origin/destination areas); ranges from 0 to the best facility possible, with 1.0 reflecting an "adequate" or reference facility	Accessibility to Destinations, Directness, Quality	Explicit consideration of accessibility for people with disabilities: **Not in current forms, but could possibly be added given the complexity of the infrastructure data supporting the measure.**	Emerging	HIGH

DESCRIPTION

Bicycle RQI is an emerging measure that is still largely in the research phase. Portland, OR has been the leader in developing and applying RQI measures. It allows for a more nuanced, complex assessment of quality compared to other measures because it takes into account additional variables such as trip purpose (e.g. commute versus noncommute), roadway slope, and detailed intersection attributes. Several variations of a Route Quality Index (RQI) have been applied, all of them based on route choice models developed at Portland State University (Broach, Dill, and Gliebe 2012) in conjunction with Portland Metro MPO.

The route choice models provide weights for a range of network attributes, including separation from traffic, delay factors, intersection crossing aids and traffic volumes, and terrain. The weights can be used to generate lowest cost or "best" routes to represent the connectivity between a given origin point and some defined set of destination points. Individual routes are typically aggregated and standardized to create an indexed score for use in planning applications. A related technique was developed using a different route choice model developed in San Francisco, CA (Hood et al., 2011).
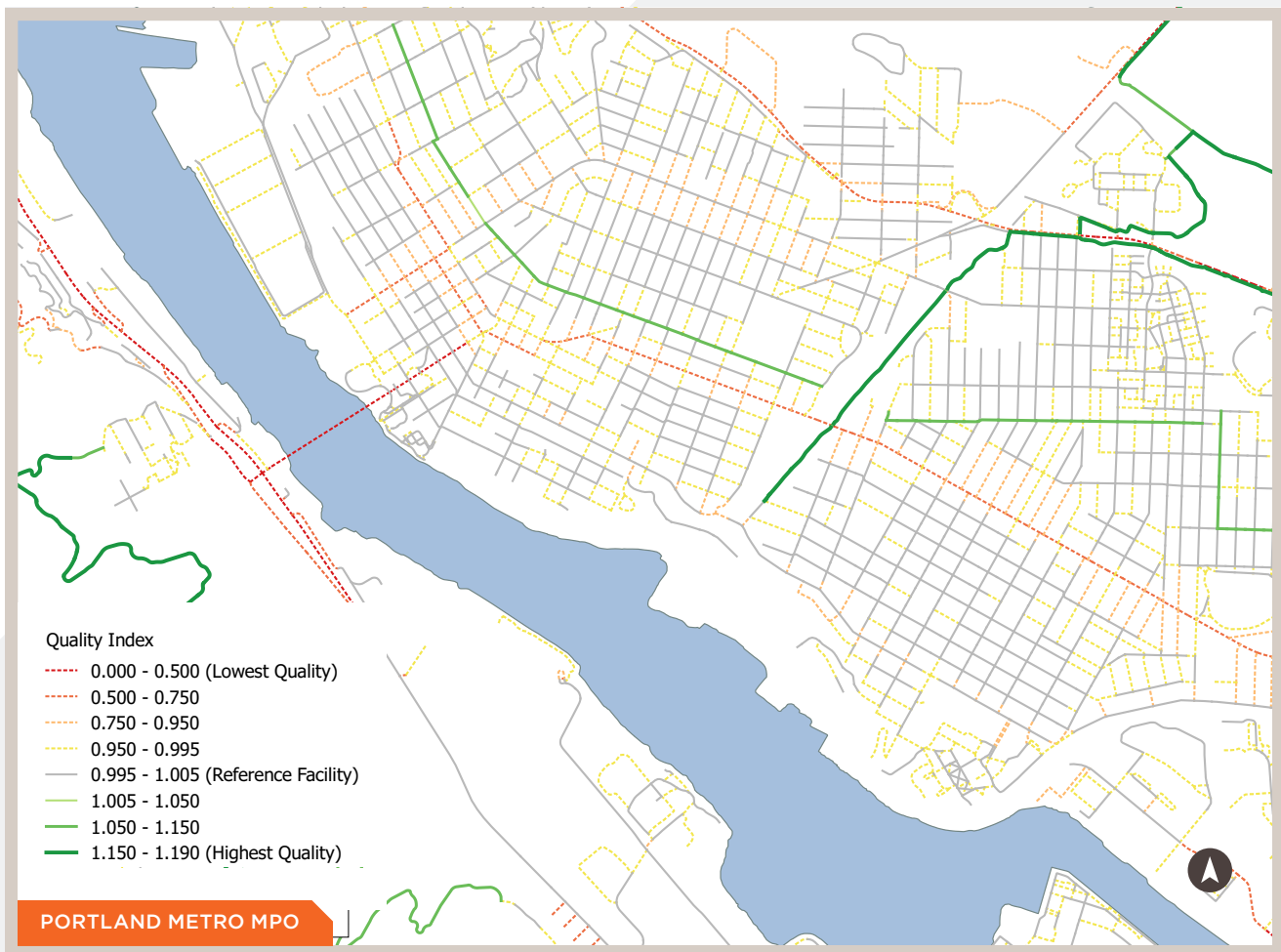
The primary use of RQI-type measures has been in regional bicycle travel demand models. However, recent extensions have applied RQI as a standalone connectivity measure to test scenarios and predict bicycle use.

EXAMPLE PLANNING APPLICATION(S)

- To identify the relative demand for particular routes
- To set priorities for projects that help to support higher demand on key routes and to attract new bicycle trips in corridors that currently score lower on the index
- To select among competing projects based on predicted mode shift

TYPICAL DATA

- Nonmotorized network: Bike lanes, shared-use paths (regional, local use), bicycle boulevards, road slope
- Transportation infrastructure: Traffic signals, stop signs, traffic volume (or functional class), major bridges, one-way streets
- Traveler origins, destinations, and trip purposes (commute/noncommute)

Quality Index
- - - - - 0.000 - 0.500 (Lowest Quality)
- - - - - 0.500 - 0.750
- - - - - 0.750 - 0.950
- - - - - 0.950 - 0.995
——— 0.995 - 1.005 (Reference Facility)
——— 1.005 - 1.050
——— 1.050 - 1.150
——— 1.150 - 1.190 (Highest Quality)

PORTLAND METRO MPO

PEER APPLICATION

- Portland Metro MPO uses a version of RQI to measure bicycle connectivity in its regional travel model. Various research applications have been reported as well (Broach and Dill 2016; Broach and Dill 2017).

➕ ADVANTAGES

- Quality weights cover a broad range of factors and are supported by revealed preference route choice data

- Relatively low data requirements for a route-based measure

- Validated against use using both individual trip and aggregate Census commute data

- Acknowledges difference between commute and noncommute connectivity

- Can be used to calculate bike commute shares under future scenarios

- Captures intersection crossing difficulty

- Includes slope of roads in assessing connectivity

❓ CONSIDERATIONS

- Application of the method is complex

- Data on traffic volumes, stop signs, and other key elements are not always available

- No attempt is made to capture quality differences among similar bike facilities (e.g. bike lane widths or pavement quality)

- The measure does not account for some roadway attributes (e.g. parking, speed, width) captured by related quality measures

- The measure has so far been applied exclusively in particularly bike-friendly urban areas; transferability of quality weights is not yet established for use in different types of places

PEDESTRIAN INDEX OF THE ENVIRONMENT (PIE)

Where are the most walkable areas ("zones") of a city?

| MODE	METHOD	OUTPUTS	CONNECTIVITY ANALYSIS METHODS	ACCESSIBILITY	USE IN PRACTICE	LEVEL OF EFFORT
🚶	Calculate a series of form-based factors around a given destination. Enter the factors into a weighting equation to calculate PIE	PIE, a standardized score of walkability (20 to 100) at the Pedestrian Analysis Zone (PAZ) scale. Predicted walk share of trips to given destination, based on PIE, is also possible with additional demand data	Directness, Accessibility to Destinations, Quality	Explicit consideration of accessibility for people with disabilities: **No, but could potentially be added**	Experimental	HIGH

DESCRIPTION

PIE measures indicate the quality and attractiveness of the walking environment based on facilities and the presence of pedestrian destinations/amenities (Clifton et al. 2013). PIE is somewhat unusual among walkability indicators in that it starts with locating pedestrian-oriented destinations and works backwards to define walkability. PIE is a composite index of various form-based measures, combined in a weighted equation that was developed and validated against travel survey data. Data needs are relatively low, with the exception of specific business types, and all of the measures can be calculated using simple GIS analysis techniques. PIE was developed as one component of a Regional Pedestrian Travel Model. PIE is not widely used at this time, though it has the potential to effectively describe improvements to pedestrian networks in terms of network use.

EXAMPLE PLANNING APPLICATION(S)

- To identify areas with high potential pedestrian travel demand
- To set priorities for projects that support high demand areas
- To identify projects that could increase pedestrian attractiveness in designated areas

TYPICAL DATA

- Off street paths or trails, sidewalks
- Block size
- Activity density (population and employment)
- Land use (retail, restaurants, schools, etc.)

Source: FHWA
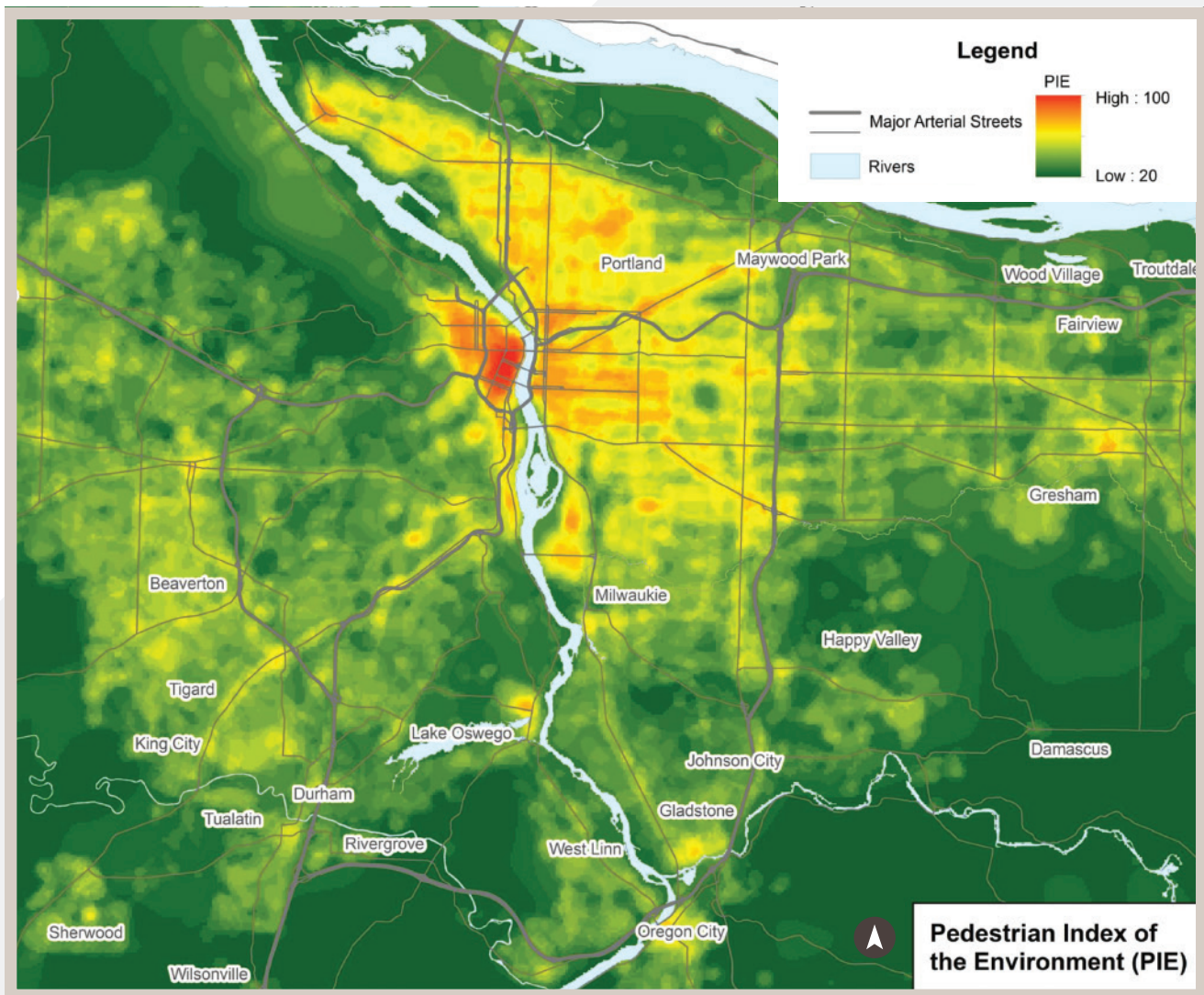
Source: Clifton, K. J., Singleton, P. A., Muhs, C. D., Schneider, R. J., & Lagerwey, P. (2013). Improving the representation of the pedestrian environment in travel demand models, Phase I. Oregon transportation research and education consortium (OTREC-RR-510). http://ppms.trec.pdx.edu/media/project_files/Clifton_510_final_combined.pdf

PEER APPLICATION

- Portland Metro MPO (Oregon) is in the process of implementing PIE as part of their regional travel demand model. A related project to gauge transferability to other regions is also underway.

➕ ADVANTAGES

- Quality weights are supported by revealed preference travel survey data

- The data and computation needs are modest

- The tool was validated as a predictor of walking using travel survey data

- A simple grid is used to define destinations; no need to define origins and destinations

- With additional data overlays, it can be used to predict walk mode share

❓ CONSIDERATIONS

- Form-based measures are not very sensitive to specific network connectivity or quality improvements

- The tool assesses bicycle facilities to measure pedestrian network quality

- The initial version does not provide summary scores for varying aggregation levels

- The tool has only been used in Portland, though additional applications are currently underway

CONNECTIVITY MEASURE

PEDESTRIAN LEVEL OF SERVICE (PLOS)

How well does network infrastructure support pedestrian travel, including interaction with other modes, based on perceived pedestrian comfort levels?

MODE	METHOD	OUTPUTS	CONNECTIVITY ANALYSIS METHODS	ACCESSIBILITY	USE IN PRACTICE	LEVEL OF EFFORT
	Inputs entered in a weighted model to calculate link score (*Note: calculations also available for intersections, but these are very complex*)	Numeric scores converted by formula to a six-point scale (A through F)	Quality	Explicit consideration of accessibility for people with disabilities: **No**	Common	LOW

DESCRIPTION

Similar to Bicycle Level of Service (BLOS), PLOS is an attempt to adapt a commonly applied measure of motorized network performance to pedestrian facilities (Landis et al. 2001). PLOS measures indicate the level to which the infrastructure supports pedestrian travel, and how well pedestrian travel interacts with other modes, based on perceived pedestrian comfort levels. PLOS variables and thresholds are supported by stated preference assessments of perceived comfort and safety on various road segments. Originally developed to support a statewide evaluation tool in Florida, PLOS measures include formula-driven weights for links, intersections, and "segments" (combined, directional links and intersection approaches).

Despite relatively high data requirements, PLOS has been a popular measure in planning practice. It is supported by the original stated preference data and a version has been included in the Highway Capacity Manual. Several versions (many simplified) have been developed across a range of planning applications, mostly related to documenting existing conditions, identifying connectivity gaps, and evaluating network-wide quality.

EXAMPLE PLANNING APPLICATION(S)

- To assess the potential impacts of changes such as building or removing a major pedestrian facility on an area-wide network

- To identify the performance of subareas, zones, and corridors within the network

- Not generally useful for subarea analyses of specific links or corridors such as local streets, paths, and trails, nor for individual project development plans

TYPICAL DATA

- Sidewalks (including widths and barrier heights, if any)

- Motorized traffic data: Traffic volumes, traffic speeds, percent heavy vehicles

- Street network data: Number of lanes, outside lane width, bicycle lane width, width of paved shoulder, presence of curbs, on-street parking occupancy, buffer width between road and sidewalk, driveway access frequency and volume

- Defined set of destinations or origin/destination zones and routable network to extend analysis to destination access
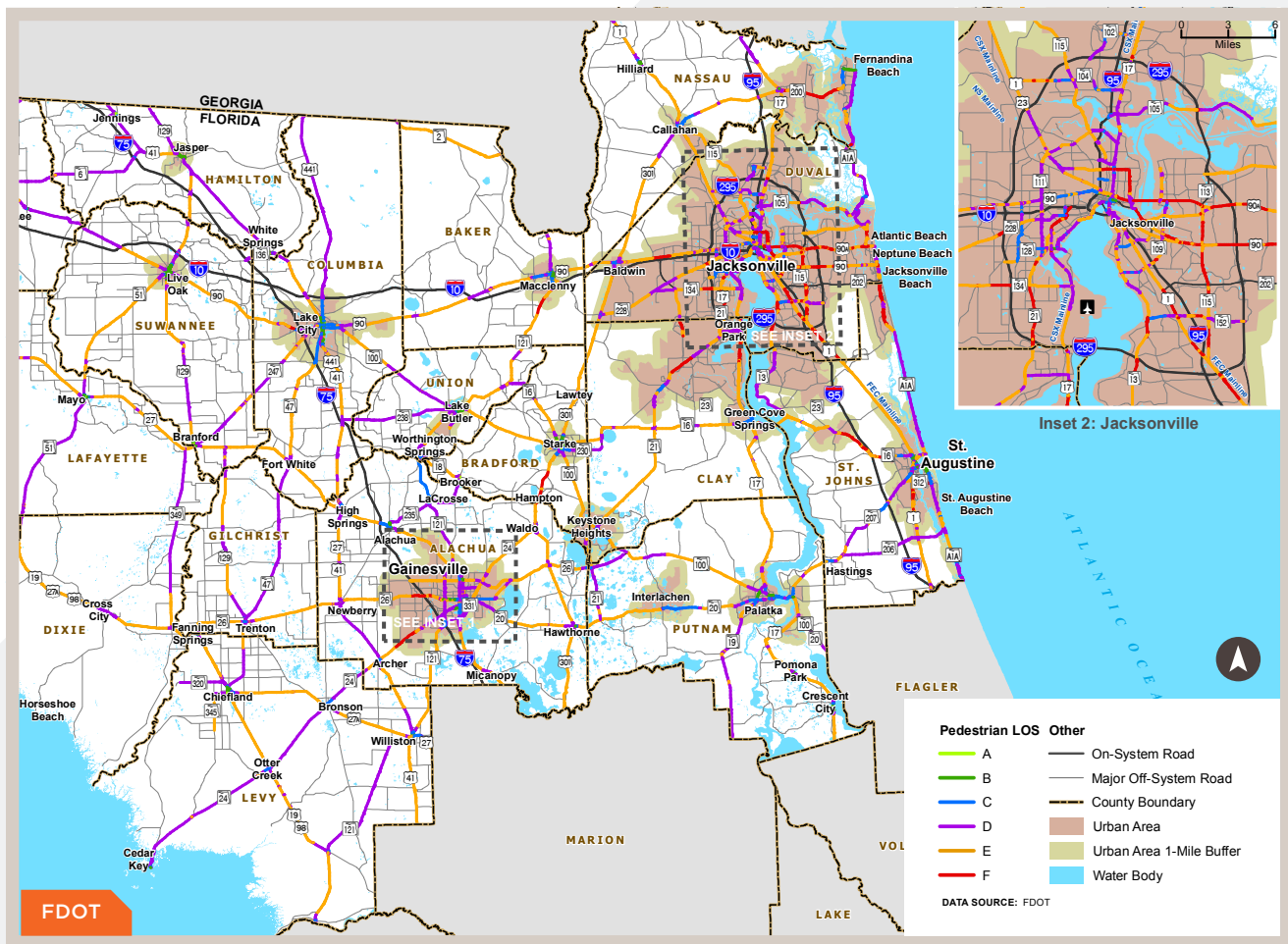
Florida Department of Transportation. 2015. "Bicycle and Pedestrian Gap Study."
http://www.fdot.gov/planning/systems/programs/sm/los/districts/district2/Bike_Ped/Bicycle_and_Pedestrian_Level_of_Service.pdf.

PEER APPLICATION

- PLOS standards are used by the Florida Department of Transportation in the review of actions that directly impact the State Highway System for all planning and permitting processes. Methods are outlined in the Quality/Level of Service Handbook (2013).

➕ ADVANTAGES

- It is related to vehicle LOS, which is widely used and understood

- An adopted measure included in the Highway Capacity Manual

- It captures the quality of facilities, with a strong focus on the extent to which vehicle traffic and parking make pedestrians feel unsafe or uncomfortable

❓ CONSIDERATIONS

- It is data-intensive, particularly in the adopted HCM version

- The results are not applicable to quiet local streets, paths, or trails

- The measure is not designed for route-level assessment

- The measure has not been validated by use or behavior data

- The measure has a low sensitivity to changes in sidewalk width and buffer presence

PEDESTRIAN LEVEL OF TRAFFIC STRESS (PLTS)

What is the extent to which pedestrians feel safe and comfortable using the network?

| MODE	METHOD	OUTPUTS	CONNECTIVITY ANALYSIS METHODS	ACCESSIBILITY	USE IN PRACTICE	LEVEL OF EFFORT
🚶	Classify sidewalk segments by type by highest stress attribute	Pedestrian stress rating of 1 through 4 for sidewalk centerline and intersections	Directness, Accessibility to Destinations, Quality	Explicit consideration of accessibility for people with disabilities: **Yes**	Emerging	HIGH

DESCRIPTION

Pedestrian LTS measures indicate the relative level of comfort for pedestrians using a given network, taking into account the variety of abilities and trip purposes among different types of people. The categories of pedestrian traveler characteristics, including user types and trip purposes, are similar to those developed for Bicycle LTS measures. Criteria and thresholds are customized for pedestrians, as described in the Oregon Department of Transportation's Analysis Procedures Manual (2016). Links are classified based on their most stressful feature, including the impact of crossings. Application to measures of connectivity are done best in conjunction with form-based measures.

EXAMPLE PLANNING APPLICATION(S)

- To identify factors that contribute to low- and high-stress corridors and routes

- To set priorities for locations that need specific types of improvements

TYPICAL DATA

- Sidewalk centerlines, widths, surface types, surface quality

- Crossing locations, marking, lighting

- Curb ramps and other infrastructure supporting access for people with disabilities

- Motorized traffic data: Traffic volumes, traffic speeds

- Street network data: Number of lanes, lane width, width of paved shoulder, presence of curbs, on-street parking

- Pedestrian origins and destinations

PEDESTRIAN LEVEL
OF TRAFFIC STRESS
— 1 - Low Stress
— 2
— 3
— 4 - High Stress
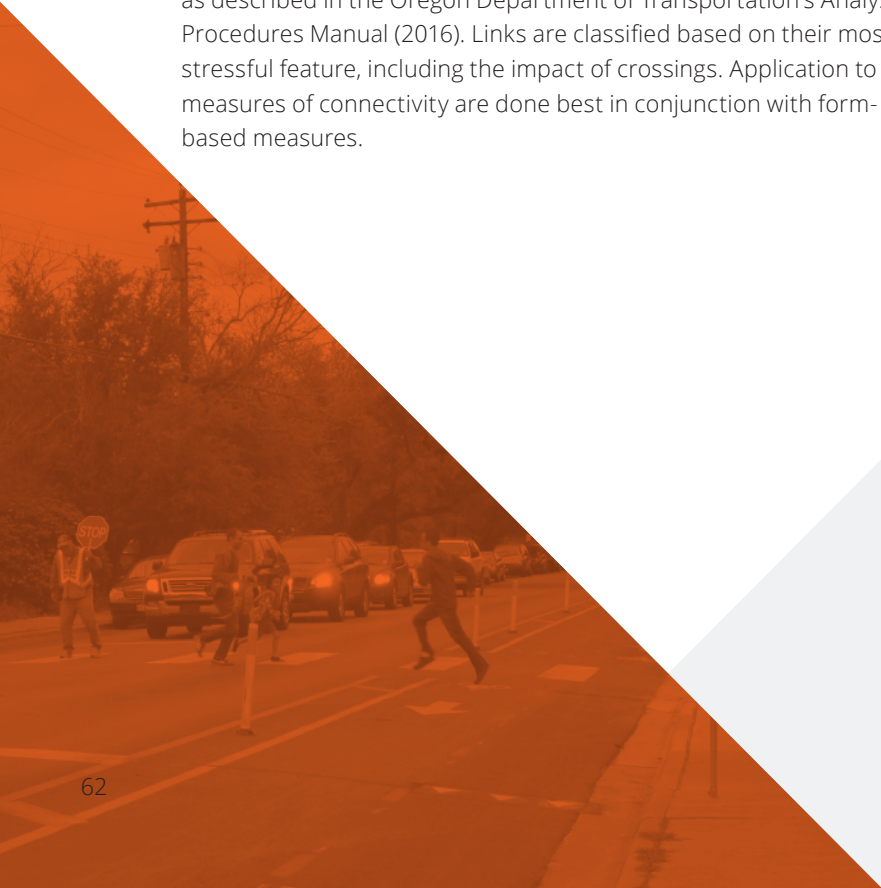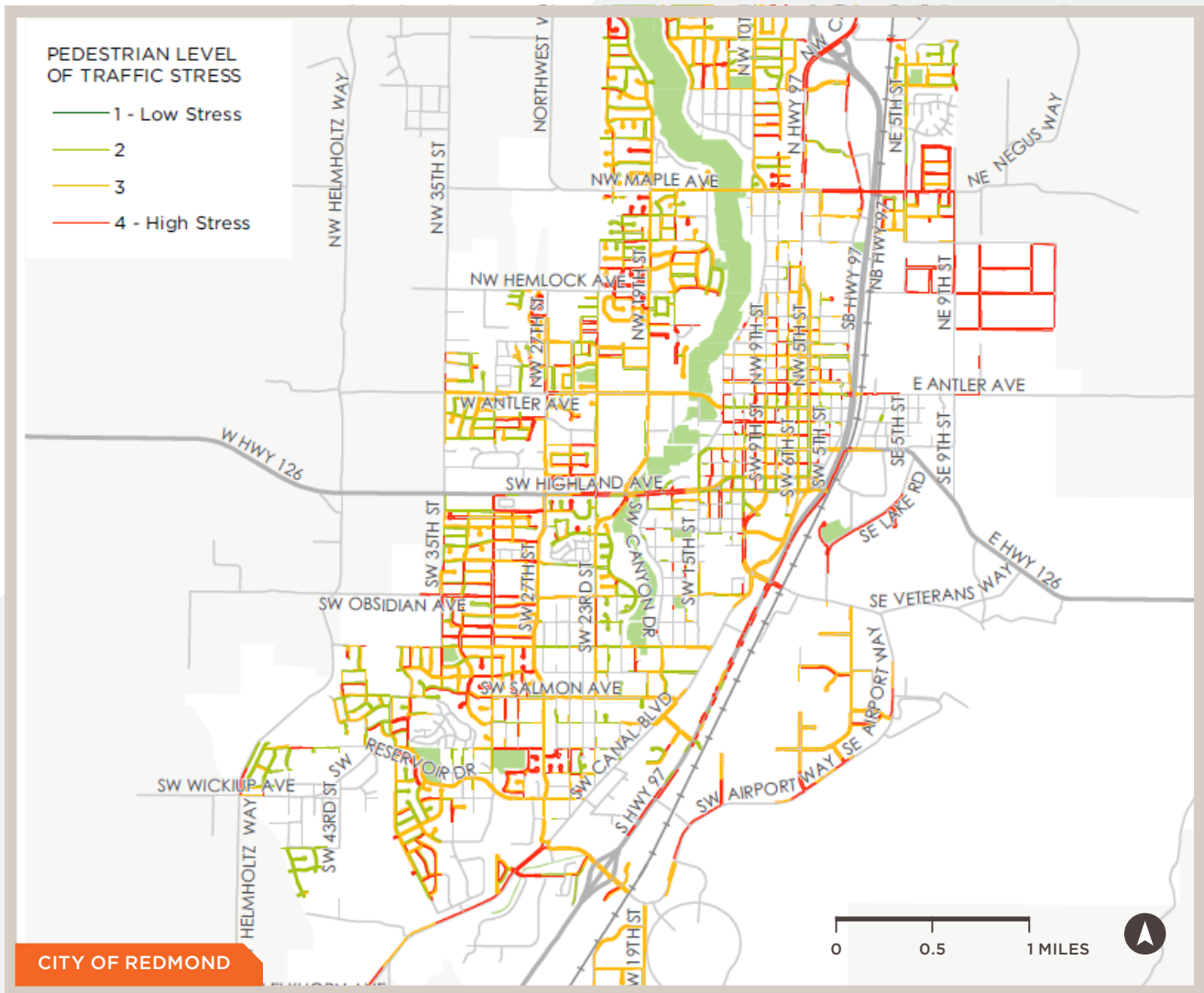
CITY OF REDMOND

Steve Faust and Anais Mathez, Cogen Owens Green to Deborah McMahon, City of Redmond. May 22, 2017.
Redmond Neighborhood Revitalization Plan: Draft Technical Memorandum #1 Existing and Future Conditions.

PEER APPLICATION

- In Oregon, Pedestrian LTS is the preferred method defined by the DOT for Regional Transportation Plans and Transportation System Plans. It can also be used on a screening-level basis for project development and development review. The recommended PLTS measurement methodology will be outlined in the updated ODOT Analysis Procedures Manual. [1]

1   http://www.oregon.gov/ODOT/Planning/Pages/APM.aspx

ADVANTAGES

- Provides a comparable measure to BLTS

- Provides a detailed understanding of individual sidewalk centerline segments and provides visually descriptive picture of physical conditions

- The tool is sensitive to disability access concerns, including ramp quality and surface quality

- It allows adjustments for additional treatments or infrastructure intended to improve the pedestrian environment

CONSIDERATIONS

- The tool is data-intensive

- The data cannot easily be used

- The results are not validated against behavior/use data

- The classification is sensitive only to "weakest link" improvements

- The current methodology precludes improvements in certain areas based on land use types

- In rural areas, the definition of sidewalks and criteria within the measure may need to be adjusted to reflect nonurban characteristics

04

LESSONS
LEARNED

This FHWA resource highlights ways that different communities have mapped their existing and proposed bicycle networks. It shows examples of maps at different scales, while also demonstrating a range of mapping strategies, techniques, and approaches.

https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/strategic_agenda/fhwahep16086.pdf.
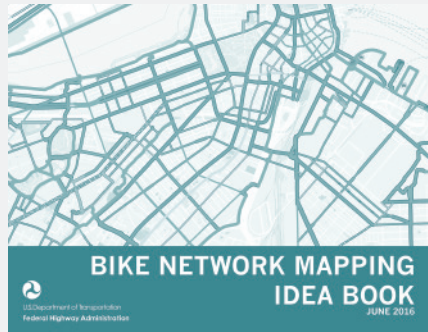
LESSONS LEARNED

To support the development of this guide, FHWA reached out to numerous transportation planners through webinars, interviews, and focus groups for input and advice about their experiences with analyzing multimodal connectivity. The research team also worked directly with five agencies to conduct assessments that involved the methods and measures described in this guide. The comments in this chapter are a synthesis of reflections and suggestions from both the case study participants and other peer participants in this research. More specific details on the processes conducted and lessons learned by each case study agency are included as an appendix to this guide.

STEP 1: IDENTIFYING THE PLANNING CONTEXT

• Articulate a clearly defined network vision and analysis goal to help analysts determine the right level of detail for the analysis purpose. Networks are complex, and collection of detailed facility data is highly time intensive. The key is to balance the tradeoffs between simplifying data attributes in order to improve the efficiency of network data collection and limiting the questions that can be answered by the analysis.

STEP 2: DEFINING THE ANALYSIS METHOD

• Select a method appropriate for the intended application. Refer to the planning context identified in Step 1 that defines how the analysis will be used in order to help determine the appropriate analysis method and measures. Consider how the measures and analysis results could be used over time and in conjunction with other processes to help fine-tune the decision.

• To enhance accountability, select measures that can be tracked over time. Taking into account the potential availability of data for future analyses, and the possibility that the measures or analysis parameters might need to be changed over time, select measures that are likely to be useful, replicable, and comparable for years to come.

• Select methods and measures appropriate for the study area context. The analysis techniques discussed in this guide provide varying levels of detail about the multimodal network. Not all measures are appropriate for all development contexts. Communities with extensive existing bicycle and pedestrian networks may need to use more sophisticated connectivity measures to capture the full impact of planned projects. Simple methods such as network density analyses capture only the extent to which

facilities do or could exist on the ground. More complex approaches such as low-stress indices enable planners to consider the benefits of recent or potential improvements to a mature network. For example, the bicycle and pedestrian network in many areas of the Portland region is largely built out. Metro uses low-stress analyses to help set priorities for filling gaps and improving existing facilities rather than focusing on building new facilities. In rural communities or newly growing suburbs, the network may be too sparse to allow for meaningful analyses of detailed connectivity measures such as stress indices.

• Consider potential implications when modifying existing methods and measures. Agencies commonly adapt connectivity measures to fit available data and technical capacity. This is understandable given the complexity of some measures, but it can make results harder to compare over time, and may require additional research support and validation.

• Stay informed about emerging connectivity analysis methods and measures. Researchers and practitioners are continually refining measures and developing new computation techniques that may be more sensitive to local policies and priorities. Although the implications of applying new methods or measures should be considered carefully, it is important to keep striving for richer, more accurate information to support well-informed decisions.

STEP 3: ASSEMBLING DATA

- Promote consistent standards for local bicycle and pedestrian facility data. Local governments often use different attributes to describe bicycle facilities, and apply different metadata, geographic units, and accuracy standards to GIS datasets. This creates difficulty in merging datasets. Ideally, spatial data for both current facilities and planned projects should use the same attributes and reference networks. Promoting bicycle facility data standards for use by local governments up front can streamline data assembly and analysis for regional agencies and improve the quality of analysis results.

- Establish data storage parameters that are consistent with the selected measure. By storing data in formats that limit the need for extensive processing in order to run the selected analysis, agencies increase their efficiency and their ability to replicate analyses.

- Develop policies and procedures to ensure that the standards for maintaining and updating data with appropriate frequency and levels of accuracy are consistent among various departments and agencies. The quality of an analysis depends on the quality and accuracy of the datasets. These policies can also define important operational elements, such as the lead agencies and staff members responsible for maintaining different datasets.

STEP 4: COMPUTING METRICS

- Be prepared to conduct secondary research and validation exercises to increase the accuracy of the results. All analysis methods and measures have strengths and weaknesses, and could present a distorted picture if not examined carefully. For example, the weakest-link methodology of Level of Traffic Stress analyses is conservative, restricting potential travel to only the lowest-stress facilities. Additional research and validation might be required to understand more fully which representation of user behavior is more accurate, and whether a hybrid behavior profile is the most accurate approach.

- Test connectivity measures before committing to them. One of the case study communities was able to use the technical assistance to test measures that had been agreed with stakeholders but not tested for practical application. The technical assistance process provided a valuable opportunity to refine the methodology, check whether the measures captured what the stakeholders really intended to measure, and think about how to communicate results.

STEP 5: PACKAGING RESULTS

- View the picture from several perspectives. Using several different connectivity analysis tools allows staff, decisionmakers and the public to interpret the network through multiple lenses including safety, equity, and accessibility. This can mitigate the weaknesses of a single technique and lead to a more comprehensive understanding of conditions.

- Overlay the analysis results with a variety of other information. For example, travelshed analyses offer rich visual information that helps to illustrate how well low-stress facilities connect to different parts of each study area. Overlaying quantitative measures with travelshed information makes it much easier to interpret results and compare the benefits of different projects or planning scenarios.

- Consider how subarea or segment analyses can be reflected in a network level. Simply measuring the quality of selected pieces of a multimodal network may not be sufficient to meet many analysis goals. Consider how, for example, the ways in which segments that have been evaluated on a stress index could (or do) connect to form routes that provide access to specific destinations, or how well a combination of routes can provide access to key destinations. The process of layering analyses of nodes, segments, and networks at different scales can inform a broad range of connectivity questions.

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APPENDIX

CASE STUDIES

As part of the development of this guidebook, the following five transportation planning agencies volunteered to test one or more of the connectivity analysis methods and measures described:

- Atlanta Regional Commission

- City of Baltimore

- California Department of Transportation District Four office

- City of Fort Collins

- Portland Metro

Each agency worked with the project team through the five-step process of identifying the planning context, defining the analysis method, assembling data, computing metrics, and packaging the results. Illustrations throughout the guidebook include maps and insights provided by the case study communities, and Chapter 4 summarizes advice to practitioners based on the lessons learned from the case studies. A full description of the case studies is available in the Appendix.[1]

1 https://www.fhwa.dot.gov/environment/bicycle_pedestrian/