Evaluation of Bicycle Network Connectivity Using Graph Theory and Level of Traffic Stress

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Abstract: The quality of the bicycle network determines ridership, safety, connectivity, equity, and livability. Very few former research studies investigated network connectivity for individual user types and identify network needs and barriers based on these rider types. This study measures the network connectivity for different rider types using level of traffic stress (LTS) and graph theory concepts. As a symbolic representation of a road network and its connectivity, a graph represents the structural properties of networks and compares one measure over another by taking into account spatial features. In addition, this study defines a bicycle network for different types of riders using LTS metrics based on traffic speed, road geometry, and traffic volume. This study evaluates the OpenStreetMap (OSM) bicycle network for Portland, Oregon, as a case study. Three transit stations in the downtown, riverside, and residential area were considered to assess the connectivity and barriers with a home at block level for last and first-mile coverage. The analysis shows that 29% of links in Portland need to be improved with more bicycle facilities to provide access to basic adult riders, and 33% of links require improvement for children. The networks are well connected for "strong and fearless" and "confident and enthused" users but not well connected for basic adults and children in many neighborhoods with low alpha and grid tree pattern (GTP) indices. The results indicate that planners and designers need to improve their network connectivity for all types of users to ensure equal active transportation opportunities beyond a particular portion of the network. **DOI: 10.1061/JTEPBS.TEENG-7776.** *© 2023 American Society of Civil Engineers.*

Practical Applications: In general, a well-connected network is important to provide the shortest route from origin to destination and safe traveling paths for all ages of people. It is critical for cities or government agencies to understand how their network is connected to different users because this knowledge will provide a fundamental basis for resource prioritizations on bicycle network improvement. This study developed a strategy using traffic stress and geometric properties of the network to assess their network connectivity. Practitioners can apply these techniques on a small scale (e.g., around transit stations) as well as large scale (e.g., entire city network) to identify the network connectivity. This study extends the applications to evaluate transportation equity in bicycle networks using served/ unserved populations where disparities in network connectivity exist to favor higher-income people.

Author keywords: Graph; Traffic; Stress; Bicycle; Network; Connectivity.

Introduction

According to the National Center for Chronic Disease Prevention and Health Promotion (NCCDPHP), 6 in 10 adults in the US have a chronic disease. These diseases cause death and disability and cost $4.1 trillion in annual health care, and lack of physical activity represents one of the major causes of chronic diseases (CDC 2019). The Centers for Disease Control and Prevention (CDC) recommend 150 min (30 min a day, 5 days a week) of moderate-intensity aerobic exercise per week, and muscle strengthening at least twice a week to reduce the possibility of chronic disease (CDC 2022). Cycling for recreation or commuting represents an excellent option for people to meet the CDC's physical activity requirements. Still, cycling activities largely depend on the bicycle network's connectivity between origins and destinations to attract users, which requires city or state agencies to provide a better-connected network for all types of riders.

A well-connected road network can decrease bicycle travel distance and increase route options from origin to destination. This network should have several links, three- and four-way intersections, and minimum dead ends. More local street connections and intersections enhance bicycle and pedestrian travel. For instance, linking sidewalks, paths, bicycle lanes, and streets reduces the destinations' distance and potentially increases walking, bicycling, and transit trips. A strongly connected network plays an significant role in encouraging more cycling activities, improving public health through physical activities, and making the environment green (Koohsari et al. 2014; Rojas-Rueda 2011).

However, every link within the bicycle network is not suitable for all riders to feel comfortable and safe. Rider types can be categorized into four groups based on their skill and willingness to use links with higher level of traffic stress (LTS) as described by Furth et al. (2012). LTS uses road geometry (i.e., lane width, number of lanes, and speed), and traffic volume to define the riders willing to use different links. The low skill level and ease of distraction that "children" riders exhibit limit their safe bicycle network to LTS 1 links because these links have both low speeds and low motor vehicle traffic. These LTS 1 facilities may also physically separate

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riders from traffic. Basic "adult" riders use LTS 2 road links, which have slightly higher levels of traffic stress in addition to the children's network (LTS 1). However, they still need to interact with only occasional low-speed motor vehicles and face almost no difficulty crossing other links because most motorists provide unambiguous priority to cyclists. Children and basic adult riders need network connectivity on low-stress links between their origins and desired destinations to encourage them to ride. "Enthused and confident" riders may feel comfortable riding on multilane facilities (LTS 3), and "strong and fearless£ riders will generally use almost any arterial that permits bicyclists (LTS 4). To provide comfort and safe riding, planners and designers must ensure that most origins can access many destinations using low-stress links with reasonable shortest-path travel times.

The quality of the bicycle network requires investigation to identify the network's weaknesses and recommend improvements. Although link-level evaluation using traffic stress or bicycle level of service (BLOS) research exists, few past studies investigated the network connectivity for different rider types. Traffic stress may make portions of the network uncomfortable or unusable by particular rider types. As a result, link characteristics, network connectivity, and other characteristics may directly or indirectly influence bicycle ridership. Good-quality links along certain local roads or paths do not present the whole network and may leave different rider types with limited or no connectivity to preferred activities or destinations. These gaps, as well as overall bicycle network performance, require evaluation to help city designers and planners identify the link and intersection improvements. This study evaluates the bicycle network connectivity for the entire network and subnetworks based on rider type and addresses the following research questions:

- What network connectivity measures effectively capture the needs and barriers for different rider types?
- How does network connectivity vary for different rider types?

This paper discusses the importance of the study and research objectives in the "Introduction," followed by the relevant literature review in the "Background" section. The "Study Area" section details the network investigated, followed by the research methodology in the "Methodology" section. The "Analysis and Results" section provides a detailed analysis of the networks using graph theory metrics on different traffic stress networks. Finally, the study discusses the findings and recommendations in the "Conclusion" section.

Background

The connectivity of the road network should be measured to provide insight into where agencies/planners and designers need to improve the infrastructure to provide better connections for different rider types. Street connectivity can be defined as the directness and availability of alternative routes between home and local destinations (Frank and Engelke 2005). Some previous researchers conceptually defined street connectivity as the number of three-way or more intersections per land-area unit (Dill 2004; Wang et al. 2013). Streets with a low intersection density, barriers that prevent direct routes, and few route choices can be characterized as low connectivity. In contrast, high connectivity occurs in areas where a grid pattern for street layout exists (Handy et al. 2003).

Past research used varying types of network connectivity metrics. For instance, McNeil (2011) examines bike accessibility in Portland, Oregon, by listing essential destination types (e.g., restaurants, banks, parks, and open public spaces) and assigning a point value for each type of destination. The author calculated the accessibility score (0 to 100) for each destination by summing the points within a 20-min bike ride to provide a conceptual understanding of the network quality. Faghih Imani et al. (2019) examined the level of traffic stress for cyclists on the street and path network in the City of Toronto. Researchers concluded that cycling accessibility measure through low-stress network links significantly impacts choosing cycling as a mode of travel.

Lowry et al. (2012) assessed community-wide bike-ability using BLOS but did not assess the connectivity of the links. Later, Lowry and Loh (2017) used marginal rate of substitution (MRS)-based bicycle routing stress to find the projects that need to be prioritized based on accessibility to important destinations, but calculating individual actual MRS values is challenging and their simple method of MRS calculation may produce biased stress as a bicyclist would probably not substitute a bike lane with an off-street path at a linear rate. Koohsari et al. (2014) examined the association of street connectivity with utilitarian destination availability and walking for transport frequency and found a significant association; their study calculated street connectivity as the ratio of the number of intersections to census collection district land area, to calculate an intersection density. Still, questions remain about the best choice of connectivity measures.

Several other studies created metrics that calculate a score to classify a bikeway or other link in the bicycle network on a spectrum from desirable to undesirable, including the following:

- bicycle safety index rating (BSIR) (Davis 1995),
- BLOS (Jensen 2007),
- bicycle suitability assessment (BSA) (Emery 2018),
- bicycle compatibility index (BCI) (Harkey and Reinfurt 1998),
- bicycle suitability score (BSS) (Turner et al. 1997),
- bicycle suitability rating (BSR) (Mitman et al. 2008),
- interaction hazard score (HIS) (Landis 1994),
- road condition index (RCI) (Epperson 1994), and
- bicycle stress level (BSL) (Sorton and Walsh 1994).

The existing metrics of bicycle link evaluation do not provide a complete picture of varying levels of difficulty bicyclists experience under different traffic conditions. In addition, the existing metrics (such as BLOS) use elaborate input parameters that require complex data collection. The Australian-based Geelong bikeplan team (King et al. 1978) provided the first concept of bicycle stress to evaluate lane-sharing width on high-traffic-volume roads, but their method failed to measure the extent of traffic volume, vehicle speed, and curb lane width impact on bicycling difficulty. To cover these gaps, Sorton and Walsh (1994) introduced BSL as a method of supplying the missing information and determining bicycle compatibility on roadways. They categorized BSL from low (=1) to very high (=5) based on traffic volume, vehicle speed, and curb lane width. Recently, Mekuria et al. (2012) developed the LTS method, which produces four ratings ranging from LTS 1 to LTS 4 that align with the common rider classifications; they similarly used the number of vehicle lanes, speed limit, and bike lane width and introduced bike lane blockage, parallel parking, and the presence of traffic signals.

The popularity of LTS continues to increase because agencies can easily classify links with readily available key road attributes from OpenStreetMap (OSM) using the python library pybna (Gardner et al. 2017). LTS can also evaluate the network link level connectivity for different rider types. Connectivity is one measure for assessing network quality because connectivity between origin and destination provides essential access to activities and encourages bicycle flow across the network. Bicycle facilities' quality and presence impact network connectivity (Cohen et al. 2008; Koohsari et al. 2014; Saelens et al. 2003) for different rider types. Lowry and Loh (2017) compared bicycle network connectivity for different types of bicyclists and various destinations (e.g., grocery stores, banks, and schools). Their analysis confirmed that bicycle network connectivity varies across communities and bicyclist types/trips. Utilitarian bicycle trips positively increased with an increase of network connectivity, which means commuters prefer better connections to reach their destination within the minimum travel time. Researchers used the LTS as the key indicator to measure bicycle connectivity.

Although previous studies investigated bicycle link quality using several metrics, very few research studies examined the connectivity of the bicycle network by rider type. Varying skill levels of bicyclists likely impact their choice of bicycle routes, facilities, and even bicycle activities. Therefore, in-depth knowledge of network connectivity and stress level by rider types is critical to accurately evaluate the quality of bicycle infrastructure. This research aims to advance the evaluation of bicycle network quality using LTS and different graph theory concepts to understand network connectivity and identify possible network improvements. This study applies these network connectivity measures to investigate access in a network or small subnetwork to evaluate the bicycle network's multimodal connectivity.

Study Area

This study evaluates the Portland, Oregon, bicycle network as a use case for analyzing network connectivity. Researchers consider a 2.41-km (1.5-mi) extended bounded OSM network from the city of Portland to capture the complete road network for Portland. Portland has a total of 11,370 km (7,065 mi) of directional road network, and 1,986 km (1,234 mi) of road have a marked centerline to separate the direction of traffic. The prevailing speed limit varies from 8 km (5 mi/h) to 96.56 km (60 mi/h), and the number of lanes varies from one to six. A total of 16,681 links (11.57% = 986.53 km or 613 mi) out of 144,220 links have a bike lane.

The study did not exclude any specific roadways to provide generalized framework to estimate LTS level networkwide. Federal law does not prohibit riding bicycles on freeways/highways even though a state may prohibit it. Most western states allow bicycles to use interstate highways or other freeways while restricting bicycle use in urban or other congested areas (Thomas 2017). The program assigned high stress (LTS 4) for those links.

According to the US Census, the city of Portland has a population of 1,888 per km^2 (4,890 per square mile), and 75.3% of the population is white alone. The Portland Bureau of Transportation (PBOT 2017) reported that 6.3% of commuters (22,647 workers) used bicycles in 2017, whereas this percentage is 0.5% nationwide. Additionally, 374% more people biked to work in 2017 compared with 2000, indicating that Portland is one of the large bike-friendly US cities.

This study calculates the network connectivity for four different riders in both directions of the road links because the link characteristics from OSM require classifying the LTS for both directions of travel. Fig. 1(a) shows the children-friendly networks, which include only LTS 1 links for safety and comfort, and Fig. 1(b) shows the basic adult network. Basic adult riders prefer links with stress no greater than LTS 2. Fig. 1(c) depicts the network with LTS 1 to 3, including the enthused and confident riders who use LTS 3 links along with LTS 1 and LTS 2. Fig. 1(d) shows the complete network with LTS 1 to LTS 4 links. LTS 4 links are a strong and fearless rider's network. The results show that the subsequent removal/adding of the road links with a particular LTS for different riders may significantly impact network connectivity.

Methodology

Graph Theory

Road network topology is the graphical representation of intersections and road links. Graph theory describes the road network in terms of nodes and edges. A graph consists of a set of nodes/vertices $V = \{v_1, v_2, v_3, \ldots, v_n\}$ and a set of edges $E = \{e_1, e_2, e_3, \ldots, e_m\}$; these edges connect the nodes and are described as $G = (V, E)$. The evaluation of the network in graph form can assess its connectivity between nodes.

Connectivity Measures for the Whole Network

Connectivity measures the intensity of connections between links through intersections. A well-connected network should have many short links, intersections, and minimal dead ends to provide continuous and direct routes from origins to destinations. Geographers view the spatial nature of a road network as an important input to regional development (Rodrigue 2020). Recently, there has been growing interest in understanding the topology of the transport network that connects intersections in geographic space (Gastner and Newman 2006). A past study (Xie and Levinson 2007) quantified the network by investigating the potential application of network measures such as heterogeneity, connection pattern, and continuity, which are subsequently used to identify the change in network characteristics over time (Erath et al. 2009).

Earlier studies proposed several indices to measure the connectivity of a road network; the most popular indices include the alpha, beta, gamma, eta (Dill 2004; Kansky 1963; Rodrigue et al. 2019; Sreelekha et al. 2016), and grid tree pattern (Watanabe 2010) indices. These indices are more complex methods than nongraph techniques to represent the graph's structural properties because they involve comparing one measure over another by considering spatial features (e.g., distance).

The alpha index measures the ratio between the observed number of circuits and the maximum number of circuits. It ranges from zero to one, and an index of one indicates that the network is entirely interconnected, whereas zero means no circuits occur. Trees and simple networks will have an alpha index zero

$$\alpha = \frac{E - V + P}{2V - 5} \tag{1}$$

where E = number of edges in the road network; V = number of nodes/vertices in the network; and P = number of subgraphs.

The beta index measures the level of connectivity of a network and can be defined as the number of links per node. A connected network with one cycle has a beta value of one, and a simple and tree network's beta value should be less than one. A more complex network may have a value greater than one

$$\beta = \frac{E}{V} \tag{2}$$

Ewing et al. (2019) suggested that a beta value of 1.4 is a good target for network planning purposes and at least three cities used beta values as a standard of 1.2 and 1.4 (Susan et al. 2003). Increasing the value of beta increases the connectivity.

The gamma index considers the relationship between the actual number of edges to the maximum possible number of edges. It is an efficient value that can measure the progression of a network in time. The gamma values vary from zero to one where a value of one indicates an entirely connected network, which is unlikely in reality

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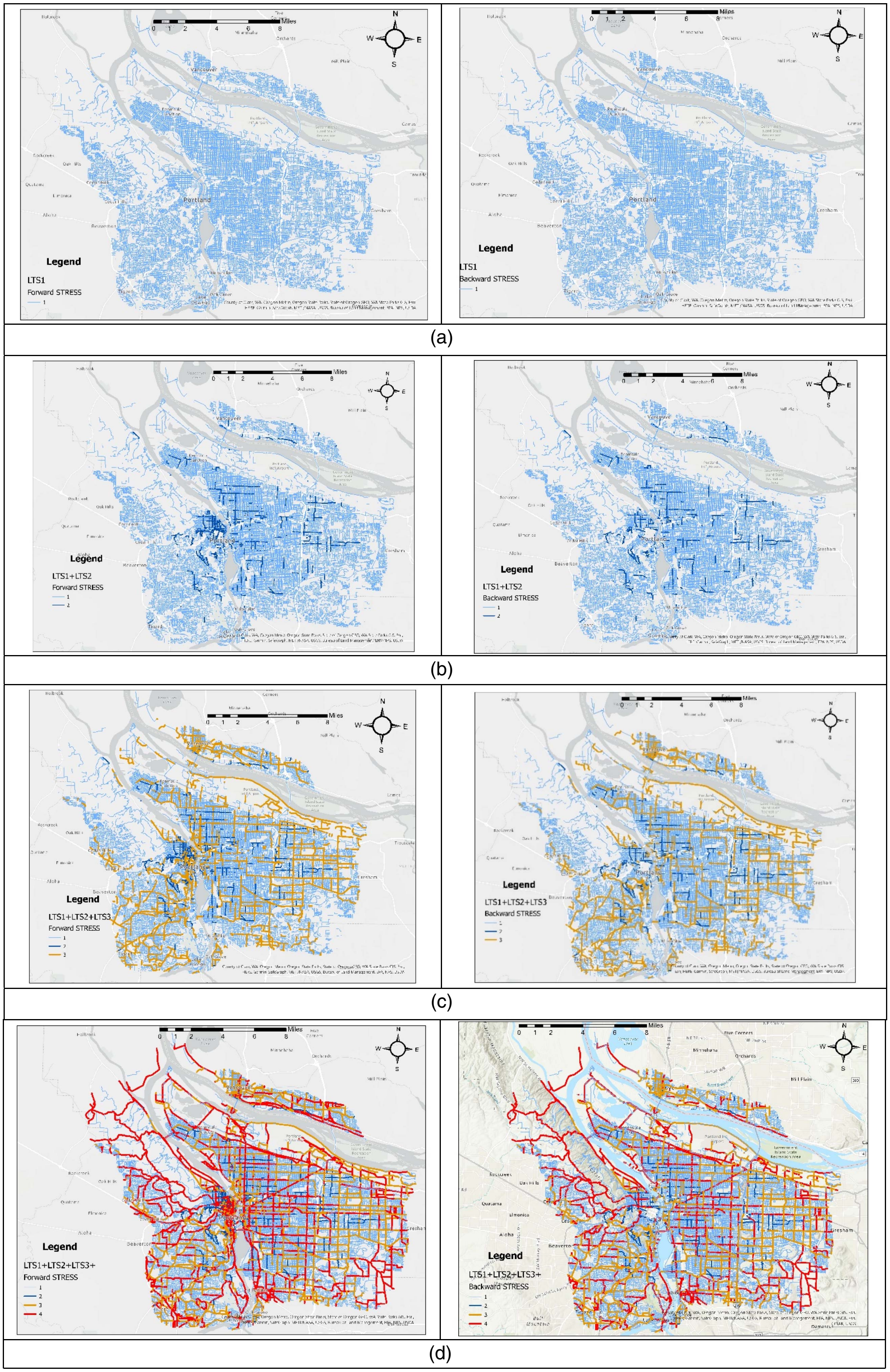

Fig. 1. Four different rider types of networkwide LTS in Portland: (a) children-friendly rider, network LTS 1; (b) basic adult rider networks, LTS 1+LTS 2; (c) enthused and confident rider networks, LTS 1+LTS 2+LTS 3; and (d) strong and fearless rider network, LTS 1+LTS 2+LTS 3+LTS 4. (Base map data from Oregon Metro, Oregon State Parks, State of Oregon, GEO, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPA, USDA.)

$$\gamma = \frac{E}{3(V-2)} \tag{3}$$

The eta index represents the average length per link. The eta index will decrease with the addition of new nodes. Complex networks should have a low eta index

$$\eta = \frac{L}{E} \tag{4}$$

where L = total network length (km).

The grid tree proportion/pattern (GTP) index identifies the network pattern, and the value varies from zero to one. A zero value indicates a tree pattern, and a one means a grid pattern

$$\text{GTP index} = \frac{E-V+P}{\left(\sqrt{v}-1\right)^2} \tag{5}$$

Level of Traffic Stress

Furth et al. (2012) defined LTS to evaluate link level acceptability for different rider types and evaluate and guide bicycle network planning; they defined LTS based on infrastructure geometry and average daily traffic (ADT). They classified traffic stress into the following four categories:

- LTS 1: suitable for most ages and abilities including children.
- LTS 2: most mainstream basic adults will tolerate.
- LTS 3: tolerated by cyclists who are "enthused and confident" but prefer having their own dedicated space for riding.
- LTS 4: represents a greater level of stress but can be tolerated by people having "strong and fearless" rider characteristics.

Furth et al. (2012) also assessed the traffic stress for three different link configurations. The mixed traffic criteria include the number of lanes per direction, effective ADT, and prevailing speed. The case of bike lanes and shoulders not adjacent to a parking lane considers the number of lanes per direction, bike lane width, and prevailing speed. For bike lanes alongside a parking lane, the criteria include bike lane reach (bike + parking lane width), number of lanes per direction, and prevailing speed.

This study used the pybna python package version 1.0.2 developed by Gardner et al. (2017) to calculate the network link stress. The pybna uses the general concepts of LTS developed by Furth et al. (2012). Compared with the official Mekuria LTS rating system, some deviations were made by Furth et al. (2012). For example, a bike lane blockage was not considered in pybna because this usually represents a temporary condition rather than the bicycle network configuration. Except for this minor deviation, no significant differences in segment stress between the two methods appear to exist. Moreover, the pybna package can apply assumptions for locations where necessary inputs (e.g., number of lanes, speed, bike lane width, and parking lane width) are not available.

Appendixes I and II provide the LTS classification criteria, and the details can be found on the pybna GitHub Page. This study relies on OSM network therefore assumes some values for missing data required to determine LTS as indicated in Table 1. These assumptions were based on the Portland Bureau of Transportation design guidelines (Wheeler et al. 2015) which provides standard value of bike lane, buffered bike lane and parking lane width across the city of Portland.

Lastly, this study develops the subnetwork link (SL) index, which represents the ratio of change in the number of subnetworks and links when the network transitions from one rider type to another rider type. This index measures how the network is connected for different rider types. The index value ranges from zero to one or is expressed as a percentage. For instance, a SL value of 20% for adult riders indicates that one subnetwork forms for every five links removed from the enthused and confident rider network to create the adult rider network

$$\text{SL} = \left|\frac{\text{Subnet}_j - \text{Subnet}_i}{\text{Link}_j - \text{Link}_i}\right|$$

Fig. 2 shows how a subnetwork impacts the connectivity for adult users. Enthused and confident users have network i, which

Table 1. Assumptions made in case of OSM missing data

Road class	Number of lanes	Speed [km/h (mi/h)]	Centerline	Buffered bike lane width [m (ft)]	Bike lane width (with/without parking) [m (ft)]	Parking lane width [m (ft)]
Primary	2	64 (40)	True	1.83 (6)	1.83 (6)/1.52 (5)	2.44 (8)
Secondary	2	64 (40)	True	1.83 (6)	1.83 (6)/1.52 (5)	2.44 (8)
Tertiary	1	48 (30)	True	1.83 (6)	1.83 (6)/1.52 (5)	2.44 (8)
Residential	0	40 (25)	False	N/A	N/A	N/A
Living street	0	32 (20)	False	N/A	N/A	N/A
Unclassified	0	40 (25)	False	N/A	N/A	N/A
Any others	1	40 (25)	True	N/A	N/A	N/A

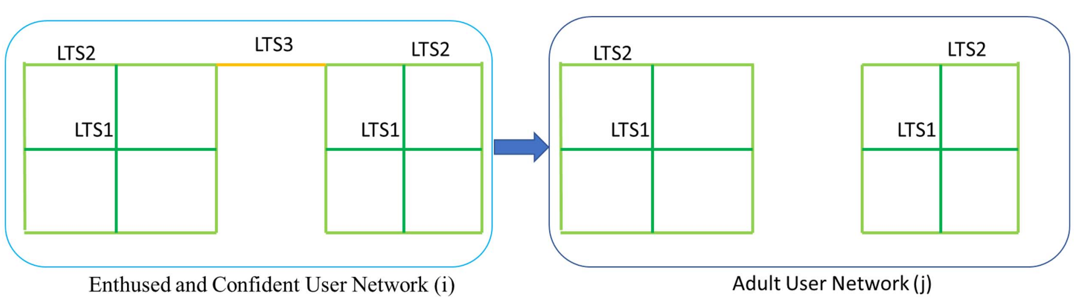

Fig. 2. Subnetwork concepts.

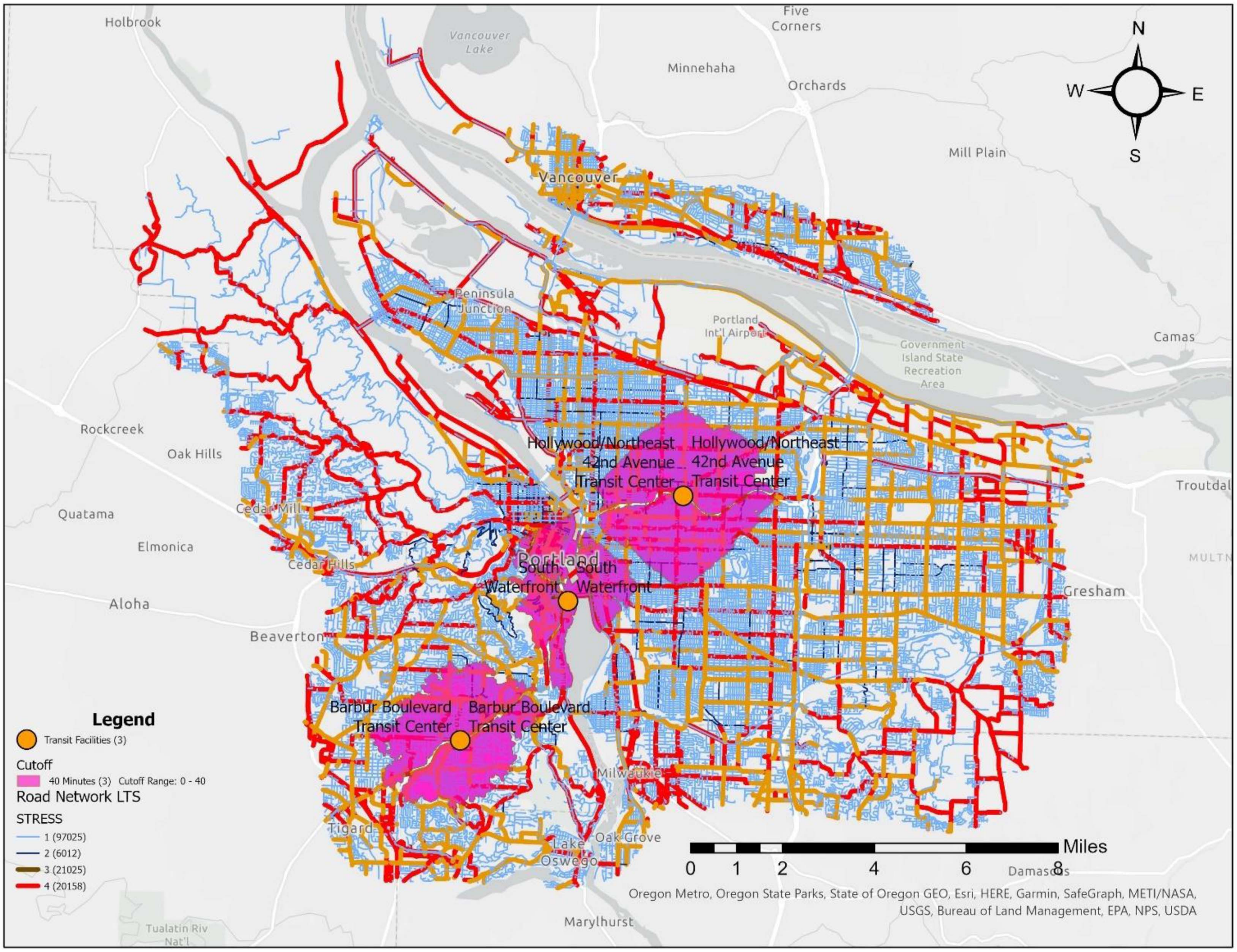

Fig. 3. Forty-min equivalent walking distance subnetworks from transit station with road link LTS for Portland. (Base map data from Oregon Metro, Oregon State Parks, State of Oregon, GEO, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPA, USDA.)

includes LTS 1, LTS 2, and LTS 3 links; however, the LTS 3 link is a barrier for adult users due to high stress. Without this LTS 3 link, the number of subnetworks increases from one to two because two disconnected subnetworks the left-side grid network from the right-side grid network in the adult user network j. The SL index for transitioning to the adult user network using the SL index equation is 100% because the removal of one link creates an additional subnetwork and makes the network 100% disconnected between the subnetworks.

Connectivity Measures for Subnetwork

In addition to the connectivity measures for the whole network, the study also defines average travel time by rider type for subnetwork analysis. This metric calculates the shortest-path distance for each rider type and converts the distance to travel time using the average bicyclist speed by rider types suggested by BikeLockWiki (2018) and Whitehouse (2019), which are 16 km/h (10 mi/h) for children riders, 23 km/h (14 mi/h) for adults, 32 km/h (20 mi/h) for enthused and confident riders, and 39 km/h (24 mi/h) for strong and fearless riders.

The analysis determines the shortest path from the transit station to each center of block (not block group) using the different rider-type subnetworks and records the travel distance to calculate the travel time. At the same time, the study tracks each of the blocks with a shortest-path route based on rider types to calculate the number of connected/disconnected blocks within the catchment area. If a block can be reached through the shortest path, then the analysis counts it as a connected block, but otherwise, it counts it as disconnected. The study totals the connected block populations as served populations and the total disconnected block population as unserved populations for each rider types. The analysis also calculates the median household income for connected blocks to evaluate the income level of the connected households by rider types. The baseline demographic median income was calculated by taking the median of all of the blocks presented in a particular subnetwork regardless of connectivity.

Transit Center Subnetwork Creation

The study introduces subnetwork analysis to represent the bicycle network within the geographic area served by a transit center; this transit center–based analysis supports the evaluation of multimodal connectivity, too. The study evaluates connectivity to transit centers, such as bus or train stations, because a bicycle can increase first-and-last-mile accessibility to the public transportation system. An effective bicycle network may increase public transportation access for all rider types and provide access to opportunities for all residents. Additionally, connecting the transit center to a well-connected bicycle network may attract more people to bike and reduce auto use, which will save energy, improve public health, and reduce traffic congestion and air pollution.

To illustrate the use of a subnetwork for evaluating critical inter-connectivity, the researchers select three major transit centers at South Waterfront (SWF), Hollywood/Northeast 42nd Avenue Transit Center (HTC), and Barbur Boulevard Transit Center (BBTC) with significantly different surrounding land uses and road networks (Fig. 3). The BBTC is located in a residential area without a formal grid structure, whereas the HTC represents an older mixed-use area with a formal grid structure. The SWF transit center is south of downtown and near the Willamette River. The researchers created the subnetworks using a 40-min walking distance equivalent polygon subnetwork to represent bicycle riders' first and last mile to transit stations.

Analysis and Results

The research team evaluated the entire Portland bike rider network and compared it with the subnetwork connectivity. Fig. 3 shows the full network LTS and the selected subnetworks for the three transit centers.

Table 2. Network connectivity evaluation parameters

Network	Rider types	Number of edges, E (% of the link)	Number of nodes, N	Sub-network, P	Percentage of SL[a]	Alpha index	Beta index	Gamma index	Eta index (m)	GTP index
Complete network	Strong and fearless	71,921 (100)	58,849	321	—	0.113	1.221	0.407	80	0.229
	Enthused and confident	61,854 (86)	53,052	1,024	6.98	0.093	1.166	0.389	81	0.187
	Adult	51,354 (71)	46,314	1,856	7.92	0.075	1.109	0.370	85	0.151
	Children	48,350 (67)	44,428	2,060	6.79	0.068	1.089	0.363	87	0.136
South Waterfront	Strong and fearless	4,468	3,984	133	—	0.071	1.106	0.369	47	0.147
	Enthused and confident	3,577	3,352	136	0.34	0.053	1.063	0.354	48	0.109
	Adult	2,968	2,913	186	8.21	0.041	1.017	0.339	48	0.085
	Children	2,548	2,554	189	0.71	0.036	0.997	0.333	50	0.075
Hollywood/Northeast 42nd Avenue Transit Center	Strong and fearless	6,204	4,642	28	—	0.171	1.336	0.446	69	0.352
	Enthused and confident	5,368	4,258	51	2.75	0.137	1.26	0.421	73	0.280
	Adult	4,834	3,962	67	3.00	0.119	1.220	0.407	76	0.245
	Children	4,457	3,746	91	6.37	0.107	1.190	0.397	77	0.222
Barbur Boulevard Transit Center	Strong and fearless	3,131	2,723	16	—	0.078	1.150	0.384	76	0.162
	Enthused and confident	2,876	2,593	44	0.85	0.063	1.109	0.370	78	0.131
	Adult	2,195	2,105	113	10.13	0.048	1.043	0.348	86	0.101
	Children	2,079	2,022	119	5.17	0.043	1.029	0.343	88	0.091

[a]Percentage of SL $= |(\text{Subnet}_j - \text{Subnet}_i)/(\text{Link}_j - \text{Link}_i)| \times 100$.

Table 3. Number (percentage) of connectivity of crossings (junctions) between LTS

Network	Stress level	LTS 1	LTS 2	LTS 3	LTS 4	Total
Complete network	LTS 1	97,025 (40)	13,733 (6)	37,686 (15)	33,161 (14)	181,605 (75)
	LTS 2	—	6,012 (2)	2,553 (1)	2,277 (1)	10,842 (4)
	LTS 3	—	—	21,025 (9)	9,769 (4)	30,794 (13)
	LTS 4	—	—	—	20,158 (8)	20,158 (8)
	Total	—	—	—	—	243,399 (100)
South waterfront transit network	LTS 1	4,975 (33.1)	1,103 (7.3)	1,800 (12.0)	1,766 (11.8)	9,644 (64.2)
	LTS 2	—	833 (5.5)	425 (2.8)	427 (2.8)	1,685 (11.2)
	LTS 3	—	—	1,198 (8.0)	778 (5.2)	1,976 (13.2)
	LTS 4	—	—	—	1,713 (11.4)	1,713 (11.4)
	Total	—	—	—	—	15,018 (100)
Hollywood/Northeast 42nd avenue transit center network	LTS 1	8,876 (38.9)	1,967 (8.6)	2,905 (12.7)	4,427 (19.4)	18,175 (79.7)
	LTS 2	—	745 (3.3)	293 (1.3)	273 (1.2)	1,311 (5.7)
	LTS 3	—	—	1,056 (4.6)	620 (2.7)	1,676 (7.3)
	LTS 4	—	—	—	1,654 (7.2)	1,654 (7.2)
	Total	—	—	—	—	22,816 (100)
Barbur Boulevard transit center network	LTS 1	4,136 (40.4)	347 (3.4)	2,013 (19.7)	985 (9.6)	7,481 (73.1)
	LTS 2	—	232 (2.3)	104 (1.0)	53 (0.5)	389 (3.8)
	LTS 3	—	—	1,344 (13.1)	508 (5.0)	1,852 (18.1)
	LTS 4	—	—	—	508 (5.0)	508 (5.0)
	Total	—	—	—	—	10,230 (100)

This study considered nine different network parameters, as indicated in Table 2, to evaluate the complete and subnetwork connectivity. The authors stratified the evaluation by rider types for each network and subnetwork and generate the results using the python Networkx (Hagberg et al. 2008) and Geopandas libraries (Jordahl 2014).

The complete network evaluation indicated that 67% of the total links (average length 87 m) are suitable for children riders with a GTP index of 0.136, gamma index of 0.363, and alpha index of 0.068. These indices indicate that a large number of links are not fully interconnected for this user category because a fully interconnected grid network should have a GTP/alpha/gamma value of 1.0. The child-friendly network has 2,060 subnetworks in the Portland network, meaning a large portion of the network is disconnected for continuous rides. The proportion of subnetworks for enthused and confident riders lost almost 8% of subnetworks when transitioning to basic adult riders. The strong and fearless riders' network has lower connectivity, with 321 subnetworks.

The HTC subnetwork is more connected compared with the complete network. Its GTP index exceeds the values for the complete and other subnetworks and varies from 0.222 to 0.352 for different users. It indicates that the HTC subnetwork has more of a grid pattern than others with shorter link lengths (average length varies from 47 to 50 m). This subnetwork is a highly connected and complex network pattern for all rider types because its gamma index ranges from 0.446 to 0.397 and beta value exceeds 1.0. All nodes have more than a connected link (beta index >1), indicating that all considered networks showed medium complexity rather than exhibiting simple or tree structures. Even as travel stress removes some of the links in the HTC subnetwork, it does not cause the formation of a large proportion (≤ 3%) of subnetworks until the children subnetwork, which exceeds 6%.

Although connectivity within the SWF and BBTC subnetworks remains good for the enthused and confident and strong and fearless riders, the basic adult and children rider types face limited connectivity. The transition from the enthused and confident rider network to the basic adult network produces more than one subnetwork for every 10 links removed, which causes the alpha index to drop by almost 25%. The Willamette River causes the GTP in the SWF subnetwork to drop below all other subnetworks and the overall network.

Table 3 presents the connectivity in the form of a 4 × 4 matrix for LTS connection for complete and subnetworks. The study used the ArcGIS Pro Space version 3.0.0 Time matches tool to count the number of links present in each intersection by direction and by LTS to cover all possible approaches at the intersection, except U-turn connectivity between the opposite direction of the same roads.

The analysis indicated that although LTS 1 links represent 67% of the overall network, almost 40% of their total connections occur with LTS 3 and LTS 4 facilities, which limit connectivity to lower levels of LTS and thus may represent a barrier to riders not captured by the previous metrics. LTS 2 facilities only represent 4% of total links, but a quarter of their connections occur with LTS 4 facilities. Overall, 30% of connections represent abrupt two category shift in level of traffic stress. The BBTC subnetwork exhibits a similar pattern as the overall network, but closer to a third of the total connections in the HTC subnetwork appear abrupt, with almost 20% of the overall connections occurring between LTS 1 and LTS 4 facilities. The abrupt connections shrink to about 25% of the total connections in the SWF subnetwork. These unbalanced connections represent potential barriers within the network.

Overall, more than one-third of the connections are children-friendly and almost 50% of the network connections are accessible for basic adult riders for the network and all subnetworks.

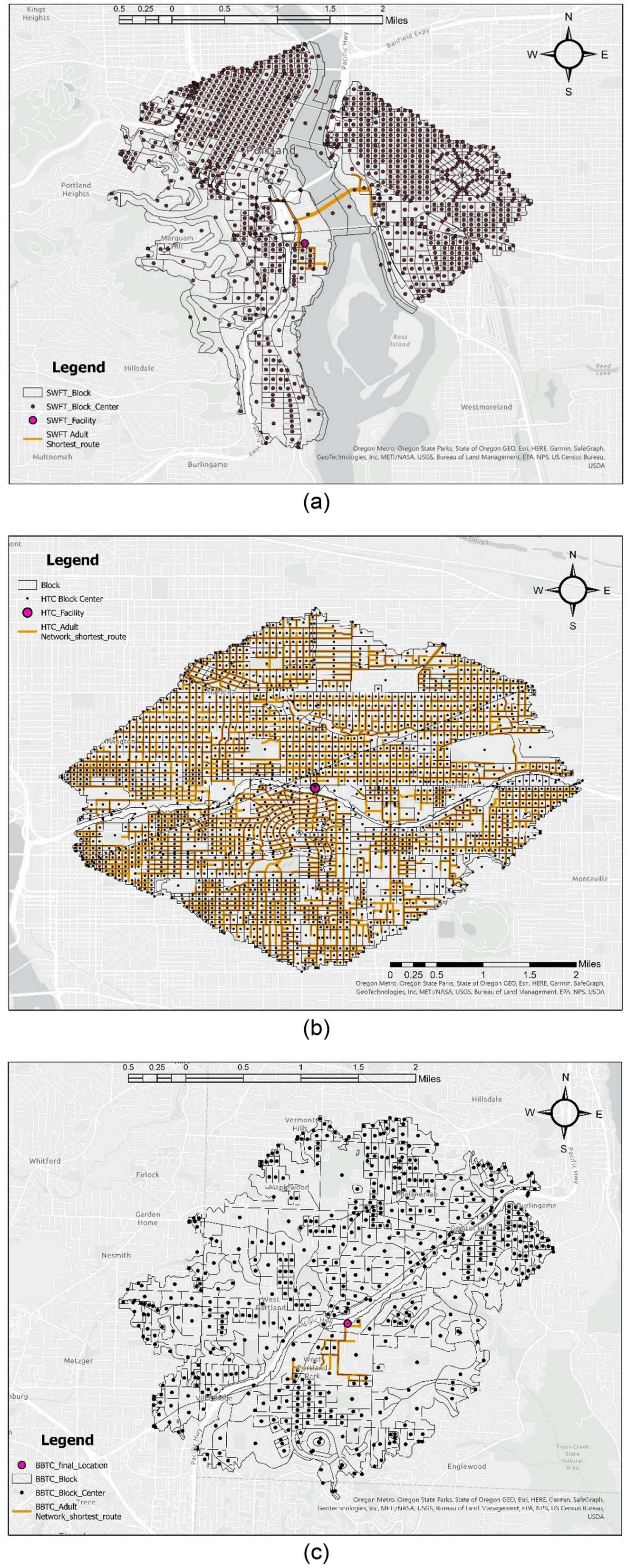

Fig. 4. Connectivity of block and transit center through different LTS using shortest-path algorithms: (a) SWFT adult subnetwork shortest path; (b) HTC adult subnetwork shortest path; and (c) BBTC adult subnetwork shortest path. (Base map data from Oregon Metro, Oregon State Parks, State of Oregon, GEO, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPA, USDA.)

Table 4. Travel time connection by rider types

	South waterfront transit network (min)				Hollywood/Northeast 42nd avenue transit center network (min)				Barbur Boulevard transit center network (min)			
Rider types	Minimum	Maximum	Standard deviation (Std.)	Average	Minimum	Maximum	Standard deviation (Std.)	Average	Minimum	Maximum	Standard deviation (Std.)	Average
Strong and fearless	0.03	10.25	2.16	5.57	0.10	5.59	1.26	3.72	0.50	10.35	2.04	5.03
Enthused and confident	0.04	7.48	1.44	5.35	0.11	9.79	1.75	4.91	0.65	20.49	4.40	10.13
Adult	0.06	4.66	1.38	1.99	0.16	26.84	5.82	12.68	0.93	4.30	1.21	2.68
Children	0.08	6.85	1.90	2.61	0.23	17.78	3.61	10.14	1.30	6.02	1.70	3.75

Table 5. Connected/disconnected and served/unserved population connection by rider types

	South waterfront transit network				Hollywood/Northeast 42nd avenue transit center network				Barbur Boulevard transit center network			
Rider types/parcel connectivity	Connected block (#)	Disconnect block (#)	Served population (%)	Unserved population (%)	Connected block	Disconnected block	Served population (%)	Unserved population (%)	Connected Block	Disconnected block	Served population (%)	Unserved population (%)
Strong and fearless	1,016	53	96.11	3.89	1,949	11	99.53	0.47	594	7	99.20	0.80
Enthused and confident	483	586	31.73	68.2	1,925	35	97.74	2.26	563	38	93.39	6.61
Adult	27	1,042	8.41	91.59	1,886	74	95.71	4.29	16	585	5.34	94.66
Children	21	1,048	8.41	91.59	680	1,280	33.12	66.88	16	585	5.34	94.66

Table 6. Demographics coverage by rider types

Rider types/demographics	Median household income (USD)		
	South waterfront transit network	Hollywood/ Northeast 42nd avenue transit center network	Barbur Boulevard transit center network
Baseline demographic	69,707	81,857	86,509
Strong and fearless	56,150	81,958	86,115
Enthused and confident	60,922	82,147	85,528
Adult	72,429	82,322	70,525
Children	71,733	73,693	70,525

The remaining 50% of network connections pose some risk for children and basic adult riders, which may indicate the need for bicyclist traffic safety support when crossing these junctions.

This study measured the connectivity between transit station and its surrounding block residents to understand the network connectivity variation for different rider types and their demographics. Fig. 4 shows example of the connectivity between transit stations and center of a block through the adult network (LTS 1+LTS 2) shortest paths for each of the subnetworks. The figure indicates that the HTC adult network is highly connected (1,886 blocks out of 1,949) compared with the South Water Front Transit Centre (SWFTC) network (27 blocks out of 1,016), and BBTC (16 out of 594). The research team tracked the block GISJOIN ID for each shortest path, and calculated the travel time, connected/disconnected block, served/unserved population, and median income for each of the subnetworks and rider types. Appendix I presents the results of this analysis.

Tables 4–6 describe the travel time, geography, and sociodemographic connections for different rider types at three different subnetworks. The average travel time [Fig. 4(a)] from the SWF transit center to home is 5.57 min for strong and fearless riders who can travel to or from 1,016 blocks out of 1,069 blocks (95%) because they have the most complete form of the network. Only strong and fearless riders flourish in this subnetwork because the population with access drops from 96% to 32%. The average travel times for lower-skilled riders decreased in all cases where a significant decrease in access occurs between rider types because the only members of the lesser-skilled rider type with access will be close to the transit center.

The HTC subnetwork includes 1,960 blocks [Fig. 4(b)], which is higher than the other two subnetworks. A basic adult rider can reach most of these blocks (1,886 out of 1,960) in an average of 12.7 min and a maximum of 26.8 min. As travel times approach the maximum value in this subnetwork, many potential riders may decide that the travel time exceeds their threshold for accessing transit. This subnetwork also has children-friendly bikeways that provide access to about a third of the blocks. The somewhat lower-income households appear in the neighborhoods with child-friendly access to transit.

The BBTC subnetwork is in the southwest of the city of Portland, which is mostly a residential area. This subnetwork comprises 601 blocks, which can be reached within a maximum of 20.59 min for enthused and confident riders. Although this network is highly connected for strong and fearless and enthused and confident riders, this network is not suitable for basic adults and children due to the lack of available low-stress bicycle routes from home to the transit station. Only 5.34% the basic adult population has accessibility to the transit station. The entire network's average travel time varies from 2.68 to 10.13 min.

Overall, the HTC subnetwork has better access with the transit center to address all rider types' last- and first-mile needs. The alpha indices and GTP significantly exceed the values of the other subnetworks for all rider types; therefore, more basic adult riders and children may access the transit center and the strong and fearless and enthused and confident riders have shorter travel times to the transit center. The other transit center subnetworks have very poor access to basic adult and child riders. The limited access for children and primary adult riders to the SWF favors higher-income households. Overall, adult users with higher median income enjoy better connectivity compared with lower-income adult users [Fig. 4(c)]. City and agencies need to work with similar networks to determine where more low-stress bicycle links need to be added to the network.

Table 7. Confusion matrix for the length (percentage) of road length between city and OSM speed limit

City speed limit [km/h (mi/h)]	OSM speed limit [km/h (mi/h)]											
	0	16 (10)	24 (15)	32 (20)	40 (25)	48 (30)	56 (35)	64 (40)	72(45)	80 (50)	89 (55)	97 (60)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16 (10)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24 (15)	0.00	0.00	2.08 (0.06%)	1.51 (0.05%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32 (20)	51.72 (1.55%)	0.10 (0.003%)	6.24 (0.19%)	2,430.87 (72.64%)	68.27 (2.04%)	3.54 (0.11%)	5.01 (0.15%)	3.75 (0.11%)	0.84 (0.02%)	0.05 (0.01%)	0.00	0.00
40 (25)	1.75 (0.05%)	0.00	0.00	18.35 (0.55%)	243.65 (7.28%)	15.91 (0.48%)	2.84 (0.09%)	0.02 (0.0004%)	0.00	0.00	0.00	0.00
48 (30)	1.51 (0.05%)	0.00	0.00	1.32 (0.04%)	5.49 (0.16%)	199.66 (5.97%)	20.49 (0.61%)	0.26 (0.01%)	0.10 (0.03%)	0.00	0.00	0.00
56 (35)	4.65 (1.44%)	0.00	0.00	1.09 (0.03%)	1.26 (0.04%)	4.46 (0.13%)	96.34 (2.88%)	14.37 (0.43%)	0.43 (0.01%)	0.00	0.27 (0.01%)	0.00
64 (40)	2.62 (0.08%)	0.00	0.00	0.50 (0.01%)	0.22 (0.01%)	2.22 (0.07%)	2.03 (0.06%)	64.25 (1.92%)	0.53 (0.02%)	0.08 (0.002%)	0.00	0.02 (0.001%)
72 (45)	3.98 (0.12%)	0.00	0.00	1.17 (0.04%)	0.77 (0.02%)	0.10 (0.03%)	0.64 (0.02%)	0.92 (0.03%)	50.23 (1.50%)	0.29 (0.01%)	0.00	0.00
80 (50)	0.00	0.00	0.00	0.05 (0.001%)	0.00	0.00	0.00	0.00	0.24 (0.01%)	0.84 (0.03%)	0.00	0.00
89 (55)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32 (0.01%)	0.00	0.00	6.05 (0.18%)	0.00
97 (60)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Conclusion and Discussion

This study used the city of Portland's network as a case study to implement the graph theory and LTS concept to demonstrate connectivity for different rider types. The results indicated that although Portland is a bike-friendly city, about a third of the links remain unsuitable for children, and basic adult riders will find 29% of the links too stressful. The HTC subnetwork's high alpha and GTP indices indicate its grid pattern makes it more connected than the riverside (SWF) and residential (BBTC) networks. The entire network has more than 50% of links connected with either LTS 3 or LTS 4, making the network potentially unsafe for children and basic adult users.

The connectivity of the road network varied across the entire network, and travel time from home to transit station varied based on connectivity for each rider type. SWF and BBTC subnetwork transit stations rarely connect with home for basic adult and children riders, which their low alpha and GTP indices support. In particular, 96.22% of blocks of the HTC subnetwork are connected with the transit station, and basic adult users need on an average 12.68 min to access the station, whereas only 2.53% of the SWF blocks and 2.66% of the BBTC blocks are connected with transit station for basic adult riders. People living in these latter two locations are not getting facilities compared with people in downtown because their network is not well-connected with the transit station through their desired routes. The new SL index effectively captures the impact of removing links from the network and the corresponding creation of subnetworks; future system improvements may target the links critical to preventing the formation of subnetworks.

The new aggregate measure of network discontinuity introduced by the researchers effectively captures the proportion of junction challenges that different rider types may face. This provides an easy-to-represent metric that may be used to compare the willingness of lower-skilled riders to travel far from their home regardless of network accessibility metrics. The simple analysis strategy demonstrated in this study can be implemented in any other city to understand network quality and its impact on access to opportunities.

The study has limitations that can be filled in future research. This research depended on data available in OSM and assumed some values for some missing data required to determine LTS (e.g., number of lanes, speed, presence of centerline, and bike and parking lane width), which may impact the connectivity evaluation results. In addition, because network coverage and speed represent the important parameters for determining the LTS, this study validated the speed data in the OSM network with city-provided speed values. Results showed that the OSM network of 3,925.7 km (2,439.3 mi) for only Portland City without the 2.41-km (1.5-mi) extended buffer included more coverage than the city-provided network [3,346.24 km (2,079.26 mi)].

The speed comparison only considered the OSM links that match with the city road network links and calculated the percentage of matched and deviated speeds based on road length kilometers for 12 different speed limit categories. The results indicated (Table 7) that 92.46% (3,093.96 out of 3,346.24 km) of the OSM links had the same speeds as the city-provided speed limits, which indicates that 7.54% of the road length had a different speed limit from the city-provided speed. A future study should investigate how these differences in speed and network coverage impact the LTS calculation.

Moreover, the study only considered Portland and may be extended to other geographic areas in the future and compare the network connectivity between cities. Although this study focused on evaluating the network link connectivity due to the riders' constant exposure to traffic stress, future studies should expand the network metrics to include the crossing LTS to include comparisons between the network metrics with and without the crossing LTS. The slope effects on LTS were not considered for this study, which can also be integrated in a future study. Future investigations may need to create travel-time-driven subnetworks that assess the total population with access within a given access time.

Appendix I. Stress on Segments for Primary, Secondary, and Tertiary Roads

Facility type	Speed [km/h (mi/h)]	Number of lanes	Parking	Facility width [m (ft)]	Stress
Cycle track	—	—	—	>	Low
Buffered bike lane	>56 (35)	>1	—	>	High
		1	—	>	High
	56 (35)	>1	—	>	High
		1	Yes	>	High
			No	>	Low
	48 (30)	>1	Yes	>	High
			No	>	Low
		1	—	>	Low
	≤40 (25)	—	—	>	Low
Bike lane without parking	>48 (30)	—	—	>	High
	40 (25) to 48 (30)	>1	—	>	High
		1	—	>	Low
	≤32 (20)	>2	—	>	High
		≤2	—	>	Low
Bike lane with parking	—	—	>	≥4.57 (15)	Treat as buffered lane
				3.96 (13) to 4.27 (14)	Treat as bike lane without parking
				<3.96 (13)	Treat as shared lane
Shared lane	≤32 (20)	1	—	>	Low
		>1	—-	>	High
	>32 (20)	—	—	>	High

Source: Data from Gardner et al. (2017).

Appendix II. Stress on Segments for Residential and Unclassified Roads

Facility type	Speed [km/h (mi/h)]	Number of lanes	Parking	Road width [m (ft)]	Stress
Cycle track	—	—	—	>	Treat as tertiary
Buffered bike lane	—	—	—	>	Treat as tertiary
Combined bike/parking lane	—	—	—	>	Treat as tertiary
Bike lane	—	—	—	>	Treat as tertiary
Shared lane	≥48 (30)	—	—	>	Treat as tertiary
	40 (25)	>1	—	>	Treat as tertiary
		1	One side or none	≥5.79 (19)	Low
				5.49 (18)	High
				<5.49 (18)	High
			Both sides	≥8.23 (27)	Low
				7.92 (26)	High
				<7.92 (26)	High
	≤32 (20)	>1	—	>	Treat as tertiary
		1	One side or none	≥5.79 (19)	Low
				5.49 (18)	Low
				<5.49 (18)	Low
			Both sides	≥8.23 (27)	Low
				7.92 (26)	Low
				<7.92 (26)	Low

Source: Data from Gardner et al. (2017).
Note: Low stress means LTS 1 or LTS 2, and high stress means LTS 3 or LTS 4. The details of specific LTS values can be found here.

Data Availability Statement

The data and python code generated by the researchers during and/or analyzed during the current study is available online at https://github.com/mintu07ruet/Evaluation-of-Bicycle-Network-Connectivity-Using-Graph-Theory-and-Level-of-Traffic-Stress-.

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