A Tool for Measuring and Visualizing Connectivity of Transit Stop, Route and Transfer Center in a Multimodal Transportation Network

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Abstract

Agencies at the federal, state and local level are aiming to enhance the public transportation system (PTS) as one alternative to alleviate congestion and to cater to the needs of captive riders. To effectively act as a viable alternative transportation mode, the system must be highly efficient. One way to measure efficiency of the PTS is connectivity. In a multimodal transportation system, transit is a key component. Transit connectivity is relatively complex to calculate, as one has to consider fares, schedule, capacity, frequency and other features of the system at large. Thus, assessing transit connectivity requires a systematic approach using many diverse parameters involved in real-world service provision. In this paper, we use a graph theoretic approach to evaluate transit connectivity at various levels of service and for various

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components of transit, such as nodes, lines, and transfer centers in a multimodal transportation system. Further, we provide a platform for computing connectivity over large-scale applications, using visualization to communicate results in the context of their geography and to facilitate public transit decision-making. The proposed framework is then applied to a comprehensive transit network in the Washington-Baltimore region. Underpinning the visualization, we introduce a novel spatial data architecture and Web-based interface designed with free and open source libraries and crowd-sourced contextual data, accessible on various platforms such as mobile phones, tablets and personal computers. The proposed methodology is a useful tool for both riders and decision-makers in assessing transit connectivity in a multimodal transit network in a number of ways such as the identification of under-served transit areas, prioritization and allocation of funds to locations for improving transit service.

Keywords: transit connectivity, graph theory, public transportation, multimodal transportation system, GIS

1. Introduction

Transit service is widely used as a means of transport for captive riders in urban and suburban areas. The connectivity of transit is crucial in providing adequate levels of service to these riders. However, measuring connectivity can be a complex and elusive task. As context, it is important to understand that analyzing a transit network is significantly different from analyzing other transport networks such as a highway. For example, links in a multimodal transit network have different characteristics from those in a road network. While a link in a highway network is a physical segment that connects one node to another, a link in a multi-modal transit network is part of a transit line that serves a sequence of transit stops (nodes). Since different transit lines can serve a single stop, multiple transit links may exist between nodes in a multi-modal transit network. In contrast, in the case of a highway network, only one link exists between two nodes. Moreover, transit nodes are composed of a different set of characteristics than highway nodes. While some defining characteristics of transit links are common to both types of networks (such as speed and capacity), their meaning in the context of connectivity may be quite different. Interpretation of properties of these networks may also vary considerably. Indeed, some terms like headway and frequency are completely foreign to road networks, but are critical characteristics of transit networks.

Among riders, transit choice between modes of travel depends on two principal components. First, the number of factors related to service quality, such as walking distance, in-vehicle travel time, waiting time, number of destinations served and number of transfers needed to reach destinations makes transit connectivity a multidimensional problem. Second, a transit system consists of many different routes, and determining the extent to which routes are integrated and coordinated so that the transit system is connected is an important task (Lam and

Schuler 1982). Because the structure of a public transit network is critical in determining its performance, coverage, and service of the network, the network connectivity that structure supports can be used as a measure to study the performance of the transit system, which will assist decision-makers in prioritizing transit investments and deciding which stops or lines need immediate attention in regard to operation and/or maintenance (Hadas and Ceder 2010). Network structure is therefore a significant operational consideration: in this context, connectivity is one of the index measures that can be used to quantify and evaluate transit performance (Borgatti 2005).

Measures of transit connectivity can be used for a number of purposes. First, in a public or quasi-public agency, connectivity can be used to quantify transit stop and route performance and to evaluate overall system performance so as to direct public spending in the most efficient manner. Second, in a rural or suburban area, where exact information on transit ridership, boardings, and alightings are not always available (such data are generally obtained from a sophisticated travel demand model or from an advanced transit system where smart cards are used to keep track of revenues), connectivity measurement can be used to obtain a measure of performance for developing service delivery strategies. Third, connectivity can serve as a performance measure in a large-scale urban multi-modal transit network containing local buses, express buses, metro, local light rail, regional light rail, bus rapid transit, and other transit services, where such services are provided by multiple public and private agencies with little coordination. In light of these uses for connectivity information, we introduce a system that can be developed for small and medium scale transit agencies with functionality that provides (1) a methodological framework for transit connectivity, (2) tools for empirical measurement of connectivity on transit data, and (3) a robust visualization and exploration tool for users and decision-makers to explore connectivity in complex multi-modal systems.

The research presented in this paper offers a unique approach to measuring transit connectivity, particularly for applications where transit assignment models or ridership tracking tools are not available. The key innovations that we present are as follows. First, the method incorporates a graph theoretic approach to determine the performance of large-scale multimodal transit networks by quantifying measures of connectivity at multiple levels and components, including node, line and transfer center. This is achieved through an assessment of connectivity that incorporates unique qualities of each transit line and stop, as well as measures of accessibility. Second, by combining these criteria into a single connectivity index, a quantitative measure of transit performance is developed that goes beyond the traditional measure of centrality. The new connectivity index significantly extends the set of performance analysis tools that decision makers can use to assess the quality of a transit system. Third, we provide an operational tool that can be delivered via the Web to a variety of devices, built with the flexibility to scale to wide-areas of geography and large volumes of transit data. The tool is based on free and open source libraries and also makes use of crowd-sourced spatial data in the public domain.

The next section presents a literature review highlighting the evolution of connectivity measures in past research, followed by the identification of gaps in current understanding and technique to which this research makes a significant contribution. The methodology section describes a step-by-step process of calculating transit connectivity. A case study shows how the concept can be applied in real world applications. The next section shows how the results of the study can be used as a robust, operational, network visualization tool. Finally, findings of the study are discussed in the conclusions section.

2. Literature Review

One of the more common measures of connectivity is known as the degree of centrality. Centrality measures have been studied extensively in past research (Bell et al., 1999), however, their application to public transit is rare. Degree centrality is the most widely used measure of connectivity in the literature. This measure is calculated by summing the total number of direct connections from a particular node to other nodes in a system, then dividing by the total number of system nodes, minus one. The use of degree centrality spans multiple disciplines including *network and graph theory* (Freeman 1978; Costenbader and Valente 2003; Borgatti 2005; Martinez and Porter 2006; Latora and Marchiori 2007); *computer and information science* (Bell et al. 1999; White 2003; Costenbader and Valente 2003; Liu et al. 2005); *gene-disease research* (Aittokallio and Schwikowski 2006; Özgür et al. 2008); and *epidemiology* (Guimerà et al. 2005; Junker et al. 2006). Connectivity is also used in *shortest path estimation* (Borgatti 2005; Ahmed et al. 2006; Opsahl et al. 2010); and *transportation network analysis* (Jiang and Claramunt 2004; Guimerà et al. 2005; Derrible and Kennedy 2009).

The degree centrality $D_c(n)$ is straightforward: it is used to count the number of direct connections a node has to other nodes in the network, but does not account for the quality of the connection or indirect accessibility to other nodes. A more advanced measure of connectivity is known as eigenvector centrality. This measure acknowledges that not all connections are equal. It assigns relative 'scores' to all nodes in the network based on the principle that connections to high-scoring nodes contribute more to the score of the node in question than equal connections to low-scoring nodes. The eigenvector centrality succeeded the development of degree centrality and is used for a number of studies including research on network and graph theory (Ruhnau 2000; Bonacich and Lloyd 2001; Bonacich 2007) and weighted or imbalanced networks in the social sciences (Moore et al. 2003; Newman 2004; Carrington et al. 2005; Estrada and Rodríguez-Velázquez 2005; Ahmed et al. 2006; Garroway et al. 2008).

Another formulation of connectivity is called closeness centrality. In this measure, nodes with low closeness scores are short distances from others and will tend to be more accessible. Nodes with higher closeness scores, meanwhile, represent longer distances from other nodes and are not easily accessible. In topology and related fields in mathematics, closeness is one of the basic concepts in a topological space.

Betweenness centrality is defined as the share of times that a specific node relies on another specific node (whose centrality is being measured) in order to reach a third node via the shortest path. In other words, betweenness centrality essentially counts the number of geodesic paths that pass through a node. Betweenness centrality has been adopted by researchers in network and graph theory (White and Borgatti 1994; Otte and Rousseau 2002; Newman 2005; Crucitti et al. 2006); computer and information science (Bell et al. 1999; Goh et al. 2003; Barthlemy 2004; Liu et al. 2005); and to find the shortest path through a set of edges and vertices (Brandes 2001; Ahmed et al. 2006).

Previous node indices did not take into account transit characteristics. Park and Kang (2011) and Mishra et al. (2012) introduced transit characteristics into node centrality measures and proposed a connectivity index as a true measure of a transit node (Park and Kang 2011; Mishra et al. 2012). The Connectivity index of a node can be defined as the sum of connecting powers of all lines crossing through a node *n*. The total connecting power of a node is the multiple of connecting power of a line at node *n*. The characteristics of a link contain the performance of a series of nodes in that link. A link is a part of the transit route, which in turn is a function of the speed, distance, frequency, headway, capacity, acceleration, deceleration, and other factors. Since a route will contain both in-bound and out-bound, the line performance will in part depend upon the directionality of the transit route, that is, whether the line is circular or bidirectional. The total connecting power of line *l* at node n is the average of outbound and inbound connecting power. In this paper, we demonstrate a more advanced connectivity measure that incorporates the quantification of underlying socio-economic data and the cost of transfers in a multimodal system.

3. Motivation

Many measures of transit service and accessibility have been put forth in the literature, but few offer a metric to measure the quality of service and performance of a large multi-modal regional transit system. Building these metrics requires significant amounts of data: not only about the transit system, but also of the complete demographics of the service area that it serves. Other methods require full transportation demand and transit assignment models: tools that are prohibitively expensive for many localities.

Nevertheless, measuring transit system performance and service quality at many different levels is vital to transit management and planning functions. Agencies with an objective to improve the transit system using external funds often make the case that the project will make worthwhile improvements to the overall system performance. At the same time, agencies in the quest for investigating the potential effect of removing a stop, group of stops or transit line from service must know the potential effect it will have on the performance of the system. In the absence of complex transportation demand models, this information is nearly impossible to obtain. A methodology that reduces the need for heavy data analysis yet provides relevant and straightforward information on system performance is critical to the decision-making process. Transit planning agencies may also be interested in applying such an index to determine the best use of land surrounding well-connected transit nodes. Beyond Transit Oriented Development (TOD) style plans, the connectivity index provides a way for planners to measure passenger acceptance rates and accessibility for a single node based on its access within an entire multi-modal regional transportation network.

The objectives of this paper are several-fold, with the overall goal of providing a strong measure of system performance with the lowest possible data requirements. First, we seek to construct a list of node- and link-based commonly encountered flow processes and define them in terms of a few underlying characteristics beyond traditional attributes available in the existing literature (Mishra et al. 2012). Second, we propose a set of best-suited transit connectivity measures. Third, we examine these measures by running simulations of flow processes and comparing the results in a real world case study. Fourth, we suggest best practices that may be adopted for decision-making. Fifth, we develop a tool to operationally quantify connectivity of a public transportation system, and to communicate and visualize it via a Web-based cartographic interface that caters to a diverse range of scenarios. The notations used throughout the paper are introduced below, followed by a description of the proposed methodology and examples that demonstrate the concept.

Notation		Explanation
D_l^i	:	Inbound distance of link *l*
D_l^o	:	Outbound distance of link *l* from node *n* to destination
F_l	:	Frequency of line *l*
H_l	:	Daily hours of operation of *l*
L_{n,n_1}	:	Shortest distance between node n_1 to *n*

$P_{l,n}^{i}$		Inbound connecting power of link *l*
$P_{l.n}^{o}$	:	Outbound connecting power of link *l*
$P_{l,n}^{t}$	:	Total connecting power of line *l* at node n
S_R	:	Set of stops in region *R*
S_l	:	Set of stops in line *l*
S_σ	:	Set of stops in region center σ
V_l	:	Average Speed of link *l*
n_0	:	Initial stop
$t_{n_1,n}$	:	Transfer time from n_1 to *n*
δ_{n_1,n_2}	:	Total number of paths between n_1 and n_2
$\delta_{n_1,n_2}(n)$	:	Number of paths exist between n_1 and n_2 those pass through *n*
δ_{np}	:	A binary indicator variable for determining the degree centrality, which takes the value of 1 when node *p* is dependent on *n*, and 0 otherwise
θ_R	:	Connectivity index for region *R*
θ_l	:	Connectivity index for line *l*
θ_n	:	Connectivity index for node *n*
$\rho_{n_1,n}$	:	Passenger acceptance rate from node n_1 to *n*
ρ_R	:	Density measure for region *R*
a	:	Parameter for passenger acceptance rate
b	:	Parameter for passenger acceptance which is sensitive to travel time
L	:	Link
N	:	Node
N	:	Network system
P	:	Node dependent on *n*
α	:	Scaling factor coefficient for Capacity of line *l*
β	:	Scaling factor coefficient for Speed of line *l*
γ	:	Scaling factor coefficient for distance of line *l*
$A_{l,n}$	:	Activity density of line *l*, at node *n*
ϑ	:	Scaling factor for activity density
$H_{l,n}^{z}$	:	Number of households in zone *z* containing line *l* and node *n*
$E_{l,n}^{z}$	:	Employment for zone *z* containing line *l* and node *n*
$\Theta_{l,n}^{z}$	:	Area of *z* containing line *l* and node
Θ_{l}^{n}	:	Number of lines *l* at node *n*

4. Methodology

The methodology presented in this paper is for transit systems at different levels. The very nature of nodes, lines, and transfer centers each necessitate a unique formulation. The description below explains the mathematical construct of these transit levels in a step-by-step manner. The connectivity index is shown in equation (1.1). We incorporate a comprehensive list of quantifiable transit variables to assess connectivity at multiple system levels. These variables include inbound and outbound distance of every rail line between every system stop, transit vehicle and transit line capacity, speed, frequency of service, number of operations, number of transfers, and household and employment density at every stop. While this list could be expanded to include other less quantifiable measures, a search of the literature (Ceder et al. 2009; Hadas et al. 2011) reveals these values to be the most critical in assessing transit connectivity. Moreover, our system can adapt easily to incorporate other metrics.

The total connecting power of a node is the multiple of connecting power of a line at node n ($P^t_{l.n}$). The conditional value of presence of a line is represented by a binary indicator variable ($\mu_{l,n}$), which takes the value 1 if line l contributes to the connectivity at node n, and 0 otherwise. The characteristics of a link contain the performance of a series of nodes in that link. A link is a part of the transit route, which in turn is a function of speed, distance, frequency, headway, capacity, acceleration, deceleration, and other factors. Since a route will contain both in-bound and out-bound, the line performance will in part depend upon the directionality of the transit route, that is, whether the line is circular or bidirectional. The total connecting power of line l at node n is the average of outbound and inbound connecting power and can be defined as

$$P^t_{l,n} = \frac{P^o_{l,n} + P^i_{l,n}}{2} \tag{1.1}$$

The outbound connecting power of a line l, at node n can be defined as (Park and Kang 2011)

$$P^o_{l,n} = \alpha C_l \times \beta V_l \times \gamma D^o_{l,n} \tag{1.2}$$

where, C_l is the capacity of line l, V_l is the speed of line l, and $D^o_{l,n}$ is the distance of line l from node n to the destination. The parameter α is the scaling factor coefficient for capacity, β is the scaling factor coefficient for speed, and γ is the scaling factor coefficient for distance. Similarly, the inbound connecting power of line *l* can be defined as

$$P_{l.n}^{i} = \alpha C_l \times \beta V_l \times \gamma D_{l,n}^{i} \tag{1.3}$$

where, $P_{l.n}^{i}$ is the inbound connecting power of line *l* at node *n*. While the outbound connecting power of a transit line at a certain transit stop represents connectivity from the stop to the downstream stops of the transit line, the inbound connecting power measures connectivity from the upstream stops of the transit line to the stop under consideration.

4.1. Node Connectivity

The proposed methodology consists of more expansive representations of transit node index measures. In the proposed formulation we consider the congestion effects achieved because of lane-sharing of transit lines of buses, light rail, bus rapid transit, and other similar transit facilities. We have redefined the connecting power of a transit line, as the other measures have not incorporated transit attractiveness as per the land use and transportation characteristics of the area the transit line is passing through. As discussed previously, the connecting power of a transit line is a function of the inbound and outbound powers, as the connecting power may vary depending on the direction of travel. The inbound and outbound connecting power of a transit line can be redefined as follows.

$$P_{l,n}^{o} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D_{l,n}^{o} \times \vartheta A_{l,n} \tag{2}$$

$$P_{l,n}^{i} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D_{l,n}^{i} \times \vartheta A_{l,n} \tag{3}$$

In equation 3, ($P_{l,n}^{i}$) is a term for activity density of transit line "l" at node "n", and ϑ is the scaling factor for the area type variable. The density measurement represents the development pattern based on both land use and transportation characteristics. The literature defines the level of development a number of ways, but for simplification purposes we have considered it to be the ratio of households and employment in a zone to the unit area. Mathematically, activity density (equation (4)) is defined as

$$A_{l,n} = \frac{H_{l,n}^{z} + E_{l,n}^{z}}{\Theta_{l,n}^{z}} \tag{4}$$

The connectivity index measures aggregate connecting power of all lines that are accessible to a given node. However, not all lines are equal; nodes with access to many low quality routes may attain a connectivity index score equal to a node with only a couple of very high quality transit lines. This means that while both nodes are able to provide good access, the node with the fewest lines provides the most access with the lowest need to transfer. To scale the index scores based on the quality of individual lines, that is, scaling for the least number of transfers needed to reach the highest number and quality of destinations, the node scores are adjusted by the number of transit lines incident upon the node. The inbound and outbound connecting power of a transit line can be further refined as

$$P_{l,n}^{o} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D_{l,n}^{o} \times \vartheta A_{l,n} \times \varphi T_{l,n} \tag{5}$$

$$P_{l,n}^{i} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D_{l,n}^{i} \times \vartheta A_{l,n} \times \varphi T_{l,n} \tag{6}$$

This equation adds the number to transit lines “l” at node “n”, and φ is the scaling factor for the number of transit lines. The transfer scale is simply the sum of the connectivity index scores for each of the transit lines that cross a node divided by the count of the number of lines that are incident with the node. The transfer scaled index [equation (7)] is defined as

$$T_{l,n} = \frac{\sum \ P_{l,n}^{t}}{\Theta_{l}^{n}} \tag{7}$$

4.3. Line Connectivity

The total connecting power of a line is the sum of the averages of inbound and outbound connecting powers for all transit nodes on the line as presented in equation (1.1), scaled by the number of stops on each line. The scaling measure is used to reduce the connecting score of lines with many stops (such as bus lines) to properly compare to lines with only a few stops (such as rail). The line connectivity can be defined as follows:

$$\theta_{l} = (|S_{l}| - 1)^{-1} \sum P_{l,n}^{t} \tag{8}$$

4.4. Transfer Center Connectivity

The concept of a connectivity index of a transfer center is different from the connectivity measure of a conventional node. Transfer centers are groups of nodes that are defined by the ease of transfer between transit lines and modes based on a coordinated schedule of connections at a single node or the availability of connections at a group of nodes within a given distance or walk time. In this paper, we define a transfer center as the group of nodes within half a mile of any rail station in the transit network. The sum of the connecting power of each node in the transfer center is scaled by the number of nodes on the transfer center. Thus, a transfer center in a heavily dense area is made comparable to a transfer center in a less dense area. This scaling procedure is particularly important when comparing transfer centers in a multimodal network, where one transfer center may be primarily served by a well-connected commuter rail line and another may have many bus lines and rail lines connecting to the center. The following equation shows the connectivity index of a transfer center.

$$\theta_{tc} = (|S_{\omega}| - 1)^{-1} \sum P_{l.n}^{t} \left(\rho_{n_1,n}\right) \tag{9}$$

The methodology is demonstrated using an example problem and is presented in Appendix-A.

5. Network Visualization and Interaction

While the development and implementation of a true multimodal connectivity index is challenging, the result produces significant amounts of data that may be even more difficult to use and conceptualize in a meaningful way. Moreover, the number of inter-related parameters creates opportunities for highly interactive experimentation with the metrics, relative to real-world urban and transport geography. To aid in the use of such data, we developed a visualization tool for planners and users to examine the performance of a given node, line and/or transfer center. The geovisualization component, which allows connectivity measures to be embedded in an extensible Geographic Information System (GIS) and displayed via cartographic interfaces, accessible across a variety of media, as discussed in the next section.

5.1 Geovisualization Structure

In addition to standalone access to these metrics and standard cartographic representation using traditional desktop or server-side Geographic Information Systems, we built a flexible and scalable on-demand access and visualization infrastructure to explore transit connectivity measures. In doing so, our design goals were to provide (1) a richly interactive user experience; (2) in an on-demand capacity that could shift seamlessly to mobile as well as tablet and desktop media; (3) using self-service modes of access that require little prior knowledge of GIS; (4) using platforms that are free from licensing costs; (5) with the ability to ingest crowd-sourced cartographic base data that is available in the public domain; (6) that will refresh as those crowd-sourced data are dynamically updated in the public domain; (7) that is scalable to large numbers of users and query-loads; and (8) provided in an extensible framework that supports future modification and alteration.

We used a three-layer approach to the on-demand infrastructure. First, we developed a spatial database management and spatial data access layer, with standard spatial (and network) data models, metadata schemes, access procedures, and query abilities. This “back-end” infrastructure can actually be reused or repurposed, using desktop GIS or client/server access schemes, or by plugging it into other Web applications or services. Second, we developed a middle layer of *Web Services* that can broker data requests and exchange between the interface and the “back-end” data infrastructure. The third component is a visual canvas layer that provides interactive interfacing to the other layers and services. As distinct from standard desktop GIS, this canvas layer *tiles* data layers and cartography dynamically, relative to users’ interactions. The canvas is rendered in the browser and is therefore free from the need of any client-side software. Similarly, the data access between the canvas and the “back end” data infrastructure are mediated as standard queries and returns JavaScript calls and queries to the browser, which takes us away from the need to deploy the usual forms of server-side GIS software. This permits access from a wide variety of devices and platforms—iPhone OS, Android, desktop, tablet, etc., while maintaining the same user interaction experience. As we mentioned, this also means that our system can be docked with other software (including desktop GIS, transport modeling packages, and analyses suites), services, and applications.

5.2 On-Demand GIS Implementation

The on-demand GIS infrastructure has several advantages. First, it is relatively inexpensive. No proprietary software licenses are required. Moreover, underlying base maps can be pulled from a variety of sources such as an organization's own database, commercial providers, or free "citizen-volunteered" data-sets such as OpenStreetMap. Second, the user experience is relatively straightforward and requires no prior knowledge of GIS or data-query. Users can interact with the data by tapping, and using multi-touch gestures on their devices . Third, the infrastructure is secure. Data that are sent to devices are tiled as rasters and delivered as images (rather than data); the underlying information remains on the "back-end" database and no shapefiles are delivered to the user. Fourth, the scheme is extensible. Because it is based on Web services and Web Markup conventions, it can be coupled with a wide variety of other Web services, such as syndication services, geolocation services that can automatically pull a user's location (and deliver the necessary map services for that location), animation schemes using WebGL (the Web-based version of the Open Graphics Library, for 2D and 3D visualization and animation), and any number of other "mash-ups". It can also be integrated with other markup schemes, such as the Geographic Markup Language (GML; http://www.opengeospatial.org/standards/gml/), or other emerging markup schemes in urban and transportation planning and management, such as CityGML (http://www.citygml.org/) or the NCHRP's TransXML for transportation data (http://www.transxml.org/). Fifth, the system is dynamic, such that as data changes, the interface will refresh the canvas to accommodate the changes. A schematic of the web interface development is shown in Figure 1.

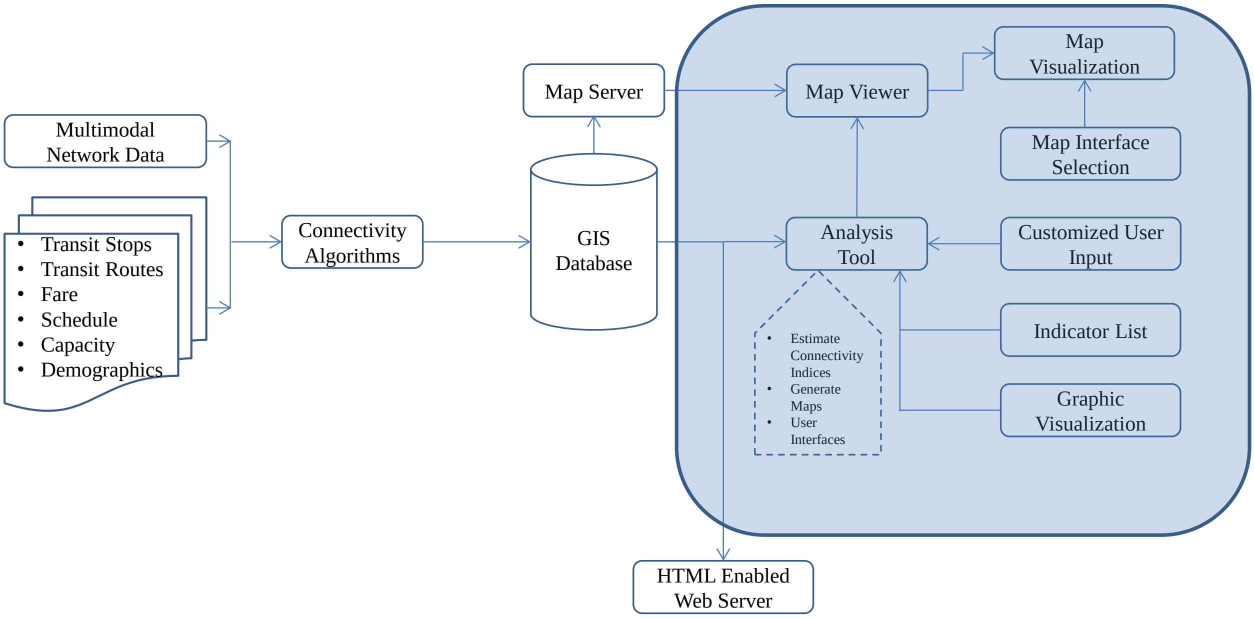


Fig. 1. Methodology of Web Interface Development

6. Case Study

To demonstrate how the approach may be used in an operational context, we have applied the framework to a comprehensive transit network in the Washington-Baltimore region. The complete transit network is adapted from Maryland State Highway Administration data. The transit database consists of the two largest transit systems in the region, namely, Washington Metropolitan Area Transit Authority (WMATA), and Maryland Transit Administration (MTA). WMATA is a tri-jurisdictional government agency that operates transit service in the Washington, D.C. metropolitan area, including the Metrorail (rapid transit), Metrobus (fixed bus route) and Metro Access (demand response), and is jointly funded by the District of Columbia, together with jurisdictions in suburban Maryland and northern Virginia. WMATA has an annual capital, operating and maintenance budget of approximately $300 million. Half of this funding comes from Federal sources and the other half comes in equal proportions of $50 million from Washington DC, Northern Virginia and suburban Maryland.

WMATA has the second highest rail ridership in the US with over 950,000 passengers per day. The WMATA Metro provides an extensive heavy rail system with 106.3 route miles. The WMATA bus system also serves an extensive ridership of over 418,000 unlinked daily trips. Figure 2(a) shows the WMATA network at Union Station.

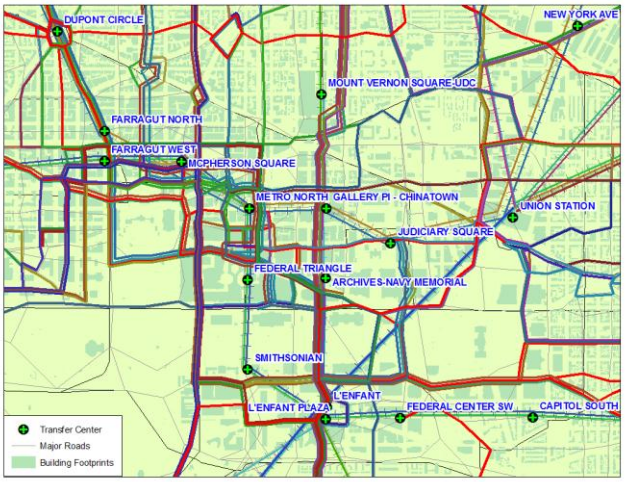


Fig. 2(a). Thematic of the transit lines in Washington DC

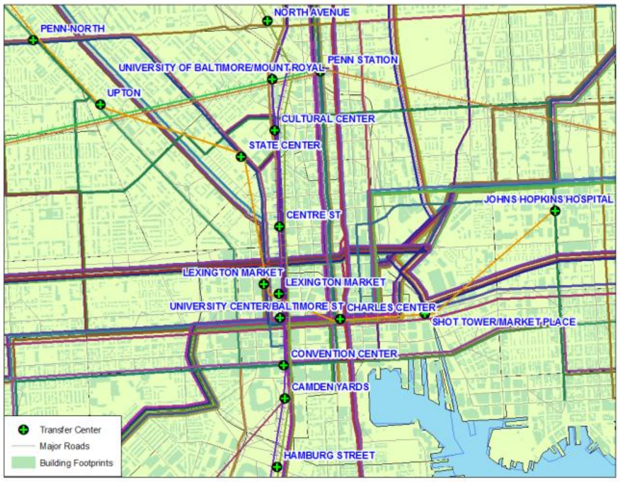


Fig. 2(b). Thematic of the transit lines in Baltimore

On the other hand, MTA is a state-operated mass transit administration in Maryland. MTA operates a comprehensive transit system throughout the Baltimore-Washington Metropolitan Area. There are 77 bus lines serving Baltimore's public transportation needs. The system has a daily ridership of nearly 300,000 passengers along with other services that include the Light Rail, Metro Subway, and MARC Train. The Baltimore Metro subway is the 11th most heavily used system in the US with nearly 56,000 daily riders. Nearly half the population of Baltimore lack access to a car, thus the MTA is an important part of the regional transit picture. The system has many connections to other transit agencies of Central Maryland: WMATA, Charm City Circulator, Howard Transit, Connect-A-Ride, Annapolis Transit, Rabbit Transit, Ride-On, and TransIT. Figure 2(b) shows MTA network around Camden station in downtown Baltimore. Both the WMATA Metro rail system and the Baltimore transit system are connected by the MARC commuter rail system. This system has a daily ridership of over 31,000. In the next section, results of the proposed methodology are discussed.

7. Results

The case study application of methods developed in this paper is applied on a large-scale multi-modal network of the Washington-Baltimore region. The system represents one of the largest and most heavily patronized transit systems in the county. The application of the methodology to this complex network provides a demonstration of the scalability of the connectivity index.

7.1. Region-wide View

The Washington-Baltimore region has a significant number of transit nodes, each of which provides a varying degree of connectivity to the network. Determining network connectivity and funding prioritization is a highly complex task in a multi-modal network. Funding prioritization is additionally aided by the connectivity index by providing decision-makers with a tool to measure network resilience. As with any network, transit systems are designed to interact with many different nodes, while remaining functional in the event that a particular node becomes inaccessible. Additionally, resiliency tests based on connectivity can reveal if there is an over concentration of connections which rely on a given node, line, or region. Figure 3 provides a three-dimensional view of connectivity for transit network in the study area. The image illustrates how useful visualization can be in understanding the topography of network connectivity. However, this type of visualization requires significant amounts of computing power, knowledge of GIS software and lacks interactivity both for planners and end-users. Next we describe a computationally feasible, interactive tool we have developed to make the type of visualization seen in Figure 3, useful for a broad audience. Baltimore, Washington DC, and Silver Spring are three areas with extensive transit connectivity. The highlighted node 64 is the most connected station in the Baltimore-Washington DC region. A graphical user interface of the case study is shown in Appendix-B.

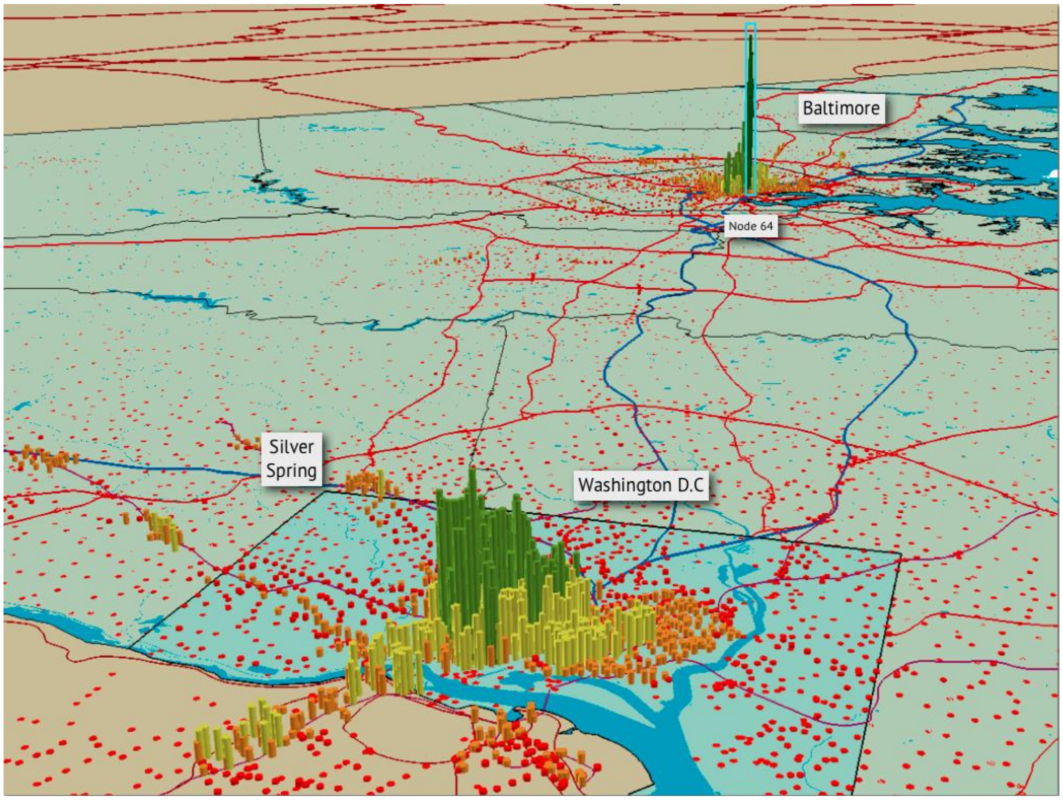
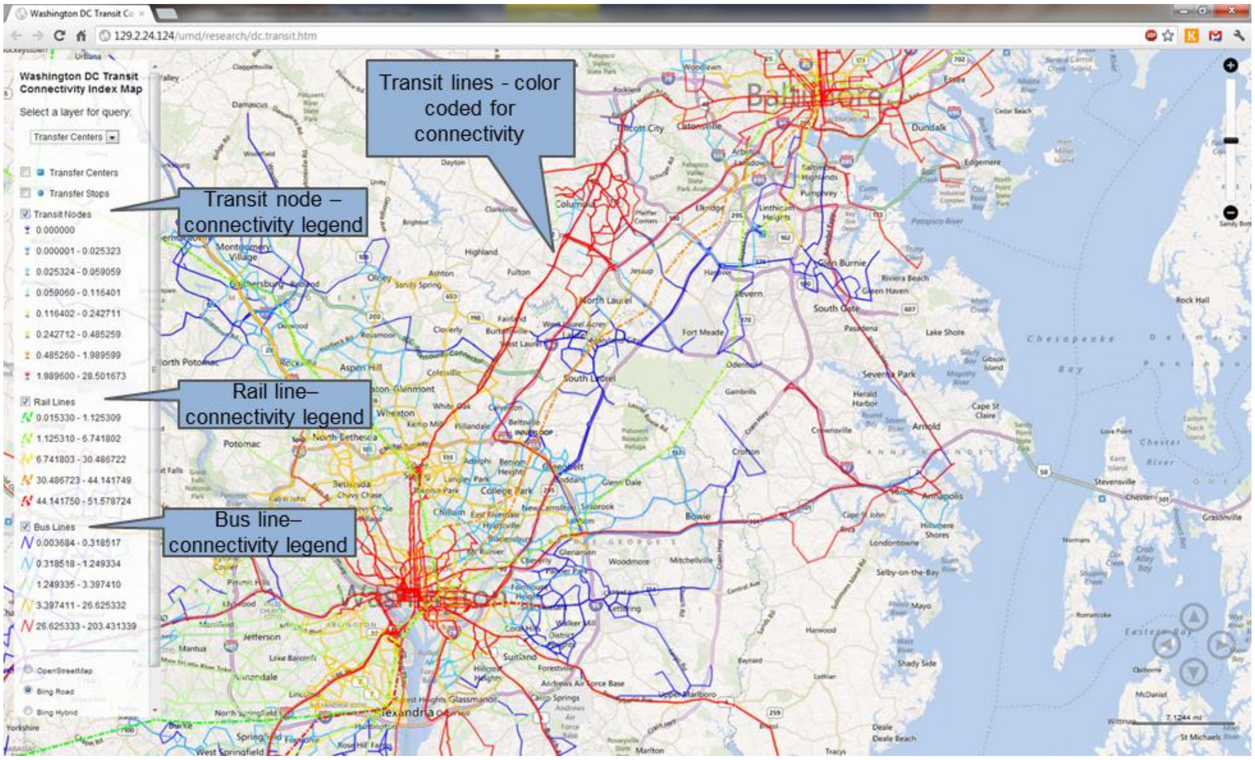


Fig. 3. Regional Node Connectivity in a GIS Map

7.2 Multi-level Network Visualization

The network visualization interface allows users to view connectivity at three distinct levels. At the highest level, line connectivity provides an overview of the entire transportation system, its interaction with each mode and a quick way to determine the best and least connected parts of the network. Figure 4(a) provides a screenshot of the line-level overview. In the image, the red lines represent the highest levels of connectivity while the blue lines show the lowest connectivity for buses and green show the lowest connectivity for rail. In this case, the lines that serve the Baltimore and Washington cores and the major links between the two cities are very well connected.

At a less macro level, the transfer center analysis provides users with connectivity scores of major intermodal transit stations. For each transfer center connectivity score, the index value is derived from a combination of the walking time from smaller facilities and their respective score, for stops that are within a half-mile of the major facility. Figure 4(b) shows the transfer center results in the user interface window. Transfer centers are given a vertical bar that represents the level of connectivity. When the bar is clicked, all of the associated transit stops (the stops that contribute to the transfer center score) are highlighted.



Transit lines - color coded for connectivity

Transit node – connectivity legend

Rail line– connectivity legend

Bus line– connectivity legend

Fig. 4(a). Line level connectivity

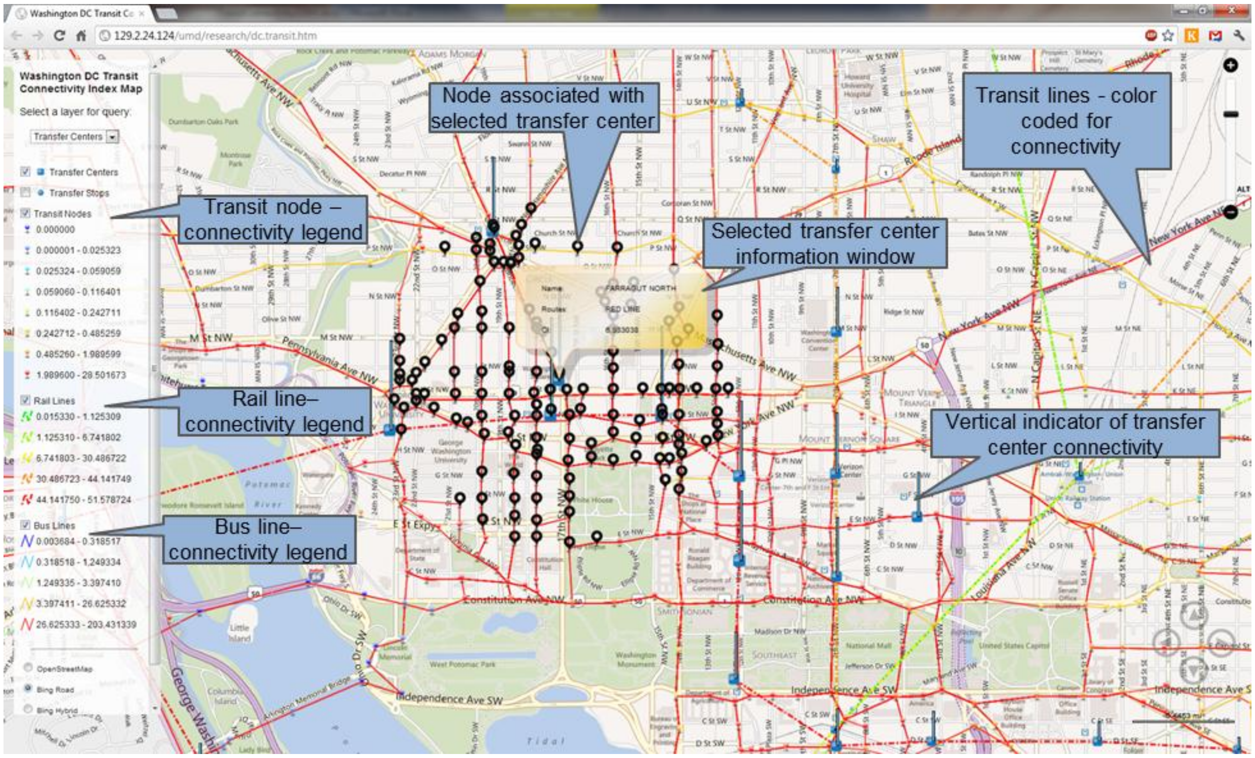


Fig. 4(b). Transfer center level connectivity

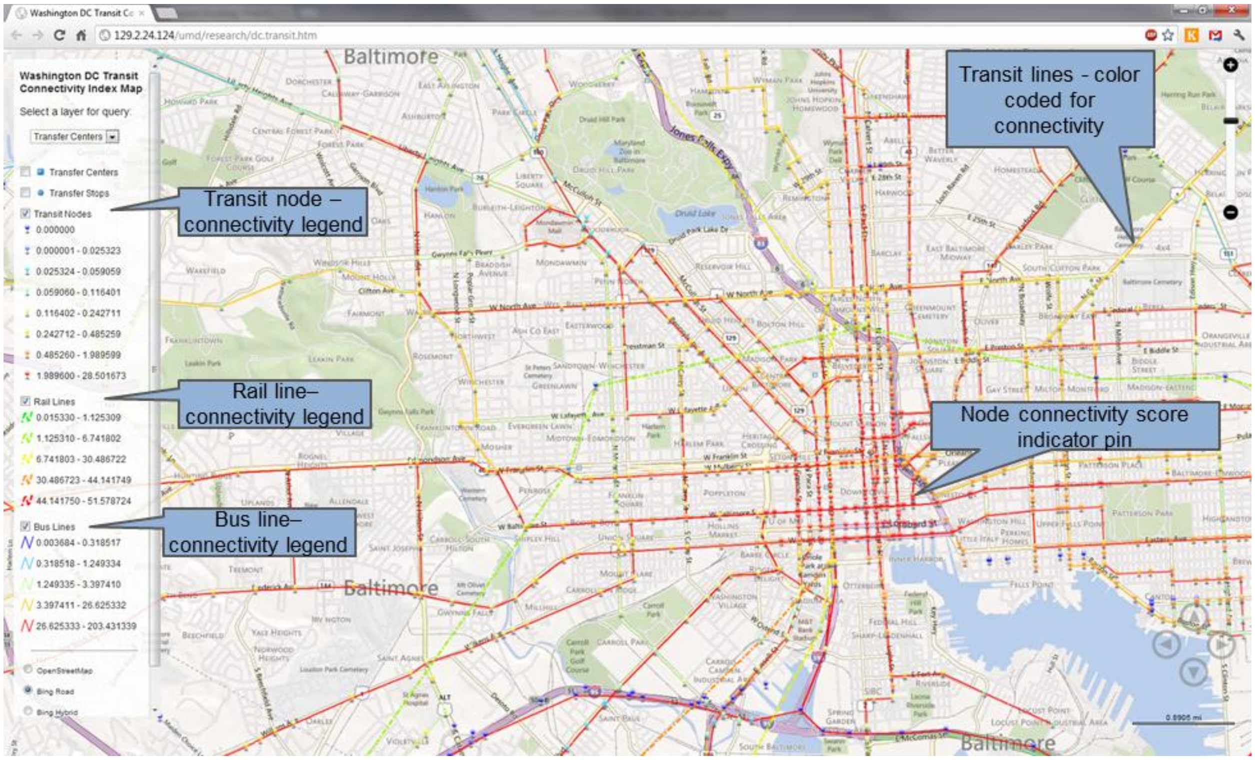


Fig. 4(c). Node level connectivity

At the lowest level, node connectivity shows how well connected each transit stop is in the entire system, relative to the rest of the network nodes. Figure 4(c) shows the Baltimore transit network at the node level. Like the line level index, the red nodes denote the best connected transit stops while yellow is less connected, and blue shows the nodes with the least amount of connectivity. The visualization at this level provides a good tool for planners to quickly assess locations that may be important but not fully connected to the rest of the transit network. Typically, several adjacent nodes have similar levels of connectivity and the ability to easily display them provides one import way to prioritize the need for future transit investment.

7.3. Cross Platform Compatibility

The connectivity GUI shown in the previous section is compatible with a broad range of software and hardware platforms. This cross-compatibility makes the index useful for a variety of purposes and end users. In figure 5(a) and 5(b), the interface is shown on a PC. The first figure (a) shows what users will see when the first load the interface, providing an overview of the entire network. The second figure (b) provides an example of the zoomed view of then network with connectivity scores. Figures 5(c) and 5(d) show the mobile capabilities of the index and user interface, displayed here on an iPad. The network levels are the same as with the PC view. With a mobile device, users can pan and scroll using the built-in navigation controls, or by using the finger gestures supported by their mobile device.

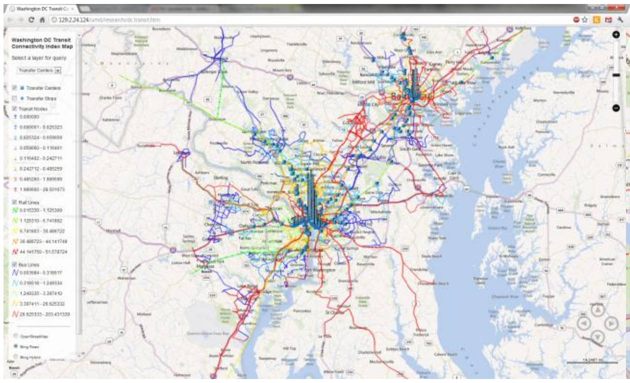


Fig. 5(a) GUI Interface on PC – Full Network

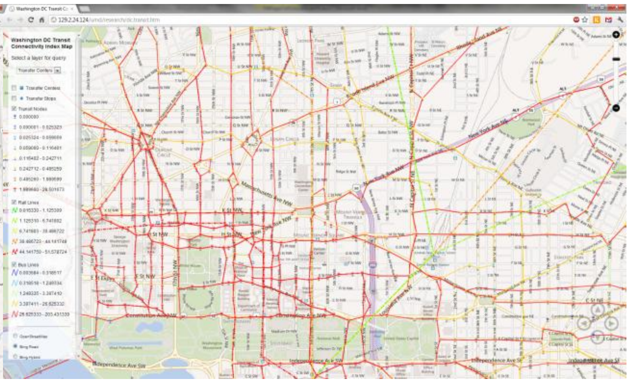


Fig. 5(b) GUI Interface on PC – Node and Links

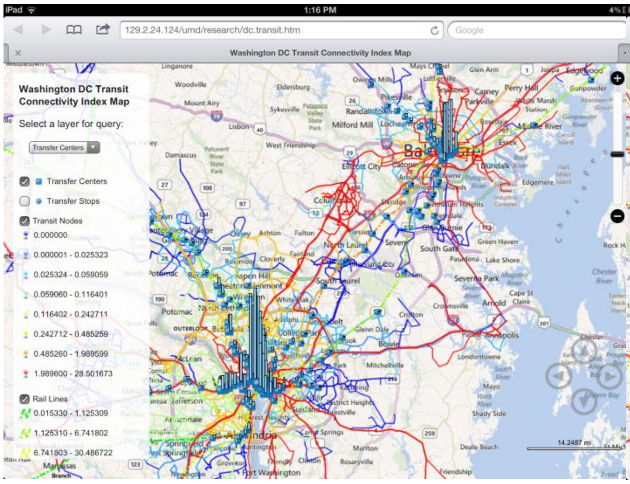


Fig. 5(c). GUI Interface on iPad – Full Network

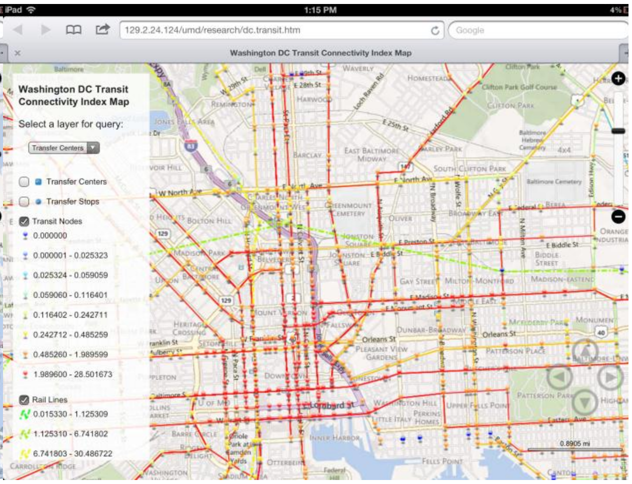


Fig. 5(d) GUI Interface on iPad – Node and Links

Figure 6 shows step-by-step instructions to the use of the proposed Web-based visualization. Any user or transit agency can seamlessly view the connectivity index results with eight step process: (1) open the website with the URL- http://www.geosimulation.org/transit.html; (2) select the desired connectivity index to be displayed, for example stop, bus/rail line, and transfer center; (3) select the background map on which the connectivity index results will be displayed; (4) view the resulting categorical color schemes of the index chosen in step-3 in the left panel of the window; (5) view the results on the background map; (6) on the left hand side of the panel the user has the choice of using a dropdown menu to select a specific connectivity index (please note that this is an alternative to step-2); (7) the user has flexibility to view results in any desired zoom level and the icon is provided in the left had panel; (8) finally, the user can click on the resulted map to view station information and the connectivity index score. The demonstration presented in Figure 6 is for transit nodes only. Similar procedure can be followed for connectivity index for bus/rail lines, and transfer centers.

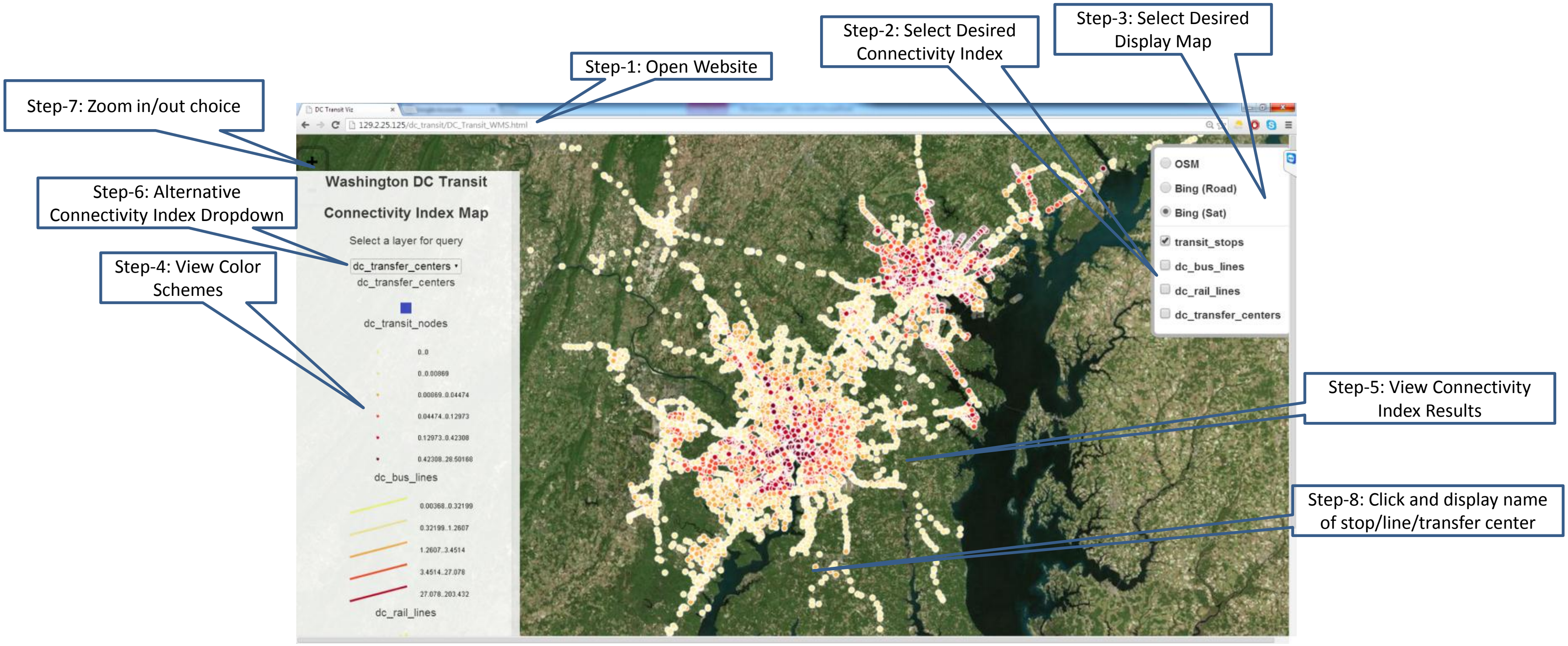


Fig. 6. User steps for viewing web based connectivity index results

7.4. Examining Network Sensitivity

At the node level, the removal of specific transfer centers can have a wide spread impact on the entire transit network. Figure 7 shows a three-dimensional representation of connectivity and resulting change when selected transfer centers are removed from service. In the base case, the first graphic layer over the network represents all transfer centers at full capacity. Connectivity is very high at the center of the network with peaks at transfer centers along major corridors.

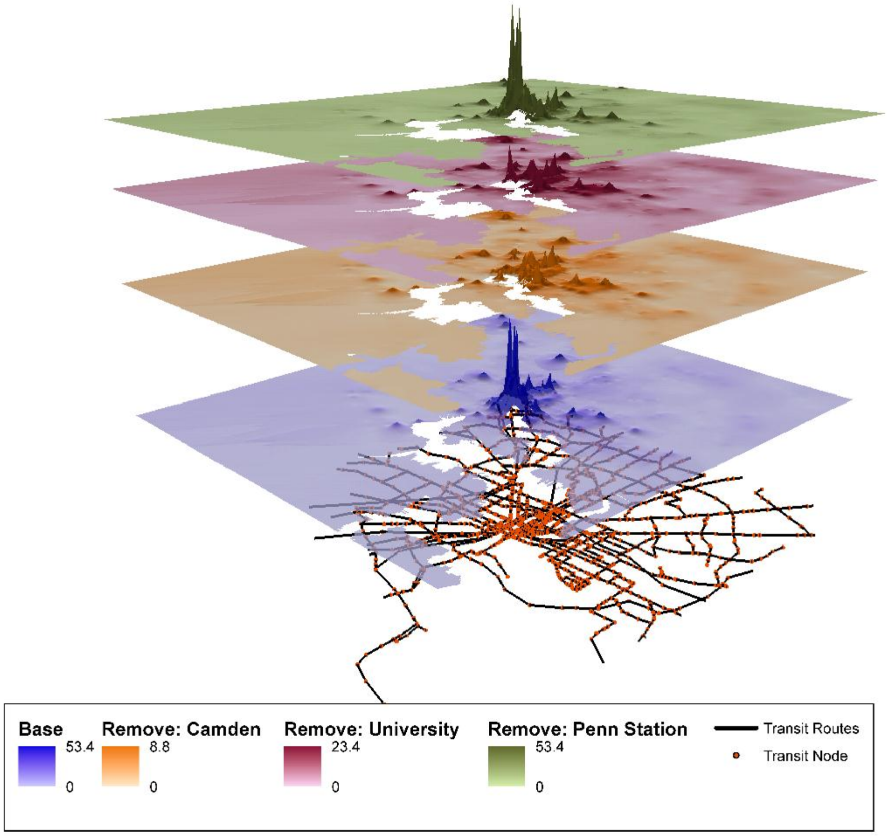


Fig. 7. Sensitivity of node-level connectivity to disruptions

When we remove one of the centers with a very high level of connectivity (Camden Yards, for example), the second layer shows that total connectivity falls, especially in the center of the study area. The same occurs with our other selected high connectivity center (University), as shown in the third layer. When a transfer center with a small connectivity score is removed from service, the node-level impact is virtually undetectable, as shown in the fourth layer. The purpose of examining sensitivity is to assess changes in connectivity and to show validity of the proposed connectivity measures.

8. Conclusions

In this paper, we present connectivity indicators to represent the potential ability of a transit system encompassing comprehensive clustered development in a multimodal transportation network. The paper is constructed around two broad themes. The first theme discusses the concept of connectivity depicted in terms of a graph theoretic approach. The second theme emphasizes a flexible and reusable interactive canvas for leveraging GIS interfaces and interactions with the metrics via a wide variety of media and with the ability to couple it to a diverse array of Web services.

Connectivity defines the level of coordination of the transit routes, coverage, schedule, speed, operational capacity, urban form characteristics, and is an influential element of the image of any transit network. The difficulty for development of connectivity indicators lies in the complex interacting factors embedded in a multimodal transit network that encompasses various public transportation modes with different characteristics, such as buses, express buses, subways, light rail, metro rail, commuter and regional rail. In addition, multimodal transit networks, like road networks, consist of nodes and links. However, links in a multimodal transit network have different characteristics from those in a road network as links in a multimodal transit network are part of a transit line that serve a sequence of transit stops (nodes) and a stop can be served by different transit lines; multiple links may exist between nodes in a multimodal transit network. The indicator development process is further complicated as connectivity varies by urban form with differences among geographical, land use, highway and trip pattern characteristics between regions. A good performance indicator should, therefore, include all the aforementioned complexities and should be quantified to portray connectivity of the multimodal transportation network.

We proposed a set of connectivity indexes for (1) nodes, (2) links, and (3) transfer centers. The node connectivity index includes the transit lines passing through it, their characteristics such as speed, capacity, frequency, distance to destination, activity density of the location, and degree centrality. The link connectivity index is the sum of connectivity indices of all stops it passes through and normalized to the number of stops. The concept of a connectivity index for a transfer center is different from the connectivity measure of a conventional node. Transfer centers are groups of nodes that are defined by the ease of transfer between transit lines and modes based on a coordinated schedule of connections at a single node or the availability of connections at a group of nodes within a given distance or walk time. The sum of the connecting power of each node in the transfer center is scaled by the number of nodes in the transfer center. Thus, a node in a heavily dense area is made comparable to a transfer center located in a less dense area.

Network connectivity is a complex concept, especially in the context of a multimodal transportation system. In this paper we propose theoretically robust connectivity index for such a system. Though the theory is complex, the application of this index is simple and its results provide important insights on system performance, yielding useful tools for transportation planners and policy-makers. Though such an index alone can be a powerful tool, we also demonstrate an interface for user interaction with the connectivity index. With this interface, planners and other end-users can easily locate highly connected or poorly connected nodes, links, routes and transfer centers. The interface can reveal much more about system performance than pages of tables or numbers. Planners can easily use this tool to develop, prioritize and justify transit investments. Other users can interact with the index and map to determine the level of transit service in their city or neighborhood.

The paper has significant importance to research and practice. Major contributions of the paper include (1) extending the graph theory approach to determine the performance of the multimodal transit network; (2) quantifying the measures of connectivity at the node, line, and transfer center; (3) demonstrating a Web service and interactive canvas layer that can be deployed in cross-platform applications with online query, browsing and exploring capabilities for all features of the connectivity performances in a multimodal transit network; (4) providing a comprehensive framework for analyzing connectivity, and efficiency of transit networks for agencies that do not have access to well-developed travel demand and transit assignment models, and (5) demonstrating the applicability of the proposed framework in a heavily used multimodal transit network in the Washington-Baltimore region. In future research, transit network resiliency can be incorporated in a web GIS platform with features such as updating connectivity measures in real time; and adding connectivity features of which are catered to pedestrians.

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APPENDIX –A: Example Problem

To demonstrate the methodology, two example problems are illustrated. The example problems show how to estimate the parameters used for connectivity estimation.

Example-1: One-Node Problem

A one-node problem is illustrated in Figure 1. In this example, there are two bus lines passing through the node. The capacity, frequency (or number of operations), speed of the bus, distance from the origin, and distance to the destination are given as the input data. The first task is to estimate the parameters to obtain connectivity.

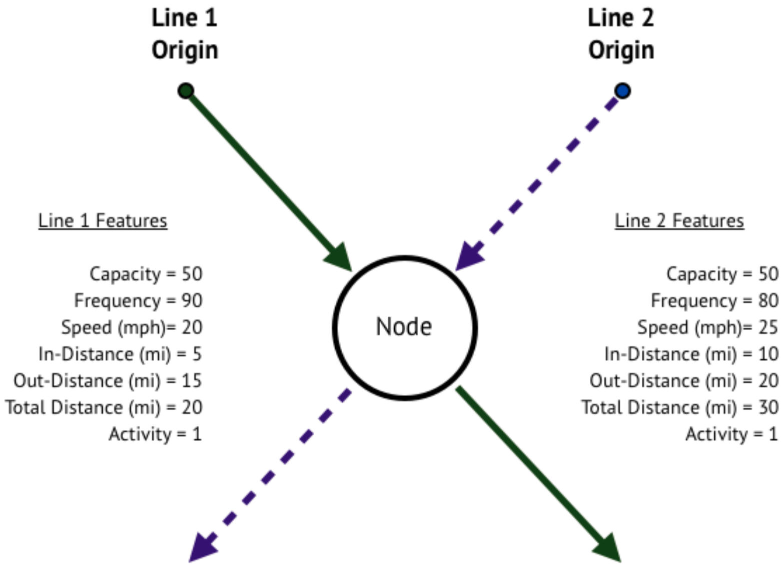


Fig. A-1. One Node Example Problem

α = the sum-product of capacity and frequency is estimated as [(50*90) + (50*80)]/(90+80) =50

β = Average of speeds = (20+25)/2 = 22.5

γ = Average of distances = (20+30)/2 = 25

φ = Average of activities = (1+1)/2 = 1

Connectivity of Line 1 = [(50*90)/4250] * [20/22.5] * [20/25] * [1] = 0.3951

Connectivity of Line 2 = [(50*80)/4250] * [25/22.5] * [30/25] * [1] = 0. 5926

The result shows that connectivity of line 2 is higher than that of line 1.

Point connectivity is the sum of connectivity of all lines passing through the node.

Point connectivity = 0.3951 + 0.5926 = 0.9877.

Example-2: Four-Node Problem

A four-node example problem is presented in Figure A-2. Four transit lines serve the four nodes in the second example problem. Each line is bi-directional. The input data for each line is also shown in Figure A-2. The first task is to estimate the parameters. For example looking at the first row of Table A-1, α is the product of average capacity and frequency.

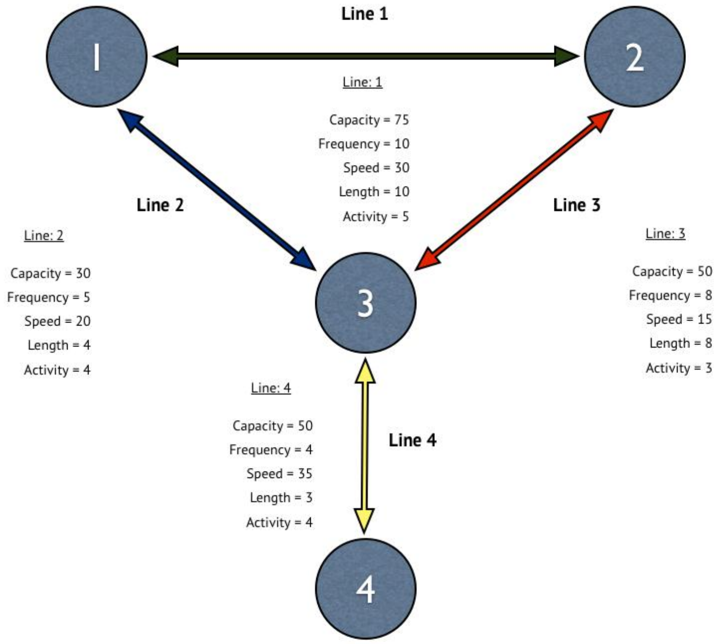


Fig. A-2. Four-Node Example Problem

Similarly, β is the average of all speeds and γ is the average of all distances. φ is the average of all area types to include urbanization of the location of transit nodes. Using equations (6) and (7), the outbound and inbound connecting power of lines is determined. The last column shows the total connecting power, which is the sum of inbound and outbound connecting powers. The detailed parameter estimates and estimation of connectivity is shown in Table A-1. The total connectivity of all lines and nodes are summarized in Table A-2.

Table A-1

Step-by-Step Estimation of Four-Node Problem

Line	Distance	Node	Origin Distance	Destination Distance	Speed	Operations	Capacity	Activity	α	β	γ	φ	$P^{o}_{l,n}$	$P^{i}_{l,n}$	$P^{t}_{l,n}$
1	10	1	10	0	30	10	50	4	332.22	28.33	7.33	4.5000	1.9316	0.0000	0.9658
1	10	2	0	10	30	10	50	4	332.22	28.33	7.33	4.5000	0.0000	1.9316	0.9658
2	4	1	4	0	25	5	30	4	332.22	28.33	7.33	4.5000	0.1932	0.0000	0.0966
2	4	3	0	4	25	5	30	5	332.22	28.33	7.33	4.5000	0.0000	0.2414	0.1207
3	8	2	8	0	30	8	50	5	332.22	28.33	7.33	4.5000	1.5453	0.0000	0.7726
3	8	3	0	8	30	8	50	5	332.22	28.33	7.33	4.5000	0.0000	1.5453	0.7726
4	3	4	3	0	35	4	50	4	332.22	28.33	7.33	4.5000	0.2704	0.0000	0.1352
4	3	3	0	3	35	4	50	4	332.22	28.33	7.33	4.5000	0.0000	0.2704	0.1352
1	10	1	0	10	30	10	50	4	332.22	28.33	7.33	4.5000	0.0000	1.9316	0.9658
1	10	2	10	0	30	10	50	4	332.22	28.33	7.33	4.5000	1.9316	0.0000	0.9658
2	4	1	0	4	25	5	30	4	332.22	28.33	7.33	4.5000	0.0000	0.1932	0.0966
2	4	3	4	0	25	5	30	5	332.22	28.33	7.33	4.5000	0.2414	0.0000	0.1207
3	8	2	0	8	30	8	50	5	332.22	28.33	7.33	4.5000	0.0000	1.5453	0.7726
3	8	3	8	0	30	8	50	5	332.22	28.33	7.33	4.5000	1.5453	0.0000	0.7726
4	3	4	0	3	35	4	50	4	332.22	28.33	7.33	4.5000	0.0000	0.2704	0.1352
4	3	3	3	0	35	4	50	4	332.22	28.33	7.33	4.5000	0.2704	0.0000	0.1352

Table A-2

Summary of Network Connectivity for Example-2

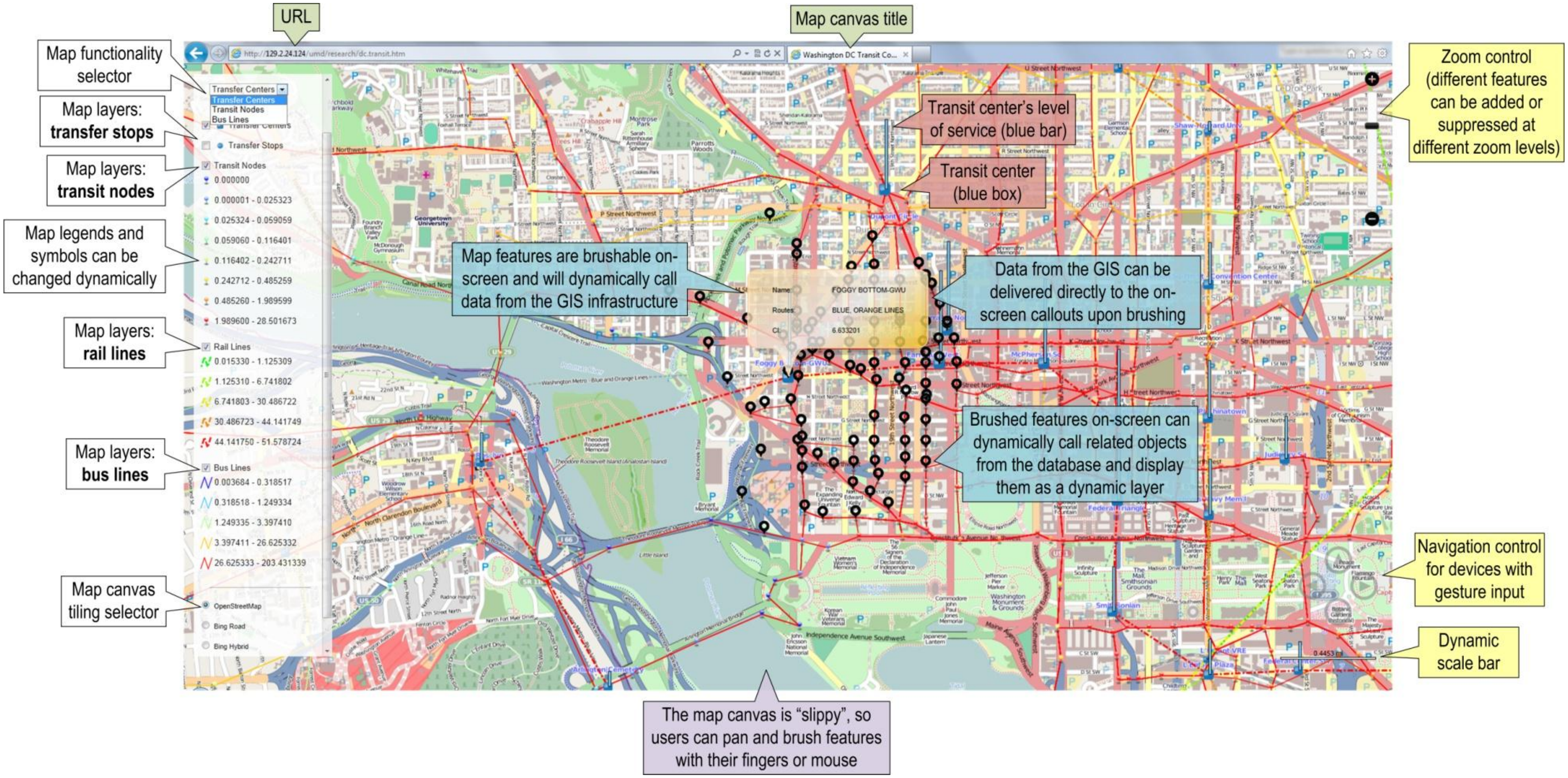
Network	Number	Connectivity
Line	1	3.7344
	2	2.7879
	3	3.6893
	4	1.5517
Node	1	0.5312
	2	0.8692
	3	0.3429
	4	0.1352
Transfer Center	3	2.3284

APPENDIX-B: The Graphical User Interface

Several innovations are provided in the Graphical User Interface (GUI). First, the graphical experience of the interface remains the same, regardless of the device from which the map is accessed, and regardless of the browser that is used to view the map. This is significant as it allows the tool to be used on different screen-sizes, different platforms, and different operating systems, without any required intervention from the user, while constantly preserving a similar experience.

Second, a variety of data-layers can be added to the interface. In Figure B-1, we show four dimensions of transit connectivity (transfer stops, transit nodes, rail lines, and bus lines), overlaid and georeferenced to a base map that illustrates major landmarks, political boundaries, street-names, routes, and features along the D.C./Northern Virginia border. This canvas “backdrop” could show anything: historical maps, dynamic weather patterns, population density, aerial photography, and so on.

Third, the symbology on the map can be swapped on-the-fly using Cascading Style Sheets (CSS). In essence, CSS allows for the specification of a set of themes that can be substituted at will, for example, when a particular scaling factor is invoked, when a particular functionality is called, or when a particular action is initiated. The CSS schema can be ported from other applications and they are easily loaded without further input from the user.


URL

Map canvas title

Map functionality selector

Map layers: **transfer stops**

Map layers: **transit nodes**

Map legends and symbols can be changed dynamically

Map layers: **rail lines**

Map layers: **bus lines**

Map canvas tiling selector

Transit center's level of service (blue bar)

Transit center (blue box)

Map features are brushable on-screen and will dynamically call data from the GIS infrastructure

Data from the GIS can be delivered directly to the on-screen callouts upon brushing

Brushed features on-screen can dynamically call related objects from the database and display them as a dynamic layer

Zoom control (different features can be added or suppressed at different zoom levels)

Navigation control for devices with gesture input

Dynamic scale bar

The map canvas is "slippy", so users can pan and brush features with their fingers or mouse

Fig.B-1. GUI Interface of the Transit Connectivity Tool

Fifth, data elements on the canvas can be dynamic (or not). The entire canvas can be panned and zoomed using standard gestures on mobile devices (or using overlaid zoom and pan controls that we have provided for devices that do not support gesture control or mouse-based input). Similarly, users can use their fingers to tap or brush objects on-screen, which will return data for that feature from the database. As shown in Figure B-1, these tap-queries can also be used to perform spatial (or temporal) queries, returning nearby features of relevance.

Figure B-1 shows the graphical user interface (GUI) to the transit connectivity tool. A transfer center (a blue square) at Foggy Bottom (a Metro station in Washington DC) has been selected by brushing the icon on-screen. This action, in turn, sends a query to the database to return the participating transfer stops (highlighted as black circles) that have been used in calculating the center's level of service (which is illustrated by a blue bar above the center's icon). The symbology in the map legend can be changed dynamically, or allied to Cascading Style Sheets. Different map features can be added and suppressed at different zoom levels. Different canvases can be loaded as a backdrop to the data layer. In Figure B-1, an OpenStreetMap canvas is shown. As data are altered in the spatial database, the results will be immediately available in the mapping interface. An increased zoom level of connectivity is shown in Figure B-2.

Name: SMITHSONIAN
Routes: BLUE, ORANGE LINES
CI: 3.478991

Fig.B-2. The same data, shown with increased zoom and aerial photography as the canvas backdrop