Transit Service Indicators for Alternative Route Structure Analysis

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Abstract: - This paper proposes a unique approach to measuring transit system performance, particularly as it relates to network connectivity. The method developed incorporates a graph theoretic approach to determine the performance of alternative transit network structures by quantifying measures of connectivity at the node, line, zone, and regional level. The method is then applied to a case study of alternative routes implemented in 2011 by StarMetro, the public transit authority in Tallahassee, Florida. The study compares level of service between an old centralized route structure and a new decentralized network. The results of the paper indicate that the decentralized transit system reduced overall regional network connectivity by nearly 40%. While the new transit structure generally underperforms at all levels, the results also provide insight on how network performance can be improved with limited resources. The method presented in this paper provides a framework for planners and policy-makers to quickly and efficiently determine the quality of service resulting from proposed transit network changes and provides new tools for transit service planning.

Key-Words: - public transportation, connectivity, graph theory, transit alternatives analysis.

1 Introduction
The level of service provided by a transit network is a difficult and complex transportation measure. This is a difficult task for the following reasons. First, the number of factors related to service quality, such as walking distance, in-vehicle travel time, waiting time, number of destinations served and the number of transfers needed to reach destinations makes the measurement of transit connectivity a multidimensional problem. Second, the transit system consists of many different routes; determining the extent to which each route is integrated and coordinated with the broader network so that the entire transit system is connected is a difficult task [1]. Third, determining level of service not only requires a measure of how the transit system is performing, but also a measure of the quantity and number of opportunities the system provides access to. In this context, connectivity is one of the index measures that can
be used to quantify and evaluate transit performance [2] [3].

Planners and policy-makers interested in measuring and potentially improving the level of transit service require a method that can be applied to existing transit network data. In addition, the method should be flexible enough, and with limited data requirements, so that a single index number can be obtained from the current route structure and compared to the index of proposed alternative route structures. In applying such an index, transit planners can not only avoid capital-intensive transit assignment models, but also obtain high quality measures of alternative route structures that allow for better-informed service planning decisions.

This paper proposes a unique approach to measuring transit system performance, particularly as it relates to network connectivity that differs from the usual connectivity measures. The most common method for evaluating network connectivity is the degree centrality, which has been used in a wide array of fields including computer science, epidemiology and social science [4] [5] [6] [7] [8]. However, while this method works well for some applications, it is too simplistic to accurately measure the quality and connectivity of a complex network like transit.

The method developed in this paper incorporates a graph theoretic approach to determine the performance of alternative transit network structures to quantify the measures of connectivity at the node, line, zone, and regional level. An assessment of connectivity is achieved by incorporating the unique qualities of each transit line and measures of accessibility such as route characteristics, schedules, socio-economic, demographic, and spatial activity patterns. By combining these criteria in 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 assessment tools decision makers can utilize to assess the quality of a transit system. In addition to the ease of quantification which provides a high level of tractability, the method is generalizable to any transit system.

As noted earlier, in this paper we develop a graph theoretic approach to transit performance measurement as it relates to connectivity; create a connectivity index for three levels of the transit network: node, line and zone/regional; and apply the methodology to a real case study of the StarMetro bus service in Tallahassee Florida.

2 Problem Formulation

The methodology presented in this paper is for transit systems at different levels. As the very nature of nodes, lines, zones and regions, each require a unique formulation. The description below explains the mathematical construct of these transit levels in a step-by-step manner.

2.1 Node Connectivity

The proposed methodology consists of better representations of transit node index measures than existing centrality and connectivity measures provide. 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 other measures have not incorporated the transit attractiveness as per the land use and transportation characteristics of the area the transit line is passing through [9]. 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 defined as follows.

\[ P_{l,n}^i = \alpha C_l \times \beta V_l \times \gamma D_{l,n}^o \times \vartheta A_{l,n} \]  
\[ P_{l,n}^o = \alpha C_l \times \beta V_l \times \gamma D_{l,n}^o \times \vartheta A_{l,n} \]

Where, \( C_l \) is the capacity of line \( l \), \( V_l \) is the speed of line \( l \), and \( D_{l,n}^o \) is the distance of line \( l \), from node \( n \) to the destination. The parameter \( \alpha \) is the scaling factor coefficient for capacity, \( \beta \) is the scaling factor coefficient for speed, and \( \gamma \) is the scaling factor coefficient for distance. The additional variable \( A_{l,n} \) in equations (1) and (2) is the activity density of transit line \( l \) at node \( n \), and \( \vartheta \) is the scaling factor for activity. The activity density represents the development pattern based on both land use and transportation characteristics. The activity density is the ratio of activity of a zone to the unit area. Activity can be defined as the sum of household and employment in the zone. In the literature activity is defined in a number of ways, but for simplification purposes, we have considered activity to be confined to household and employment only. All the
nodes within a zone will receive the same activity density. Mathematically, activity density (equation (3)) is defined as:

\[ A_{l,n} = \frac{H_{l,n}^z + E_{l,n}^z}{\Theta_{l,n}^z} \]  

(3)

where \( H_{l,n}^z \) is the number of households in zone \( z \) containing line \( l \) and node \( n \), \( E_{l,n}^z \) is employment for zone \( z \) containing line \( l \) and node \( n \) and \( \Theta_{l,n}^z \) is the area of zone \( z \) containing line \( l \) and node \( n \).

The connectivity index measures the 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:

\[ P_{l,n}^o = \alpha C_{l} \times \beta V_{l} \times \gamma D_{l,n}^o \times \vartheta A_{l,n} \times \varphi T_{l,n} \]  

(4)

\[ P_{l,n}^i = \alpha C_{l} \times \beta V_{l} \times \gamma D_{l,n}^i \times \vartheta A_{l,n} \times \varphi T_{l,n} \]  

(5)

In the above equations, “\( l \)” is the number of transit lines at node “\( n \)”, and \( \varphi \) 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 upon the node. The transfer scaled index (equation (6)) is defined as:

\[ T_{l,n} = \frac{\sum_{i \in l} P_{l,n}^t}{\Theta_{l,n}^n} \]  

(6)

where \( P_{l,n}^t \) is the total connecting power of line \( l \) at node \( n \) and \( \Theta_{l,n}^n \) is the number of lines \( l \) at node \( n \).

### 2.2 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. It is defined as:

\[ p_{l,n}^t = \frac{P_{l,n}^o + P_{l,n}^i}{2} \]  

(7)

The connecting power of all transit nodes is summed and scaled by the number of stops on the transit line to calculate the line’s connectivity index value. The scaling measure is used to reduce the connecting score of lines with many stops like bus lines to properly compare to lines with only a few stops like rail. The line connectivity can be defined as follows:

\[ \theta_{l} = (|S_{l}| - 1)^{-1} \sum P_{l,n}^t \]  

(8)

where \( S_{l} \) is the set of stops on line \( l \).

### 2.3 Zonal/Regional Connectivity

The level of connectivity of a zone or region provides a measure of transit performance at a local and regional level for transit networks that is otherwise difficult to ascertain. The performance of a given area is the sum of the connectivity of all nodes within that area scaled by the total number of nodes in the area. This scaling method makes it possible to compare the quality of connectivity between areas of differing size and density. The regional connectivity index equation is shown below.

\[ \theta_{R} = (|S_{R}| - 1)^{-1} \sum P_{l,n}^t \]  

(8)

Where \( S_{R} \) is the set of stops in area \( R \).

### 3 Case Study

The proposed analytical framework for this transit service alternative route analysis is applied to a case study of the StarMetro bus system in Tallahassee Florida. In the years leading up to 2011, StarMetro, the city transit authority, undertook a significant route restructuring from a centralized bus network (figure 1a) which is referred to in the paper as Old StarMetro (OSM) to a new decentralized network (Figure 1b) called “NOVA 2010” (N2010) [10].
Though the change in route structure was a well thought-out plan with a long review process, the reaction to the new system has been mixed. This paper applies the proposed service indicator index to determine if the decentralization of routes in the study area has, as many critics claim, actually reduced transit service quality in terms of network connectivity and quality of access.

The characteristics of each route structure are presented in the table 1. The OSM network consisted of more bus routes, route miles and stops than the new N2010 route structure. StarMetro marketed the N2010 as an improvement in efficiency by providing better service to more desirable locations with fewer resources. The reduction in these resources is evident when comparing the two network characteristics.

As table 1 indicates, the N2010 route structure reduced the number of bus routes by 68% and the number of route miles by 24%. Both systems have routes that cross 390 zones, but the N2010 network has stops in 25% fewer of these zones and serves a total of about 58% fewer bus stops (nodes served).

Four levels of connectivity were measured and compared for the two alternative bus route structures: node, line, region and zone (TAZ). The summary results for the first three measures are presented in table 2. The results indicate that the OSM network outperforms the new N2010 structure on each of the three connectivity measures.

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Table 1 Network Characteristic Comparison

<table>
<thead>
<tr>
<th>Network Characteristic</th>
<th>OSM</th>
<th>N2010</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routes</td>
<td>38</td>
<td>12</td>
<td>-68.42%</td>
</tr>
<tr>
<td>Route Miles</td>
<td>373</td>
<td>283</td>
<td>-24.13%</td>
</tr>
<tr>
<td>Ave. Miles per Route</td>
<td>9.82</td>
<td>23.58</td>
<td>140.26%</td>
</tr>
<tr>
<td>Nodes Traversed</td>
<td>1759</td>
<td>1518</td>
<td>-13.70%</td>
</tr>
<tr>
<td>Zones Traversed</td>
<td>390</td>
<td>390</td>
<td>0.00%</td>
</tr>
<tr>
<td>Nodes Served</td>
<td>751</td>
<td>317</td>
<td>-57.79%</td>
</tr>
<tr>
<td>Zones Served</td>
<td>332</td>
<td>247</td>
<td>-25.60%</td>
</tr>
</tbody>
</table>

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Table 2 Network Connectivity Measure

<table>
<thead>
<tr>
<th>Connectivity Measure</th>
<th>OSM</th>
<th>N2010</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node</td>
<td>306.77</td>
<td>134.85</td>
<td>-56.04%</td>
</tr>
<tr>
<td>Line</td>
<td>28.08</td>
<td>16.02</td>
<td>-42.93%</td>
</tr>
<tr>
<td>Region</td>
<td>990.20</td>
<td>614.85</td>
<td>-37.91%</td>
</tr>
</tbody>
</table>

At the node level, which represents a stop in the transit system, the new N2010 structure provides 56% less connectivity than the previous OSM structure, node for node. At the transit line level the combined quality of service for the new system is 43% worse than the old network. Finally, with the implementation of the new decentralized system, the entire region has nearly 40% less connectivity. The results indicate that the quality of service at all levels is worse with the new decentralized transit system.

Each of the network zones, based on the geography of traffic analysis zones (TAZs) was ranked in order of relative density. Density is a good measure of potential transit trip productions and attractions and
signals a connection to a desirable location. The level of service to each of these zones from each route structure is compared. Table 3 presents the results of the analysis.

### Table 3 Zonal Connectivity

<table>
<thead>
<tr>
<th>Connectivity Measure</th>
<th>ROUTE</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OSM</td>
<td>N2010</td>
</tr>
<tr>
<td><strong>Top 10 Regional zones</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Serviced</td>
<td>8.00</td>
<td>6.00</td>
</tr>
<tr>
<td>Connectivity</td>
<td>561.60</td>
<td>419.89</td>
</tr>
<tr>
<td><strong>Concurrent Zones (n=215)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connectivity</td>
<td>591.19</td>
<td>595.63</td>
</tr>
<tr>
<td>Service to top 10</td>
<td>397.80</td>
<td>491.89</td>
</tr>
</tbody>
</table>

The results show that overall; the OSM network performs better than the N2010 network in service provision and connectivity at the zonal level. N2010 does perform better when comparing connectivity of zones that both systems served. This means that where the two systems operated in the same zone, the new decentralized structure provides more connectivity than the old centralized structure. This indicates that a decentralized network structure has the capacity to provide higher levels of connectivity than the centralized system, but requires careful planning to properly connect high activity zones in an efficient manner.

When comparing the connectivity each system offers to the top ten densest zones, the OSM network outperforms. The centralized zone is able to provide access and transfers between higher quality locations more efficiently than the decentralized network. The decentralized network, despite forcing most riders to the center of the system, is still able to provide more direct service to locations that are likely more desirable.

Figures 2a and 2b show a close-up of the two transit system structures and their interaction with the top 10 zones (cross-hashed squares) in terms of activity density with each bus node and line scaled by the calculated level of connectivity. Two observations become evident from these figures: (1) the centralized network approximates a network configuration around the highest levels of activity and (2) the bus lines that provide service to these dense areas are of a higher quality in terms of connectivity with the OSM structure than the N2010.

The analysis indicates that the decentralization of the Tallahassee bus system did not improve the transit network performance and by many measures actually decreased service. The removal of routes and transit stops from the densest activity zones negatively impacted the overall quality of the transit system. Further, while the old structure resembled more of a radial pattern than a network, a dense network structure was adopted in the densest activity area, which added a higher level of connectivity to the system while the decentralized nature of the N2010 system came at the cost of excluding many dense zones and reduced transfer efficiency. This results is a new bus route structure that significantly underperforms the old route structure.

### 4 Conclusion

This paper develops a graph theoretic approach to determine the level of connectivity of a transit network as an indicator of service quality.
Performance is measured at the node, line, zone, and regional level. The method is then applied to a case study of alternative routes implemented in 2011 by StarMetro, the public transit authority in Tallahassee, Florida. The study compares level of service between an old centralized route structure and a new decentralized network.

The results of the paper indicate that the decentralized transit system reduced overall regional network connectivity by nearly 40% and the new transit structure generally underperforms at all levels. The analysis shows that for zones served by both systems the new structure performs better, which indicates that a decentralized network structure has the capacity to provide higher levels of connectivity than a centralized system, but requires careful planning to achieve greater levels of service overall. The results further indicate that while the current route structure does not provide as high a level of connectivity as the old structure, with improvements of stop location and small modifications to the route structure the system could substantially increase network connectivity with fewer resources than the previous structure.

This paper provides a new analytical framework for the measurement of alternative route structure analysis. This is particularly important due to the difficulty of measuring transit network performance and connectivity and the expense of using existing transit assignment models. With this framework, planners can quickly and efficiently determine the quality of service resulting from proposed transit network changes. The framework of this study can be extended to analyze changes in the service indicators with changes to individual system nodes as a sensitivity analysis and measure of network resiliency, incorporation of other attributes to the current formulation, and extension of the proposed research for optimizing transit quality of service.

References: