AN ABSTRACT OF THE THESIS OF

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Title: A Comprehensive Methodology for Measuring the Performance of Transit Networks

Abstract approved

J. David Porter

The performance of transit networks must be measured on a regular basis to understand how well these complex systems fulfill their intended purpose and to identify potential opportunities for improvement. Measuring transit network performance is only achievable by defining a specific set of *transit network performance indicators* (TNPIs). Different schemes have been proposed to identify TNPIs and to use these TNPIs to measure transit network performance. Graph Network Theory (GNT) is a common method used to identify TNPIs, whereas Multi-Criteria Decision Making (MCDM) models have been used as mechanisms to measure the performance of a transit network based on the identified TNPIs. The main motivation of this research was the lack of evidence of prior work that has attempted to develop TNPIs to assess the performance of a public transit network based not only on its physical and operational

characteristics, but also on the *demand* and *population changes* experienced in the area the transit network serves. Population changes (i.e., increases or decreases) in the area served by the transit system is arguably one of the main drivers of demand. A significant advantage of considering the effects of population changes on the performance of a transit system is that it enables transit planners to predict the performance of the transit system based on future population changes and apply any necessary changes in advance, thus potentially preventing a decrease in the level of service provided by the transit system.

The main objective of this research was to develop a methodology to assess the quality of service provided by a transit network as the demand (driven by population changes) on the transit network changes over time. The proposed methodology attempts to identify existing or future gaps between the *level of service* and the *level of need* in the target area served by a transit network with the expectation that a more informed awareness of such a gap could help transit planners when revising future service plans.

The results obtained from two case studies demonstrate that the proposed methodology can help transit planners to estimate the effects on the performance level of a transit network due to fluctuations in demand driven by population changes. The proposed methodology also facilitates the analysis that hypothetical changes to the transit network (e.g., adding a new route, increasing service frequency, etc.) have on the level of performance of the transit network.

A Comprehensive Methodology for Measuring the Performance of Transit Networks

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Mehrdad Rahanjam, Author

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1.0 INTRODUCTION

The performance of transit networks must be measured on a regular basis to understand how well these complex systems fulfill their intended purpose and to identify potential opportunities for improvement. Performance indicators such as existing demand trends, peaks of operation, existing stakeholders concerns, and unmet service needs can be helpful for monitoring, evaluating economic performance, administering the organization, communicating the organization's achievements and challenges, developing service design standards, and noting community benefits (Transportation Research Board, 2003). Performance indicators can also provide essential information to guide the decision making process regarding transit planning, management, and finance (Nurul Hassan, Hawas, & Ahmed, 2013).

The service reliability of public transit networks is gaining increased attention as agencies face immediate problems in providing credible service and attempting to reduce operational costs. Unreliable service has been cited as the major deterrent element for existing and potential passengers (Hadas & Ceder, 2010). Moreover, the personal automobile is currently the preferred transportation mode for most Americans due to its convenience. In 2010, Americans drove for 85 percent of their daily trips (Buehler, 2014). In order for public transit networks to compete effectively with the personal automobile, they must provide an acceptable level of convenience, including greater coverage and more frequent service to peripheral areas (Wiley, 2009). As a result, ensuring the quality of service of transit networks is an essential task for transportation engineers and transportation authorities.

1.1 RESEARCH MOTIVATION

Public and private transit agencies are always in need of an awareness of their performance level. In recent years, a significant amount of research has focused on developing new methods for evaluating the performance of transit networks (Karlaftis, 2004; Mishra, Welch, & Jha, 2012). Measuring transit network performance is only achievable by defining a specific set of *transit network performance indicators* (TNPIs).

Different schemes have been proposed to identify TNPIs and to use these TNPIs to measure transit network performance. Graph Network Theory (GNT) is a common method used to identify TNPIs, whereas Multi-Criteria Decision Making (MCDM) models have been used as mechanisms to measure the performance of a transit network based on the identified TNPIs. Most of the prior research in this area has focused on a limited number of factors affecting the performance of a transit system. For example, most of the TNPIs based on GNT focus only on the topological factors of a transit system (e.g., connectivity, complexity, etc.), whereas other transit network performance methods rely exclusively on operational TNPIs (e.g., delay times, service hours, etc.) thus making them incapable of assessing the level of performance of a transit system in a comprehensive manner.

The main motivation of this research was the lack of evidence of prior work that has attempted to develop TNPIs to assess the performance of a public transit network based not only on its physical and operational characteristics, but also on the *demand* and *population changes* experienced in the area the transit network serves. Population changes (i.e., increases or decreases) in the area served by the transit system is arguably one of the main drivers of demand. A significant advantage of considering the effects of population changes on the performance of a transit system is that it enables transit planners to predict the performance of the transit system based on future population changes and apply any necessary changes in advance, thus potentially preventing a decrease in the level of service provided by the transit system.

1.2 RESEARCH OBJECTIVE

The main objective of this research was to develop a methodology to assess the quality of service provided by a transit network as the demand (driven by population changes) on the transit network changes over time. The proposed methodology attempts to identify existing or future gaps between the *level of service* and the *level of need* in the target area served by a transit network with the expectation that a more informed awareness of such a gap could help transit planners when revising future service plans.

1.3 RESEARCH CONTRIBUTIONS

The main contribution of this research was a methodology to assess the quality of service provided by a transit network as the demand (driven by population changes) on the transit network changes over time. The proposed methodology has several salient features:

- It simultaneously considers different factors that are particular to the transit network being analyzed (e.g., topology, performance, operations, etc.) and produces a comprehensive final performance score.
- It incorporates two new TNPIs which take into account the effect of demand changes on the performance of a transit network.
- It implements a new process to categorize TNPIs.
- It is capable of ranking the areas served by a transit network for comparison purposes.

The results obtained in this research demonstrate that the proposed methodology can help transit planners to estimate the effects on the performance level of a transit network due to fluctuations in demand driven by population changes. The proposed methodology also facilitates the analysis that hypothetical changes to the transit network (e.g., adding a new route, increasing service frequency, etc.) have on the level of performance of the transit network.

2.0 LITERATURE REVIEW

The main objective of this research was to develop a methodology to assess the quality of service provided by a transit network as the demand on the transit network changes over time. In the context of this research, the demand placed on a transit network is influenced mainly by changes in population.

The main findings of a literature review conducted in the areas of transit network performance measuring, identification of population groups in need of public transportation (i.e., transport disadvantaged), and the general transit feed specification (GTFS), are synthesized in this chapter.

The rest of this chapter is organized as follows. Section 2.1 discusses diverse approaches for assessing the quality of service of a transit network based on performance indicators. Section 2.2 discusses previous research in identification of population groups in need of transportation. Section 2.3 discusses data collection approaches as well as methods for utilizing current available data about transit networks and their associated agencies. Finally, section 2.4 summarizes the findings of the literature review, identifies specific research gaps, and describes how this research addresses those gaps.

2.1 PERFORMANCE INDICATORS AND PERFORMANCE MEASUREMENT OF TRANSIT NETWORKS

The performance of transit networks must be measured to understand how well they fulfill their intended purpose and to identify potential opportunities for improvement. Measuring transit network performance is only achievable by defining a specific set of performance indicators.

Different schemes have been proposed in the literature to identify *transit network performance indicators* (TNPIs) and to use these TNPIs to measure transit network performance. *Graph Network Theory* is a common method used to identify performance indicators, whereas *Multi-Criteria Decision Making* (MCDM) models have been used as mechanisms to measure the performance of a transit network based on the identified TNPIs.

Figure 2.1 depicts the main steps to develop a performance score for a transit network. The first step involves identifying the metrics (e.g., number of stops, number of routes, people over 60 years of age, etc.) needed for the development of TNPIs. Once these metrics are identified, TNPIs can be calculated based on the mathematical relationships among metrics. The calculated TNPIs are then used to derive the criteria needed for the application of the MCDM methods. Finally, a performance score is obtained based on the selected and calculated criteria.

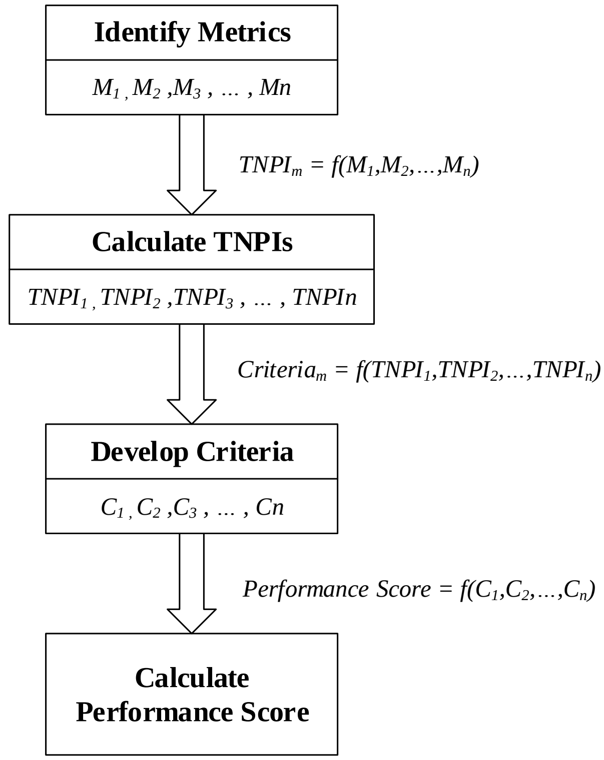


Figure 2.1: Methodology to measure the performance of a transit network using graph network theory and MCDM methods

2.1.1 Graph Network Theory Performance Indicators

Transit networks can be abstracted using models where the links (or *edges*) of the graph represent routes and the nodes (or *vertices*) of the graph represent stops. Using a graph as an abstraction of the transit network facilitates the application of typical formulas used in graph network theory to derive TNPIs (e.g., the connectivity index of a stop).

In mathematics and computer science, graph theory is the study of *graphs*, which are mathematical structures used to model pairwise relations between objects. A graph is made up of vertices (or nodes) and lines called edges that connect them. The application of graph theory in transportation first emerged in the 1950s (Derrible & Kennedy, 2010). Garrison and Marble (1962, 1964) were the leaders in incorporating graph theory into transportation networks by introducing three graph network theory performance indicators (GNTPIs) for network design: *circuits* (i.e., close loops formed by nodes joined by edges in a graph), *degree of connectivity* (i.e., ratio of the actual number of edges over the potential number of edges), and *complexity* (i.e., ratio of edges over nodes). Equations 2.1, 2.2, and 2.3 show how the GNTPIs *circuits* (α), *degree of connectivity* (γ), and *complexity* (β) are calculated.

$$\alpha = \frac{E - V + p}{2(V - 5)} \tag{2.1}$$

$$\gamma = \frac{E}{3(V - 2)} \tag{2.2}$$

$$\beta = \frac{E}{V} \tag{2.3}$$

Where E is the number of edges, V is the number of nodes, and p is the number of non-connected graphs (isolated networks).

More recently, Derrible and Kennedy (2009) classified the edges of a transit network as either single edges ($\mathbf{E^S}$) or multiple edges ($\mathbf{E^M}$). A single edge is a link connecting any pair of adjacent vertices, whereas multiple edges are additional links connecting a pair of adjacent vertices that are already connected by a single edge. Figure 2.2a illustrates the concept of a single edge. The links (edges) E2 and E3 in Figure 2.2b illustrate the concept of multiple edges.

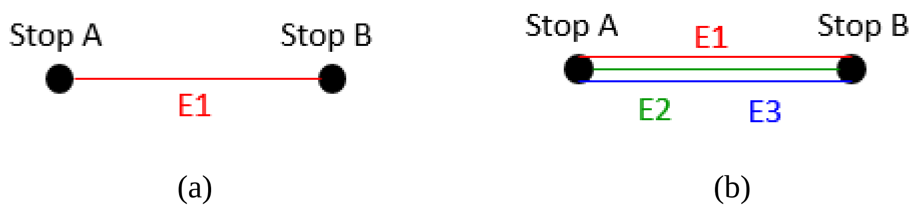


Figure 2.2: Example of single (E1) and multiple (E2 and E3) edges

Derrible and Kennedy (2009) also developed the three GNTPIs *coverage* (i.e., the area accessible by a transit network); *directness* (i.e., the total route length divided by the longest route possible in the network); and *connectivity* (i.e., the ability to travel freely in the network or travel path choices) using such inputs as the number of stops, number of routes, route lengths, and the maximum number of transfers of a network. Equations 2.4, 2.5, and 2.6 show how the GNTPIs *coverage* (σ), *directness* (τ), and *connectivity* (ρ) are calculated. The necessary inputs to calculate these GNTPIs are explained in Table 2.1.

$$\sigma = \frac{N_{STOP} \times \pi \times r^2}{A} \tag{2.4}$$

$$\tau = \frac{n_L}{\delta} \tag{2.5}$$

$$\rho = \frac{V_c^t - E^M}{V^T} \tag{2.6}$$

Table 2.1: Inputs to calculate the GNTPIs *coverage* (σ), *directness* (τ), and *connectivity* (ρ)

Inputs	**Description**
N_{STOP}	Number of stops in the transit network
r	Threshold value of 500 meters radius for a coverage area
A	Area served by the transit network
n_L	Total number of lines of a network
δ	Maximum number of transfers needed to go from any stop to another
V_c^t	Number of transfer possibilities
V^T	Number of transfer vertices
E^M	Number of multiple edges

Simple and multiple regression models were developed to test the validity of the three proposed GNTPIs. First, simple regression analyses were performed using *boardings per capita* as the response variable and each separate GNTPI as the explanatory variable. Next, a multiple regression analysis was performed that incorporated all the GNTPIs together as explanatory variables and *boardings per capita* again as the response variable. The results of the regression analyses showed relatively the same adjusted r-squared value of 0.75 and all the t-statistics of the explanatory variables were significant. It was concluded that all three proposed GNTPIs play a key role in the network design and had an important impact on *boardings per capita*.

Derrible and Kennedy (2010) characterized subway networks using the following features:

- **State**. Measured the complexity of a subway network.
- **Form**. Measured the link between a subway system and the region it serviced.
- **Structure**. Measured the structural connectivity and directness of current subway networks.

The GNTPIs *complexity* and the *degree of connectivity*, developed by Garrison and Marble (1962), were used to assess the *state* of a subway network. To assess *form*, the authors developed the GNTPIs *average line length* and *inter-station spacing* (i.e., ratio of total route length over number of stops). Finally, the authors assessed *structure* using the GNTPIs *connectivity* and *directness* (Derrible and Kennedy, 2009). A total of 33 subway networks from around the world were assessed using the proposed characterization scheme and corresponding performance indicators. Since this was an extension of their previous work, no validity tests on the indicators were conducted.

Quintero-Cano (2011) used the three network examples depicted in Figure 2.3 to prove that the TNPIs *degree of connectivity* (γ) and *complexity* (β) proposed by Garrison & Marble (1962) were not accurate enough and might produce misleading results.

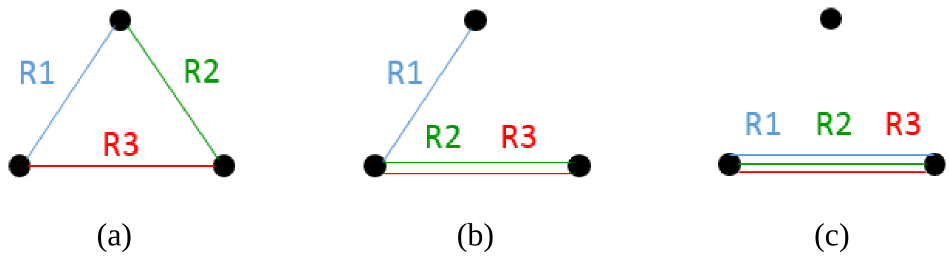


Figure 2.3: Example of three networks with different structures, but the same number of edges (Quintero-Cano, 2011)

Figure 2.3 shows three networks with different structures (i.e., the way their nodes are connected to each other through edges), but the same number of nodes and routes (i.e., R1, R2, and R3). However, when estimating the values of γ and β using equations 2.2 and 2.3, the results are the same for all the three networks. It is easy to see that the network illustrated in Figure 2.3*a* is the most connected, followed by the network in Figure 2.3*b*, and then the network in Figure 2.3*c* (i.e., the least connected).

Table 2.2: Calculation of γ and β for networks in Figure 2.3 (Quintero-Cano, 2011)

Network	**E^S**	**E^M**	**E**	**V**	**γ**	**β**
A	3	0	3	3	1	1
B	2	1	3	3	1	1
C	1	2	3	3	1	1

To address this issue, Quintero-Cano (2011) suggested that only single edges should be considered, and that the effects of operational factors such as frequency of routes should also be taken into account when calculating γ and β. Equations 2.7 and 2.8 are the modified versions of the original formulas for γ and β (i.e., equations 2.2 and 2.3) proposed by Garrison and Marble (1962).

$$\gamma" = E^f \times \gamma(E^S) = E^f \times (\frac{E^S}{3(v-2)}) \tag{2.7}$$

$$\beta" = E^f \times \beta(E^S) = E^f \times (\frac{E^S}{v}) \tag{2.8}$$

Where $\gamma(E^S)$ and $\beta(E^S)$ represent the connectivity indicators for γ and β, but using the number of single edges E^S instead of the total number of edges E (which includes the number of both single and multiple edges).

Quintero-Cano (2011) refers to E^f as the "number of edges normalized by frequency of routes," and proposes the following mathematical expression:

$$E^f = \frac{0.5(\sum_{k=1}^{q}\sum_{j=1}^{p}\sum_{i=1}^{n} f_{ijk})}{f_{max}} \tag{2.9}$$

Where f_{ijk} is the frequency of the k^th route linking vertex *i* to vertex *j*. The numerator is multiplied by 0.5 because Quintero-Cano (2011) assumed that each direction of an edge connecting two adjacent vertices should be counted as half an edge. Finally, f_{max} is the maximum sum of frequencies between any pair of adjacent vertices *i* and *j* in the whole transit network. Equation 2.10 shows how f_{max} is calculated.

$$f_{max} = \max\,[\textstyle\sum_{k=1}^{1}(f_{ijk} + f_{jik})] \tag{2.10}$$

In order to validate the newly proposed connectivity indicators (i.e., γ" and β"), Quintero-Cano (2011) conducted a multiple regression analysis that incorporated γ" and β" as well as a few other indicators (from the existing literature) as explanatory variables and *ridership* as the response variable. The results of the multiple regression analyses showed a positive linear relationship between the explanatory variables and the response (r-squared of 0.61 for γ" and

0.58 for β'') which indicated that the addition of new links (i.e., bus routes) or an increase in bus route frequencies will tend to create more ridership.

Yang, Zhang, and Zhuang (2007) used *connectivity* (i.e., the existence of one or more public transportation routes between stops) as a GNTPI. The authors developed two different models to measure connectivity. In the first model, connectivity was based on inputs such as the planning area, the number of connected stops in the planning area, the average linear distance between two adjacent stops, and the total mileage of the transit network roads in the planning area. In the second model, connectivity was based on inputs such as the number of stops in the transit network, the average distance between the stops in the transit network, and the total linear length of the transit network. Table 2.3 shows the different connectivity ratings that a transit network may obtain based on these two models. No direct validation of the *connectivity* GNTPIs was performed, but the two models were applied in a case study conducted in a town in China using the macroscopic simulation software TransCAD, which calculated the required inputs for a transit network and determined its connectivity score based on the two different models.

Table 2.3: Connectivity spans and the corresponding evaluations (Yang, Zhang, and Zhuang (2007))

Span of Connectivity	**Evaluation of Connectivity**
$C \leq 1.0$	Public transport network connectivity is worse
$1.0 \leq C \leq 2.0$	Public transport network connectivity is good
$2.0 \leq C \leq 3.22$	Public transport network connectivity is consummate
$C \geq 3.22$	Public transport network connectivity reaches an ideal state

Mishra, Welch, and Jha (2012) used the concept of connectivity to develop new measures to assess the GNTPIs *node connectivity*, *route connectivity*, *connectivity of a transfer center* (i.e., groups of nodes defined by ease of transfer between lines), and *regional (large area) connectivity*. The inputs operating speed, transit network capacity, number of trips, density (i.e., the ratio between the population and the corresponding area), and population were used to measure the proposed GNTPIs. The validity of the GNTPIs was tested using a very small graph that represented a public transit network. The results of the validation showed that the new measures used for assessing GNTPIs gave different results compared to other measures found in their literature review that were previously used to assess the proposed GNTPIs. The authors justified the differences observed as being due to the different inputs considered by the measures used for assessing GNTPIs, and the fact that they favored their proposed connectivity GNTPIs since they considered more inputs in their measurements resulting in more accurate and rational results. The applicability of the proposed GNTPIs was later tested using a comprehensive transit network located near the Washington, D.C.-Baltimore region.

Hadas and Ceder (2010) developed spatial-based performance indicators based on geographic entities such as streets and public transit routes, which could be helpful in the design phase of public transit networks. Spatial and non-spatial data were used to develop GNTPIs. The analysis was conducted in two phases; the spatial analysis was conducted first and then the connectivity performance indicators were calculated. The first GNTPI developed measured the quality of service and considered the ease of transfer weighted by the demand and the headway. The second GNTPI measured the ease of transfer alone. The validation of the proposed GNTPIs was tested by applying them to two transit networks in two mid-sized cities in Israel.

Table 2.4 summarizes the GNTPIs selected from the literature of this section that were relevant to the methodology of this research.

Table 2.4: Relevant topological indicators of the literature review chapter

Indicator	**Symbol**	**Equation**	**Proposed by**
Complexity	β	$\beta = \frac{E}{V}$	Garrison & Marble (1962)
Degree of Connectivity	γ	$\gamma = \frac{E}{3(V-2)}$	Garrison & Marble (1962)
Complexity (Normalized by route frequency)	β”	$\beta'' = E^f \times \frac{E^S}{v}$	Quintero-Cano (2011)
Degree of Connectivity (Normalized by route frequency)	γ”	$\gamma'' = E^f \times \frac{E^S}{3(v-2)}$	Quintero-Cano (2011)
Structural Connectivity	ρ	$\rho = \frac{V_c^t - E^M}{V^T}$	Derrible & Kennedy (2009)
Coverage	σ	$\sigma = \frac{N_{STOP}\pi r^2}{A_{served}}$	Derrible & Kennedy (2009)

2.1.2 Transit Network Performance Measurement Based on Multi-Criteria Decision Making Methods

When buying a car, it is not uncommon to consider multiple alternatives. Additionally, there are different criteria (or attributes) that should be considered such as price, safety, comfort, fuel economy, etc. It is obvious that the cheapest car would not provide the most comfort. As a result, there is a tradeoff among the desired criteria. In situations where decisions have to be made considering (usually) conflicting criteria, multi-criteria decision making (MCDM) methods are used. A variety of MCDM approaches exist, some of which are based on assigning scores to alternatives, whereas others try to select the alternative that is closest to the ideal solution (Xu & Yang, 2001). In the context of Transit Network Performance Measurement (TNPM), different MCDM methods have been utilized such as the *technique for order preference by similarity to ideal solution* (TOPSIS) and *data envelopment analysis* (DEA).

Nurul Hassan et al. (2013) developed a general, five-step framework to evaluate the performance of a transit system according to a number of selected criteria including passenger loading performance, vehicle performance, operator performance, economic performance, and user satisfaction. Different TNPIs were used to assess the selected criteria, including *ridership*, *travel time*, *cost*, *revenue*, *route length*, *number of operating vehicles*, *total number of operators*, and *number of stops*. A simple weighting processes was utilized to estimate the weight of each criterion and each TNPI. A TOPSIS model was used to assess the route performance using a weighted criteria and weighted TNPIs. Two separate groups of experts were asked to assign weights to the TNPIs and an average for each TNPI was then calculated. The applicability of the framework for TNPM was tested on a real case study in a city in the United Arab Emirates, where a transit network was analyzed at the route level and as an overall system (i.e., aggregation of the route assessments).

Another common MCDM method used for TNPM is DEA. Transit systems consume mainly *labor*, *fuel*, and *capital* to produce an output. Defining outputs is more complicated in terms of efficiency, effectiveness, and an overall or combined performance measure. Fielding (1987) suggested that vehicle-miles are related to service efficiency and passenger-miles are related to effectiveness; a combination of vehicle-miles and passenger-miles would be related to a combined or overall performance measure. These outputs (i.e., vehicle-miles, passenger-miles, and a combination of these two) play the role of the criteria in the context of the DEA literature in TNPM.

Barnum, Karlaftis, and Tandon (2011) categorized DEA articles considering two criteria. The first criterion involved the mode of transportation and included subway and bus transit types such as urban, highway, fixed-schedule, and demand-responsive (i.e., paratransit). The second criterion was based on the way the DEA articles used inputs and outputs among the different types of bus transit. One category of DEA articles included those that considered outputs and inputs as separate variables for each type of bus transit. A second category included DEA articles where the values of most input and output variables were entered separately for each type of bus transit, but there were also shared inputs and outputs among types of bus transit. A third category included DEA articles that used aggregated inputs and outputs from different modes of public transportation (i.e., bus and subway) in large urban areas from around the world. Since aggregated data across multiple modes of transportation were used, only the overall efficiency of public transportation in each urban area was measured but not the efficiency of individual modes of public transportation.

Karlaftis (2004) considered the total number of employees as the input for labor; the total annual amount of fuel used by the system (in gallons) as the input for fuel; and the total number of vehicles operated by the system as the input for capital. These inputs were fed into three separate models: an efficiency model that produced total annual vehicle-miles as output; an effectiveness model that produced total ridership as the output; and a multi-output model that produced both annual vehicle-miles and annual ridership as outputs. Considering each output as a criterion, the final outcome of the research was a summary table of scores obtained from the DEA approach on efficiency, effectiveness, and a combined score of both efficiency and effectiveness for different transit networks. The validity of the outputs was not tested, but the applicability of the approach was demonstrated by using data from 265 U.S. transit systems to calculate scores for the criteria.

Barnum et al. (2011) developed a method based on DEA to measure the efficiency of an urban transit organization. The transit organization was divided into four subunits based on the four most common ways of delivering public transportation in the U.S., i.e., self-operated motorbus, outsourced motorbus, self-operated paratransit, and outsourced paratransit. The authors constructed two DEA-based models to measure the efficiency of the subunits and the overall efficiency of the urban transit organization, respectively. The operating expenses was the only input fed into each of the DEA-based models, whereas seat-hours was the sole output. The output of the DEA-based models was an efficiency score that facilitated the identification of the subunits of the organization that needed improvement. The applicability of the proposed approach was tested using data from 52 transit agencies from the U.S. National Transit database.

2.2 POPULATION GROUPS IN NEED OF PUBLIC TRANSIT SERVICES

This section focuses on identifying population groups that are in need of public transportation services and may face transport inequality (i.e., lack of service that is required to satisfy their transportation needs). Transport inequality is not a new theme within the transportation literature. The study of transport inequality dates back to the early 1970s when physical mobility was identified as a major contributor to social and economic inequality in the U.S. (Wachs and Kumagai, 1973). The population affected by transport inequality is typically referred to in the literature as *transport disadvantaged* (Lucas, 2012; Currie, 2004; Dodson et al., 2010).

In the U.S., approximately 92% of all households have access to a private vehicle. African Americans are far less likely to own and drive a car than White Americans, with 20% of all African American households not having access to a car (Lucas, 2012). There is also considerable evidence to suggest that low income, non-car owning households in the U.S. have less access to public transit (Garcia & Rubin, 2004) and thus experience considerable difficulties in accessing jobs and other key facilities (Cervero, 2004).

Currie (2004) conducted a study in Hobart, Australia, where census data from the population groups *adults without cars*, *adults over 60 years of age*, *persons on a disability pension*, *adults on a low income*, *adults not in the labor force*, and *students* were used to quantify the distribution of transportation needs using a single transport needs index. The six population groups (sourced from an analysis of the Adelaide Household Travel Survey) as well as an accessibility measure of the natural convenience or difficulty a person experiences when traveling from home to basic services (e.g., doctors, hospitals, schools, etc.) were the indicators used to derive a single needs score for different geographic areas of Hobart. Each indicator was standardized by resetting its value between 0 and 100 based on the relationship of the indicator value to the highest value in its series. The standardized values were then weighted and added together resulting in a finalized single needs score. The finalized needs scores were standardized to obtain needs scores between 0 and 100 for all areas of Hobart. The result of the need analysis was then used in a gap analysis between the need for transportation services and the service supply in Hobart.

Dodson, Burke, Evans, Gleeson, and Sipe (2010) conducted a study to investigate transport inequality in Gold Coast City (GCC), Australia. Household travel data for GCC were obtained from the *South East Queensland Travel Survey – Coastal Survey* (SEQTS-CS) in order to identify transport disadvantaged individuals using such variables as *age*, *gender*, *main activity*, *household size*, *household type*, *household structure*, *household income*, and *capacity to drive*. Then, clustering techniques were used to divide the identified transport disadvantaged individuals into the following six cluster groups:

- Group 1. Low-income sole parents.
- Group 2. Working poor.
- Group 3. Students in secondary or tertiary education.
- Group 4. Licensed single retired female.
- Group 5. Unlicensed single retired female.
- Group 6. Unlicensed partnered retired elderly.

Several metrics were defined to assess the travel behavior of the six transport disadvantaged groups, including the average number of trips per day (i.e., the trip rate), mode share, the number of kilometers traveled per capita by mode, and trip purpose. Data were collected for all metrics and all clusters and then compared against data collected for the same metrics for the overall GCC population.

2.3 DATA COLLECTION

Assessing the quality of a transit network would not be possible without having access to up-to-date data about the transit network being studied. This information may include the number of routes, the number of stops, service times, etc.

Prior to 2005, software engineers had to "data scrape" an agency's web site or were required to submit Freedom of Information Act requests to obtain transit data (Roth, 2010). This situation complicated the assessment of single transit networks, let alone performing a state-wide or region-wide study. The advent of the General Transit Feed Specification (GTFS) changed this constrained landscape and motivated transit operators to release their schedules and route information to third party developers. The GTFS is a common format for public transportation schedules and associated geographic information. Using the GTFS specification, a public or private transit agency can describe such characteristics of their transit network as service calendar, stop times, stop locations, trips (a specific stop pattern) and routes (collection of trips), to name a few. The resulting GTFS feed can be used to acquire public transportation information about an agency in space and time. Many transit agencies in the U.S. (and across the world) have already created and adopted the GTFS data standard to make information about their network available to users (googletransitdatafeed Homepage, 2014).

In the state of Oregon, approximately 85% of fixed route transit providers have GTFS data for their services (State of Oregon GTFS Feeds Homepage, 2014). GTFS data has been analyzed by transportation planners and researchers.

Wong (2013) studied 50 large transit agencies in the U.S with available GTFS feeds. He also investigated GTFS field usage and the agencies' operations at the stop, route, and system levels using open source scripts and found GTFS data a versatile and comprehensive data source suitable for archiving and combining with other available data sources to form robust analytic tools.

Lee, Hickman, and Tong (2012) used GTFS to develop a stop aggregation model (SAM) for a transit network. It was assumed that the activities of transit users in the SAM were associated with a specific area that may contain more than one stop rather than associating the users' activities with an individual stop. As a result, the goal of the SAM is to define an aggregate area around a number of stops which can be represented as a single node in the network depending on the level of aggregation. The authors used the GTFS files *stop_time.txt* and *stop.txt* to obtain the times that a vehicle arrives and departs from individual stops for each trip, and to obtain information about stop locations.

Lee, Tong, and Hickman (2013) used GTFS as a data source to measure spatial accessibility of bus stops through an investigation of the willing-to-walk distance. In this research, the GTFS data were used to obtain the detailed location of individual stops for a case study of a single route serving the Minneapolis-St. Paul metropolitan area.

2.4 LITERATURE REVIEW SUMMARY

Measuring the performance of a transit network is not a new subject in the transportation literature. However, there is a lack of evidence of prior work that has attempted to develop TNPIs to assess the performance of a public transit network based not only on its physical characteristics but also on the population changes experienced in the area the transit network serves. Another interesting finding from the literature review is that no evidence exists of any work done in the U.S. that has considered transport disadvantaged populations.

Thus, there is a need for a methodology to analyze the effect that changes in population have on the performance of a public transit network over time. The methodology proposed in this research attempts to identify existing or future gaps between the *level of service* and the *level of need* in the target area served by one or more transit agencies with the expectation that a more informed awareness of such a gap could help public transit agencies when revising their future service plans.

3.0 METHODOLOGY

This chapter describes a proposed methodology to assess the quality of service provided by a transit network as the demand on the transit network (driven by population changes) changes over time. The main phases of the proposed methodology are depicted in Figure 3.1.

In the first phase, the target transit network and the geographic area it serves are identified. The transit network must be converted into a *directed* graph by representing transit stops as *nodes* and routes as *directed* edges. Also, the geographic area serviced by the target transit network must be divided into Traffic Analysis Zones (TAZs). Once a directed graph is obtained, basic metrics such as the number of stops, the number of routes, and the population served, can be calculated for the transit network at the TAZ level.

In the second phase, different transit network performance indicators (TNPIs) are calculated to evaluate the target transit network. These performance indicators are grouped into the categories *topological*, *performance*, and *operational*. The basic metrics calculated in the first phase of the methodology become the main inputs when calculating the different TNPIs.

In the third phase, individual scores are calculated for each TNPI category. In the fourth and final phase, a final score is calculated for the target transit network using the multi-criteria decision making (MCDM) method Analytic Hierarchy Process (AHP).

The rest of this chapter is organized as follows. Section 3.1 discusses in detail the process of identifying the target transit network and defining its service area. Section 3.2 explains how TNPIs are calculated from the metrics obtained in the first phase. Section 3.3 explains how individual scores are calculated for each TNPI category. Finally, Section 3.4 explains how a final score is calculated for the target transit network using AHP.

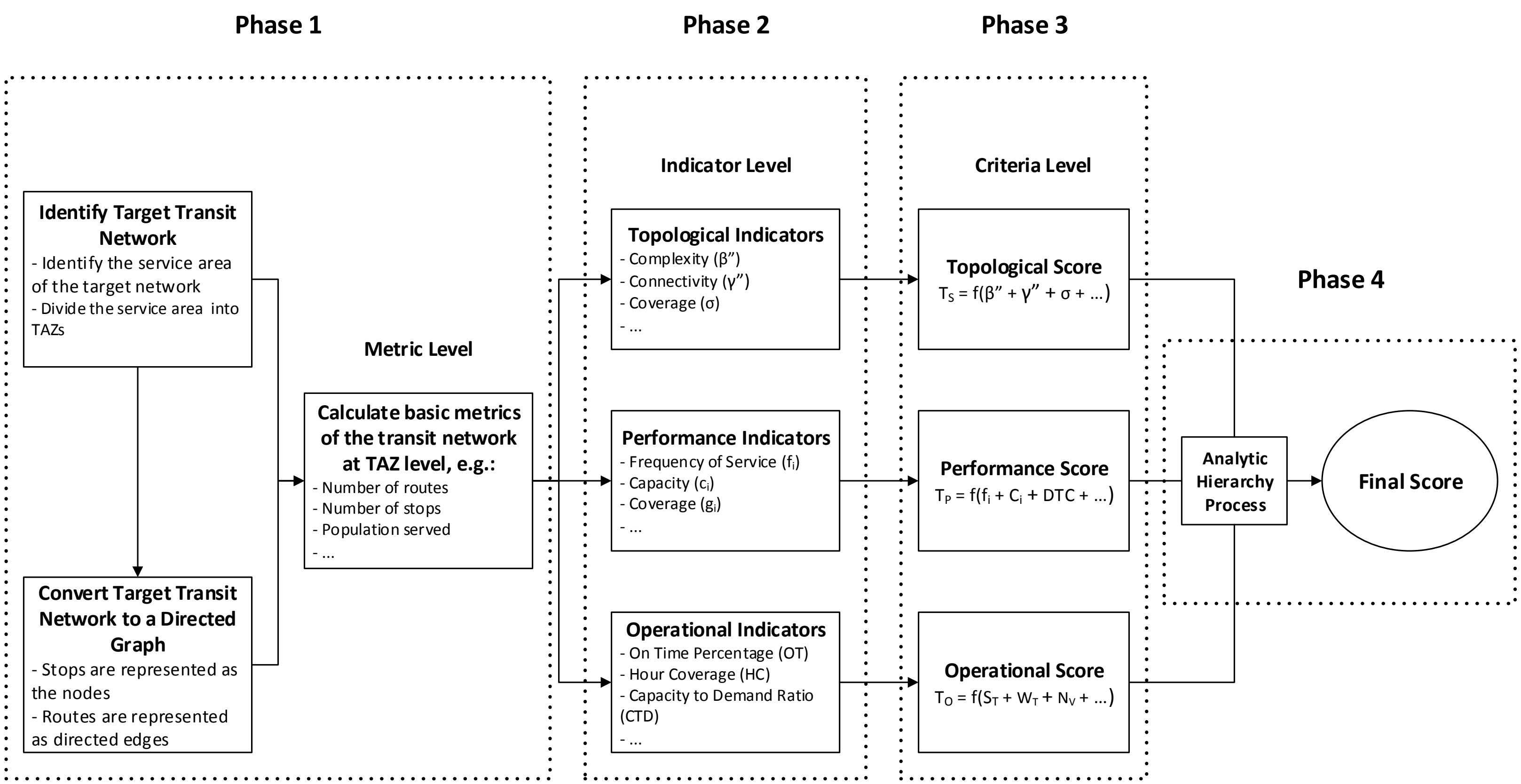


Figure 3.1: Methodology phases to develop/identify criteria, TNPIs, and metrics

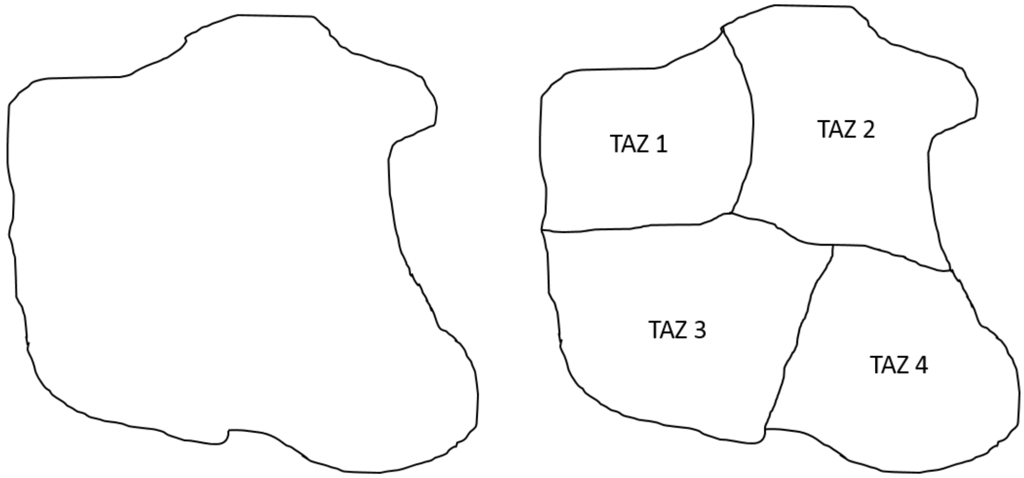
3.1 TARGET TRANSIT NETWORK AND SERVICE AREA

3.1.1 Identifying the Target Transit Network and Its Service Area

In the first phase of the proposed methodology, the target transit network and the geographic area it serves are identified. Then, the service area must be divided into Traffic Analysis Zones (TAZs).

A TAZ is a geographical unit frequently used in the transportation literature and in planning models. Although there is no specific standard for delineating TAZs, they usually represent areas that contain approximately 3,000 people (Miller, Harvey, and Shaw, 2001). It is important to mention that suburban TAZs tend to be larger than metropolitan TAZs due their differences in population density. Other important factors that are considered when delineating TAZs are the number of automobiles per household, household income, and employment within the TAZs (Caliper Corporation, 2007).

The advantages of performing the network analysis of a transit network at the TAZ level include facilitating zonal comparison and simplifying the identification of those TAZs that may need improvement on a particular indicator/criterion within a transit network. Figure 3.2 depicts a geographical area before and after it is divided into TAZs.



(a) (b)

Figure 3.2: A geographical zone before (a) and after (b) being divided into TAZs

3.1.2 Converting a Transit Network into a Directed Graph

Once the service area of the target transit network has been divided into TAZs, the target transit network contained within the service area must be converted to a *directed* graph. The approach used in this research to convert a transit network to a directed graph was adapted from an approach proposed by Quintero-Cano (2011), which in turn had modified a procedure developed by Derrible and Kennedy (2010) originally intended to convert a subway network into a directed graph.

The first modification made by Quintero-Cano (2011) accounts for the potentially large number of transit stops and routes that may exist in a transit network when compared to a subway network. Quintero-Cano (2011) dealt with this issue by breaking a transit network into smaller geographical zones (i.e., TAZs), and then conducting the network analysis at the TAZ level.

The second modification involved converting the target transit network into a *directed* graph. First, the transit network must be represented as a network graph where transit stops and routes are represented by *nodes* and *edges*, respectively. Network graphs can be of two types: undirected or directed. An undirected graph is one whose edges do not consider the direction of travel. Thus, an undirected graph is converted into a directed graph by specifying whether an edge connecting two nodes allows travel in a single direction or in both directions. Figure 3.3a depicts an example of an undirected graph comprised of three nodes and three undirected edges. Figure 3.3b depicts the same graph, but now the undirected edges have been converted into directed edges.

(a) (b)

Figure 3.3: Representing an undirected graph (a) versus a directed graph (b)

Figure 3.4 depicts an example of the service area of a transit network that has been divided into four adjacent TAZs. The numbered dots represent the stops serviced by the transit network, whereas the different colored lines represent transit routes. All the edges shown in Figure 3.4 are assumed to be two-way edges, thus no arrows as displayed on the edges.

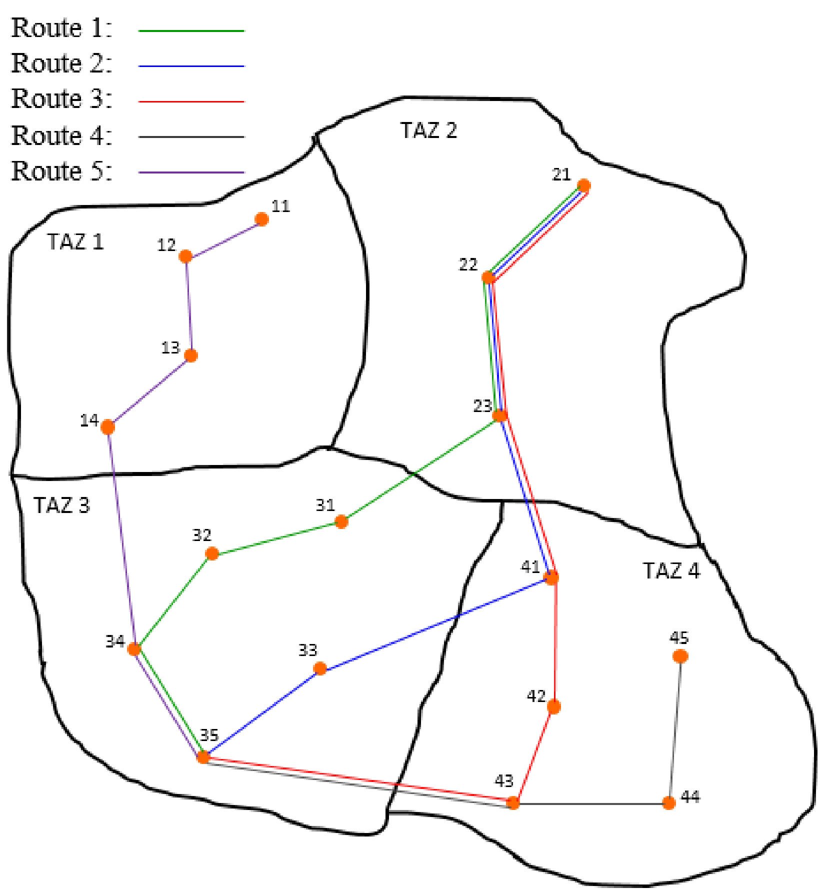


Figure 3.4: Example of a transit network serving four adjacent TAZs

Figure 3.5 depicts the result of separating the transit network in Figure 3.4 into four zonal graphs (based on their corresponding TAZ). When a transit network is separated into zonal graphs, some of the stops and edges actually connect multiple TAZs. Therefore, rules must be established regarding how to account for these stops an edges in each individual TAZ.

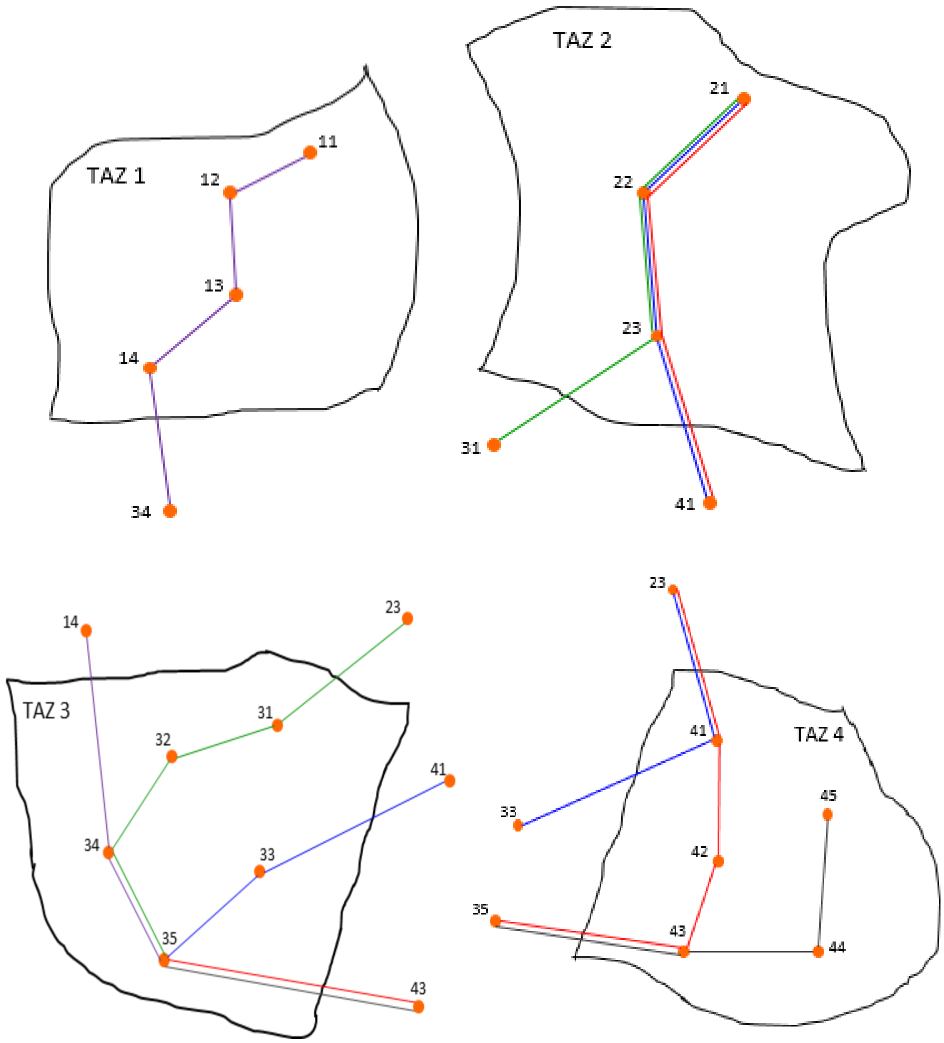


Figure 3.5: Four individual zonal graphs

For example, consider stop 23 in Figure 3.5. Stop 23 will not only be counted in the TAZ where it is physically located (i.e., TAZ 2), but it will also be counted in the TAZs that it helps to connect (i.e., TAZ 3 and TAZ 4). Sections 3.1.2.1, 3.1.2.2, and 3.1.2.3 explain the assumptions and the rules considered in this research for counting the number of stops and edges for each TAZ.

3.1.2.1 *Types of Stops in a Directed Graph*

When analyzing a transit network, three different types of stops can be identified:

- **Transfer stops**. These are stops at which it is possible to switch routes without exiting the transit network. Stop 22 in Figure 3.5 is an example of a transfer stop.
- **End stops**. These are stops at the end of a route where there is no possibility to transfer to a different route. Stop 45 in Figure 3.5 is an example of an end stop.
- **Intermediate stops**. These are stops that are neither transfer stops nor end stops. Stop 31 in Figure 3.5 is an example of an intermediate stop.

Quintero-Cano (2011) considered only transfer stops and end stops when redrawing transit networks as directed graphs. This is a reasonable assumption when the analysis mainly deals with the physical structure and characteristics (e.g., connectivity, complexity, etc.) of the transit network. However, since population is a driving factor in this research when measuring the performance of a transit network, *all* the population served by each individual stop in the transit network must be taken into account. Thus, intermediate stops will also be considered for analysis purposes.

For example, Figure 3.6 depicts a TAZ that contains five stops. In the approach proposed by Quintero-Cano (2011), only stop 1 (transfer stop), stop 3 (transfer stop), and stop 5 (end stop) were considered for analysis purposes. In this research, the intermediate stops 2 and 4 were also considered to account for the entire population served by the stops in the TAZ.

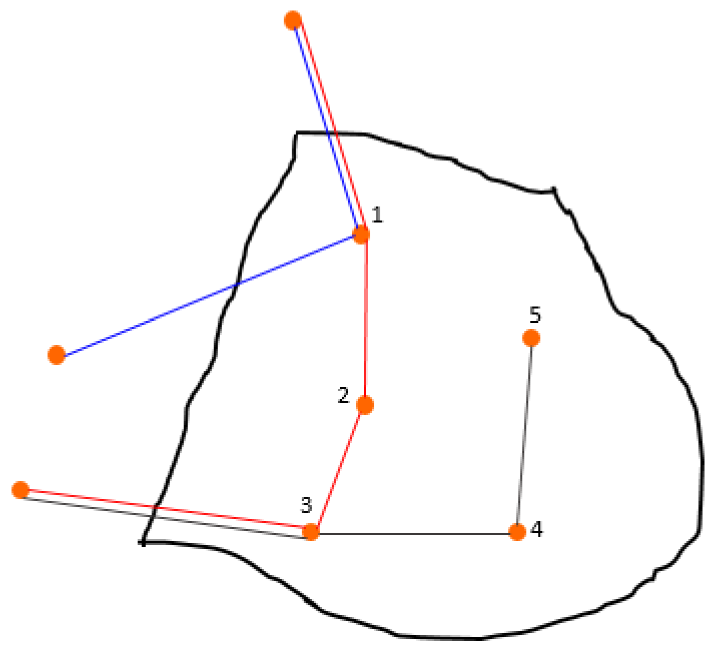


Figure 3.6: TAZ with transfer, end, and intermediate stops

3.1.2.2 *Counting the Edges per TAZ in a Directed Graph*

Converting a transit network into a directed graph changes the way edges are accounted for in each TAZ. In general, a one-way directed edge has a total weight of ½, whereas a two-way directed edge has a total weight of 1 (i.e., a weight of ½ in each direction). The following edge counting rules (adapted from Quintero-Cano (2011)), were also used:

- If a one-way edge connects two stops that are located in two different TAZs, the TAZ that contains the destination stop will receive a weight of ½. For example, if the edge that connects stop 14 (in TAZ 1) and stop 34 (in TAZ 3) in Figure 3.5 were a one-way edge directed toward TAZ 3, then TAZ 3 will receive a weight of ½.
- If a two-way edge connects two stops that are located in two different TAZs, then each TAZ will receive a weight of ½. For example, if the edge connecting stop 23 (in TAZ 2) and stop 31 (in TAZ 3) depicted in Figure 3.5 were a two-way edge, then both TAZ 1 and TAZ 3 will receive a weight of ½.

3.1.2.3 *Counting the Stops per TAZ in a Directed Graph*

Converting a transit network into a directed graph also changes the way stops are accounted for in each TAZ. The following stop counting rule (adapted from Quintero-Cano (2011)) was also used:

- Stops that are connected to edges that enter/exit TAZ *i*, but are located outside of TAZ *i*, are still considered when counting the number of stops of TAZ *i*. However, these stops will be assigned a weight that is proportional to the number of TAZs they connect. For example, Figure 3.5 shows that stop 22 is located in TAZ 2 and it is only connected to edges inside TAZ 2 (i.e., it does not connect TAZ 2 to any other TAZ). As a result, stop 22 receives a weight of 1 and it is counted as one stop for TAZ 2. However, stop 23 connects TAZ 2, TAZ 3, and TAZ 4. Therefore, TAZ 2, TAZ 3, and TAZ 4 will each receive a weight of ⅓ for this stop.

3.1.3 Calculating the Basic Metrics of a Transit Network at the TAZ level

Table 3.1 shows the basic metrics that can be calculated once a directed graph has been divided into TAZ-based graphs.

Table 3.1: Basic metrics of a transit network

Parameter	Description
$\mathbf{N_R}$	Number of routes
$\mathbf{V}$	Number of nodes
$\mathbf{E^S}$	Number of single edges
$\mathbf{E^M}$	Number of multiple edges
$\mathbf{E}$	Total number of edges

Derrible and Kennedy (2010) classified the edges of a transit network as either single edges ($\mathbf{E^S}$) or multiple edges ($\mathbf{E^M}$). A single edge is a link connecting any pair of adjacent nodes (i.e., stops), whereas multiple edges are additional edges connecting a pair of adjacent nodes that are already connected by a single edge. Figure 3.7a illustrates the concept of a single edge. The edges E2 and E3 in Figure 3.7b illustrate the concept of multiple edges.

(a) (b)

Figure 3.7: Example of single (E1) and multiple (E2 and E3) edges

TAZ 3 in Figure 3.8 will be used to illustrate the process to calculate the metrics described in Table 3.1.

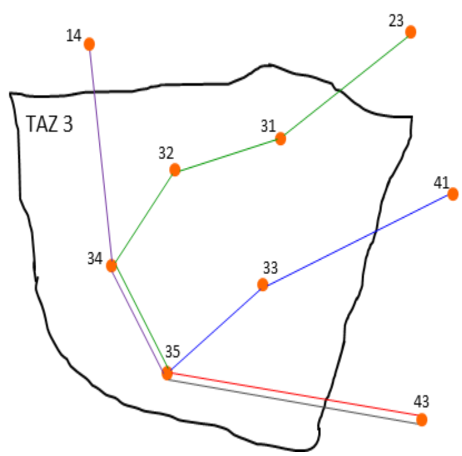


Figure 3.8: Stops and edges in TAZ 3

First, the value for the metric *number of routes* (**N_R**) is five since all five routes cross TAZ 3. The metric *number of nodes* (**V**) is determined based on the weights assigned to each stop in TAZ 3, as described in section 3.1.2.3. Stop 32 in TAZ 3 is considered an intermediate stop and thus carries a weight of 1. Stops

31, 33, 34, and 35 each carry a weight of ½. Stops 43 and 14 also carry a weight of ½. Finally, stops 23 and 41 each carry a weight of ⅓. Equation 3.1 shows how the metric **V** is calculated.

$$V = 1 + (4 \times \tfrac{1}{2}) + (2 \times \tfrac{1}{2}) + (2 \times \tfrac{1}{3}) = 4.66 \quad (3.1)$$

The metric *number of single edges* ($\mathbf{E^S}$) is determined based on the number of edges connecting each pair of adjacent stops. The individual stops in the stop pairs (31, 32), (32, 34), (34, 35) and (33, 35) are connected to each other by two-way single edges, thus accounting for a total weight of 4. The individual stops in the stop pairs (14, 34), (23, 31), (33, 41) and (35, 43) are also connected to each other by two-way single edges. However, only the edge whose direction is toward TAZ 3 counts in this case, resulting in a total weight of 2 (i.e., each link has a weight of ½). Equation 3.2 shows how the metric $\mathbf{E^S}$ is calculated.

$$E^S = 4 + (4 \times \tfrac{1}{2}) = 6 \quad (3.2)$$

The metric *number of multiple edges* ($\mathbf{E^M}$) accounts for any additional edges connecting each pair of adjacent stops. For example, the stop pair (34, 35) is connected by two edges; one edge is a single edge and the other is a multiple edge. Thus, the additional (i.e., multiple) edge connecting the stop pair (34, 35) accounts for a weight of 1. The stop pair (35, 43) is also connected by two edges. In this case, also the direction of the additional edge that is toward TAZ 3 counts as a multiple edge for TAZ 3. Therefore, this edge carries a weight of ½. Equation 3.3 shows how the metric $\mathbf{E^M}$ is calculated.

$$E^M = 1 + (1 \times ½) \quad = 1.5 \qquad (3.3)$$

The metric *total number of edges* (**E**) is determined by adding the values of the metrics *number of single edges* ($\mathbf{E^S}$) and *number of multiple edges* ($\mathbf{E^M}$). As mentioned before, there were six single edges and 1.5 multiple edges in TAZ 3. Equation 3.4 shows how the metric **E** is calculated.

$$E = E^S + E^M = 6 + 1.5 = 7.5 \qquad (3.4)$$

Table 3.2 summarizes the basic metrics calculated for the TAZs of the sample network depicted in Figure 3.5. The same approach was used to calculate the basic metrics for other TAZs in Figure 3.5.

Table 3.2: Basic metrics calculated for the TAZs of the sample network in Figure 3.5

	BASIC METRICS				
TAZ #	**N_R**	**V**	**E^S**	**E^M**	**E**
1	1	4	3.5	0	3.5
2	3	3.16	3	4.5	7.5
3	5	4.66	6	1.5	7.5
4	1	5.16	5.5	1	6.5

3.2 TRANSIT NETWORK PERFORMANCE INDICATORS

As depicted in Figure 3.1, the objective of the second phase of the methodology is the identification and/or development of different transit network performance indicators (TNPIs) to evaluate a target transit network. The TNPIs are grouped into the categories *topological*, *performance*, and *operational*. The basic metrics introduced in section 3.1.3 become the main inputs when calculating the different TNPIs.

3.2.1 Topological Indicators

The topology of a transit network refers to the arrangement of its vertices (i.e., stops) and edges (i.e., routes). Therefore, the topology of a transit network is usually evaluated using graph network theory performance indicators (GNTPIs).

Four GTNPIs were selected based on the findings of the literature review (see Table 2.4 at the end of section 2.1.1) for use in the proposed methodology.

The GNTPIs *structural connectivity* (ρ) and *connectivity* (σ) developed by Derrible & Kennedy (2009) were applied in their original form. The GNTPIs *degree of connectivity* (γ") and *complexity* (β") developed by Quintero-Cano (2011) were used as a basis to develop new GNTPIs.

Quintero-Cano (2011) suggested that the effects of operational factors such as frequency of routes, speed of routes, distance between stops, and capacity versus demand of links should be taken into account when calculating the GNTPIs *degree of connectivity* (γ") and *complexity* (β"). However, only frequency of routes was utilized in her calculations.

Quintero-Cano (2011) also demonstrated that in order to obtain more accurate values for the GNTPIs γ" and β", only single edges of a transit network must be considered when counting the number of edges. Equation 2.2 and equation 2.3 (see section 2.1.1) show how the original GNTPIs γ and β are calculated. These equations use the total number of edges (**E**) (i.e., both single and multiple) as well as the number of nodes (**V**) as inputs. However, if only single edges ($\mathbf{E^S}$) are considered, equations 2.2 and 2.3 would be replaced by equations 3.5 and 3.6.

$$\gamma(\boldsymbol{E^S}) = \frac{E^S}{3(V-2)} \tag{3.5}$$

$$\beta(\boldsymbol{E^S}) = \frac{E^S}{V} \tag{3.6}$$

Figure 3.9 depicts two networks with different structures, but the same number of single edges and vertices. An issue with equations 3.5 and 3.6 is that they are unable to distinguish the differences between the degree of connectivity (γ") and the complexity (β") of networks *a* and *b* in Figure 3.9, as evidenced by the results presented in Table 3.3. However, from a topological perspective, one can easily appreciate that network *a* has larger γ" and β" values because both route 2 (R2) and route 3 (R3) serve stops 2 and 3, which adds more capacity and frequency of service to network *a*.

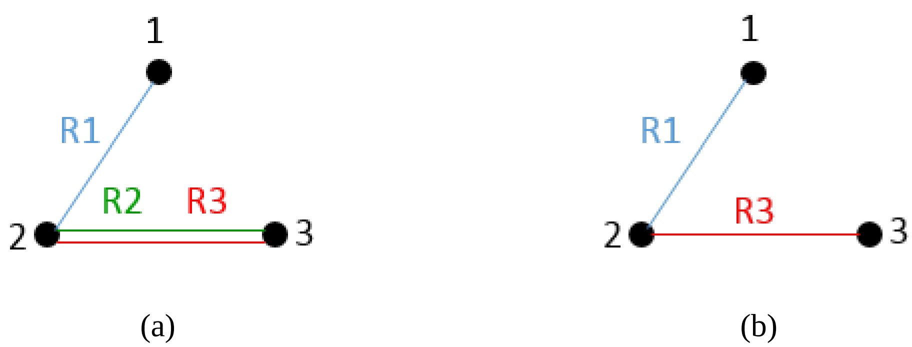


Figure 3.9: Example of two networks with different structures but the same number of single edges ($\mathbf{E^S}$) & nodes ($\mathbf{V}$)

Table 3.3: Calculation of $\gamma(\mathbf{E^S})$ and $\beta(\mathbf{E^S})$ for networks in Figure 3.9

Network	$\mathbf{E^S}$	**V**	$\boldsymbol{\gamma}(E^S)$	$\boldsymbol{\beta}(E^S)$
a	2	3	2/3	2/3
b	2	3	2/3	2/3

Quintero-Cano (2011) addressed the problem of using $\gamma(E^S)$ and $\beta(E^S)$ by adding a multiplier to equations 3.5 and 3.6 referred to as the *number of edges normalized by frequency*. This multiplier incorporates the effect of route (i.e., service) frequencies in the calculation of the GNTPIs *degree of connectivity* (γ") and *complexity* (β").

However, there is a problem with using *route frequency* as the operational factor when calculating γ" and β", which is that the resulting values will rely solely on the topology of the network (i.e., number of stops and the number of routes and their frequencies), but will not take into account the effectiveness of the transit network in terms of its ability to provide enough capacity to satisfy the demand. Therefore, this research incorporates the *capacity-to-demand* (CTD) ratio as an additional operational factor when calculating modified versions of the GNTPIs γ" and β". Equation 3.7 shows how the CTD ratio of TAZ *i* is calculated.

$$CTD_i = \frac{C_i}{D_i} \tag{3.7}$$

Where:

CTD_i: Capacity to demand ratio for TAZ *i*

C_i: Capacity of TAZ *i*

D_i: Demand for TAZ *i*

Sections 3.2.1.1 and 3.2.1.2 explain how capacity and demand are calculated for a transit network to be used in the calculation of the CTD ratio.

3.2.1.1 *Capacity*

The capacity of a transit network is usually calculated at the route level. Equation 3.8 shows how the theoretical capacity (C_i^T) of route *i* of a transit network is calculated.

$$C_i^T = f_i \times N_{seats} \tag{3.8}$$

Where:

C_i^T: Theoretical capacity of route *i*

f_i: Frequency of route *i* (i.e., the number of vehicles per hour serving route *i*)

D_i: Number of seats per bus serving route *i*

The literature indicates that not all of the theoretical capacity C_i^T will be used since passengers arrive at uneven rates at stops and the service should be designed so as not to leave any passengers behind (TRB and Kittelson & Associates, 2003). Thus, the use of a *peak hour factor* (PHF) is suggested to reduce the theoretical capacity C_i^T to a person (i.e., practical) capacity (C_i) that can be sustained on a daily basis. Equation 3.9 shows how the PHF is calculated.

$$PHF = \frac{P_h}{4P_{15}} \tag{3.9}$$

Where:

PHF: Peak hour factor

P_h: Passenger volume during the peak hour

P_{15}: Passenger volume during the peak 15 minutes

The literature also suggests that in the absence of actual data to estimate the PHF, a default value of 0.75 may be used for bus services (TRB and Kittelson & Associates, 2003). Thus, equation 3.10 shows how the practical capacity of route *i* of a transit network was calculated in this research.

$$C_i = PHF \times f_i \times N_{seats} = 0.75 \times f_i \times N_{seats} \tag{3.10}$$

Where:

C_i: Practical capacity of route *i*

PHF: Peak hour factor = 0.75

f_i: Bus frequency of route *i* (vehicles per hour)

N_{seats}: Number of seats per bus serving route *i*

Table 3.4 summarizes how the *practical capacity* of each route depicted in Figure 3.4 was calculated. In this example, N_{seats} was assumed to be 40 and hypothetical numbers were used to represent the frequency f_i for each route.

Table 3.4: Capacity of routes in Figure 3.4

Route #	**f_i (vehicle per hour)**	**Practical Capacity *(C_i)***
1	0.6	0.75 × 0.6 × 40 = **18.0**
2	1	0.75 × 1 × 40 = **30.0**
3	0.55	0.75 × 0.55 × 40 = **16.5**
4	0.6	0.75 × 0.6 × 40 = **18.0**
5	0.55	0.75 × 0.55 × 40 = **16.5**

3.2.1.2 *Demand*

Schmenner (1976) suggested four variables that can be utilized to represent the demand of a transit network:

- Estimated ridership
- Estimated ridership per bus-mile or per bus-hour
- Revenue
- Revenue per bus mile or per bus-hour.

Since the demand data available for this research were for a fare-free transit network, the third and fourth options could not be employed. Therefore, the estimate of ridership *number of boardings per route* was used instead.

To produce an estimate of ridership, the demand data must be available at the stop level (i.e., number of boardings at each bus stop). However, most of the data accessible in this research were provided at the route level, meaning that for each route, the number of boardings were sorted by route segments and time periods (i.e., AM Peak, Midday, PM Peak, and Evening).

Thus, to estimate the demand at each bus stop, the population and number of employees within a radius of 400 meters of each bus stop was calculated (Wiley & Kanaroglou, 2010; Dhariwal, Meakes, & Tan, 2010). The distance of 400 meters (approximately ¼ of a mile) represents the maximum suitable walking distance to a bus stop (Derrible & Kennedy, 2009). Then, the population and number of employees over all the stops serving a route was aggregated. Finally, the number of boardings were allocated to stops based on the ratio of the population and number of employees around each stop to the total population and employees of the all the stops serving the route.

Figure 3.10 is used to demonstrate the process of estimating the demand for each stop in a transit network. TAZ 1 in Figure 3.10 is served by a single route (i.e., route 5) and contains four stops. In this example, it is assumed that the number of boardings for route 5 in TAZ 1 is 140. Table 3.5 shows the resulting demand allocated to each stop in TAZ 1.

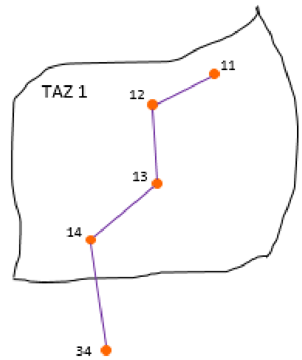


Figure 3.10: TAZ 1 from Figure 3.4

Table 3.5: Allocating number of boardings on route 5 to the stops in TAZ 1

Stop #	**Population and Employment within a Radius of 400m of the Stop**	**Proportion to Total Population and Employment**	**Allocated Boardings**
11	96	96 / 700 = **0.14**	140 × 0.14 = **19.6**
12	175	175 / 700 = **0.25**	140 × 0.25 = **35.0**
13	186	186 / 700 = **0.26**	140 × 0.26 = **36.4**
14	243	243 / 700 = **0.35**	140 × 0.35 = **49.0**
Total	**700**	**1.00**	**140**

3.2.1.3 *Modified Connectivity and Complexity Indicators*

As previously stated, this research adds the operational factor CTD ratio to the calculation of the GNTPIs *degree of connectivity* (γ”) and *complexity* (β”) developed by Quintero-Cano (2011) and proposes two modified GNTPIs: γ^{CTD} and β^{CTD}. The modified GNTPIs *degree of connectivity* (γ^{CTD}) and *complexity* (β^{CTD}) are more than just topological indicators of a transit network for the purposes of this research. They also measure how effective a transit network is in moving people as fast and conveniently as possible, and in satisfying the demand.

The CTD ratio not only takes into account the effects of route frequency (f_i) by including this element as an input in the practical capacity formula (see section 3.2.1.1), but it also considers the effects of demand. Since changes in population is one of the most influential factors on the fluctuations of demand (especially changes in population groups in need of public transit services), using the CTD ratio helps with the understanding of the effects of population changes on the GNTPIs γ^{CTD} and β^{CTD}. Equation 3.11 shows how the CTD ratio of TAZ m is calculated.

$$CTD_m = \frac{\sum_{i=1}^{k} \frac{C_i}{D_i} \times n_s^i}{\sum_{i=1}^{k} n_s^i} \qquad (3.11)$$

Where:

CTD_m: Capacity-to-Demand ratio of TAZ m

C_i: Capacity of route i in TAZ m

D_i: Demand of route i (i.e., sum of the demand of route i at each stop) in TAZ m

n_s^i: Number of stops serving route i in TAZ m

Table 3.6 shows hypothetical values for the demand and the capacity of the routes for networks *a* and *b* depicted in Figure 3.9.

Table 3.6: Demand and capacity of the routes for the networks *a* and *b* in Figure 3.9

Route #	**Demand**	**f_i (vehicle per hour)**	**C_i**
1	74	3	0.75 × 3 × 40 = 90
2	57	2	0.75 × 2 × 40 = 60
3	43	2	0.75 × 3 × 40 = 60

Equation 3.12 and 3.13 show how the CTD ratio is calculated for networks *a* and *b* in Figure 3.9 using the information from Table 3.6.

$$\text{CTD}_a = \frac{\sum_{i=1}^{3} \frac{C_i}{D_i} \times n_s^i}{\sum_{i=1}^{3} n_s^i} = \frac{\frac{90}{74}\times 2 + \frac{60}{57}\times 2 + \frac{60}{43}\times 2}{2+2+2} = 1.22 \quad (3.12)$$

$$\text{CTD}_b = \frac{\sum_{i=1}^{2} \frac{C_i}{D_i} \times n_s^i}{\sum_{i=1}^{2} n_s^i} = \frac{\frac{90}{74}\times 2 + \frac{60}{43}\times 2}{2+2} = 1.30 \quad (3.13)$$

Note that in the calculation of the ratios CTD_a and CTD_b, all the routes have CTD ratios larger than one. For example, route 1 has a CTD ratio of 1.21 (i.e., 90/74), which indicates that it satisfies its demand (i.e., it has extra capacity). In such cases, the CTD ratios of the routes will be truncated to one. This is done because in cases where there are multiple routes crossing a TAZ, those routes with relatively large CTD ratios significantly increase the CTD ratio of the TAZ, even after being normalized by the number of stops they serve in the TAZ. Also, the fact that some of the routes are not satisfying the demand (i.e., routes with small CTD ratios) will not be evident. By applying this rule, all the routes in the networks *a* and *b* depicted in Figure 3.9 will have CTD ratios of 1. As a result, CTD_a and CTD_b are equal to one.

It is important to mention that CTD ratios with values greater than one imply additional capacity for potential demand growth. The importance of this additional capacity is considered in section 3.2.3 where actual values of route CTD ratios are considered in calculating CTD ratios of a TAZ which represent a separate operational indicator.

Finally, equations 3.14 and 3.15 show how the modified GNTPIs *degree of connectivity* (γ^{CTD}) and *complexity* (β^{CTD}) are calculated using the CTD ratio as a multiplicative factor.

$$\gamma^{CTD} = CTD \times \gamma(E^S) = CTD \times \frac{E^S}{3(V-2)} \tag{3.14}$$

$$\beta^{CTD} = CTD \times \beta(E^S) = CTD \times \frac{E^S}{V} \tag{3.15}$$

Table 3.7 displays the values of γ^{CTD} and β^{CTD} for the TAZs in Figure 3.4 using information from Table 3.2. Table 3.8 summarizes the final topological indicators that will be used to assess the topological score of a transit network.

Table 3.7: γ^{CTD} and β^{CTD} of the TAZs in Figure 3.5

TAZ #	**CTD**	$\boldsymbol{E^S}$	$\boldsymbol{V}$	$\boldsymbol{\gamma(E^S)}$	$\boldsymbol{\beta(E^S)}$	$\boldsymbol{\gamma^{CTD}}$	$\boldsymbol{\beta^{CTD}}$
1	0.66	3.5	4	0.58	0.87	**0.38**	**0.57**
2	0.94	3	3.16	0.86	0.95	**0.81**	**0.89**
3	0.87	6	4.66	0.75	1.28	**0.65**	**1.12**
4	0.93	5.5	5.16	0.58	1.06	**0.54**	**0.99**

Table 3.8: Final topological indicators

Indicator	**Symbol**	**Equation**	**Proposed by**
Complexity (Normalized by CTD)	β^{CTD}	$\beta^{CTD} = CTD \times \frac{E^S}{v}$	Rahanjam (2015)
Degree of Connectivity (Normalized by CTD)	γ^{CTD}	$\gamma^{CTD} = CTD \times \frac{E^S}{3(v-2)}$	Rahanjam (2015)
Structural Connectivity	ρ	$\rho = \frac{V_c^t - E^M}{V^T}$	Derrible & Kennedy (2009)
Coverage	σ	$\sigma = \frac{N_{STOP}\pi r^2}{A_{served}}$	Derrible & Kennedy (2009)

3.2.2 Performance Indicators

Performance indicators are used to measure the level of performance of a transit network. In this category, the evaluation is based on a comprehensive transit network performance indicator (TNPI) called *Local Index of Transit Availability* (LITA). The LITA was proposed by Rood (1998) and was first used to evaluate the intensity of traffic in Riverside County, California. The LITA has also been used to measure transit performance in Vancouver, Canada (Dhariwal, Meakes, & Tan, 2010), and the Greater Toronto and Hamilton area (Wiley & Kanaroglou, 2010).

The LITA relates the amount of transit service in a TAZ to the population and land area of the same TAZ. The LITA considers three performance sub-indicators that are designated as the most effective at quantifying the availability of service (Henk & Hubbard 1996). The three performance sub-indicators are *frequency of service* (f), *capacity* (c^p), and *coverage* (g). The performance sub-indicator *coverage* (g) is sometimes referred in the literature as *service coverage*.

3.2.2.1 *Frequency of Service*

The performance sub-indicator *frequency of service* (f_i) is the ratio of the total number of daily transit vehicles for each route entering and stopping at least once in TAZ i, to the area of developed land in TAZ i. Land is classified as *developed* if it falls in the following categories: commercial; government and institutional; parks and recreational; residential; resource and industrial. Conversely, land is classified as *undeveloped* if it is a body of water or an open area (i.e., an area without human built structures). Equation 3.16 shows how f_i is calculated.

$$f_i = \frac{v_i}{a_i} \tag{3.16}$$

Where:

f_i: Frequency of service

v_i: Total daily transit vehicles entering and stopping at least once in TAZ *i*

a_i: Area of developed land in TAZ *i*

3.2.2.2 *Capacity*

The performance sub-indicator *capacity* (c^p) is the ratio of the daily available transit seats on all routes to the total number of riders (i.e., residents and employees) using the transit system. Equation 3.17 shows how c_p is calculated.

$$c_i^p = \frac{(v_i \times s_i) \times (r_i)}{P_i + E_i} \tag{3.17}$$

Where:

c_i^p: Capacity of TAZ *i*

v_i: Total number of transit vehicles entering TAZ *i*

s_i: Number of seats of the daily buses entering TAZ *i*

P_i: Population of TAZ *i*

E_i: Employment in TAZ *i*

r_i: Total length of physical routes within TAZ *i*

3.2.2.3 *Coverage*

The performance sub-indicator *coverage* (g_i) is measured as the density of the transit stops within the TAZ *i* and is calculated as shown by equation 3.18. Note that stops located in the border of two TAZs are multiplied by a factor of 0.5 for each TAZ.

$$g_i = \frac{o_i + 0.5 q_i}{a_i} \tag{3.18}$$

Where:

g_i: Coverage

o_i: Number of transit stops inside TAZ *i*

q_i: Number of transit stops located at the border of TAZ *i*

a_i: Area of developed land in TAZ *i*

Table 3.9 shows how the performance sub-indicators *frequency of service* (*f*), *capacity* (c^p), and *coverage* (*g*) are calculated using equations 3.16, 3.17, and 3.18 for the TAZs depicted in Figure 3.5. Note that *capacity* (c^p) is calculated under the assumption that each bus has 40 seats. Also, the values for frequency of routes (f_i) are derived from Table 3.4.

Table 3.9: Performance indicators calculations for TAZs in Figure 3.5

TAZ #	v_i	a_i **(m²)**	P_i	E_i	o_i	q_i	t_i **(km)**	r_i **(km)**	f_i	c_i^p	g_i
1	14.4	0.45	700	160	3	1	0.6	0.2	**32.00**	**0.47**	**7.78**
2	51.6	0.84	1540	780	2	1	0.6	0.7	**61.43**	**0.85**	**2.98**
3	51.6	0.73	2400	1400	1	4	0.85	0.72	**70.68**	**0.66**	**4.11**
4	79.2	1.07	1970	1130	3	2	0.8	0.5	**74.02**	**1.07**	**3.74**

Once the scores for all three performance sub-indicators are calculated for each TAZ, they are standardized to produce a z-score (i.e., standard score). The z-score is the number of standard deviations an observation is above/below the mean. Therefore, a positive z-score indicates an observation above the mean, while a negative z-score indicates an observation below the mean. In order to obtain the overall LITA score, the three z-scores are averaged for each TAZ. More details on calculating the overall LITA score are provided in section 3.3.2.

3.2.3 Operational Indicators

The operational indicators are used to evaluate how well transit operations are being performed. The operational indicators utilized in this research (based on the availability of data) were *on time percentage*, *capacity-to-demand* (*CTD*) *ratio*, and *hour coverage*.

The CTD ratio is a metric that has not been considered before when analyzing the performance of a transit network (see section 3.2.1.3). Although *on time percentage* and *hour coverage* have been used as metrics in prior research, the specific formulation shown in the following sections was developed specifically for the purposes of this research.

3.2.3.1 *On Time Percentage*

The operational indicator *on time percentage* represents the percentage of times a route of a transit network is performing on time. For the purposes of this research, on time performance is defined as a route having a delay of no more than three minutes during a 24-hour period. Since *on time percentage* is calculated for each route of a transit network, a weighted average of the resulting route percentages is calculated for a TAZ with the frequency of each route used as the weight. Equation 3.19 shows how the *on time percentage* of TAZ *m* is calculated.

$$\mathrm{OT_m} = \frac{\sum_{i=1}^{n} f_i \times OT_i}{\sum_{i=1}^{n} f_i} \tag{3.19}$$

Where:

OT_m: *On time percentage* of TAZ *m*

f_i: Frequency of route *i* serving TAZ *m*

OT_i: *On time percentage* of route *i*

Table 3.10 displays the *on time percentage* of the routes of the transit network depicted in Figure 3.5.

Table 3.10: On Time Percentages of routes in Figure 3.5

Route #	On Time Percentage
1	51%
2	81%
3	77%
4	94%
5	86%

Equation 3.20 shows how the *on time percentages* for TAZ 4 depicted in Figure 3.5 is calculated. Note that only routes 2, 3, and 4 cross TAZ 4. The route frequencies from Table 3.4 and the *on time percentages* of routes from Table 3.10 were used to calculate OT_4.

$$OT_4 = \frac{(1\times 81)+(0.55\times 77)+(0.6\times 94)}{(1+0.55+0.6)} = 83.6\ \% \tag{3.20}$$

The *on time percentages* for the other TAZs depicted in Figure 3.5 are shown in Table 3.11.

Table 3.11: On Time Percentages of TAZs in Figure 3.5

TAZ #	**On Time Percentage**
1	86.0%
2	71.6%
3	78.0%
4	83.6%

3.2.3.2 *Capacity-to-Demand Ratio*

The operational indicator *capacity-to-demand (CTD) ratio* is the multiplier used in the calculation of the proposed topological indicators *degree of connectivity* (γ^{CTD}) and *complexity* (β^{CTD}) (see equations 3.14 and 3.15).

The CTD ratio is considered as a separate operational indicator because it helps to reveal whether or not a TAZ is being over/under served and also whether or not there is excess capacity available for future growth. Furthermore, the CTD ratio takes the demand of the service area as an input in its mathematical expression (see equation 3.11), which is directly affected by the population changes of the service area (an important factor in this research).

The calculation of the CTD ratio is explained in section 3.2.1. When used as an operational indicator, the actual value of the CTD ratio of each TAZ will be used in the calculations to reflect extra available capacity (i.e., it will not be truncated to one if it exceeds this value).

3.2.3.3 *Hour Coverage*

The operational indicator *hour coverage* represents the percentage of the day (i.e., Monday through Friday only) during which the service is available for a route in the transit network. Equation 3.21 shows how to calculate the *hour coverage* of route *i*.

$$HC_i = \frac{Hours\ of\ available\ service\ in\ a\ day}{24} \times 100 \qquad (3.21)$$

The *hour coverage* of a TAZ is the maximum *hour coverage* of the routes crossing the TAZ. Equation 3.22 shows how the *hour coverage* of TAZ *m* is calculated.

$$HC_m = \max\,[HC_i] \qquad (3.22)$$

Where:

HC_m: *Hour coverage* of TAZ *m*

HC_i: *Hour coverage* of route *i* crossing TAZ *m*

Table 3.12 displays the *hour coverage* of the routes of the transit network depicted in Figure 3.5. The *hour coverages* for all the TAZs depicted in Figure 3.5 are shown in Table 3.13.

Table 3.12: Hour Coverage of routes in Figure 3.5

Route #	**Hours of service availability during the day**	**Hour Coverage**
1	12.0	(12/24) × 100 = 50%
2	13.0	(13/24) × 100 = 54%
3	12.0	(12/24) × 100 = 50%
4	12.5	(12.5/24) × 100 = 52%
5	14.5	(14.5/24) × 100 = 60%

Table 3.13: Hour Coverages of TAZs in Figure 3.5

TAZ #	**Hour Coverage**
1	60%
2	54%
3	60%
4	54%

3.3 CALCULATING PERFORMANCE SCORES FOR TNPI CATEGORIES

This section explains the third phase of the methodology where topological, performance, and operational scores are calculated from their respective transit network performance indicators (TNPIs).

3.3.1 Topological Score

The Analytic Hierarchy Process (AHP) was selected as the method to derive a single score from the four topological TNPIs listed in Table 3.8. AHP was chosen because there is no prior work in the literature that has tried to obtain a single score from the topological TNPIs. Therefore, there is no pre-established quantitative relationship between these TNPIs from which a single score can be obtained.

3.3.1.1 *Analytic Hierarchy Process*

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) approach first introduced by Saaty (1994) which can be used to solve complex decision problems. AHP uses a multi-level hierarchical structure of objectives, criteria, and alternatives. The pertinent data are derived by using a set of pairwise comparisons. These pairwise comparisons are used to obtain the weights of importance of the decision criteria, and the relative performance measures of the alternatives in terms of each individual decision criterion.

As an illustrative application of AHP, consider the case in which one wants to *buy a car* (i.e., the objective). There are a number of different cars (i.e., alternatives) available to choose from. The buyer's criteria for selecting a car may be *style*, *reliability*, and *fuel economy*. In the car example, AHP is used to suggest which might be the "best" alternative (i.e., a car) based on the buyers' criteria.

In other situations, however, one may be interested in determining the relative importance of all the alternatives under consideration. For example, AHP can be used to find the relative topological scores of TAZs. In this case, the objective is not to find the best TAZ, but rather to find the relative ranking of the TAZs in terms of the topological score so that one can visualize which TAZs are performing better topologically (and why they are doing so) compared to the TAZs that are performing poorly.

The steps of the AHP method will be illustrated through an example using the TAZs depicted in Figure 3.5 as the alternatives, and the topological TNPIs as the criteria. Table 3.14 summarizes the topological indicators calculated for the TAZs depicted in Figure 3.5 using the information in Table 3.2 and Table 3.8.

Table 3.14: Topological indicators for the TAZs in Figure 3.5

TAZ #	γ^{CTD}	β^{CTD}	ρ	σ
1	0.39	0.58	0	4.47
2	0.81	0.89	0.5	1.79
3	0.65	1.12	0.75	3.44
4	0.54	0.99	2	2.35

The first step in the AHP method is to rank the criteria (i.e., the topological TNPIs) based on their relative importance using a pairwise comparison. Saaty (1980) suggested the use of the importance scores shown in Table 3.15 when comparing two criteria.

Table 3.15: Scale of relative importance

Importance Score	**Definition**	**Explanation**
1	Equal Importance	Two criteria contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	A criterion is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Table 3.16 shows the importance matrix developed for the topological TNPIs using the importance scores shown in Table 3.15. The importance scores are allocated to the topological TNPIs based on the relative importance of the

inputs they consider in their mathematical formulas. For example, the topological TNPI γ^{CTD} is assumed to be five times more important than the topological TNPI ρ because γ^{CTD} takes more characteristics of the transit network as inputs (i.e., the number of single edges, the number of vertices, and the CTD ratio) than ρ which takes the number of multiple edges, the number of transfer possibilities, and the number of transfer stops as inputs (see Table 3.8). However, γ^{CTD} and β^{CTD} are considered equally important since they use the same inputs in their mathematical formulas.

Table 3.16: Importance matrix of the topological TNPIs

	$\boldsymbol{\gamma^{CTD}}$	$\boldsymbol{\beta^{CTD}}$	$\boldsymbol{\rho}$	$\boldsymbol{\sigma}$
$\boldsymbol{\gamma^{CTD}}$	1	1	5	3
$\boldsymbol{\beta^{CTD}}$	1	1	5	3
$\boldsymbol{\rho}$	0.2	0.2	1	0.33
$\boldsymbol{\sigma}$	0.33	0.33	3	1

The next step is to perform pairwise comparisons between the alternatives (i.e., the TAZs) based on each criterion. The original AHP suggests the use of the importance scores from Table 3.15 in this step. However, since a numerical value for each criterion (i.e., topological TNPIs) has already been calculated for each alternative (i.e., the TAZs), the ratios of the topological TNPIs (i.e., γ^{CTD}, β^{CTD}, ρ, and σ) between two TAZs become the entries of the pairwise comparison matrix.

This is done to avoid any subjectivity from using the importance scores from Table 3.15.

For example, Table 3.14 shows that TAZ 1 and TAZ 2 have connectivity scores (i.e., γ^{CTD}) of 0.39 and 0.81, respectively. Therefore, the relative importance of TAZ 1 over TAZ 2 for the connectivity criterion is 0.39/0.81 = 0.48. The same rule is applied to the pairwise comparisons between TAZs based on the other criteria (i.e., complexity, structural connectivity, and coverage). Table 3.17, Table 3.18, Table 3.19, and Table 3.20 show the results of the pairwise comparisons between the TAZs depicted in Figure 3.5 for each criterion using the topological TNPI values from Table 3.14.

Table 3.17: Pairwise comparisons between TAZs in Figure 3.5 for $\boldsymbol{\gamma^{CTD}}$

$\boldsymbol{\gamma^{CTD}}$	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	0.48	0.59	0.71
TAZ 2	2.10	1.00	1.24	1.50
TAZ 3	1.70	0.81	1.00	1.21
TAZ 4	1.40	0.67	0.82	1.00

Table 3.18: Pairwise comparisons between TAZs in Figure 3.5 for $\boldsymbol{\beta^{CTD}}$

$\boldsymbol{\beta^{CTD}}$	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	0.65	0.52	0.58
TAZ 2	1.55	1.00	0.80	0.90
TAZ 3	1.94	1.26	1.00	1.13
TAZ 4	1.72	1.11	0.88	1.00

Table 3.19: Pairwise comparisons between TAZs in Figure 3.5 for $\boldsymbol{\rho}$

ρ	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	0.50	0.33	0.13
TAZ 2	2.00	1.00	0.67	0.25
TAZ 3	3.00	1.50	1.00	0.38
TAZ 4	8.00	4.00	2.67	1.00

Table 3.20: Pairwise comparisons between TAZs in Figure 3.5 for $\boldsymbol{\sigma}$

σ	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	2.49	1.30	1.90
TAZ 2	0.40	1.00	0.52	0.76
TAZ 3	0.77	1.92	1.00	1.47
TAZ 4	0.53	1.31	0.68	1.00

The next step is to extract the relative importance of each alternative implied by the pairwise comparisons (i.e., how important are the four TAZs when they are considered in terms of each criterion). Saaty (1980) asserts that to answer this question, the *right principal eigenvector* of the previous matrices should be estimated. Given a pairwise comparison matrix, the corresponding maximum left eigenvector is approximated by using the geometric mean of each row. Equation 3.23 shows how the geometric mean of $a_1, a_2, \ldots, a_n$ is calculated.

$$\overline{a_i} = \sqrt[n]{\prod_{i=1}^{n} a_i} = \sqrt[n]{a_1 a_2 \ldots a_n} \tag{3.23}$$

Table 3.21 shows the geometric means for the criterion $\boldsymbol{\sigma}$ for the TAZs depicted in Figure 3.5. Equation 3.24 illustrates how the geometric mean of the first row of Table 3.21 is calculated:

$$\overline{a_1} = \sqrt[4]{1 \times 2.49 \times 1.30 \times 1.90} = 1.57 \tag{3.24}$$

In the next step, the geometric means are normalized by dividing the value obtained for each TAZ by the sum of the geometric means over all TAZs (i.e., 4.25). The normalized geometric means for the topological TNPI $\boldsymbol{\sigma}$ are also shown in Table 3.21.

Table 3.21: Geometric means and their normalized values for $\boldsymbol{\sigma}$

σ	**Geometric Mean**	**Normalized Mean**
TAZ 1	1.57	**0.37**
TAZ 2	0.76	**0.15**
TAZ 3	1.21	**0.29**
TAZ 4	0.83	**0.19**
Column Sum	**4.25**	**1.00**

The normalized values for each TAZ in Table 3.21 are called *local weights* of TAZs with regards to the topological TNPI **σ.** Table 3.22 summarizes the local weights of each TAZ with regards to each individual topological TNPI.

Table 3.22: Matrix of local weights of the TAZs

	γ^{CTD}	β^{CTD}	ρ	σ
TAZ 1	0.16	0.16	0.07	0.37
TAZ 2	0.34	0.25	0.14	0.15
TAZ 3	0.27	0.31	0.21	0.29
TAZ 4	0.23	0.28	0.57	0.19

To obtain a single topological score for each TAZ, the local weights shown in Table 3.22 should be multiplied by their corresponding criterion global weight. The global weights are obtained by performing the same normalization process (i.e., right principal eigenvector) for the values obtained in the pairwise comparison matrix of the criteria (see Table 3.16). Table 3.23 shows the global weights of the criteria (i.e., topological TNPIs) obtained after normalizing the values of Table 3.16.

Table 3.23: Global weights of the topological TNPIs

Topological TNPI	**Global Weight**
γ^{CTD}	0.39
β^{CTD}	0.39
ρ	0.07
σ	0.15

As previously stated, the final topological score of each TAZ can be obtained by multiplying the local weight of the TAZ with regards to each criterion by the criterion's global weight. Equation 3.25 shows how the topological score for the TAZ 1 depicted in Figure 3.5 is calculated.

$$TAZ1_{TS} = (0.39 \times 0.16) + (0.39 \times 0.16) + (0.07 \times 0.07) + (0.15 \times 0.37) = 0.19 \tag{3.25}$$

Table 3.24 summarizes the final topological scores of the TAZs depicted in Figure 3.5.

Table 3.24: Topological scores of the TAZs in Figure 3.5

TAZ #	Topological Score
TAZ 1	0.19
TAZ 2	0.26
TAZ 3	0.29
TAZ 4	0.26
Total	1.00

According to results in Table 3.24, TAZ 3 has the highest topological score (i.e., 0.29), TAZ 2 and TAZ 4 both have a topological score of 0.26, and TAZ 1 has a topological score of 0.19. It is important to note that the sum of the scores in Table 3.24 is one. This is always the case with scores obtained with the AHP method because they are *relative* scores, i.e., the scores for each alternative are always normalized and compared to scores of another alternative. As a result, comparing the results obtained from two different AHP analyses is difficult since the scores are relative (i.e., there is no *global* index that can be used as a basis for comparison).

As illustrated by the example, AHP is very helpful when there is no sample output to help develop a mathematical relationship among the topological TNPIs. AHP is also the most widely accepted MCDM method, and is considered by many as the most reliable MCDM method (Triantaphyllou & Mann, 1995). However, some of the steps of the AHP process require the user to assign arbitrary weights which makes it subjective. Therefore, the final results obtained from the AHP method should be used only as a guide to what may be the best results rather than literal results.

3.3.2 Performance Score

As explained in section 3.2.2, the three performance TNPIs *frequency of service* (*f*), *capacity* (*c*), and *coverage* (*g*) are sub-indicators of the comprehensive TNPI *Local Index of Transit Availability* (LITA). This section explains how the three performance sub-indicators are combined to produce a single performance score (i.e., the LITA index).

Once the scores for all three sub-indicators are calculated for each TAZ, they must be standardized. The standardization process consists of subtracting the values of the performance TNPIs for each TAZ from their means and then dividing the result by the corresponding standard deviation to produce a z-score. Equation 3.26 shows how the z-score for the performance TNPI *frequency of service* (*f*) of TAZ *i* is calculated.

$$z_i^f = \frac{f_i - \mu(f)}{\sigma(f)} \tag{3.26}$$

Where:

z_i^f: z-score of performance TNPI *f* for TAZ *i*

f_i: Frequency of service for TAZ *i*

$\mu(f)$: Mean of the frequency of services of all TAZs

$\sigma(f)$: Standard deviation of the frequency of services of all TAZs

Using equivalent equations to equation 3.26, the z-scores for the performance TNPIs *capacity* (*c*) and *coverage* (*g*) can be obtained. Wiley (2009) justifies the use of z-scores by stating that the distribution of z-scores of the performance TNPIs is similar. Therefore, it is acceptable to use the z-score standardization process to enable an average score to be obtained from observations of each distribution.

Next, a ranked percentile scheme is employed to translate the z-scores into a numerical level of performance (Wiley, 2009). First, a performance score is calculated for each TAZ by averaging the standardized z-scores of the three performance TNPIs. Then, the total number of performance scores is divided into five quintiles, each accounting for 20% of the total number of performance scores. Each 20% quintile is then assigned a level. Each of these levels can be translated into a qualitative level of availability, as shown in Table 3.25 (Wiley, 2009).

Table 3.25: Ranked percentile scheme to translate the z-scores into a numerical level of performance

Level	**Quintile Range**	**Description**
1	0-20	No service or extremely limited availability
2	20-40	Sparse to less than average levels of availability
3	40-60	Average levels of availability
4	60-80	Average to good levels of availability
5	80-100	Excellent levels of availability; best in region

However, since numerical values (i.e., scores) must be obtained for each TAZ in this research, each TAZ is assigned a performance score according to its performance level. For example, if a TAZ has a performance level of 2, then a value of 2 is assigned to the TAZ as its performance score.

Table 3.26 displays the average standardized z-scores obtained for the TAZs depicted in Figure 3.5 using the information in Table 3.9. Table 3.27 displays the percentiles calculated for the average standardized z-scores in Table 3.26 using the R statistical software package (R Core Team, 2012).

Table 3.26: Standardized z-scores of the TAZs in Figure 3.5.

TAZ	z_i^f	z_i^c	z_i^g	Average of z-scores
TAZ 1	-1.45	-1.13	1.46	-0.37
TAZ 2	0.13	0.33	-0.78	-0.11
TAZ 3	0.58	-0.40	-0.25	-0.03
TAZ 4	0.74	1.21	-0.43	0.51

Table 3.27: Percentiles of the average z-scores in Figure 3.5.

Percentile	Value
0th	-0.37
20th	-0.21
40th	-0.09
60th	-0.04
80th	0.18
100th	0.51

Based on the values obtained in Table 3.27, TAZs with an average z-score between -0.37 and -0.21 (i.e., 0^{th} and 20^{th} percentiles) would be assigned a performance score of 1; TAZs with average z-score between -0.21 and -0.09 (i.e., 20^{th} and 40^{th} percentiles) would be assigned a performance score of 2; TAZs with average z-score between -0.09 and -0.04 (i.e., 40^{th} and 60^{th} percentiles) would be assigned a performance score of 3; TAZs with average z-score between -0.04 and 0.18 (i.e., 60^{th} and 80^{th} percentiles) would be assigned a performance score of 4, and TAZs with average z-score between 0.18 and 0.51 (i.e., 80^{th} and 100^{th} percentiles) would be assigned a performance score of 5.

Table 3.28 shows the final performance scores assigned to the TAZs depicted in Figure 3.5 based on the information in Table 3.26 and Table 3.27.

Table 3.28: Performance scores of the TAZs in Figure 3.5

TAZ #	Performance Score
TAZ 1	1
TAZ 2	2
TAZ 3	4
TAZ 4	5

3.3.3 Operational Score

The operational score was derived from the operational TNPIs *on time percentage*, *capacity-to-demand ratio (CTD)*, and *hour coverage*. The Analytic Hierarchy Process (AHP) was selected as the method for obtaining a single operational score. As with the topological indicators, there is no prior work in the literature that has obtained a single score from the operational TNPIs. Therefore, there is no established quantitative relationship between the three operational TNPIs from which a single score can be obtained.

The TAZs depicted in Figure 3.5 will be used to illustrate how the AHP is utilized for obtaining a single operational score. As explained in section 3.3.1.1, the first step in the AHP is to rank the criteria based on their relative importance using a pairwise comparison. Table 3.29 shows the importance matrix for the operational TNPIs. The importance scores are allocated to the operational TNPIs based on the relative importance of the inputs they consider in their mathematical formulas.

Table 3.29: Importance matrix of the operational TNPIs

	OT	***CTD***	***HC***
OT	1	0.33	5
CTD	3	1	7
HC	0.2	0.14	1

The next step is to perform pairwise comparisons between the alternatives (i.e., the TAZs) based on each criterion. The ratios that result from dividing the OT, CTD, and HC values obtained for each TAZ become the entries for each pairwise comparison matrix . For example, Table 3.11 in section 3.2.3 shows that TAZ 1 has an *on time percentage* value of 0.860, whereas TAZ 2 has an *on time percentage* value of 0.716. Therefore, the relative importance of TAZ 1 over TAZ 2 based on the *on time percentage* criterion is 0.86/0.716 = 1.20. The same rule is followed in other pairwise comparisons between TAZs based on other operational

TNPIs. Table 3.30, Table 3.31, and Table 3.32 display the results of the pairwise comparisons between the TAZs depicted in Figure 3.5 for each criterion using the operational TNPI values calculated in section 3.2.3.

Table 3.30: Pairwise comparisons between TAZs in Figure 3.5 for ***OT***

OT	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	1.20	1.10	1.03
TAZ 2	0.83	1.00	0.92	0.86
TAZ 3	0.91	1.09	1.00	0.93
TAZ 4	0.97	1.17	1.07	1.00

Table 3.31: Pairwise comparisons between TAZs in Figure 3.5 for ***CTD***

CTD	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	0.70	0.76	0.71
TAZ 2	1.42	1.00	1.08	1.01
TAZ 3	1.32	0.93	1.00	0.94
TAZ 4	1.41	0.99	1.07	1.00

Table 3.32: Pairwise comparisons between TAZs in Figure 3.5 for ***HC***

HC	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	1.11	1.00	1.11
TAZ 2	0.90	1.00	0.90	1.00
TAZ 3	1.00	1.11	1.00	1.11
TAZ 4	0.90	1.00	0.90	1.00

The next step is to calculate the local weights of the TAZs with respect to the operational TNPIs using the *right principal eigenvector* method explained in section 3.3.1.1. Table 3.33 summarizes the local weights calculated for each TAZ with respect to each operational TNPI.

Table 3.33: Matrix of local weights of the TAZs

	OT	***CTD***	***HC***
TAZ 1	0.27	0.18	0.26
TAZ 2	0.22	0.28	0.24
TAZ 3	0.24	0.26	0.26
TAZ 4	0.26	0.28	0.24

The global weights, which were obtained by performing *right principal eigenvector* method on the pairwise comparison matrix of the criteria (see Table 3.29), are shown in Table 3.34.

Table 3.34: Global weights of the operational TNPIs

Operational TNPI	**Global Weight**
$\boldsymbol{OT}$	0.28
$\boldsymbol{CTD}$	0.65
$\boldsymbol{HC}$	0.07

The final operational score for each TAZ can be obtained by multiplying the local weight of each TAZ with respect to each criterion by the criterion's global weight. Equation 3.27 shows how the operational score for TAZ 1 depicted in Figure 3.5 is calculated.

$$TAZ1_{OS} = (0.28 \times 0.27) + (0.65 \times 0.18) + (0.07 \times 0.26) = 0.21 \qquad (3.27)$$

Table 3.35 summarizes the final operational scores of the TAZs depicted in Figure 3.5.

Table 3.35: Operational scores of the TAZs in Figure 3.5

TAZ #	Operational Score
TAZ 1	0.21
TAZ 2	0.26
TAZ 3	0.26
TAZ 4	0.27
Total	1.00

According to Table 3.35, TAZ 4 has the highest operational score (i.e., 0.27), both TAZ 2 and TAZ 3 are next with an operational score of 0.26, and then TAZ 1 has an operational score of 0.21.

3.4 CALCULATING THE FINAL PERFORMANCE SCORE OF A TAZ

The Analytic Hierarchy Process (AHP) was selected as the method to obtain a final performance score for a TAZ based on the *topological*, *performance*, and *operational* scores of calculate for the same TAZ.

As previously explained, the first step in the AHP method is to rank the criteria based on their relative importance using a pairwise comparison. The criteria at this level are the topological score (TS), the performance score (PS), and the operational score (OS). Table 3.36 shows the importance matrix for the TS, PS, and OS scores. As before, the importance scores were allocated based on the relative importance of each score versus the other.

Table 3.36: Importance matrix of the TS, PS, and OS

	TS	**PS**	**OS**
TS	1	5	5
PS	0.2	1	3
OS	0.2	0.33	1

Next, pairwise comparisons are performed between the alternatives based on each criterion. The ratios that result from dividing the TS, PS, and OS scores obtained for each TAZ become the entries for each pairwise comparison matrix. For example, TAZ 1 and TAZ 2 have TS values of 0.19 and 0.26, respectively.

Therefore, the relative importance of TAZ 1 over TAZ 2 with respect to the *TS* criterion is 0.73 (i.e., 0.19/0.26). The same procedure is followed with the other pairwise comparisons between TAZs. Table 3.37, Table 3.38, and Table 3.39 display the results of the pairwise comparisons between the TAZs depicted in Figure 3.5 for each criterion using the TS, PS, and OS scores calculated in section 3.3.1, section 3.3.2, and section 3.3.3, respectively.

Table 3.37: Pairwise comparisons between TAZs in Figure 3.5 for ***TS***

TS	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	0.72	0.65	0.71
TAZ 2	1.40	1.00	0.91	0.99
TAZ 3	1.53	1.10	1.00	1.08
TAZ 4	1.42	1.01	0.92	1.00

Table 3.38: Pairwise comparisons between TAZs in Figure 3.5 for ***PS***

PS	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	0.50	0.25	0.20
TAZ 2	2.00	1.00	0.50	0.40
TAZ 3	4.00	2.00	1.00	0.80
TAZ 4	5.00	2.50	1.25	1.00

Table 3.39: Pairwise comparisons between TAZs in Figure 3.5 for ***OS***

OS	**TAZ 1**	**TAZ 2**	**TAZ 3**	**TAZ 4**
TAZ 1	1.00	0.81	0.83	0.78
TAZ 2	1.23	1.00	1.02	0.97
TAZ 3	1.21	0.98	1.00	0.95
TAZ 4	1.27	1.03	1.06	1.00

The next step is to calculate the local weight for each TAZ with respect to each criterion using the *right principal eigenvector* method explained in section 3.3.1.1. The results of this calculation are summarized in Table 3.40.

Table 3.40: Matrix of local weights of the TAZs

	TS	***PS***	***OS***
TAZ 1	0.19	0.08	0.21
TAZ 2	0.26	0.17	0.26
TAZ 3	0.29	0.33	0.26
TAZ 4	0.26	0.42	0.27

The global weight of each criterion, obtained by performing *right principal eigenvector* method on the pairwise comparison matrix of the criteria (see Table 3.36), are displayed in Table 3.41.

Table 3.41: Global weights of the TS, PS, and OS

Criterion	Global Weight
TS	0.70
PS	0.20
OS	0.10

The final performance score for each TAZ can be obtained by multiplying the local weight of each TAZ with respect to each criterion by the criterion's global weight. Equation 3.28 shows how the final performance score for TAZ 1 depicted in Figure 3.4 is calculated.

$$TAZ1_{FPS} = (0.70 \times 0.19) + (0.20 \times 0.08) + (0.10 \times 0.21) = 0.17 \qquad (3.28)$$

Table 3.42 summarizes the final performance scores of the TAZs in Figure 3.5.

Table 3.42: Final performance scores of the TAZs in Figure 3.5

TAZ #	**Final Performance Score**
TAZ 1	0.17
TAZ 2	0.24
TAZ 3	0.29
TAZ 4	0.30
Total	1.00

According to Table 3.42, TAZ 4 has the highest final performance score (i.e., 0.30), TAZ 3 has the second highest performance score (i.e., 0.29), followed by TAZ 2 and TAZ 1 with final performance scores of 0.24 and 0.17, respectively.

4.0 RESULTS

This chapter presents the results of applying the proposed methodology to evaluate the quality of service of the transit network that operates in the city of Corvallis, Oregon.

The rest of this chapter is organized as follows. Section 4.1 describes the transit network operated by the Corvallis Transit System, which is the basis of the two case studies presented in this chapter. Section 4.2 explains the different input data sources used in the two case studies. Section 4.3 presents the results of the first case study, where the proposed methodology was applied to the current transit network operated by the Corvallis Transit System. Section 4.4 presents the findings of an analysis conducted on the criteria weights for the case study. Finally, section 4.5 presents the results of the second case study, where the proposed methodology was applied to a modified version of the transit network operated by the Corvallis Transit System.

4.1 CORVALLIS TRANSIT SYSTEM

The transit network operated by the Corvallis Transit System (CTS) was selected to conduct two case studies using the proposed methodology because sufficient data about its structure and operations were readily available.

The CTS operates a network that services the city of Corvallis, Oregon, which has a total area of 14.13 mi^2 (36.6 km^2) and has a population of 54,488

(U.S. Census Bureau, 2010). The CTS transit agency also serves a small portion of the city of Philomath, Oregon. The current route configuration operated by the CTS transit agency is depicted in Figure 4.1, and includes the 13 routes listed in Table 4.1

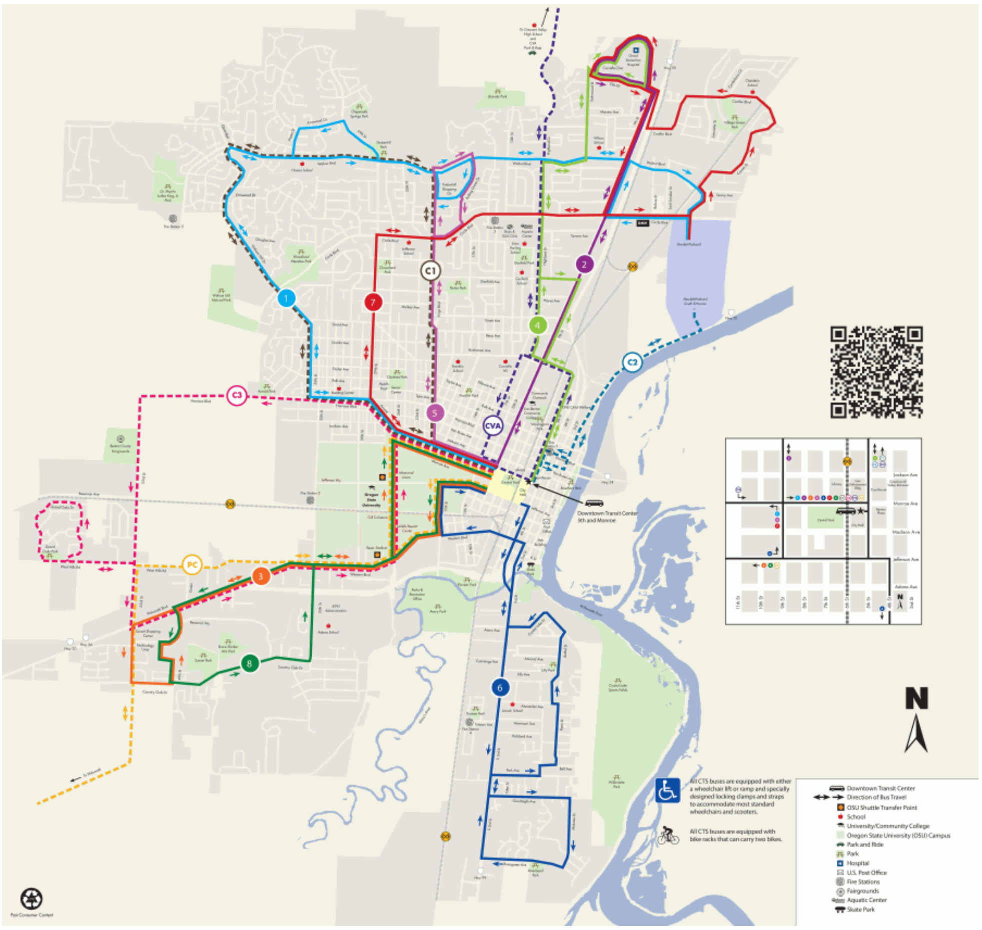


Figure 4.1: Route configuration of the Corvallis transit system (CTS Webpage, 2015)

Table 4.1: Main routes of the CTS transit system

Route Code	**Route Name**
R1	Route 1
R2	Route 2
R3	Route 3
R4	Route 4
R5	Route 5
R6	Route 6
R7	Route 7
R8	Route 8
C1	Route C1
C2	Route C2
C3	Route C3
CVA	Crescent Valley Area
PC	Philomath Connection

Table 4.2 shows all the routes of the CTS and the type of input data that were available for each route. The cells highlighted in gray in Table 4.2 indicate routes for which specific input data types were not available. Since no geographical data were available for routes C1 and CVA, and no on time report data were available for routes C1, C2, C3, CVA, and PC, only the data available for routes R1 through R8 were used in the two case studies.

Table 4.2: Availability of input data for the main routes of CTS

Route Code	Geographical Data	Demand Data	On Time Report Data	Population Data	Employment Data
R1	✓	✓	✓	✓	✓
R2	✓	✓	✓	✓	✓
R3	✓	✓	✓	✓	✓
R4	✓	✓	✓	✓	✓
R5	✓	✓	✓	✓	✓
R6	✓	✓	✓	✓	✓
R7	✓	✓	✓	✓	✓
R8	✓	✓	✓	✓	✓
C1	✗	✓	✗	✓	✓
C2	✓	✓	✗	✓	✓
C3	✓	✓	✗	✓	✓
CVA	✗	✓	✗	✓	✓
PC	✓	✓	✗	✓	✓

4.2 Input Data Sources

Several input data sources were required to apply the proposed methodology to the two case studies based on the transit network operated by the CTS, including:

- Geographical Data
- Operational Data
  - Demand Data
  - On Time Schedule Data
- Population Data
- Employment Data

4.2.1 Geographical Data

Most of the geographical data needed to evaluate the effectiveness of the CTS transit agency were obtained from its publicly available general transit feed specification (GTFS) and included location of stops, sequence of stops served by each route, route shapes and frequencies, and route service times, to name a few.

Table 4.3 displays a sample of the stop location data extracted from the GTFS feed of the CTS for route R6. Each record in the data table lists the stop ID, the sequence in which the stop is served in route R6, and the latitude and longitude coordinates of the stop.

Table 4.3: Sample stop location data for route R6 of the CTS

Stop ID	Stop Sequence	Stop Latitude	Stop Longitude
RyanSt_E_DenmanAve	90	44.54078514	44.54078514
RyanSt_E_AlexanderAve	100	44.54502398	44.54502398
ParkAve_S_GlennSt	110	44.53854492	44.53854492
3rdSt_W_ParkAve	220	44.53936239	44.53936239

Another important element of the geographical data category were the boundaries of the 27 transit analysis zones (TAZs) in which the city of Corvallis is divided, which were provided by the Oregon Department of Transportation (ODOT) in the form of a shape file. Figure 4.2 depicts the 27 TAZs of the city of Corvallis. The red dot in Figure 4.2 identifies the approximate location of the downtown area in the city of Corvallis and will be used throughout this chapter as a reference point when referring to other areas of the city of Corvallis (e.g., North, South, East, West, etc.)

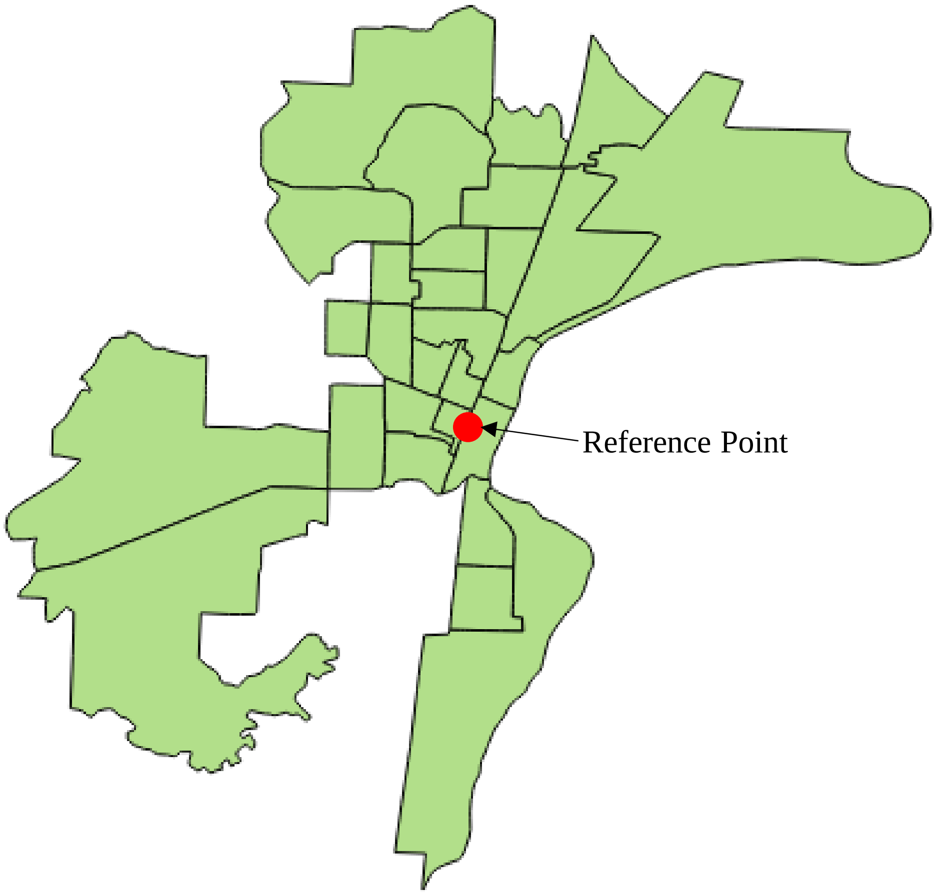


Figure 4.2: The 27 TAZs in the city of Corvallis

Using the data available from the GTFS feed of the CTS and the TAZ boundary data provided by ODOT as a basis, other relevant geographical data were derived using the open source geographic information system (GIS) software QGIS (QGIS Homepage, 2015). These additional geographical data were the area of each TAZ (in km^2), the length of the routes crossing each TAZ (in kilometers), and the number of stops located in each TAZ.

4.2.2 Operational Data

The operational data category includes demand data and on time report data.

4.2.2.1 *Demand Data*

Demand data was provided by the ODOT. As stated in section 3.2.1.2, the *number of boardings per route* was the demand parameter considered for routes R1-R8 of the CTS. Table 4.4 shows the number of boardings for each of the main routes of the CTS during the AM peak hour (i.e., 6-9am) for the fall of 2014.

Table 4.4: Demand of the main routes of CTS during the AM peak hour

Route	**Number of boardings during AM peak hour**
R1	100
R2	67
R3	51
R4	49
R5	148
R6	206
R7	119
R8	102

The number of boardings per route shown in Table 4.4 were disaggregated to the stop level using the ratio of the population and employment within a radius of 400m of a stop serving a route to the total population and employment within a radius of 400m of all the stops serving that route (see section 3.2.1.2).

4.2.2.2 *On Time Report Data*

The on time reports for routes R1-R8 of the CTS were also provided by the ODOT. As an example, Figure 4.3 shows the on time report of route R6 of the CTS.

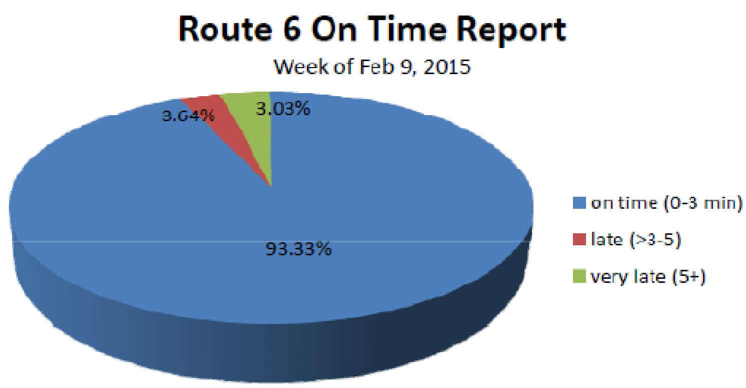


Figure 4.3: On time Report of route R6 of CTS transit system (ODOT, 2015)

4.2.3 Population Data

The population data for the city of Corvallis were gathered at the *census block* level from the 2010 census (U.S. Census Bureau, 2010). A census block is the smallest geographical unit used by the U.S. Census Bureau for demographic data collection. Therefore, a census block is smaller than a TAZ.

A hypothetical TAZ is depicted in Figure 4.4 where the orange dots represent the internal points of the census blocks that fall within the TAZ. The internal point of a geographic entity is a point inside the entity boundaries which is at or near the geographic center of the entity (U.S. Census Bureau, 2010). In this research, it was assumed that the population of a census block was concentrated on its internal point. The larger black dot in Figure 4.4 represents a transit stop in the TAZ. The blue circle centered on the transit stop has a radius of 400 meters around the transit stop and encloses some of the census block internal points. The sum of the population concentrated on the census block internal points that fall within the 400-meters radius is considered the population *within* a radius of 400 meters around the transit stop.

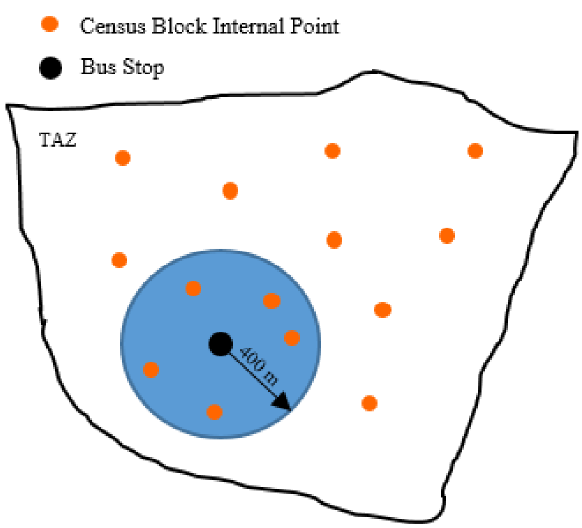


Figure 4.4: A hypothetical TAZ with census block centroids and a transit stop

The internal point of each census block within the city of Corvallis was located using the software QGIS. Then, a data table containing the geographic locations of the internal points was created and entered into the open source, object-relational database system software PostgreSQL (PostgreSQL Homepage, 2015). Then, the population within a radius of 400 meters around each stop was estimated with a spatial query written in PostgreSQL.

4.2.4 Employment Data

The employment data were also provided by the ODOT and contained the total number of employees in each of the 27 TAZs in the city of Corvallis. Table 4.5 shows an example of employment data for 10 of the 27 TAZs in Corvallis area.

Table 4.5: Total number of employees in 10 of the 27 TAZs in Corvallis area

TAZ #	Total number of employees
2389	848
2390	1513
2391	195
2392	54
2393	178
2394	2461
2395	825
2396	254
2397	205
2398	160

Since the employment data were available at the TAZ level, they were disaggregated to the stops inside each TAZ in proportion to the estimated population within the 400-meters radius around each stop.

4.3 CORVALLIS TRANSIT SYSTEM – CASE STUDY 1

This section presents the results of calculating the topological score, operational score, performance score, and a final performance score for the current transit network operated by the CTS. These scores were obtained using the proposed methodology and the input data described in section 4.2. It is important to note that any scores calculated using the AHP method are multiplied by 100 for ease of interpretation.

4.3.1 Topological Score

As explained in section 3.2.1, the topological transit network performance indicators (TNPIs) shown in Table 3.8 must be calculated before a topological score for a TAZ can be obtained. Once the values of the topological TNPIs are obtained, the final topological score is calculated using the AHP method.

Table 4.6 shows the average, standard deviation, minimum, and maximum values for the topological TNPIs and for the topological score obtained for the CTS transit network. Appendix A lists all the inputs and the values of the topological TNPIs calculated for each of the 27 TAZs in the city of Corvallis. The importance matrix, global weights, and local weights of the topological TNPIs obtained with the AHP method, as well as the topological scores calculated for each of the 27 TAZs in the city of Corvallis are included in Appendix B.

Table 4.6: Topological TNPIs and topological score for the TAZs in the city of Corvallis

	Average	**St. Dev.**	**Min.**	**Max.**
$\boldsymbol{\gamma^{CTD}}$	0.53	0.06	0.41	0.71
$\boldsymbol{\beta^{CTD}}$	0.25	0.12	0.17	0.80
$\boldsymbol{\rho}$	0.67	0.94	0.00	4.00
$\boldsymbol{\sigma}$	0.77	0.55	0.05	1.86
Topological Score	**3.70**	**1.07**	**2.18**	**7.82**

Figure 4.5 depicts four choropleth maps that show the spatial distribution of the topological TNPIs γ^{CTD}, β^{CTD}, ρ, and σ for the 27 TAZs in the city of Corvallis. The maps that correspond to the topological TNPIs γ^{CTD}, ρ, and σ, show that these values are higher for the TAZs located near the downtown areas of the city of Corvallis, but decrease for those TAZs located on the perimeter of the city of Corvallis. The exception is the topological TNPI β^{CTD} (see Figure 4.5b) where high values can be observed near the downtown area as well as in some of the zones in the perimeter of the city of Corvallis.

Figure 4.6 displays a choropleth map of the spatial distribution of the topological scores of the 27 TAZs in the city of Corvallis.

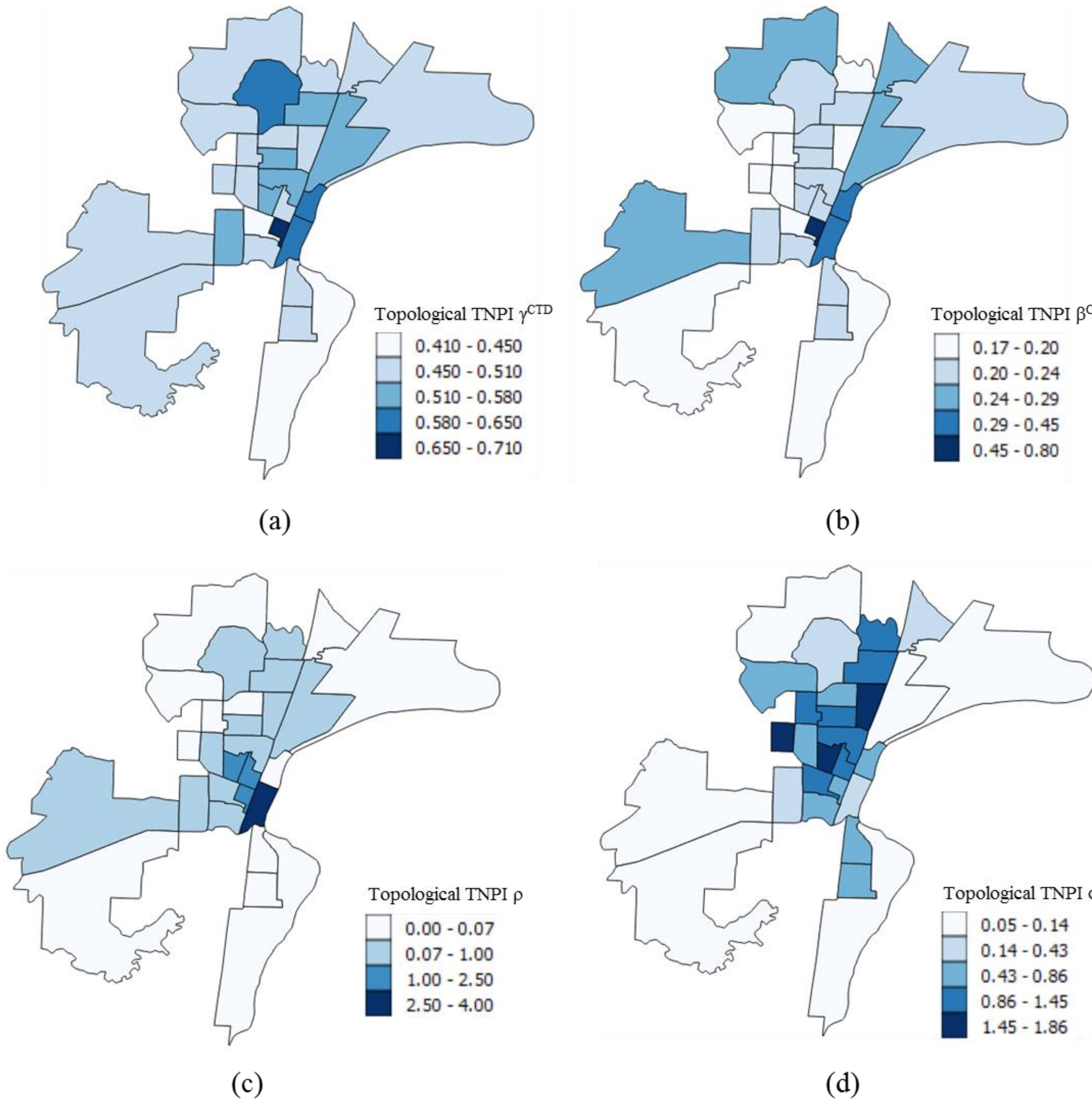


Figure 4.5: Choropleth maps of the spatial distribution of the topological TNPIs

for the 27 TAZs in the city of Corvallis

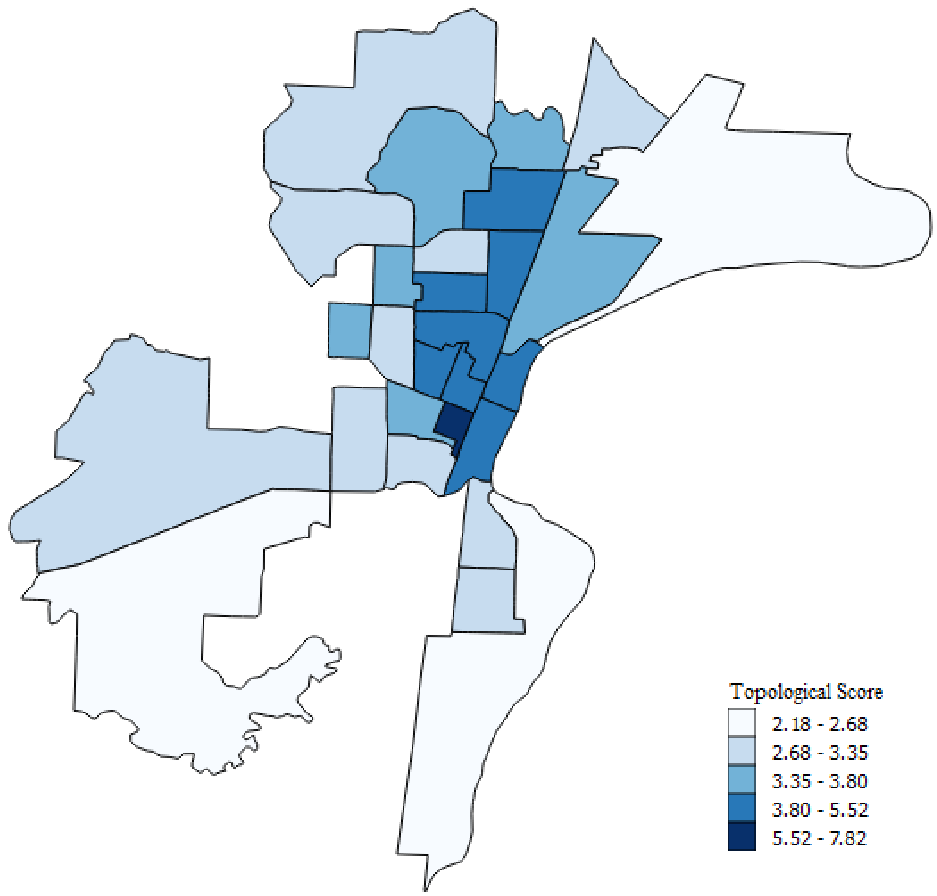


Figure 4.6: Choropleth map of the spatial distribution of the topological scores for the 27 TAZs in in the city of Corvallis

4.3.2 Performance Score

As explained in section 4.3.2, the first step in calculating a performance score for a TAZ is to obtain values for the performance sub-indicators *frequency of service* (*f*), *capacity* (c^p), and *coverage* (*g*). Then, the value of the performance score is calculated by averaging the z-scores of the performance sub-indicators.

Table 4.7 shows the average, standard deviation, minimum, and maximum values for the performance TNPIs and the performance score obtained for the CTS transit network. Appendix C lists the z-scores (i.e., averages and percentiles) obtained for each performance sub-indicator for each of the 27 TAZ in the city of Corvallis.

Table 4.7: Performance TNPIs and score of TAZs in the city of Corvallis

	Average	**St. Dev.**	**Min.**	**Max.**
f	85.53	129.22	2.73	570.11
c^p	2.04	1.49	0.35	5.29
g	8.73	6.45	0.52	23.21
Performance Score	**3.07**	**1.47**	**1.00**	**5.00**

Table 4.7 shows that the TNPI *frequency* has a large range of values (i.e., 2.73 to 570.11). This large range of values can be explained by the fact that the TNPI *frequency* represents the ratio of the number of buses entering a TAZ to the

area (in km^2) of the TAZ. As a result, TAZs with a very large area tend to have small *frequency* values, and vice versa.

Figure 4.7 depicts three choropleth maps that show the spatial distribution of the performance sub-indicators *frequency*, *capacity*, and *coverage* for the 27 TAZs in the city of Corvallis. Figure 4.7a shows that TAZs near the downtown area and in the northern parts of the city of Corvallis tend to have larger values for the TNPI *frequency*. This is explained by the fact that these TAZs have smaller areas but more routes that service them (i.e., 7-8 routes) when compared to TAZs with larger areas located on the perimeter of the city which have one or two routes servicing them (see equation 3.16).

Figure 4.7b shows that TAZs in the downtown and the northern parts of the city of Corvallis have high values for the *capacity* TNPI. High values for the *capacity* TNPI in the downtown area may be due to the large number of vehicles entering these TAZs. The high values for the *capacity* TNPI in the northern areas of the city of Corvallis may be due to less population and larger road lengths compared to other TAZs (see equation 3.17). Figure 4.7c shows similar results for the *coverage* TNPI as those depicted Figure 4.7b. TAZs with larger areas tend to have smaller values of the *coverage* TNPI. The high values for the *coverage* TNPI in TAZs near the downtown area and in the northern parts of the city of Corvallis can be explained by their high stop densities and their small areas (see equation 3.18).

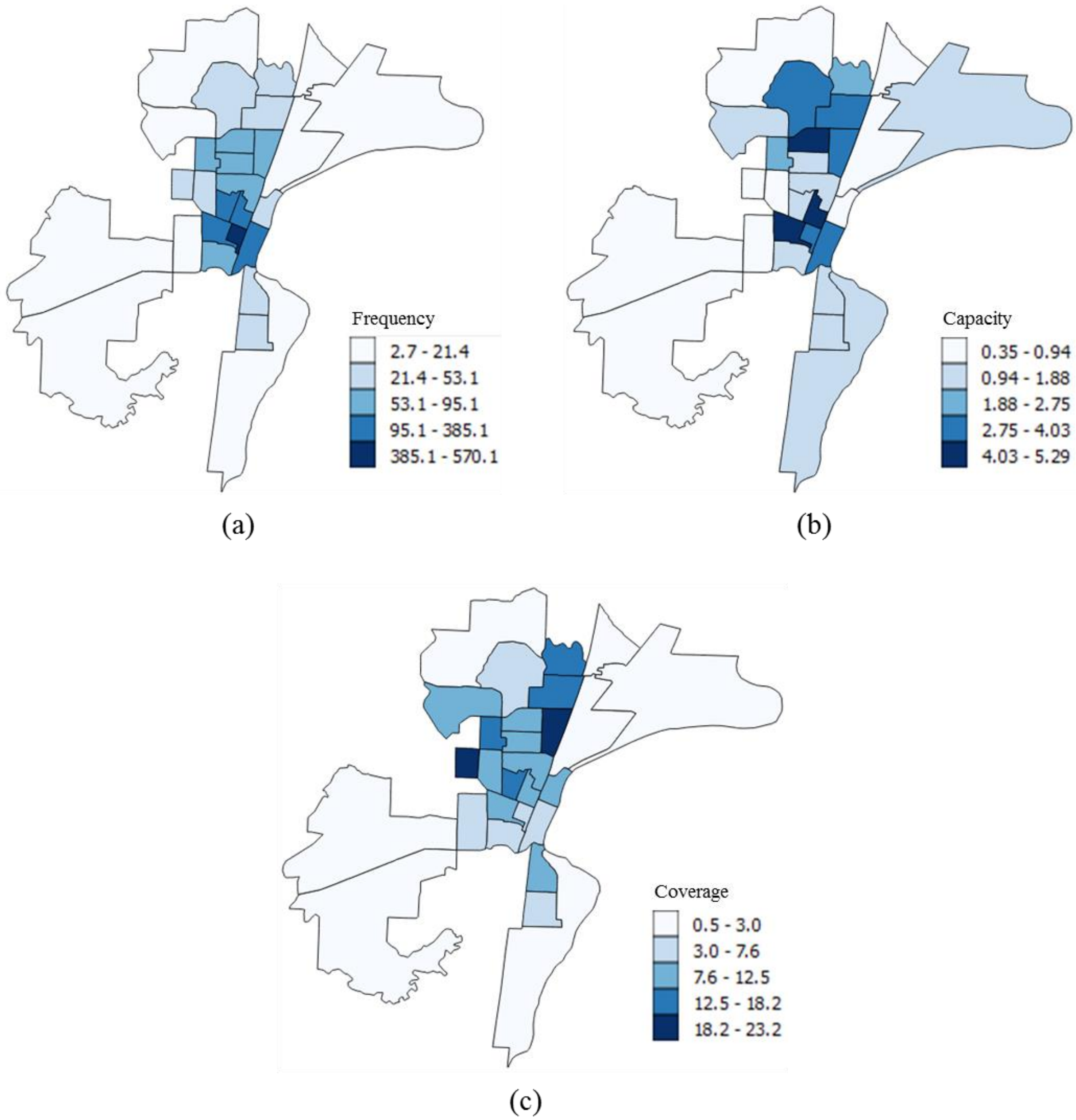


Figure 4.7: Choropleth maps of the spatial distribution of the performance sub-indicators for the 27 TAZs in the city of Corvallis

Figure 4.8 displays a choropleth map of the spatial distribution of performance scores for the 27 TAZs in the city of Corvallis.

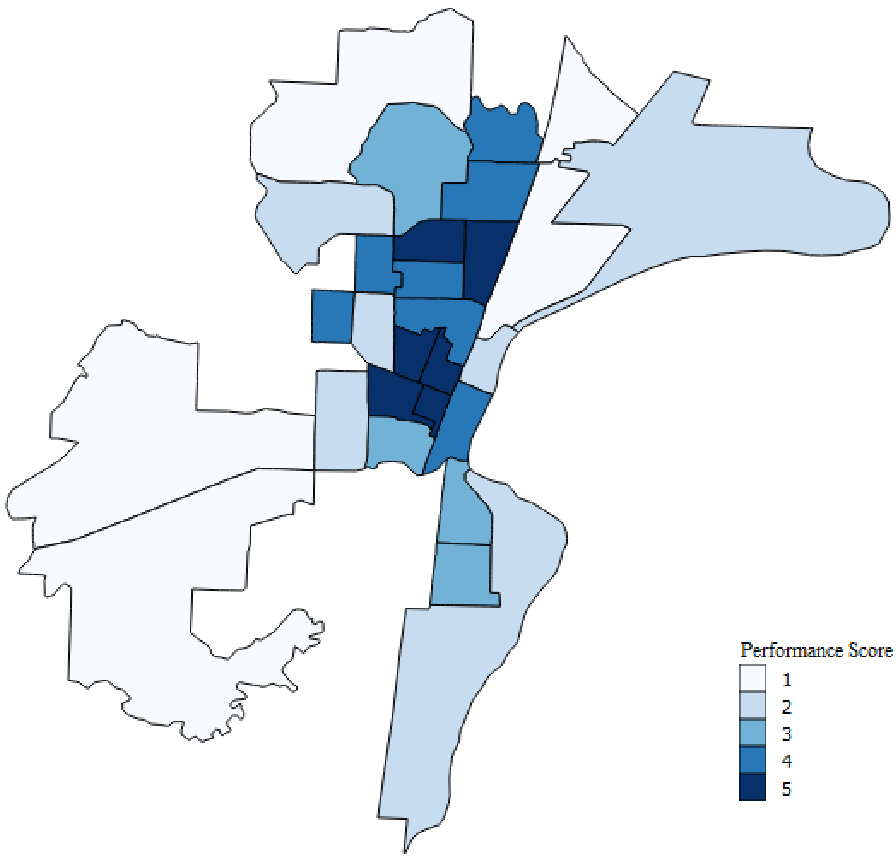


Figure 4.8: Choropleth map of the spatial distribution of the performance scores for the 27 TAZs in the city of Corvallis

4.3.3 Operational Score

As explained in section 3.3.3, the first step in calculating an operational score for a TAZ is to obtain values for the TNPIs *on time percentage* (*OT*), *capacity-to-demand* (*CTD*) *ratio*, and *hour coverage* (*HC*). Then, the final operational score is calculated using the AHP method.

Table 4.8 shows the average, standard deviation, minimum, and maximum values for the operational TNPIs and the operational score obtained for the CTS transit network. Appendix D lists all the values of the operational TNPIs calculated for each of the 27 TAZs in the city of Corvallis. Appendix E includes the importance matrix, global weights, and local weights of the operational TNPIs obtained with the AHP method, as well as the operational scores for each of the 27 TAZs in the city of Corvallis.

Table 4.8: Operational TNPIs and score of TAZs in the city of Corvallis

	Average	**St. Dev.**	**Min.**	**Max.**
OT	0.85	0.12	0.51	0.98
CTD	2.92	2.45	0.81	9.74
HC	0.55	0.04	0.50	0.60
Operational Score	3.70	2.01	1.68	9.30

The values of the operational TNPI *CTD* ratio shown in Table 4.8 are worth noting, especially the minimum value of 0.81. This means that even in the worst TAZ in the city Corvallis, 81% of the demand is satisfied by the capacity indicating that the CTS is currently doing a good job in satisfying the demand.

Figure 4.9 depicts three choropleth maps that show the spatial distribution of the operational TNPIs *on time percentage* (*OT*), *capacity-to-demand* (*CTD*) *ratio*, and *hour coverage* (*HC*) in the city of Corvallis. Figure 4.9a shows that most of the TAZs in the city of Corvallis have large values for the *on time percentage* TNPI, which implies that bus delays are not a significant issue.

Figure 4.9b shows that most of the TAZs in the southern part of the city of Corvallis have values for the *CTD* ratio TNPI that are either smaller than or close to one. These TAZs are mainly served by route R6 of the CTS, which indicates that the current capacity of route R6 is not fully satisfying the demand in these TAZs. Figure 4.9c shows higher values for the *hour coverage* TNPI for the TAZs near the downtown area as well as in some of the northern TAZs of the city of Corvallis. However, when considering the small range in the values (i.e., 0.5–0.6), it is clear that most of the TAZs have relatively close values of hour coverage.

Figure 4.10 displays a choropleth map of the spatial distribution of operational scores for the 27 TAZs in the city of Corvallis.

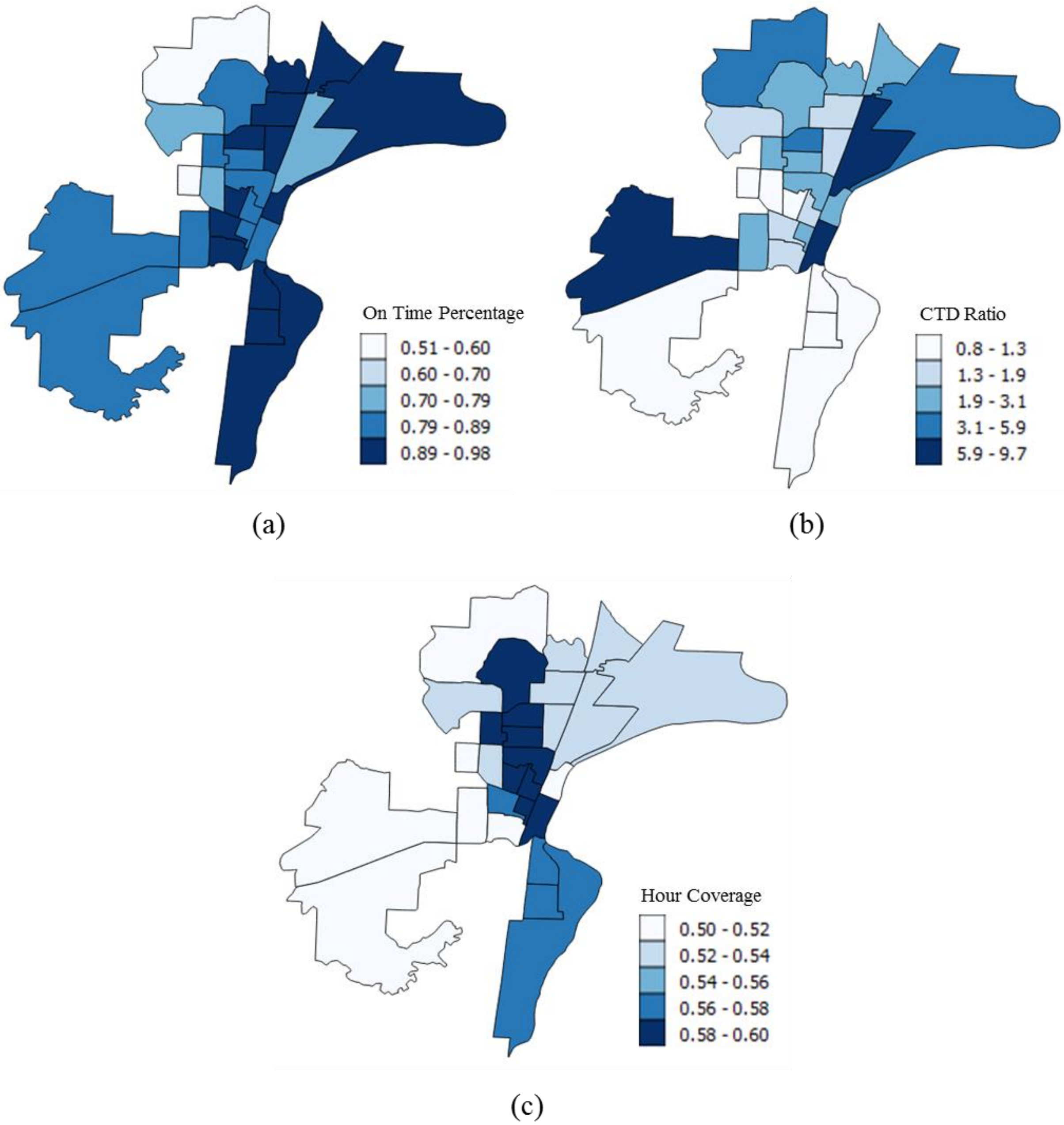


Figure 4.9: Choropleth maps of the spatial distribution of the operational TNPIs for the 27 TAZs in the city of Corvallis

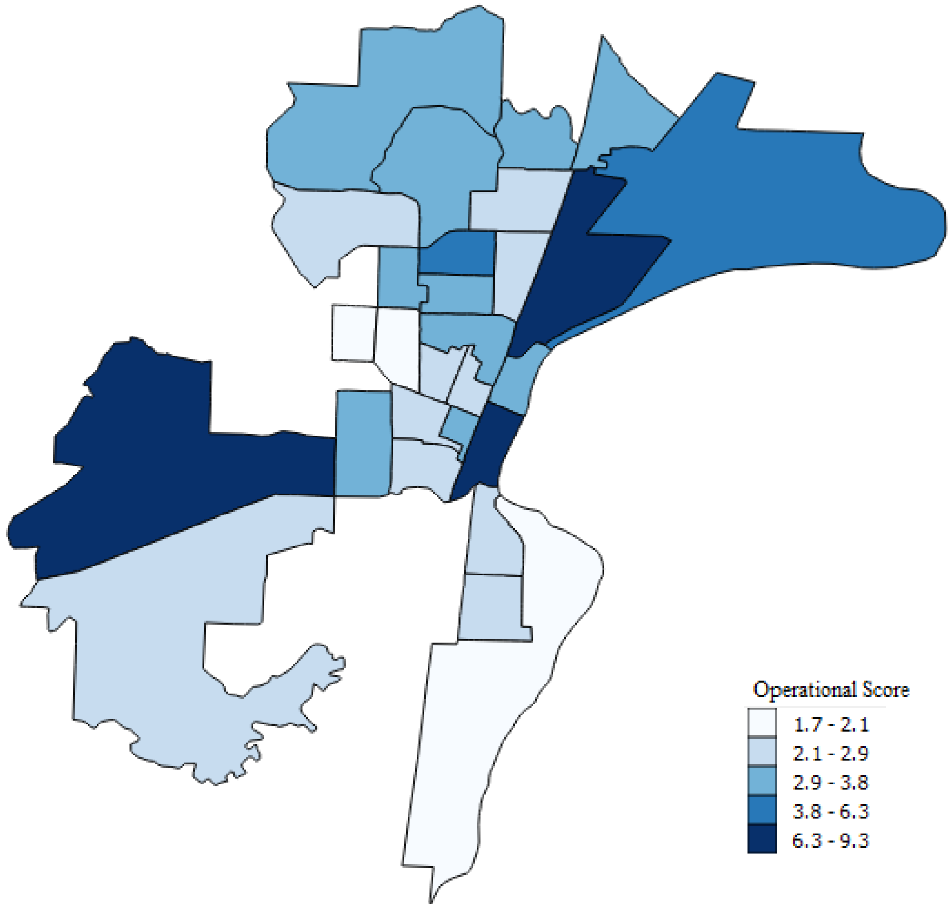


Figure 4.10: Choropleth maps of the spatial distribution of operational scores for the 27 TAZs in the city of Corvallis

4.3.4 Final Performance Score

The AHP method was used to combine the topological, performance, and operational scores of the 27 TAZs in the city of Corvallis to derive a final performance score. Appendix F includes a complete list of the final performance scores of each of the 27 TAZs in the city of Corvallis.

Table 4.9 shows the average, standard deviation, minimum and maximum values for the final performance score obtained for the city of Corvallis. Figure 4.11 depicts a choropleth map that shows the spatial distribution of the final performance scores for the 27 TAZs in the city of Corvallis.

Table 4.9: Summary statistics of the final performance scores of the 27 TAZs in the city of Corvallis

	Average	**St. Dev.**	**Min.**	**Max.**
Final Performance Score	3.71	1.01	2.22	7.02

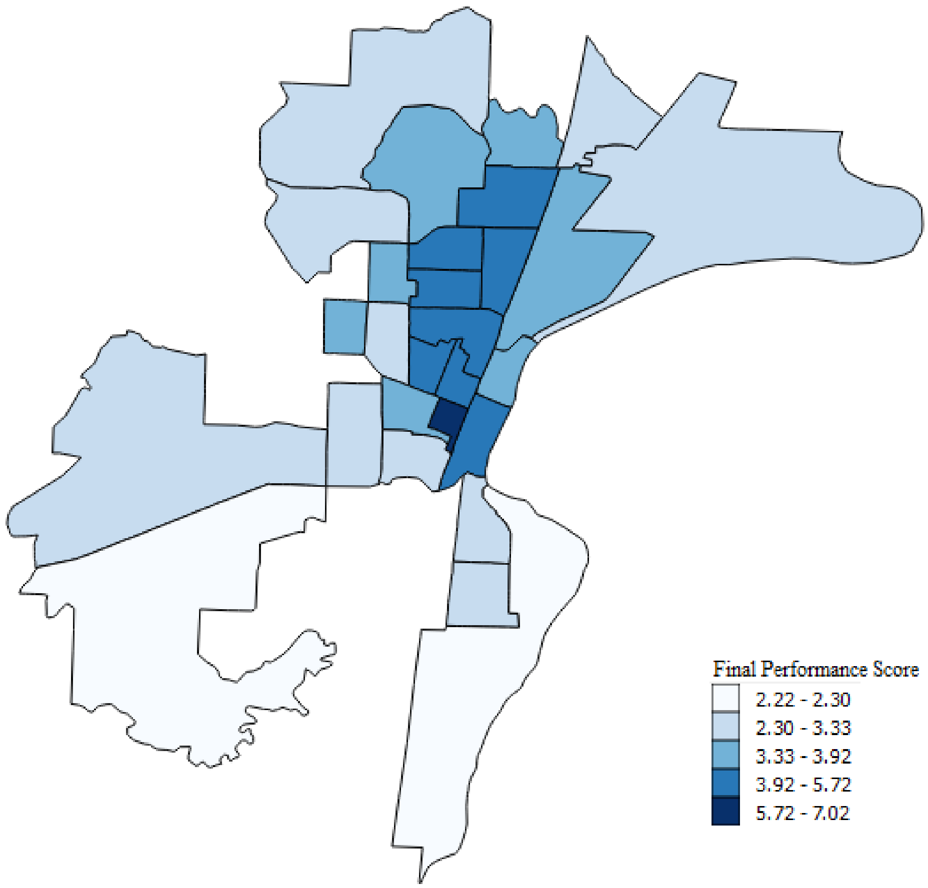


Figure 4.11: Choropleth map of the spatial distribution of the final performance scores for the 27 TAZs in the city of Corvallis

4.4 CORVALLIS TRANSIT SYSTEM – CASE STUDY 2

One of the purposes of the proposed methodology is to allow a transit planner to evaluate the impact that changes to the transit network have on its performance. These changes can be due to the addition (or elimination) of routes and stops, modifications to existing routes, and increases or reductions of the population that the transit network is supposed to serve.

In the second case study conducted on the transit network operated by the CTS, a hypothetical route was added. The first step in the second case study involved identifying the TAZs with the lowest final performance scores from the first case study (see section 4.3). A total of seven TAZ were selected from the first case study, all of them located on the periphery of the city of Corvallis. Figure 4.12 depicts the exact location of these seven TAZs (highlighted in yellow).

The red lines depicted in Figure 4.12 represent the new route added to the CTS in the second case study. Two underlying assumptions were made when adding the new route:

- The newly added route uses the currently existing stops located within the seven TAZs it serves.
- The newly added route starts from the main hub in downtown Corvallis and only stops at the seven TAZs with the lowest performance scores (it might cross other TAZs, but it will not serve any of their stops).

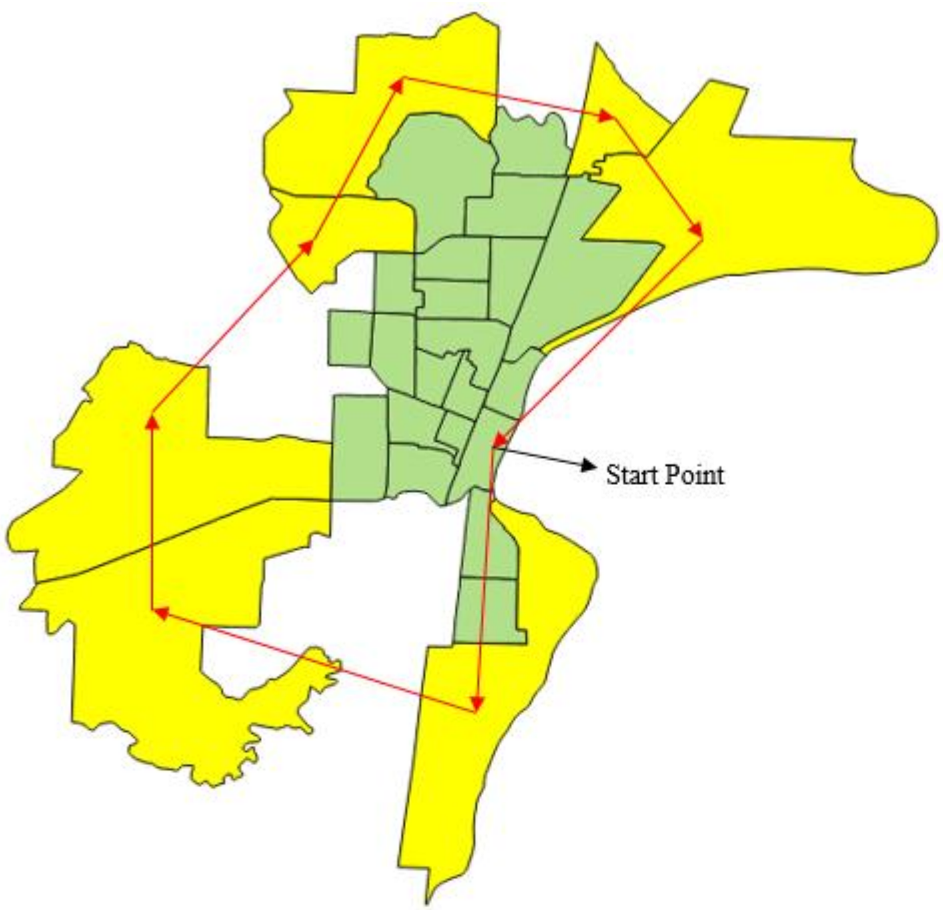


Figure 4.12 : The seven TAZs with the lowest performance scores (in yellow) and the direction of the new hypothetical route

The purpose of adding the new route was to assess how the final performance scores would change with the additional route serving the seven TAZs with the lowest final performance scores. It is important to note that adding a new route to a transit network provides more capacity and service to the whole network. However, the new route also generates additional maintenance costs. The frequency of the newly added route was assigned based on the average route frequency of the CTS (i.e., 0.54 vehicle/hour).

4.4.1 Topological Score

The same procedure described in section 4.3.1 was used to calculate the topological score in the second case study. Appendix G lists the updated inputs and the topological TNPIs calculated for each of the 27 TAZs in the city of Corvallis for the second case study, whereas Appendix H presents the importance matrix, global weights, and local weights of the topological TNPIs obtained with the AHP method as well as the topological scores for the 27 TAZs in the city of Corvallis.

Table 4.10 shows the average, standard deviation, minimum, and maximum values for the topological TNPIs and the topological score obtained for the city of Corvallis in the second case study.

Table 4.10: Topological TNPIs and score of TAZs with the newly added route

	Average	**St. Dev.**	**Min.**	**Max.**
γ^{CTD}	0.53	0.06	0.45	0.71
β^{CTD}	0.26	0.12	0.19	0.80
ρ	0.80	0.88	0.00	4.00
σ	0.77	0.55	0.05	1.86
Topological Score	**3.73**	**1.01**	**2.73**	**7.74**

Figure 4.13 depicts four choropleth maps that show the spatial distribution of the topological TNPIs γ^{CTD}, β^{CTD}, ρ, and σ for the 27 TAZs in the city of Corvallis for the second case study. Figure 4.13a and Figure 4.13b, which correspond to the topological TNPIs γ^{CTD} and β^{CTD}, show similar spatial distributions with a few TAZs in the downtown area and on the perimeter of the city of Corvallis having high γ^{CTD} and β^{CTD} values.

Figure 4.13c shows that a few TAZs in the downtown area of the city of Corvallis have high values for the topological TNPI ρ. Other TAZs have small values for the topological TNPI ρ. Figure 4.13d shows that TAZs located near the downtown area of the city of Corvallis have higher values for the topological TNPI σ, whereas TAZs located on the perimeter of the city of Corvallis have lower values for the topological TNPI σ.

Figure 4.14 displays a choropleth map of the spatial distribution of the topological scores of the 27 TAZs in the city of Corvallis for the second case study.

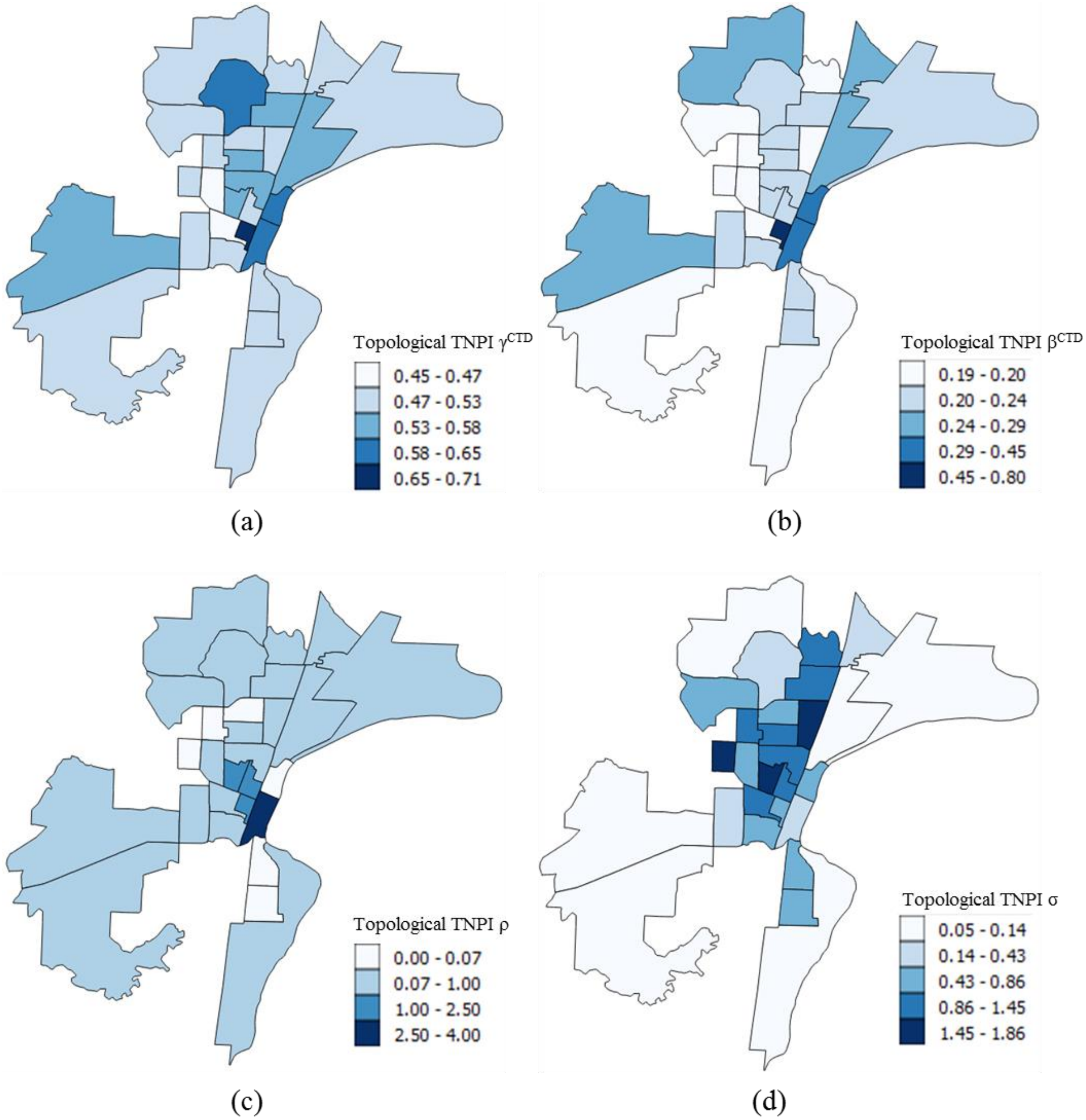


Figure 4.13: Choropleth maps of the spatial distribution of the topological TNPIs for the 27 TAZs in the city of Corvallis in the second case study

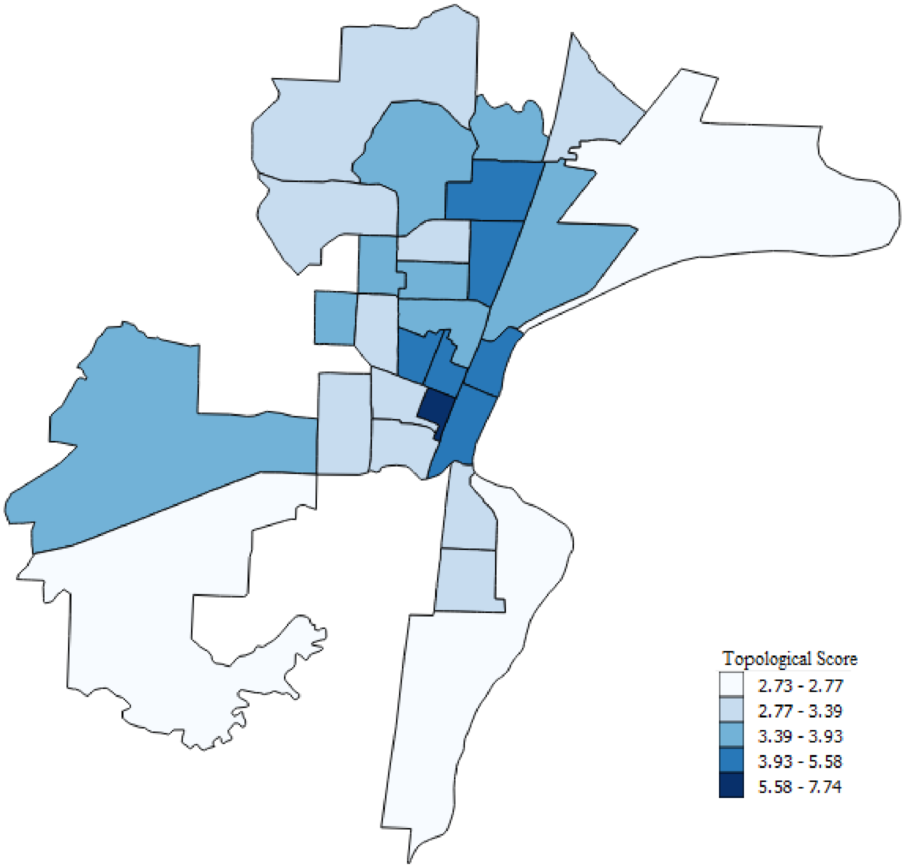


Figure 4.14: Choropleth map of the spatial of the spatial distribution of the topological scores for the 27 TAZs in the second case study

4.4.2 Performance Score

The same procedure described in section 4.3.2 was used to calculate the performance score for the second case study. Appendix I includes a complete list of the z-scores (i.e., averages and percentiles) calculated for each performance sub-indicator for each of the 27 TAZ in the city of Corvallis.

Table 4.11 displays the average, standard deviation, minimum, and maximum values for the performance TNPIs and the performance score obtained for the CTS transit network for the second case study.

Table 4.11: Performance TNPIs and score of TAZs for the second case study

	Average	**St. Dev.**	**Min.**	**Max.**
f	86.50	128.63	4.15	570.11
c^p	2.17	1.43	0.35	5.29
g	8.73	6.45	0.52	23.21
Performance Score	**3.00**	**1.49**	**1.00**	**5.00**

It is important to note that even after adding the new route, the range of values for the TNPI *frequency* is still very large (i.e., 4.15 to 570.11). This wide range of values can be explained by the fact that the number of additional vehicles entering the seven TAZs is still not large enough to account for the large areas of these TAZs since the TNPI *frequency* is derived from dividing the number of buses entering a TAZ over the TAZ area (in km^2).

Figure 4.15 depicts three choropleth maps that show the spatial distribution of the performance sub-indicators *frequency*, *capacity*, and *coverage* for the 27 TAZs in the city of Corvallis for the second case study. Figure 4.15a shows that TAZs in downtown and some of the northern areas of the city of Corvallis have larger values for the performance sub-indicators *frequency*. This is explained by the fact that these TAZs have smaller areas but more routes that service them (i.e., 7-8 routes) when compared to TAZs with larger areas located on the perimeter of the city which have one or two routes servicing them (see equation 3.16).

Figure 4.15b shows that the new route added in the second case study has not made significant changes on the spatial distribution of the performance sub-indicator *capacity*, especially for the TAZs located in the western part of the city of Corvallis. Figure 4.15c shows that the high values for the performance sub-indicator *coverage* are still concentrated in the downtown and northern parts of the city of Corvallis, even after adding the new route.

Figure 4.16 displays a choropleth map of the spatial distribution of the performance scores for the 27 TAZs in the city of Corvallis for the second case study.

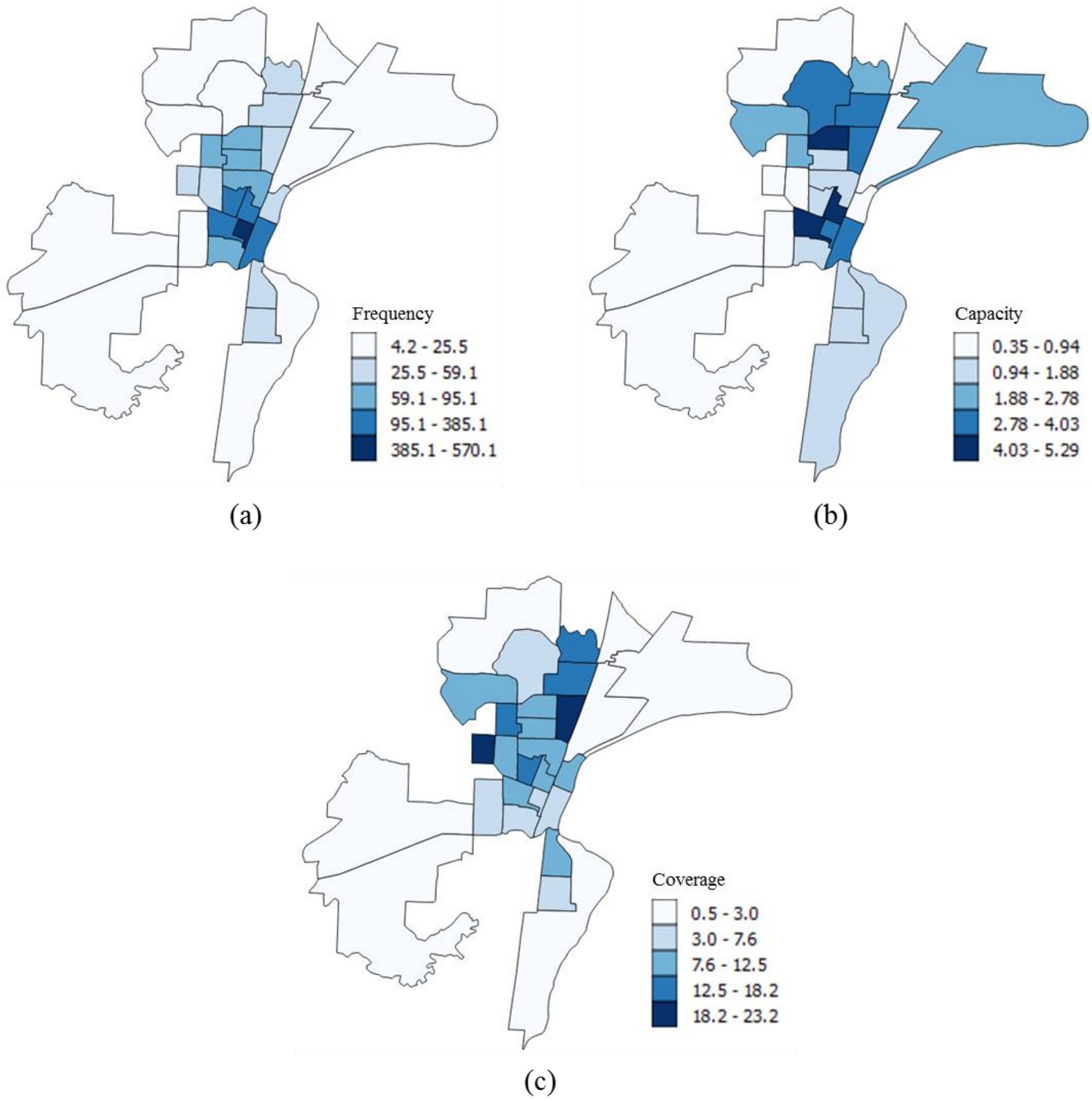


Figure 4.15: Choropleth maps of the spatial distribution of the performance sub-indicators for the 27 TAZs in the city of Corvallis for the second case study

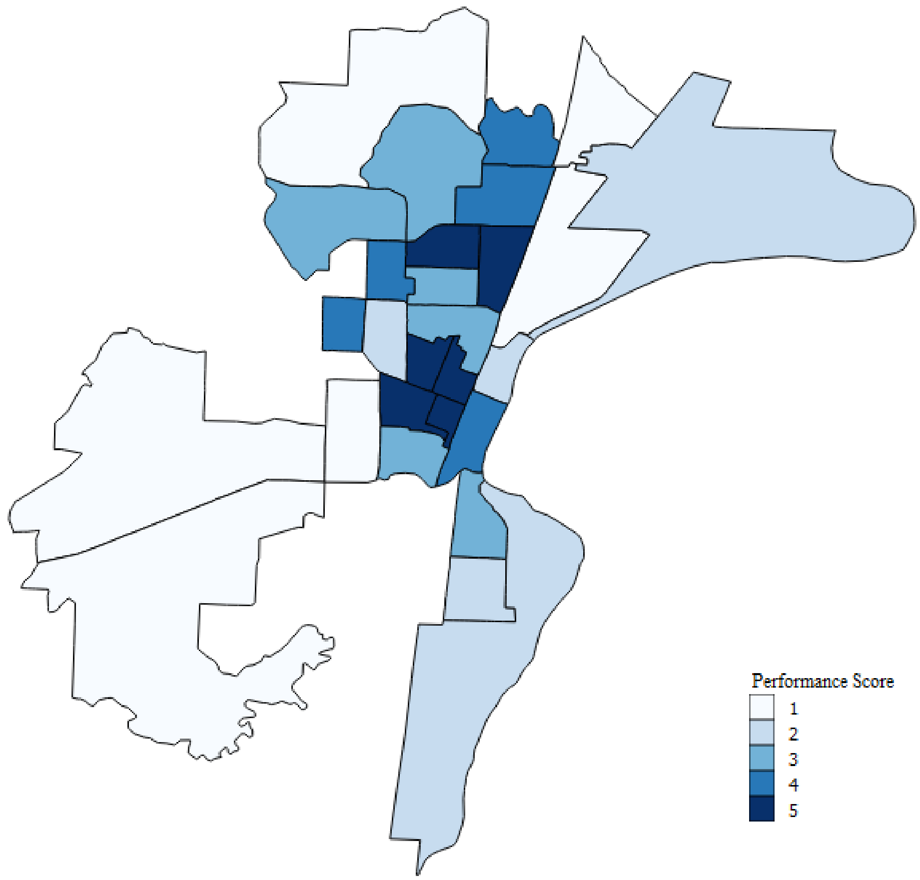


Figure 4.16: Choropleth map of the spatial distribution of the performance scores for the 27 TAZs in the city of Corvallis for the second case study

4.4.3 Operational Score

The same procedure described in section 4.3.3 was used to calculate the operational score for the second case study.

Table 4.12 shows the average, standard deviation, minimum, and maximum values for the operational TNPIs and the operational score obtained for the city of Corvallis for the second case study. Appendix J lists all the operational TNPIs calculated for each of the 27 TAZs in the city of Corvallis for the second case study, whereas Appendix K presents the importance matrix, global weights, and local weights of the operational TNPIs obtained with the AHP method as well as the operational scores for each of the 27 TAZs in the city of Corvallis in the second case study.

Table 4.12: Operational TNPIs and score of TAZs for the second case study

	Average	**St. Dev.**	**Min.**	**Max.**
OT	0.84	0.10	0.51	0.98
CTD	3.89	3.37	1.00	12.89
HC	0.55	0.04	0.50	0.60
Operational Score	3.70	2.05	1.48	9.22

Table 4.12 shows that the average value of the operational TNPI *CTD* ratio has increased by almost one when compared to the value of the average *CTD* ratio obtained in the first case study (i.e., 3.89 versus 2.92). This increase in the average

value of the *CTD* ratio can be explained by the capacity added to the transit network with the new route (while keeping the demand constant).

Figure 4.17 depicts three choropleth maps that show the spatial distribution of the operational TNPIs *on time percentage* (*OT*), *capacity-to-demand* (*CTD*) *ratio*, and *hour coverage* (*HC*) in the city of Corvallis for the second case study. Figure 4.17a shows that most of the TAZs in the city of Corvallis still have large on time percentages, which implies that bus delays are still not a significant issue. Note that the *on time percentage* value for the route added in the second case study was considered to be 76.92, which is the average *on time percentage* for the routes in the original network serving these seven TAZs.

Figure 4.17b shows that with the new route added, there are no TAZs in the city of Corvallis with *CTD* ratios smaller than one, meaning that all the demand is being satisfied by the CTS. The addition of the new route has offered more capacity for satisfying potential demand growth. Similar to Figure 4.9c for the original CTS network, Figure 4.17c shows higher values for the *hour coverage* TNPI for the TAZs located near the downtown area as well as some of the northern TAZs of the city of Corvallis. However, when considering the small range in the values (i.e., 0.5–0.6), it is clear that most of the TAZs in the second case study have relatively close values for the *hour coverage* TNPI.

Figure 4.18 displays a choropleth map of the spatial distribution of operational scores for the 27 TAZs the city of Corvallis for the second case study.

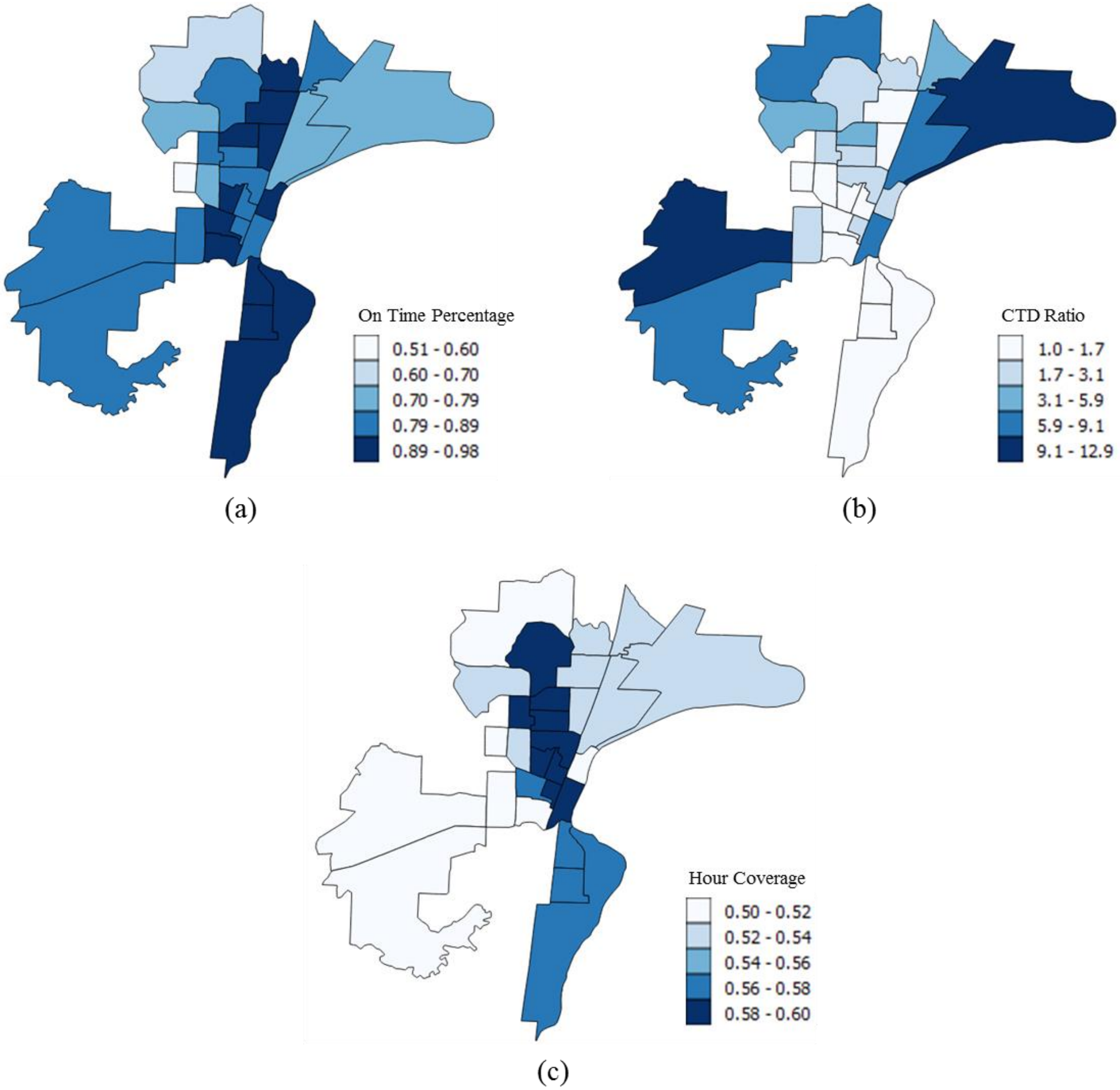


Figure 4.17: Choropleth maps of the spatial distribution of the operational TNPIs for the 27 TAZs in the city of Corvallis for the second case study

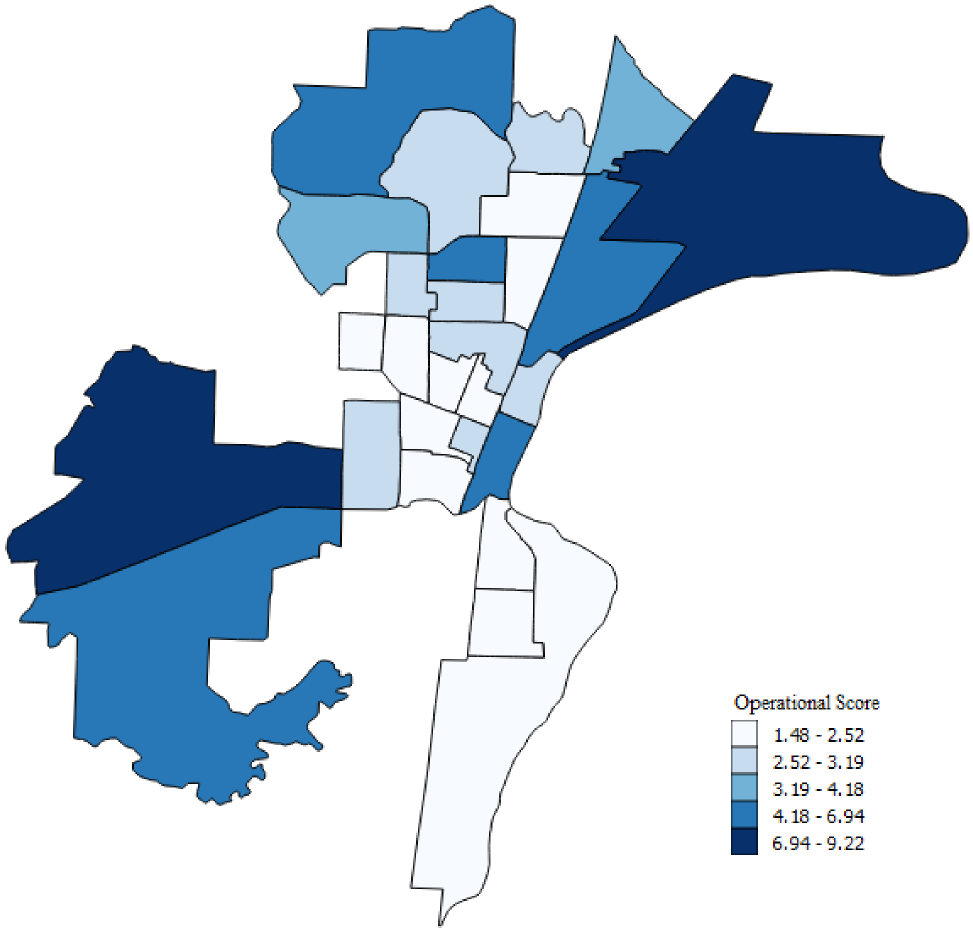


Figure 4.18: Spatial distribution of operational scores of TAZs with the newly added route

4.4.4 Final Performance Score

Table 4.13 shows the average, standard deviation, minimum, and maximum values for the final performance score obtained for city of Corvallis in the second case study. Appendix L presents a complete list of the final performance scores of each of the 27 TAZs in the city of Corvallis for the second case study.

Table 4.13 shows a smaller range for the final performance scores when compared to those obtained in the first case study (see Table 4.9). The minimum score in the second case study has increased from 2.22 to 2.61, whereas the maximum scored has decreased from 7.02 to 6.88. A plausible explanation for these changes is presented in chapter 5.0.

Figure 4.19 depicts a choropleth map that shows the spatial distribution of the final performance scores for the 27 TAZs in the city of Corvallis for the second case study.

Table 4.13: Summary statistics of the final performance scores of the 27 TAZs in the city of Corvallis for the second case study

	Average	**St. Dev.**	**Min.**	**Max.**
Final Performance Score	3.70	0.92	2.61	6.88

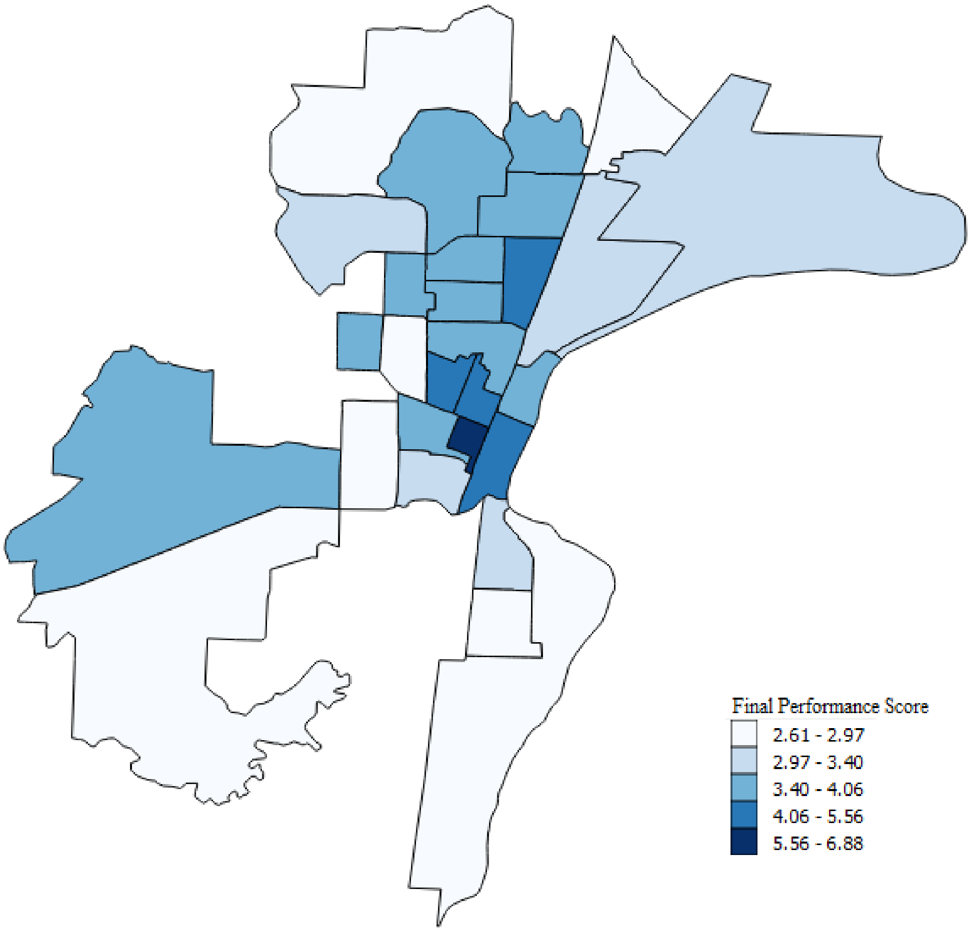


Figure 4.19: Choropleth map of the spatial distribution of the final performance scores for the 27 TAZs in the city of Corvallis for the second case study

4.5 ANALYSIS OF THE CRITERIA WEIGHTS

This section presents the results of an analysis conducted on the global weights that were used in the first case study to obtain a final performance score by combining the three criteria (i.e., topological score, performance score, and operational score) using the AHP method.

The three weight scenarios shown in Table 4.14 were tested. Scenario 1 used the original weights proposed in section 3.4 (see Table 3.40). Scenario 2 and scenario 3 explored alternative weight assignments for the three criteria.

Table 4.14: Global weight scenarios for the topological score (TS), performance score (PS), and operational score (OS) explored in the analysis

	Global Weight Scenarios		
Criterion	**1**	**2**	**3**
TS	0.70	0.20	0.10
PS	0.20	0.70	0.20
OS	0.10	0.10	0.70

Figure 4.20 depicts three choropleth maps that show the spatial distribution of the final performance score for the 27 TAZs in the city of Corvallis using the three global weight scenarios presented in Table 4.14.

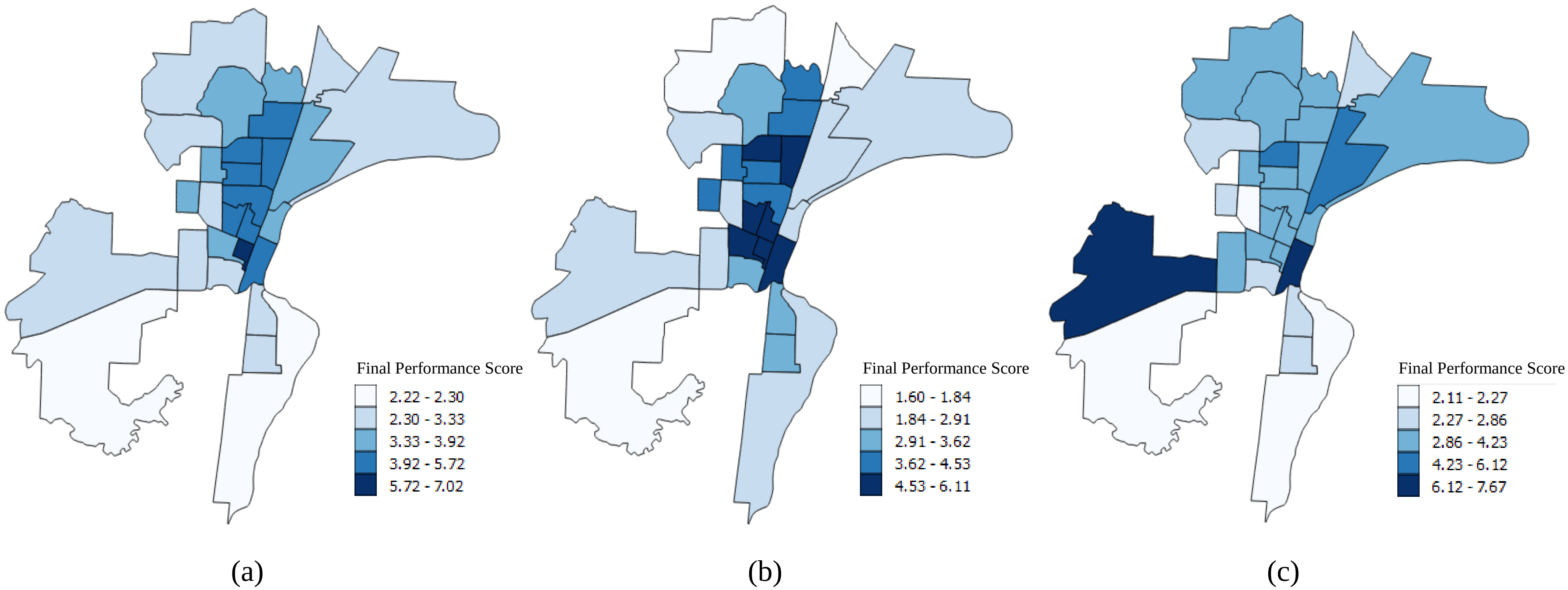


Figure 4.20: Choropleth maps of the spatial distribution of the final performance scores for the TAZs in the city of Corvallis using weight scenario 1 (a), weight scenario 2 (b), and weight scenario 3 (c)

Figure 4.21 depicts how the final performance scores behaved under the three different global weight scenarios used for the criteria in the AHP method. It is clear that using different global weights for the criteria has a considerable effect on the final performance scores of most of the TAZs in the city of Corvallis.

In addition to the global weight scenarios shown in Table 4.14, several other options were also tested and they all suggest considerable changes in the final performance scores of the TAZs. These results stress the importance of carefully assigning weights to the criteria when using the AHP method. This effect is discussed in more detail in chapter 5.0.

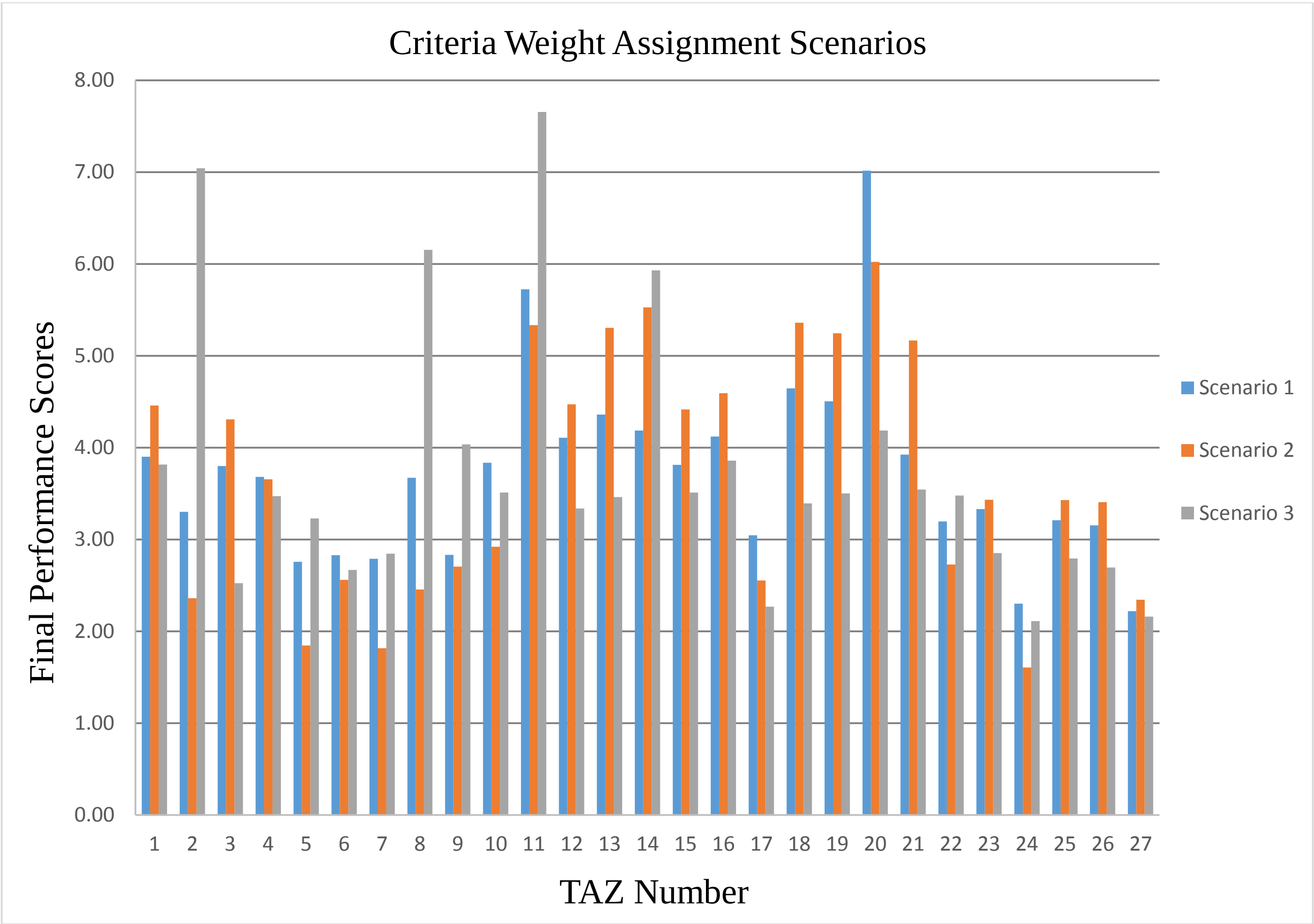


Figure 4.21: Behavior of final performance scores under different criteria weight assignment scenario

5.0 DISCUSSION

The objective of this chapter is to discuss the results obtained by applying the proposed methodology to two separate case studies based on the transit network operated by the Corvallis Transit Systems (CTS).

The rest of the chapter is organized as follows. Section 5.1 discusses the results of the first case study conducted on the transit network operated by the CTS. Section 5.2 discusses the results of the second case study conducted on the transit network operated by the CTS. Section 5.3 compares the results obtained in the first and second case studies. Finally, section 5.4 discusses the results of an analysis performed on the criteria weights.

5.1 CORVALLIS TRANSIT SYSTEM – CASE STUDY 1

5.1.1 Topological Score

The spatial distribution of the topological scores obtained for the 27 TAZs in the city of Corvallis for the first case study are depicted in Figure 4.6. The results show that the topological scores of the TAZs located near the downtown areas of the city of Corvallis are higher than the topological scores for the TAZs located on the perimeter of the city. A possible explanation for the high topological scores in the TAZs located near the downtown area is that these TAZs have more routes that traverse them (i.e., 7-8 routes), but a smaller number of stops (i.e., 4-5 stops) due to their small areas. In contrast, the TAZs located on the perimeter of the city have one or two routes traversing them and anywhere from six to 20 stops (see Appendix A).

5.1.2 Performance Score

The spatial distribution of the performance scores obtained for the 27 TAZs in the city of Corvallis for the first case study are depicted in Figure 4.8. The results show that the performance scores of the TAZs in the downtown area and some of the northern TAZs are larger than the performance scores of those TAZs located on the perimeter of the city of Corvallis. Again, the TAZs in the downtown area have more routes that traverse them (i.e., 7-8 routes) resulting in more vehicles entering these TAZs on a daily basis (i.e., more *frequency of service*) and more capacity available in these TAZs compared to the TAZs located on the perimeter of the city which have one or two routes traversing them (see Appendix B).

5.1.3 Operational Score

The spatial distribution of the operational scores obtained for the 27 TAZs in the city of Corvallis for the first case study are depicted in Figure 4.10. Unlike the topological and performance scores, the larger values of the operational score are not concentrated in the downtown area. A possible explanation for this is that the operational score is driven mainly by the CTD ratio, which tends to be abnormally large for a few of the TAZs.

5.1.4 Final Performance Score

The spatial distribution of the final performance scores obtained for the transit network operated by the CTS in the first case study are depicted in Figure 4.11. It is clear that the TAZs in the downtown area of the city of Corvallis have higher final performance scores, whereas the TAZs located on the perimeter of the city have lower final performance scores. Moreover, the spatial distribution of the final performance scores is quite similar to the spatial distribution of the topological scores. The reason for this is because of the weights assigned to the criteria when implementing the AHP method for obtaining the final performance score, i.e., the topological criterion was assigned a higher weight than the performance and the operational criteria. Therefore, it had a larger effect on the final performance score.

The type of results presented in Figure 4.11 represent the main product of the proposed methodology. More specifically, a transit planner will be able to estimate the *relative* final performance scores for the TAZs that are served by a transit network. In the case of the transit network operated by the CTS, a transit planner can easily conclude that a good level of service is being provided to the TAZs in the downtown area based on the final performance scores for those TAZs. Furthermore, the transit planner can use the "good" TAZs as a reference when considering potential changes to the service that is provided to the TAZs that have lower final performance scores.

It is important to note that the proposed methodology also estimates individual topological, performance, and operational scores which can further assist a transit planner in understanding the strengths and weaknesses of the TAZs that are served by a transit network. Potential improvements to the level of service provided to the TAZs can then focus on whatever aspect of the transit network (i.e., topology, performance, or operation) is more important to a specific transit agency.

5.2 CORVALLIS TRANSIT SYSTEM – CASE STUDY 2

5.2.1 Topological Score

The spatial distribution of the topological scores obtained for the 27 TAZs in the city of Corvallis for the second case study are depicted in Figure 4.14. The results show that the spatial distribution of the topological scores in the second case study is very similar to the spatial distribution of the topological scores in the first case study (i.e., the topological scores of the TAZs located near the downtown areas of the city of Corvallis are still higher than the topological scores for the TAZs located on the perimeter of the city). However, the values of the topological scores have increased for the seven TAZs that had the lowest final performance scores in the first case study. This issue is further discussed in section 5.3.1.

5.2.2 Performance Score

The spatial distribution of the performance scores in the second case study is very similar to those obtained in the first case study, which indicates that adding the new route did not have a significant effect on the performance scores of the seven TAZs with the lowest final performance scores. Despite the fact that adding the new route did increase both the frequency of service and the capacity of the seven TAZs with the lowest final performance scores, these increases were not sufficiently large to change the quintile in which their performance scores fall.

5.2.3 Operational Score

The distribution of operational scores in the second case study is similar to that observed in the first case study. This can be explained by the fact that even in the first case study, the seven TAZs with the lowest final performance scores were not the worst with respect to their operational score and one of them had the highest operational score due to its high CTD ratio. Adding a new route to serve these seven TAZs provided extra capacity, which resulted in maintaining high CTD ratios and operational scores for these TAZs.

5.2.4 Final Performance Score

The spatial distribution of the final performance scores obtained for the transit network operated by the CTS in the second case study are depicted in Figure 4.19. It is clear that the TAZs located on the perimeter of the city of Corvallis still have smaller performance scores compared to those located near the downtown areas. However, the minimum final performance score observed in the second case study (i.e., 2.61) is larger than the one obtained in the first case study (i.e., 2.22), whereas the maximum score observed in the second case study (i.e., 6.88) is smaller than the one obtained in the first case study (i.e., 7.02). The meaning of the changes in the minimum and maximum final performance scores is discussed in detail in section 5.3.1.

5.3 COMPARING THE CORVALLIS TRANSIT SERVICE CASE STUDIES

The second case study conducted on the transit network operated by the CTS was motivated by the low final performance scores observed in the TAZs located on the perimeter of the city of Corvallis (see TAZs highlighted in yellow in Figure 4.12). Thus, a hypothetical new route was added to service the TAZs with low final performance scores and the proposed methodology was used to assess if adding the extra route improved the final performance score of these TAZs.

Table 5.1 shows the values of the topological TNPIs obtained for the seven TAZs that had the lowest final performance scores before (i.e., CS 1) and after adding the hypothetical route (i.e., CS 2). It is clear that adding a new route to serve the seven TAZs with the lowest final performance scores did increase the values for the topological TNPI ρ. The values of the topological TNPIs γ^{CTD} and β^{CTD} improved for only a couple of TAZs. The values for the topological TNPI σ

did not change for any of the TAZs since there is no parameter in its calculation that is affected by adding an extra route (see equation 2.4)

Table 5.1: Topological indicators of the seven TAZs with the lowest final performance scores

	γ^{CTD}		β^{CTD}		ρ		σ	
TAZ	**CS 1**	**CS 2**	**CS 1**	**CS 2**	**CS 1**	**CS 2**	**CS 1**	**CS 2**
2375	0.50	0.58	0.25	0.29	0.50	0.90	0.05	0.05
2381	0.50	0.50	0.28	0.28	0.00	0.50	0.07	0.07
2382	0.50	0.50	0.19	0.19	0.00	0.50	0.63	0.63
2383	0.50	0.50	0.28	0.28	0.00	0.50	0.24	0.24
2385	0.50	0.50	0.21	0.21	0.00	0.50	0.07	0.07
2407	0.51	0.51	0.19	0.19	0.00	0.50	0.14	0.14
2411	0.41	0.50	0.17	0.20	0.00	0.50	0.12	0.12

CS 1: First case study
CS 2: Second case study

Table 5.2 shows the values of the performance TNPIs obtained for the seven TAZs that had the lowest final performance scores before (i.e., CS 1) and after adding the hypothetical route (i.e., CS 2). It is clear that adding a new route improves the values of the performance TNPIs *f* and *c*, but does not affect the values of the performance TNPI *g* since there is no parameter in its formula that can be affected by adding an extra route (see equation 3.18)

Table 5.2: Performance indicators of the seven TAZs with the lowest final performance scores

	f		***c***		***g***	
TAZ	**CS 1**	**CS 2**	**CS 1**	**CS 2**	**CS 1**	**CS 2**
2375	3.25	4.94	0.61	0.93	0.52	0.52
2381	2.73	5.46	0.35	0.70	0.84	0.84
2382	14.34	21.25	1.48	2.20	8.50	8.50
2383	10.59	20.43	0.48	0.92	3.03	3.03
2385	3.12	4.63	1.88	2.78	0.87	0.87
2407	2.73	4.15	0.43	0.65	1.96	1.96
2411	5.52	7.76	1.13	1.58	1.64	1.64

CS 1: First case study
CS 2: Second case study

Table 5.3 shows the values of the operational TNPIs *on time percentage* (*OT*), *capacity-to-demand* (*CTD*) *ratio*, and *hour coverage* (*HC*) obtained for the seven TAZs that had the lowest final performance scores before (i.e., CS 1) and after adding the hypothetical route (i.e., CS 2). It is clear that adding a new route considerably affects the values of the operational TNPI *CTD*. No changes were observed in the values of the operational TNPIs OT and HC.

Table 5.3: Operational indicators of the seven TAZs with the lowest final performance scores

	OT		***CTD***		***HC***	
TAZ	**CS 1**	**CS 2**	**CS 1**	**CS 2**	**CS 1**	**CS 2**
2375	0.85	0.82	9.74	12.89	0.50	0.50
2381	0.51	0.64	3.60	7.20	0.50	0.50
2382	0.73	0.74	1.87	4.87	0.54	0.54
2383	0.94	0.86	2.25	4.33	0.54	0.54
2385	0.94	0.74	3.98	11.40	0.54	0.54
2407	0.85	0.85	1.24	7.77	0.50	0.50
2411	0.93	0.89	0.81	1.14	0.58	0.58

CS 1: First case study
CS 2: Second case study

The results shown in Table 5.1, Table 5.2, and Table 5.3 indicate that the values for at least one TNPI in each category (i.e., topological, performance, and operational) have increased for the seven TAZs with the lowest final performance scores. This suggests an improvement in the scores for the corresponding category. However, due to some limitations of the AHP method, extra caution must be taken when comparing the scores obtained from two implementations of AHP. The next section discusses these limitations and provides some suggestions on how to interpret the results obtained from the AHP method.

5.3.1 Interpreting the Results Obtained with the AHP Method

As explained at the end of section 3.3.1.1, the final scores obtained with the AHP method are relative and always add up to one regardless of the number of alternatives being evaluated. Because of this characteristic feature of the AHP method, two problems arise when comparing two different sets of results in the context of this research:

- Assume that the proposed methodology is implemented on two different cities (i.e., one large and one small) each with a different number of TAZs. In such case, the final performance scores obtained with the AHP method are not directly comparable since the total scores for each city adds up to one. Therefore, the TAZs in the larger city would get smaller scores even if some of them are doing better than the TAZs in the smaller city. One possible solution to this problem is to avoid using multiple AHPs for comparing different geographical areas. Instead, the analysis should be performed at the city level when comparing multiple cities as opposed to the TAZ level so that each city plays the role of an alternative.
- When comparing the results of two different implementations of the AHP method on the same geographical area, extra caution must be taken on the numerical values of the scores. For example, two sets of final performance scores for the same geographical area (i.e., city of Corvallis) with two different transit network configurations were estimated with the AHP method in this research. Although the number of TAZs in this case are the same, the problem with directly comparing the final performance scores obtained for the TAZs with the AHP method is the relativity of the TAZ scores. As previously explained,

the results obtained within a single AHP method are relative to each other (and add up to one), which makes the comparison of results from two different AHPs difficult. This issue is discussed in more detail in the rest of this section.

Figure 5.1 shows the spatial distribution of the final performance scores in the first (Figure 5.1a) and the second (Figure 5.1b) Corvallis case studies.

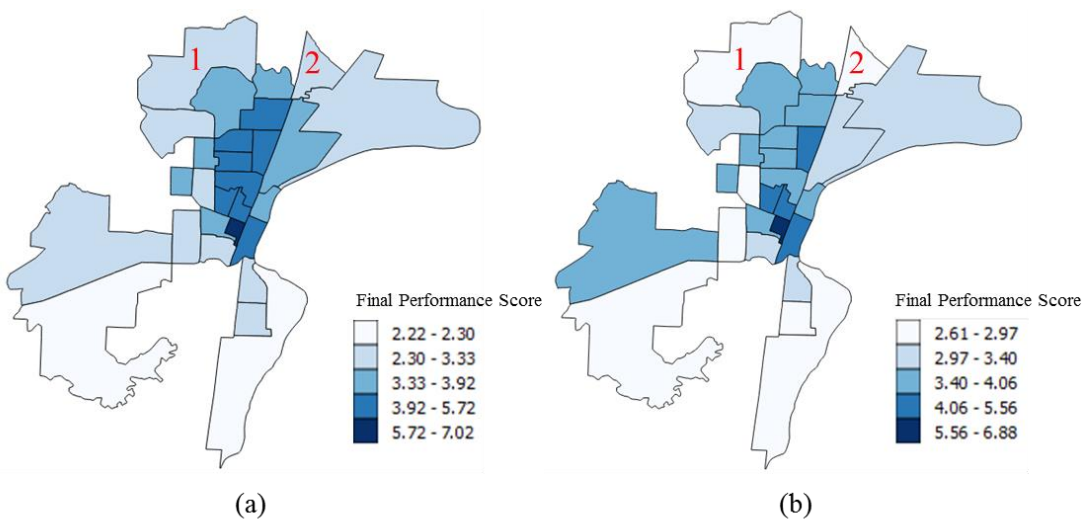


Figure 5.1: Spatial distribution of the final performance scores for the first case study (a) and the second case study (b).

The potential issues with directly comparing the results obtained for the same geographical area via two separate AHP analyses can be observed in Figure 5.1. Since these maps are generated based on the numerical values of the final performance scores, the map in Figure 5.1b suggests that the TAZs identified with the numbers “1” and “2” have become worse in terms of final performance score. In reality, however, these two TAZs have improved in terms of final performance scores.

Table 5.4 shows the average, standard deviation, minimum, and maximum values for the final performance score obtained for the first and second case studies conducted on the transit network operated by the CTS. It should be noted that the range of the final performance scores have decreased from 4.80 in the first case study to 4.27 in the second case study. This decrease in the range is an indication of closer performance levels between the worst and the best TAZs in the second case study. This is supported by the fact that no changes were made to the TAZs with high final performance score in the first case study. Thus, the decrease in the range of the scores in the second case study is a clear indication that the TAZs with the worst final performance score have increased their performance level due to the addition of the new hypothetical route.

Table 5.4: Summary statistics for the final performance scores for the first and second case studies

	Average	**St. Dev.**	**Min.**	**Max.**	**Range**
Final Performance Score (First Case Study)	3.71	1.01	2.22	7.02	4.80
Final Performance Score (Second Case Study)	3.70	0.92	2.61	6.88	4.27

Further investigation of the values of the topological, performance, and operational scores showed that the addition of the new hypothetical route was most effective on the *topological scores* of the seven worst TAZs, resulting in an improvement in the final performance scores. Table 5.5 shows the changes in the range of values of the topological and operational score after adding the hypothetical route to serve the seven worst TAZs.

Table 5.5: Changes in the ranges of values of the topological and operational score after adding the hypothetical route to the seven worst TAZs

Score	**Range (Second Case Study)**	**Range (First Case Study)**	**Change**
Topological	5.01	5.64	-0.63
Operational	7.74	7.62	0.12

According to Table 5.5, adding the new hypothetical route resulted in a decrease of 0.63 in the topological score range, and an increase of 0.12 in the operational score range. The decrease in the range of the topological score can be explained by the changes to the topology of the transit network (i.e., increase in connectivity, complexity, and etc.) when a new route is added to serve the seven TAZs with the lowest final performance score. The increase in the range of the operational score is due to the fact that even in the first case study, the seven TAZs were not the worst with respect to their operational score and one of them had the highest operational score due to its high CTD ratio. Adding a new route to serve these seven TAZs provided extra capacity which resulted in higher CTD ratios and operational scores. As a result, the gap between the best and the worst TAZ with respect to the operational score has increased.

Table 5.6 shows the changes in the performance scores of the seven TAZs with the lowest final performance score after adding the new hypothetical route. It is clear that the performance scores of the seven worst TAZs in the first case study have not changed significantly. Only TAZ 2382 had an increase of one in its performance score.

Table 5.7: Performance scores of the seven worst TAZs in the first and second case studies.

TAZ #	Performance Score (First Case Study)	Performance Score (Second Case Study)
2375	1	1
2381	1	1
2382	2	3
2383	1	1
2385	2	2
2407	1	1
2411	2	2

In conclusion, the comparison between the first and the second case studies showed that adding a new route to serve the seven TAZs with the lowest final performance score in the first case study resulted in improvements in the topological and operational scores of these TAZs, which led into improvements in their final performance scores as well. Another conclusion is that despite the fact that adding the new route did increase both the frequency of service and the capacity of the seven TAZs with the lowest final performance scores, these increases were not sufficiently large to change the quintile in which their performance scores fall.

5.4 Analysis of the Criteria Weights

The results of the analysis performed on the criteria weights were presented in section 4.5. Figure 5.2 depicts the spatial distribution of the final performance scores for three scenarios explored for the criteria weights.

The concentration of the spatial distribution of the final performance scores in Figure 5.2a and Figure 5.2b are somewhat similar. In both cases, larger values of final performance scores can be observed in the TAZs near the downtown area and northern areas of the city of Corvallis. In Figure 5.2c, however, the final performance scores are more equally distributed and there is one TAZ (i.e., TAZ 2375) in the western part of the city of Corvallis with a very high (second highest) final performance score.

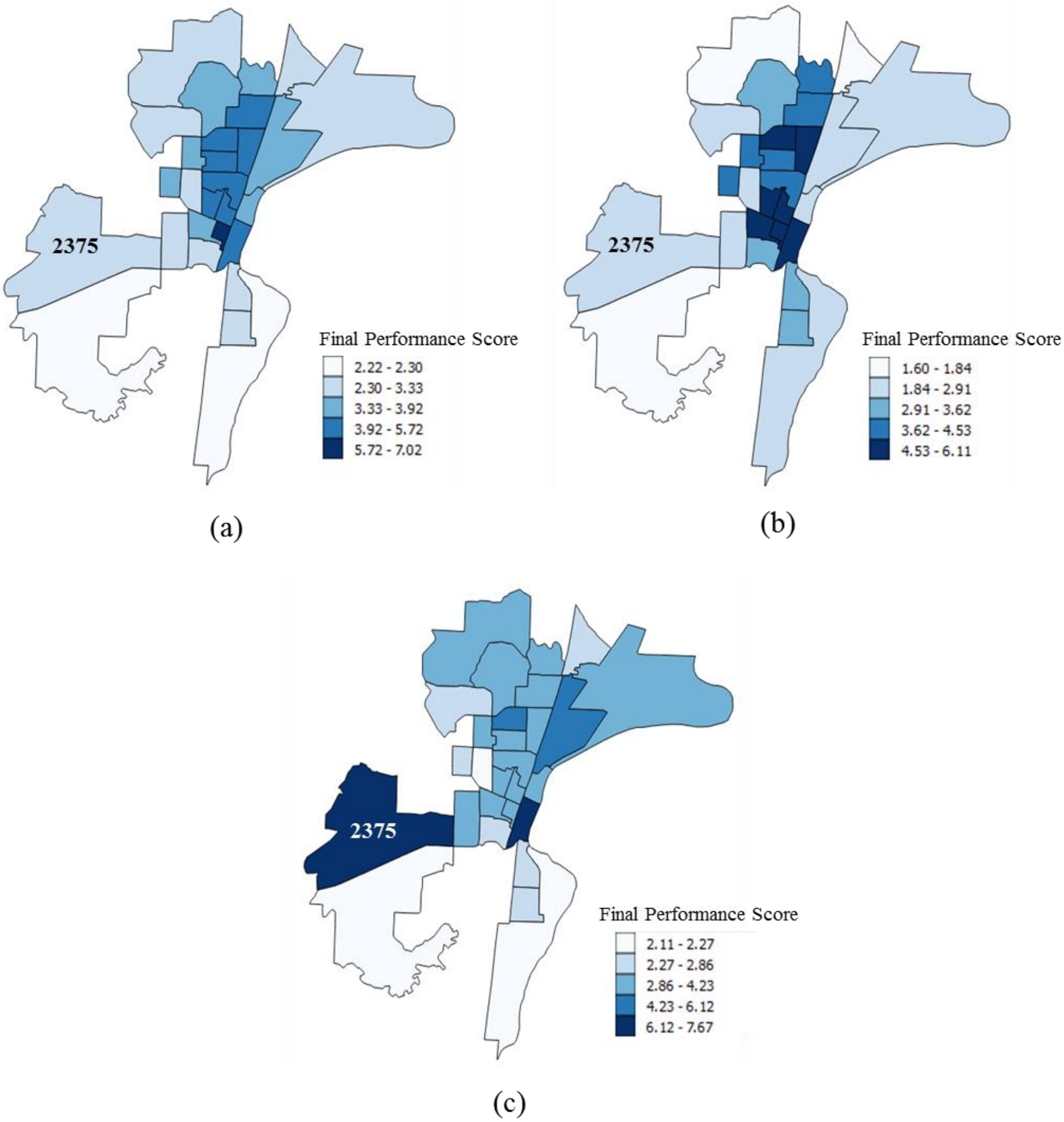


Figure 5.2: Spatial distribution of final performance scores under: a) Scenario 1 (see Table 3.40), b) Scenario 2 (see Table 4.10), and c) Scenario 3 (see Table 4.10)

The differences in the spatial distribution of the final performance scores among the three criteria weight scenarios can be explained how the individual criterion (i.e., topological, performance, and operational) were weighed in each scenario. For example, TAZ 2375 (i.e., TAZ 11 in Figure 4.21) has a low final performance score in Figure 5.2a and Figure 5.2b. The reason for that is because in Figure 5.2a, the criterion *Topological Score* has an importance weight of 0.7, and in Figure 5.2b the criterion *Performance Score* has an importance weight of 0.7. TAZ 2375 has a low topological score (i.e., 3.03) and a low performance score (i.e., 1). Therefore, its final performance score is low in both Scenario 1 (i.e., 3.3) and Scenario 2 (i.e., 2.38). Note that the maximum final performance scores are 7.02 for Scenario 1 and 6.11 in Scenario 2, respectively.

However, TAZ 2375 has the highest operational score (i.e., 9.30) due to its large CTD ratio while the average operational score is 3.70. Scenario 3 assigns an importance weight of 0.7 to the criterion *Operational Score* resulting in TAZ 2375 having the second highest final performance score of 7.05.

As previously depicted in Figure 4.13, the behavior of the final performance scores is highly dependent on the weights assigned to the criteria. Changes in the relative weights can therefore cause major changes in the final scores meaning that the final performance scores are not stable under varying criteria weights. One explanation for the instability of the final performance scores is that each criterion (i.e., topological, performance, and operational scores) covers a different aspect of a transit network making the criteria somewhat uncorrelated.

As a result, a high score in one criterion for a TAZ does not necessarily result in high score for the TAZ in another criterion. This stresses the importance of criteria weight assignments in the AHP method in the proposed methodology. Consulting experts in the area of public transit networks for the weight assignment process can significantly increase the validity of the results obtained with the AHP method.

6.0 CONCLUSIONS

In this research, a methodology was developed to assess the quality of service provided by a transit network as the demand on the transit network (driven by population changes) changes over time. The proposed methodology utilizes three different types of transit network performance indicators (TNPI): topological, performance, and operational. The analysis of a transit network was conducted at the Traffic Analysis Zone (TAZ) level. A single score for each TNPI category was calculated for each TAZ. Then, a final performance score for each TAZ was calculated by combining the TNPI scores from each TAZ using the Analytic Hierarchy Process (AHP) method. In order to test the practicality of the proposed methodology, two case studies were conducted on the transit network operated by the Corvallis Transit System (CTS). An analysis was performed on the results obtained from the first case study to test their stability with respect to the prioritization of the TNPI categories.

The rest of this chapter is organized as follows. Section 6.1 presents the conclusions reached in this study. Section 6.2 discusses the opportunities for future work.

6.1 RESEARCH CONCLUSIONS

The results obtained from the first and second case studies conducted on the transit network operated by the CTS demonstrated that the proposed methodology can help transit planners in understanding the effects of changes to the transit networks.

For example, the effects of adding a hypothetical route to serve TAZs in the city of Corvallis with low final performance scores were investigated in section 4.5. The results demonstrated improvements in the performance levels of those TAZs with low final performance scores. It might be intuitive that adding an additional route to a transit network will improve the level of service provided. However, it is important to be able to measure how much the level of service is improved. Since any improvement in a transit network comes at a cost, it is vital for a transit network planner to be able to measure the improvements in the level of service in order to assess whether it is worth to apply the necessary changes (e.g., adding a new route, increasing service frequency, etc.) in terms of operational and maintenance costs.

One of the main challenges in this research was the absence of a “ground truth” against which the obtained results could be compared. Most of the prior research found in the literature used TNPIs to establish a regression model with the TNPIs as the explanatory variables and the demand of a transit network as the response variable. However, the methodology developed in this research tries to take into account the effect of demand changes on the TNPIs of a transit network by considering the demand in the calculations of the TNPIs. Therefore, the obtained final performance score from the TNPIs reflects the effect of demand changes on the performance of the transit network.

Since there was no prior work in the literature that has tried to obtain a single final performance score for the TAZs served by a transit network, a comparative method (i.e., AHP) had to be selected for calculating the final performance scores of the TAZs. The problem with using AHP is prioritizing the criteria (i.e., topological, performance, and operational scores) based on user defined importance scores which brings subjectivity to the final results. Therefore, consulting experts in the area of public transit networks for the importance score assignment process is very important in order to increase the validity of the obtained results from the AHP.

In conclusion, the methodology developed in this research is a new way to look at the performance measurement problem of transit networks which should facilitate the decision making process for transit planners. However, due to the subjectivity of the AHP method and the absence of a "ground truth", caution must be exercised when interpreting the final performance scores.

6.2 OPPORTUNITIES FOR FUTURE WORK

There are several potential research opportunities that can extend the work performed in this study to measure the performance of a transit network:

- **Conduct a regression analysis to validate the newly developed TNPIs.** Due to the limited availability of demand data for the transit system of the city of Corvallis (i.e., CTS), a regression analysis could not be conducted on the modified connectivity and complexity indicators proposed in section 3.2.1.3. The regression analysis would use the annual demand per capita of the public transit service as the response variable, whereas the modified connectivity and complexity indicators would be used as the explanatory variable. Conducting such regression analysis can help in further validating the modified indicators and also in estimating the relationship between the modified indicators and the demand of the transit network. Another possible regression analysis that could be conducted is to consider the annual demand per capita for public transit service as the response variables, and the topological, performance, operational, and final performance scores as the response variables.

- **Incorporate transport disadvantaged population groups**. One of the original objectives of this research was to explore the demand for transit services by transport disadvantage population groups. Unfortunately, the required data to fulfill this objective could not be acquired. Nevertheless, the methodology developed in this research is flexible and can accommodate such an analysis if the necessary data for the demand of transport disadvantaged people become available.
- **Incorporate TNPIs that reflect the perspective of the customer**. All of the TNPIs that are currently considered by the proposed methodology only reflect the perspective of the transit agency (e.g., complexity, connectivity, etc.). However, data could be collected to

measure the *passenger average waiting time* for each route of the transit network to also capture the perspective of the customer. Considering customer-oriented operational indicators can improve the results that can be obtained with the proposed methodology.

- **Develop a software tool to implement proposed methodology**. Finally, the methodology developed in this research could be automated as a software tool to facilitate the pre-processing and analysis of the data and the generation of the choropleth maps. Such an automated software tool would be very helpful for transit agencies when making changes to their transit network and evaluating the effects of these changes iteratively.

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APPENDIX A

Table A.1: Inputs and the values of the topological TNPIs calculated for each of the 27 TAZs in the first case study

TAZ	N_R	N_{STOP}	V	E^S	E^M	E	V^T	V_c^t	CTD	γ^{CTD}	β^{CTD}	ρ	σ
2372	3	18	18.50	9.5	3.0	12.5	7	7	1	0.19	0.51	0.57	1.30
2375	2	6	6.00	3.0	2.0	5.0	4	4	1	0.25	0.5	0.50	0.05
2377	1	13	13.00	6.5	0.0	6.5	0	0	1	0.20	0.5	0.00	1.73
2380	3	14	14.33	9.0	0.5	9.5	5	5	1	0.24	0.63	0.90	0.40
2381	1	5	5.00	2.5	0.0	2.5	0	0	1	0.28	0.5	0.00	0.07
2382	2	19	18.83	9.5	0.0	9.5	0	0	1	0.19	0.5	0.00	0.63
2383	1	5	5.00	2.5	0.0	2.5	0	0	1	0.28	0.5	0.00	0.24
2384	2	6	6.00	3.5	0.0	3.5	1	1	1	0.29	0.58	1.00	0.14
2385	2	9	9.00	4.5	0.0	4.5	0	0	1	0.21	0.5	0.00	0.07
2387	1	5	4.83	3.0	0.0	3.0	0	0	1	0.35	0.62	0.00	0.68
2388	8	4	3.83	2.5	3.0	5.5	1	7	1	0.45	0.65	4.00	0.37
2389	4	22	21.50	12.5	2.5	15.0	8	8	1	0.21	0.58	0.69	1.33
2390	3	21	21.50	11.0	1.0	12.0	3	3	1	0.19	0.51	0.67	1.86
2391	3	8	7.83	4.0	0.0	4.0	0	0	1	0.23	0.51	0.00	0.84
2393	2	12	12.00	6.0	0.0	6.0	0	0	1	0.20	0.5	0.00	1.45
2394	3	15	14.50	8.0	0.0	8.0	1	1	1	0.21	0.55	1.00	1.18
2395	2	9	9.00	5.0	1.5	6.5	4	4	0.85	0.20	0.47	0.63	0.86
2396	5	10	10.00	6.5	4.0	10.5	4	11	0.83	0.22	0.54	1.75	1.63
2397	7	7	7.00	3.5	10.0	13.5	5	20	1	0.23	0.5	2.00	1.33
2398	7	3	2.83	2.0	6.5	8.5	3	14	1	0.80	0.71	2.50	0.85
2399	5	9	9.50	5.0	5.0	10.0	7	11	0.86	0.19	0.45	0.86	1.06
2401	2	8	8.50	4.5	3.0	7.5	7	7	1	0.23	0.53	0.57	0.43
2402	3	8	8.00	4.0	2.5	6.5	5	5	0.97	0.22	0.49	0.50	0.77
2407	2	20	19.50	10.0	0.0	10.0	0	0	0.99	0.19	0.51	0.00	0.14
2408	1	9	9.00	4.5	0.0	4.5	0	0	1	0.21	0.5	0.00	0.76
2410	1	8	8.00	4.0	0.0	4.0	0	0	1	0.22	0.5	0.00	0.61
2411	1	11	11.00	5.5	0.0	5.5	0	0	0.81	0.17	0.41	0.00	0.12

APPENDIX B

Table B.1: Importance matrix of the topological TNPIs, and their global weights

	γ^{CTD}	β^{CTD}	ρ	σ	**Geometric Mean**	**Global Weights**
γ^{CTD}	1	1	5	3	1.97	0.39
β^{CTD}	1	1	5	3	1.97	0.39
ρ	0.2	0.2	1	0.33	0.34	0.07
σ	0.33	0.33	3	1	0.76	0.15
Total	**2.53**	**2.53**	**14**	**7.33**	**5.03**	**1.00**

Table B.2: Local weights of the topological TNPIs and the topological score of each TAZ

TAZ	γ^{CTD}	β^{CTD}	ρ	σ	**Topological Score**
2372	0.036	0.028	0.034	0.062	3.67
2375	0.035	0.036	0.032	0.002	3.03
2377	0.035	0.029	0.008	0.083	3.80
2380	0.044	0.035	0.051	0.019	3.73
2381	0.035	0.040	0.008	0.003	3.04
2382	0.035	0.027	0.008	0.030	2.96
2383	0.035	0.040	0.008	0.011	3.16
2384	0.041	0.042	0.061	0.007	3.76
2385	0.035	0.031	0.008	0.003	2.68
2387	0.044	0.051	0.008	0.033	4.25
2388	0.046	0.066	0.131	0.018	5.52
2389	0.041	0.031	0.044	0.064	4.08
2390	0.036	0.027	0.043	0.089	4.12
2391	0.036	0.033	0.008	0.040	3.35
2393	0.035	0.029	0.008	0.069	3.61
2394	0.039	0.031	0.061	0.056	3.99
2395	0.033	0.029	0.042	0.041	3.35
2396	0.038	0.033	0.088	0.078	4.54
2397	0.035	0.034	0.094	0.064	4.31
2398	0.050	0.117	0.106	0.040	7.82
2399	0.032	0.028	0.054	0.051	3.46
2401	0.037	0.034	0.037	0.021	3.32
2402	0.034	0.031	0.035	0.037	3.34
2407	0.036	0.027	0.008	0.007	2.61
2408	0.035	0.031	0.008	0.036	3.18
2410	0.035	0.032	0.008	0.029	3.12
2411	0.028	0.024	0.008	0.006	2.18

APPENDIX C

Table C.1: Performance indicators, their z-scores, and the performance scores of the TAZs in the first case study

TAZ	*f*	*c*	*g*	z^f	z^c	z^g	Average of z-scores	Performance Score
2372	48.34	2.63	17.84	-0.29	0.40	1.41	0.51	4
2375	3.25	0.61	0.52	-0.64	-0.96	-1.27	-0.96	1
2377	27.58	0.94	21.22	-0.45	-0.74	1.94	0.25	4
2380	25.46	4.03	4.77	-0.46	1.34	-0.61	0.09	3
2381	2.73	0.35	0.84	-0.64	-1.14	-1.22	-1.00	1
2382	14.34	1.48	8.50	-0.55	-0.37	-0.04	-0.32	2
2383	10.59	0.48	3.03	-0.58	-1.05	-0.88	-0.84	1
2384	10.17	0.78	1.51	-0.58	-0.85	-1.12	-0.85	1
2385	3.12	1.88	0.87	-0.64	-0.11	-1.22	-0.66	2
2387	30.37	0.35	8.68	-0.43	-1.14	-0.01	-0.52	2
2388	208.79	3.21	4.44	0.95	0.78	-0.66	0.36	4
2389	53.14	3.40	15.46	-0.25	0.91	1.04	0.57	4
2390	59.08	3.30	23.21	-0.20	0.85	2.25	0.96	5
2391	95.08	5.29	8.34	0.07	2.19	-0.06	0.73	5
2393	82.78	2.75	15.40	-0.02	0.48	1.03	0.50	4
2394	71.34	1.79	12.52	-0.11	-0.17	0.59	0.10	4
2395	41.18	0.65	10.68	-0.34	-0.94	0.30	-0.33	2
2396	210.53	1.54	18.19	0.97	-0.33	1.47	0.70	5
2397	385.12	4.58	10.61	2.32	1.71	0.29	1.44	5
2398	570.11	3.45	6.73	3.75	0.95	-0.31	1.46	5
2399	157.46	4.64	10.31	0.56	1.75	0.25	0.85	5
2401	21.36	0.46	4.70	-0.50	-1.06	-0.62	-0.73	2
2402	87.14	1.34	7.64	0.01	-0.47	-0.17	-0.21	3
2407	2.73	0.43	1.96	-0.64	-1.08	-1.05	-0.92	1
2408	42.80	1.75	8.69	-0.33	-0.20	-0.01	-0.18	3
2410	39.10	1.88	7.33	-0.36	-0.11	-0.22	-0.23	3
2411	5.52	1.13	1.64	-0.62	-0.61	-1.10	-0.78	2

Table C.2: Percentiles obtained from the average z-scores in Table C.1

Percentile	0th	20th	40th	60th	80th	100th
Value	-1.00	-0.83	-0.33	0.10	0.67	1.46

APPENDIX D

Table D.1: Operational TNPIs calculated for each of the 27 TAZs in the first case study

TAZ	*OT*	*CTD*	*HC*	Operational Score
2372	0.90	2.67	0.54	3.55
2375	0.85	9.74	0.50	9.30
2377	0.51	1.00	0.50	1.68
2380	0.80	2.56	0.60	3.36
2381	0.51	3.60	0.50	3.82
2382	0.73	1.87	0.54	2.69
2383	0.94	2.25	0.54	3.26
2384	0.73	8.14	0.54	7.86
2385	0.94	3.98	0.54	4.68
2387	0.94	2.81	0.52	3.71
2388	0.85	9.06	0.60	8.79
2389	0.98	1.64	0.54	2.80
2390	0.90	1.56	0.54	2.64
2391	0.90	5.93	0.60	6.26
2393	0.88	2.13	0.60	3.11
2394	0.87	2.64	0.60	3.51
2395	0.73	1.13	0.54	2.08
2396	0.93	1.30	0.60	2.49
2397	0.84	1.74	0.60	2.74
2398	0.84	2.29	0.60	3.20
2399	0.96	1.73	0.58	2.87
2401	0.85	3.08	0.50	3.81
2402	0.90	1.52	0.50	2.58
2407	0.85	1.24	0.50	2.29
2408	0.93	1.31	0.58	2.49
2410	0.93	1.15	0.58	2.36
2411	0.93	0.81	0.58	2.08

APPENDIX E

Table E.1: Importance matrix of the operational TNPIs, and their global weights

	OT	***CTD***	***HC***	**Geometric Mean**	**Global Weights**
OT	1	0.33	5	1.18	0.28
CTD	3	1	7	2.76	0.65
HC	0.2	0.14	1	0.30	0.07
Total	4.2	1.47	13	4.24	1.00

Table E.2: Local weights of the operational TNPIs and the operational score of each TAZ

TAZ	***OT***	***CTD***	***HC***	**Operational Score**
2372	0.039	0.034	0.036	3.55
2375	0.037	0.123	0.033	9.30
2377	0.022	0.013	0.033	1.68
2380	0.035	0.032	0.040	3.36
2381	0.022	0.046	0.033	3.82
2382	0.032	0.024	0.036	2.69
2383	0.041	0.029	0.036	3.26
2384	0.032	0.103	0.036	7.86
2385	0.041	0.050	0.036	4.68
2387	0.041	0.036	0.035	3.71
2388	0.037	0.115	0.040	8.79
2389	0.043	0.021	0.036	2.80
2390	0.039	0.020	0.036	2.64
2391	0.039	0.075	0.040	6.26
2393	0.038	0.027	0.040	3.11
2394	0.038	0.033	0.040	3.51
2395	0.032	0.014	0.036	2.08
2396	0.041	0.016	0.040	2.49
2397	0.037	0.022	0.040	2.74
2398	0.037	0.029	0.040	3.20
2399	0.042	0.022	0.039	2.87
2401	0.037	0.039	0.033	3.81
2402	0.039	0.019	0.033	2.58
2407	0.037	0.016	0.033	2.29
2408	0.041	0.017	0.039	2.49
2410	0.041	0.015	0.039	2.36
2411	0.041	0.010	0.039	2.08

APPENDIX F

Table F.1: Summary of the topological, performance, operational, and final performance scores of the 27 TAZs in the first case study

TAZ	Topological Score	Performance Score	Operational Score	Final Score
2372	3.67	4	3.55	3.90
2375	3.03	1	9.30	3.30
2377	3.80	4	1.68	3.80
2380	3.73	3	3.36	3.68
2381	3.04	1	3.82	2.76
2382	2.96	2	2.69	2.83
2383	3.16	1	3.26	2.79
2384	3.76	1	7.86	3.67
2385	2.68	2	4.68	2.83
2387	4.25	2	3.71	3.83
2388	5.52	4	8.79	5.72
2389	4.08	4	2.80	4.11
2390	4.12	5	2.64	4.36
2391	3.35	5	6.26	4.19
2393	3.61	4	3.11	3.81
2394	3.99	4	3.51	4.12
2395	3.35	2	2.08	3.04
2396	4.54	5	2.49	4.64
2397	4.31	5	2.74	4.50
2398	7.82	5	3.20	7.02
2399	3.46	5	2.87	3.92
2401	3.32	2	3.81	3.19
2402	3.34	3	2.58	3.33
2407	2.61	1	2.29	2.30
2408	3.18	3	2.49	3.21
2410	3.12	3	2.36	3.15
2411	2.18	2	2.08	2.22

APPENDIX G

Table G.1: Inputs and the values of the topological TNPIs calculated for each of the 27 TAZs in the second case study

TAZ	N_R	N_{STOP}	V	E^S	E^M	E	V^T	V_c^t	CTD	γ^{CTD}	β^{CTD}	ρ	σ
2372	3	18	18.50	19	6	25	7	7	1	0.51	0.19	0.57	1.30
2375	2	6	6.00	6	4	10	4	4	1	0.58	0.29	0.90	0.05
2377	1	13	13.00	13	0	13	0	0	1	0.50	0.20	0.00	1.73
2380	3	14	14.33	18	1	19	5	5	1	0.63	0.24	0.90	0.40
2381	1	5	5.00	5	0	5	0	0	1	0.50	0.28	0.50	0.07
2382	2	19	18.83	19	0	19	0	0	1	0.50	0.19	0.50	0.63
2383	1	5	5.00	5	0	5	0	0	1	0.50	0.28	0.50	0.24
2384	2	6	6.00	7	0	7	1	1	1	0.58	0.29	1.00	0.14
2385	2	9	9.00	9	0	9	0	0	1	0.50	0.21	0.50	0.07
2387	1	5	4.83	6	0	6	0	0	1	0.62	0.35	0.00	0.68
2388	8	4	3.83	5	6	11	1	7	1	0.65	0.45	4.00	0.37
2389	4	22	21.50	25	5	30	8	8	1	0.58	0.21	0.69	1.33
2390	3	21	21.50	22	2	24	3	3	1	0.51	0.19	0.67	1.86
2391	3	8	7.83	8	0	8	0	0	1	0.51	0.23	0.00	0.84
2393	2	12	12.00	12	0	12	0	0	1	0.50	0.20	0.00	1.45
2394	3	15	14.50	16	0	16	1	1	1	0.55	0.21	1.00	1.18
2395	2	9	9.00	10	3	13	4	4	0.85	0.47	0.20	0.63	0.86
2396	5	10	10.00	13	8	21	4	11	0.83	0.54	0.22	1.75	1.63
2397	7	7	7.00	7	20	27	5	20	1	0.50	0.23	2.00	1.33
2398	7	3	2.83	4	13	17	3	14	1	0.71	0.80	2.50	0.85
2399	5	9	9.50	10	10	20	7	11	0.86	0.45	0.19	0.86	1.06
2401	2	8	8.50	9	6	15	7	7	1	0.53	0.23	0.57	0.43
2402	3	8	8.00	8	5	13	5	5	0.97	0.49	0.22	0.50	0.77
2407	2	20	19.50	20	0	20	0	0	0.99	0.51	0.19	0.50	0.14
2408	1	9	9.00	9	0	9	0	0	1	0.50	0.21	0.00	0.76
2410	1	8	8.00	8	0	8	0	0	1	0.50	0.22	0.00	0.61
2411	1	11	11.00	11	0	11	0	0	0.81	0.50	0.20	0.50	0.12

APPENDIX H

Table H.1: Importance matrix of the topological TNPIs, and their global weights

	γ^{CTD}	β^{CTD}	ρ	σ	Geometric Mean	Global Weights
γ^{CTD}	1	1	5	3	1.97	0.39
β^{CTD}	1	1	5	3	1.97	0.39
ρ	0.2	0.2	1	0.33	0.34	0.07
σ	0.33	0.33	3	1	0.76	0.15
Total	2.53	2.53	14	7.33	5.03	1.00

Table H.2: Local weights of the topological TNPIs and the topological score of each TAZ

TAZ	γ^{CTD}	β^{CTD}	ρ	σ	Topological Score
2372	0.036	0.028	0.028	0.066	3.65
2375	0.040	0.042	0.043	0.002	3.54
2377	0.035	0.028	0.006	0.087	3.83
2380	0.043	0.035	0.043	0.020	3.66
2381	0.035	0.040	0.025	0.003	3.13
2382	0.035	0.027	0.025	0.032	3.07
2383	0.035	0.040	0.025	0.012	3.26
2384	0.040	0.042	0.049	0.007	3.65
2385	0.035	0.031	0.025	0.003	2.77
2387	0.043	0.051	0.006	0.034	4.22
2388	0.045	0.065	0.145	0.019	5.58
2389	0.040	0.031	0.035	0.067	4.03
2390	0.035	0.027	0.034	0.094	4.09
2391	0.035	0.033	0.006	0.042	3.34
2393	0.035	0.029	0.006	0.073	3.63
2394	0.038	0.031	0.049	0.059	3.93
2395	0.033	0.029	0.032	0.043	3.29
2396	0.037	0.032	0.076	0.082	4.49
2397	0.035	0.034	0.084	0.067	4.26
2398	0.049	0.115	0.100	0.043	7.74
2399	0.031	0.027	0.041	0.053	3.39
2401	0.037	0.033	0.028	0.022	3.24
2402	0.034	0.031	0.025	0.039	3.28
2407	0.036	0.027	0.025	0.007	2.73
2408	0.035	0.031	0.006	0.038	3.17
2410	0.035	0.032	0.006	0.031	3.11
2411	0.035	0.029	0.025	0.006	2.75

APPENDIX I

Table I.1: Performance indicators, their z-scores, and the performance scores of the TAZs in the second case study

TAZ	*f*	*c*	*g*	z^f	z^c	z^g	Average of z-scores	Performance Score
2372	48.34	2.63	17.84	-0.30	0.32	1.41	0.48	4
2375	4.94	0.93	0.52	-0.63	-0.87	-1.27	-0.93	1
2377	27.58	0.94	21.22	-0.46	-0.86	1.94	0.21	4
2380	25.46	4.03	4.77	-0.47	1.31	-0.61	0.07	3
2381	5.46	0.70	0.84	-0.63	-1.03	-1.22	-0.96	1
2382	21.25	2.20	8.50	-0.51	0.02	-0.04	-0.17	3
2383	20.43	0.92	3.03	-0.51	-0.88	-0.88	-0.76	1
2384	10.17	0.78	1.51	-0.59	-0.97	-1.12	-0.89	1
2385	4.63	2.78	0.87	-0.64	0.43	-1.22	-0.48	2
2387	30.37	0.35	8.68	-0.44	-1.27	-0.01	-0.57	2
2388	208.79	3.21	4.44	0.95	0.73	-0.66	0.34	4
2389	53.14	3.40	15.46	-0.26	0.86	1.04	0.55	4
2390	59.08	3.30	23.21	-0.21	0.80	2.25	0.94	5
2391	95.08	5.29	8.34	0.07	2.19	-0.06	0.73	5
2393	82.78	2.75	15.40	-0.03	0.41	1.03	0.47	4
2394	71.34	1.79	12.52	-0.12	-0.27	0.59	0.07	3
2395	41.18	0.65	10.68	-0.35	-1.07	0.30	-0.37	2
2396	210.53	1.54	18.19	0.96	-0.44	1.47	0.66	5
2397	385.12	4.58	10.61	2.32	1.69	0.29	1.43	5
2398	570.11	3.45	6.73	3.76	0.90	-0.31	1.45	5
2399	157.46	4.64	10.31	0.55	1.73	0.25	0.84	5
2401	21.36	0.46	4.70	-0.51	-1.20	-0.62	-0.78	1
2402	87.14	1.34	7.64	0.00	-0.58	-0.17	-0.25	3
2407	4.15	0.65	1.96	-0.64	-1.06	-1.05	-0.92	1
2408	42.80	1.75	8.69	-0.34	-0.29	-0.01	-0.21	3
2410	39.10	1.88	7.33	-0.37	-0.20	-0.22	-0.26	2
2411	7.76	1.58	1.64	-0.61	-0.41	-1.10	-0.71	2

Table I.2: Percentiles obtained from the average z-scores in Table I.1

Percentile	0th	20th	40th	60th	80th	100th
Value	-0.960	-0.750	-0.256	0.154	0.638	1.450

APPENDIX J

Table J.1: Operational TNPIs calculated for each of the 27 TAZs in the second case study

TAZ	*OT*	*CTD*	*HC*	Operational Score
2372	0.90	2.67	0.54	3.01
2375	0.82	12.89	0.50	9.22
2377	0.51	1.00	0.50	1.48
2380	0.80	2.56	0.60	2.85
2381	0.64	7.20	0.50	5.48
2382	0.74	4.87	0.54	4.18
2383	0.86	4.33	0.54	3.99
2384	0.73	8.14	0.54	6.20
2385	0.74	11.40	0.54	8.22
2387	0.94	2.81	0.52	3.14
2388	0.85	9.06	0.60	6.94
2389	0.98	1.64	0.54	2.48
2390	0.90	1.56	0.54	2.33
2391	0.90	5.93	0.60	5.06
2393	0.88	2.13	0.60	2.69
2394	0.87	2.64	0.60	2.98
2395	0.73	1.13	0.54	1.86
2396	0.93	1.30	0.60	2.23
2397	0.84	1.74	0.60	2.40
2398	0.84	2.29	0.60	2.74
2399	0.96	1.73	0.58	2.52
2401	0.85	3.08	0.50	3.19
2402	0.90	1.52	0.50	2.28
2407	0.85	7.77	0.50	6.09
2408	0.93	1.31	0.58	2.23
2410	0.93	1.15	0.58	2.13
2411	0.89	1.14	0.58	2.07

APPENDIX K

Table K.1: Importance matrix of the operational TNPIs, and their global weights

	OT	***CTD***	***HC***	**Geometric Mean**	**Global Weights**
OT	1	0.33	5	1.18	0.28
CTD	3	1	7	2.76	0.65
HC	0.2	0.14	1	0.30	0.07
Total	4.2	1.47	13	4.24	1.00

Table K.2: Local weights of the operational TNPIs and the operational score of each TAZ

TAZ	***OT***	***CTD***	***HC***	**Operational Score**
2372	0.040	0.025	0.036	3.01
2375	0.036	0.123	0.033	9.22
2377	0.022	0.010	0.033	1.48
2380	0.035	0.024	0.040	2.85
2381	0.028	0.069	0.033	5.48
2382	0.033	0.046	0.036	4.18
2383	0.038	0.041	0.036	3.99
2384	0.032	0.078	0.036	6.20
2385	0.033	0.109	0.036	8.22
2387	0.042	0.027	0.035	3.14
2388	0.038	0.086	0.040	6.94
2389	0.043	0.016	0.036	2.48
2390	0.040	0.015	0.036	2.33
2391	0.039	0.056	0.040	5.06
2393	0.039	0.020	0.040	2.69
2394	0.038	0.025	0.040	2.98
2395	0.032	0.011	0.036	1.86
2396	0.041	0.012	0.040	2.23
2397	0.037	0.017	0.040	2.40
2398	0.037	0.022	0.040	2.74
2399	0.042	0.016	0.039	2.52
2401	0.037	0.029	0.033	3.19
2402	0.039	0.014	0.033	2.28
2407	0.037	0.074	0.033	6.09
2408	0.041	0.012	0.039	2.23
2410	0.041	0.011	0.039	2.13
2411	0.039	0.011	0.039	2.07

APPENDIX L

Table L.1: Summary of the topological, performance, operational, and final performance scores of the 27 TAZs in the second case study

TAZ	Topological Score	Performance Score	Operational Score	Final Score
2372	3.65	4	3.01	3.83
2375	3.54	1	9.22	3.62
2377	3.83	4	1.48	3.79
2380	3.66	3	2.85	3.56
2381	3.13	1	5.48	2.97
2382	3.07	3	4.18	3.29
2383	3.26	1	3.99	2.91
2384	3.65	1	6.20	3.40
2385	2.77	2	8.22	3.24
2387	4.22	2	3.14	3.74
2388	5.58	4	6.94	5.56
2389	4.03	4	2.48	4.03
2390	4.09	5	2.33	4.31
2391	3.34	5	5.06	4.06
2393	3.63	4	2.69	3.77
2394	3.93	3	2.98	3.77
2395	3.29	2	1.86	2.96
2396	4.49	5	2.23	4.58
2397	4.26	5	2.40	4.43
2398	7.74	5	2.74	6.88
2399	3.39	5	2.52	3.84
2401	3.24	1	3.19	2.82
2402	3.28	3	2.28	3.24
2407	2.73	1	6.09	2.75
2408	3.17	3	2.23	3.17
2410	3.11	2	2.13	2.86
2411	2.75	2	2.07	2.61