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Performance Evaluation of Bangalore Metropolitan Transport Corporation: An Application of Data Envelopment Analysis

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Abstract

Maintaining and enhancing public transit services in Indian cities is important to meet rapidly-growing mass mobility needs. Indian cities rely predominantly on buses for public transportation, and issues of performance measurement and efficiency analyses for bus companies have been gaining significance due to severe operational stress and financial constraints in which these bus companies provide service to people. In public transportation, multiple parameters are involved that influence the efficiency of operation. This study measures the performance of premium bus services operated by Bangalore Metropolitan Transport Corporation (BMTC) using data envelopment analysis. This approach enabled the identification of opportunities for improvement at the bus depot and route levels. The analysis indicates that most depots are efficient, but some routes have significant opportunities for improvement.

Keywords: Public transportation, Data Envelopment Analysis, efficiency analysis, transit

Introduction

From 1950–2010, the urban population in India grew from around 63 million to around 380 million and is expected to grow to around 600 million by 2030 (UN 2012). According to the 2011 census conducted by the Government of India, 53 Indian cities have 1+ million residents and 500 cities have 100,000+ residents. These urban centers face significant challenges in moving people around because of inadequate infrastructure, increasing private vehicle ownership and resulting congestion, and inefficient public transportation systems. Public transportation is increasingly seen as the sustainable solution for urban mobility. Large investments are being made in public transportation projects in India. In this background, it is significantly important for public transportation to operate efficiently to derive returns from the large investments.

The use of standard cost and operational ratios for studying the performance of public transportation entities, although useful, does not provide a holistic view of operations. Data Envelopment Analysis (DEA) is being used under such circumstances with great success. In this paper, the performance of sub-units of Bangalore Metropolitan Transport Corporation (BMTC) using DEA was studied to identify opportunities for improvement. BMTC is a public transport organization operating in Bangalore, India. The population of Bangalore has been growing steadily; the city's population of 160,000 in 1901 has reached nearly 8.4 million in 2011 (CTTP 2007). BMTC came into existence in 1997 after bifurcation from its predecessor, Karnataka State Road Transport Corporation (KSRTC), with the sole aim of providing public transportation service in the urban and suburban areas of Bangalore City. The mission of the organization is to provide safe, reliable, clean, and affordable travel to every Bangalore resident. The salient features of BMTC are summarized in Table 1.

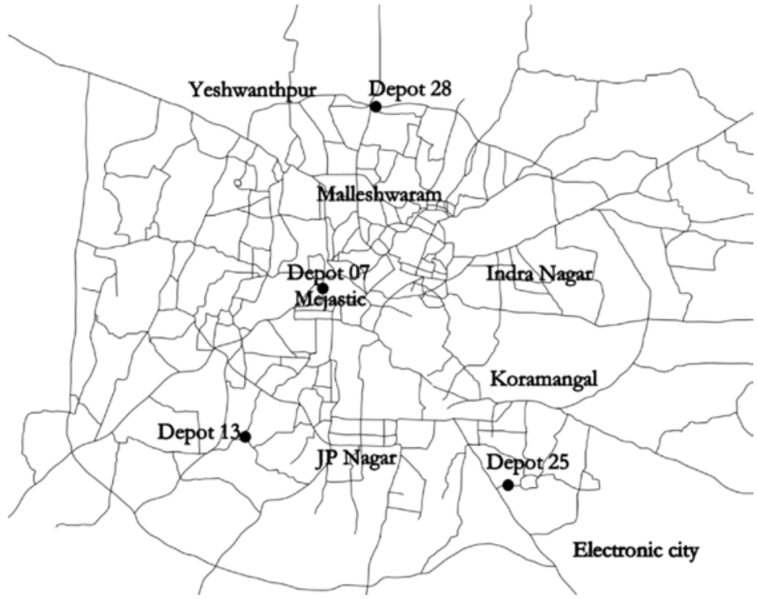
TABLE 1.
BMTC at a Glance

Number of vehicles	6,518
Number of schedules	6,232
Daily schedule (million kms)	1.3
Daily traffic revenue (rupees in million)	37.1
Number of trips	76,593
Depots	40
Staff employed	36,464
Bus staff ratio (number of staff per bus)	5.6

Source: http://www.mybmtc.com/bmtc_glance

BMTC introduced different services to cater to segments of public transportation users of Bangalore. Although some consumers are very price-sensitive, others are willing to pay a premium for comforts such as air conditioning, low-floor convenience, and mobile/laptop charging facilities. Hence, BMTC introduced premium services using the latest chassis built by TATA Marcopolo and Volvo bus companies. These premium services began operation in February 2006 and provide service to different residential and information technology (IT) hubs in the city, and the separately-branded Vayu Vajra Premium services provide seamless connectivity between various parts of the city and the Bangalore International Airport. A total of 665 Volvo and Marcopolo air-conditioned buses are operated within the city and to the airport, constituting about 10% of the total number of buses in the BMTC stock, and operate from 4 four depots (see Figure 1), providing 3,700 trips and carrying 100,000+ passengers every day.

FIGURE 1.
Depots for BMTC premium services



The main objective of this paper is to analyze the operations of the 4 premium service depots, 7 major premium service routes within the city, and 11 routes to the airport. The analysis is confined to premium services operated by Volvo buses only.

The existing literature points to ratio analysis and non-parametric techniques as the means to evaluate the performance of public transport systems. According to Nissam and Penman (2001), ratio analysis compares ratios for individual firms against comparable firms in the past and the present to get a sense of what is normal and what is abnormal. Alter (1976) used the perspective of the consumer to select six items for a composite index that included basic accessibility, travel time, reliability, directness of service, frequency of service, and passenger density for evaluation of mass transport service quality using levels of service. Feng and Wang (2001) used financial ratios for the performance evaluation of buses, with number of employees, number of maintenance employees, number of drivers, number of vehicles, fuel current assets, fixed assets, total assets, stock capital and stockholder equity as inputs and frequencies, vehicle-km, current liabilities, long-term liabilities, total liabilities, operation cost, and interest expense as product outputs. This approach typically considers one performance indicator at a time in evaluating an organization's performance and setting up benchmarks in a peer group.

The non-parametric approach provides the capability for a holistic perspective of an organization's performance. DEA is a very powerful non-parametric approach to study the relative performance of comparable organizations, referred to as decision making units (DMUs). Several studies have been carried out to analyze the efficiency of urban transport services using DEA (Levaggi 1994; Nolan 1996; Viton, 1998); Ramanathan 1999; Odeck 2000; Pina and Torres 2001; Karlaftis 2004; Agrawal et al. 2006; Odeck 2006; Sumar 2011). The major advantage of DEA is its capability to handle multiple inputs and outputs, implicit specification of the production function, and the ability to identify the source of inefficiency. The DEA method was adopted in this study aimed at evaluating the performance of BMTC.

Methodology

A complex system such as a metropolitan transportation company has many dimensions to its operations, including financial performance, network connectivity, bus stock efficiency, etc. The DEA method assists in studying these different dimensions in a holistic fashion. DEA is a non-parametric method of efficiency measurement that provides a means of calculating apparent efficiency levels within a group of DMUs. The efficiency of a DMU is calculated relative to the group's observed best practice.

The DEA model consists of solving a mathematical optimization problem for each of the DMUs with the objective of maximizing the efficiency level of the unit being studied. Thus, if we consider n homogeneous units (j=1,2,…n) with each of the units using the same set of m inputs ($x_1, x_2, \ldots x_m$) to obtain the same set of s output ($y_1, y_2, \ldots y_s$), the efficiency of DMU o is calculated by solving the following linear programming problem (Charnes et al. 1978):

$$LP_0 = Max\,\theta = \sum_{r=1}^{s} \mu_r y_{ro}$$

$$\text{Subjected to } \sum_{r=1}^{s} \mu_r y_{rj} \leq \sum_{i=1}^{m} v_i x_{ij} \qquad (1)$$

$$\sum_{i=1}^{m} v_i x_{io} = 1$$

$$\mu_1, \mu_2 \cdots \mu_s \geq 0; \qquad v_1, v_2 \cdots v_m \geq 0$$

The efficiency of the DMU is calculated by maximizing the objective function (weighted sum of outputs), subjected to the constraints that weighted sum of inputs of DMU o is standardized to 1, and the efficiency of all the DMUs should be less than or equal to 1. In the above model (LPo), the output weights are $\mu_1, \mu_2, \ldots \mu_s$, and input weights are $v_1, v_2, \ldots v_m$. The above model (LPo) in primal form does not give any information about the inefficient DMU. Hence, the following dual variant of the model with the slack and surplus variables in the constraints is typically used:

$$(DLP_0)\, Min\; h_0 = \theta_0 - \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+$$

$$\text{Subjected to } s_i^- = \theta_0 x_{i0} - \sum_{j=1}^{n} \lambda_j x_{ij} \quad , i = 1,2,\ldots m \qquad (2)$$

$$s_r^+ = \sum_{j=1}^{n} \lambda_j y_{rj} - y_{r0}, \qquad r = 1,2,\ldots s$$

$$s_r^+, s_i^i, \lambda_j \geq 0, \quad j = 1,2,\ldots n$$

In the optimal solution of model (DLP_0)

1. *If* $h_0 = 1$ *and* $s_r^+ = s_i^i = 0$, *the DMU is called DEA efficient.*
2. *If* $h_0 < 1$ *and* $s_r^+ \neq 0, s_i^i \neq 0$, *the DMU is called DEA inefficient.*

Where,

$\overset{+}{S_r}$ = represents the vector of non-negative slack associated with the output inequalities

$\overset{-}{S_i}$ = represents the vector of non-negative slack associated with the input inequalities

Analysis and Discussion

Data

The study was based on data provided by the Volvo Division Statistical Department of BMTC. The performance of the 4 depots that operate premium services, 7 premium services routes in the city, and 11 premium service routes to the airport were analyzed. The following depots that operate premium services were analyzed to evaluate their performance with the objective of identifying ways to improve their operations:

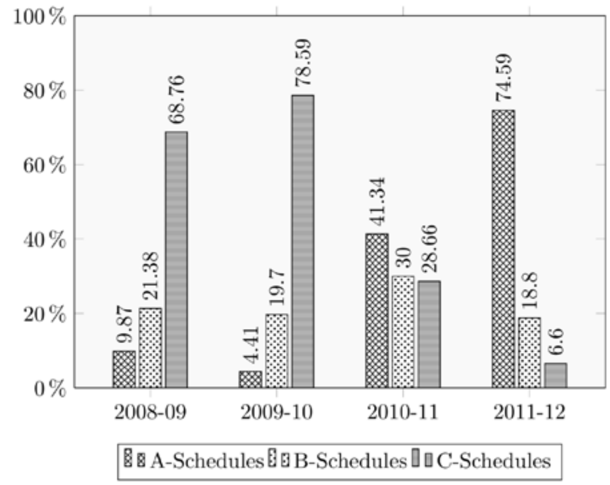
- Subashnagar (Depot-07)
- Katriguppa (Depot-13)
- HSR Layout (Depot-25)
- Hebbal (Depot-28)

BMTC classifies the premium service routes operated by these depots into three schedules:

- A-Schedules – revenues cover both variable cost and fixed cost of operation
- B-Schedules – revenues cover only the variable cost of operation
- C-Schedules – revenues are loss-making schedules whose revenues do not cover the variable cost of operation

This classification of the routes from the FY 2008/09 to FY 2011/2 is shown in Figure 2. The loss-making schedules (C-Schedules) decreased from 69% in 2008/09 to 7% in 2011/12. The profit-making schedules (A-Schedules) increased from 10% to 75% in those same years, primarily because of route rationalization. Premium bus services began in 2006 with very few buses. As demand increased, new buses were procured, and the fleet size increased from 162 in 2009/10 to 464 in 2011/12, resulting in introduction of new routes with increased frequencies. Simultaneously, the ridership for these services also increased. In addition, Bangalore, being an IT hub, has a large demand for employee transportation, which was being serviced by cabs. Introduction of premium service buses caused a switch from cabs to buses. Factors such as these increased the revenue from these premium services from 26.6 rupees per kilometer in 2009/09 to 46.6 rupees per kilometer in 2011/12.

FIGURE 2.
Variations in premium schedules 2008–2012



Some of the commonly-used input and output variables in the DEA analysis of urban transit systems identified from the literature review are summarized in Table 2.This includes some variables recommended by the Central Institute of Road Transport (CIRT) of India for monitoring the performance of transport corporations (CIRT 2009). CIRT studies the principles and practices of organizations and management in various spheres of public transportation in India, conducts research on critical issues in transport development, and provides training and education to managers and professionals engaged in public transport. It also helps the government and its agencies in evolving integrated policies and legislative frameworks to enable a balanced growth of the transport sector. Based on the list of variables from the literature and data availability from BMTC, the following variables were used for analysis.

TABLE 2.
Commonly-Used Input and Output Measures in DEA of Urban Transit Systems

Input Measures	Output Measures
Number of employees	Distance traveled
Fuel consumption	Vehicle kilometers
Fleet size	Passenger count
Average speed	Passenger kilometers
Fleet average age	Fleet size per unit distance per employee
Cost per unit distance	Accident rate
Driving hours	Revenue per passenger per unit distance
Effective kilometers traveled	Revenue per day
Number of schedules	Revenue
	Fleet utilization
	Breakdown rate
	Fuel efficiency (kilometers per liter)
	Staff productivity
	Profitability
	Vehicle utilization

Input variables included:

- Fleet size as a measure of capital input
- Number of employees as a measure of labor input
- Fuel consumed as a measure of energy input
- Number of schedules and effective kilometres as a measure of network size

Output variables included:

- Total revenue generated and profitability – the ratio of EPKM (earnings per kilometer) and cost per kilometer (CPKM) as a measure of financial performance
- Vehicle utilization, fleet utilization, staff productivity, breakdown rate, and fuel efficiency (in terms of kilometer per liter) as measures of operational effectiveness
- Accident rate as a measure of operational safety

Short Run and Long Run Effect

A metropolitan bus transport company has both fixed and variable inputs. Fixed inputs are those that cannot be changed on short notice, such as a change in the fleet size, which will involve a fixed set of administrative procedures either to procure a new vehicle or scrap an existing vehicle and, hence, typically would involve a significant amount of time. A variable such as the number of schedules is an operational decision that can be modified relatively easily. Hence, the variables were divided, and the performance of BMTC was analyzed as long-run and short-run performance based on the variables considered.

Long Run Performance Analysis

Fleet size and number of employees typically are fixed in the short run and are long-run input variables. Fuel consumed, number of schedules, and total effective kilometers traveled are inputs that can be modified regularly and are short-run input variables. The output variables that are strongly influenced by these input variables are long-run output variables. Although some long-run variables might be influenced by short-run variables and decisions, it was assumed that these short-term variables/decisions are taken optimally by the organization in performing this long-run analysis. For example, the total revenue generated by the transport company is a function of the vehicles it operates, so it is a long-run output measure. Revenue generation also is influenced by fleet scheduling, a short-run input variable. Since fleet schedules are derived for a specific fleet, we assume that the short-run fleet schedules are optimally taken while performing the long-run analysis. Further, fleet utilization, defined as the ratio of total number of vehicles on road to the total number of vehicles held by the company, is influenced by the long-run input variable of fleet size and is considered to be a long-run output measure. Similarly, the staff productivity measure, defined as the ratio of the total number of kilometers operated by all the vehicles assigned to the depot to the total number of staff assigned to the depot, is defined in terms of both long-run input measures and is taken to be a long-run output measure.

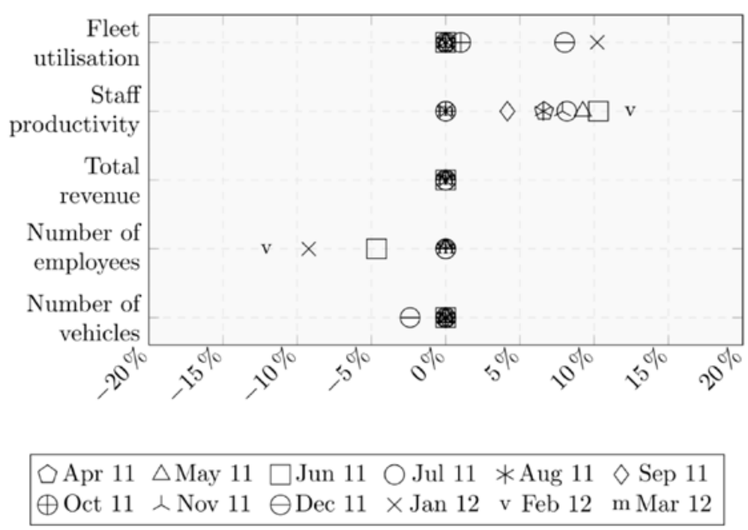
The DEA long-run analysis was performed on monthly data for FY 2011/12 using the above long-run input and output variables. The technical efficiency results are shown in Table 3.

TABLE 3.
Efficiency Scores of BMTC Premium Service Depots Using Long-Run Variables

Month	Depot-07	Depot-13 (Dual Programming)		Depot- 25	Depot-28
			Peer Group		
April 2011	1.000	0.926	07,25,28	1.000	1.000
May 2011	1.000	0.868	07,25,28	1.000	1.000
June 2011	1.000	0.891	25,28	1.000	1.000
July 2011	1.000	0.882	25,28	1.000	1.000
August 2011	1.000	0.893	07,25,28	1.000	1.000
September 2011	1.000	0.856	07,25,28	1.000	1.000
October 2011	1.000	0.892	07,25,28	1.000	1.000
November 2011	1.000	0.906	07,25,28	1.000	1.000
December 2011	1.000	0.978	25,28	1.000	1.000
January 2012	1.000	0.934	07,28	1.000	1.000
February 2012	1.000	0.978	07,28	1.000	1.000
March 2012	1.000	1.000	N/A	1.000	1.000

It can be observed from the results that the efficiency scores from the long-run DEA model for Depots 07, 25, and 28 are 100%, and Depot 13 has an average efficiency of about 91.7%. The results show that the Depots 07, 25, and 28 are consistent performers throughout the year. The average performance of all the depots is above 97% throughout the year. Depot 13 is the inefficient depot; hence, the input and output slack values were calculated using the dual linear programming (*DLPo*) model. The peer group for the inefficient DMU is also noted in Table 3. The potential for reduction in input or increase in output for Depot 13, expressed as the percentage decrease or increase from current levels, is shown in Figure 3, which shows that Depot 13 has significant potential for increases in staff productivity, fleet utilization, and reduction in number of employees.

FIGURE 3.
Slack and surplus values for Depot 13



As shown in Figure 1, Depot 07 is located in the central part of the city and is the major hub through which people transfer. Depot 25 is located in a prime residential area located close to one of the major IT hubs in Bangalore. Depot 28 is in a densely-populated area along the route to the airport and is the fastest-growing area in Bangalore. These factors could contribute to the superior performance of these depots. However, Depot 13 shows potential for improvement by reducing the number of employees or increasing staff productivity and fleet utilization. This depot is located in an area far from the IT companies and commercial settlements and mainly operates short routes, which could be a factor contributing to its lower fleet utilization and staff productivity.

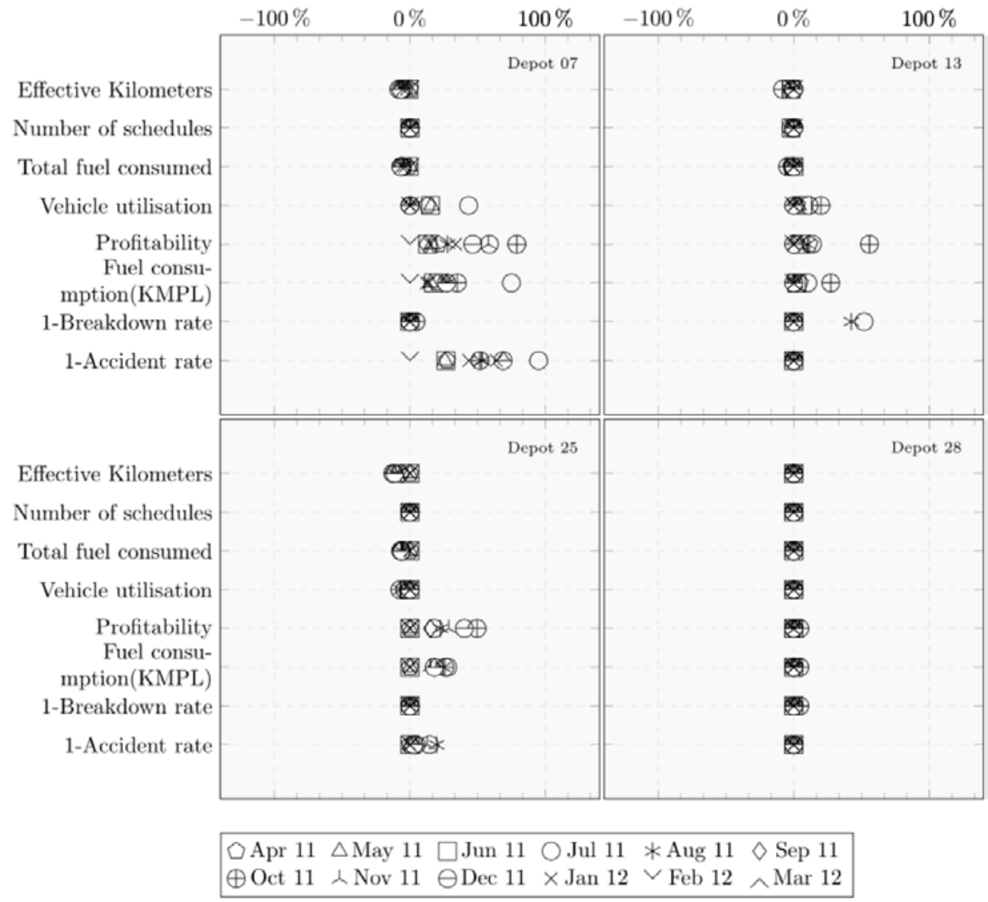
Short Run Performance Analysis

The performance of BMTC using the short-run variables was studied. The number of schedules, effective kilometers (kilometers run in a day, net of dead kilometers), and fuel consumption are the short-run input variables. The output variables affected by these inputs—namely, breakdown rate (number of vehicle breakdowns per 10,000 vehicle kilometers), accident rate (number of vehicle accidents per 100,000 vehicle kilometers), fuel efficiency (kilometers traveled per liter of fuel consumed), vehicle utilization (average daily kilometers operated per vehicle per day), and profitability (ratio of earnings per kilometer to cost per kilometer)—are the short-run output measures. The results from the DEA analysis using the short-run variables on the monthly data for the FY 2011/12 are shown in Table 4. The potential improvement for the inefficient DMUs, expressed in terms of percentage decrease or increase from the current levels, is shown in Figure 4, which shows that there is potential for improvement in breakdown rate, fuel efficiency, profitability, vehicle utilization, and effective kilometers.

TABLE 4.
Efficiency Scores of BMTC Premium Service Depots Using Short-Run Variables

Month	Depot-07	Depot- 13	Depot- 25	Depot- 28
April 2011	0.706	0.704	1.000	1.000
May 2011	0.749	0.696	1.000	1.000
June 2011	0.738	0.699	1.000	1.000
July 2011	0.787	0.739	0.898	1.000
August 2011	0.572	0.676	0.907	1.000
September 2011	0.716	1.000	0.915	1.000
October 2011	0.593	0.858	0.906	1.000
November 2011	0.717	1.000	0.999	1.000
December 2011	0.712	1.000	0.897	1.000
January 2012	0.710	1.000	1.000	1.000
February 2012	0.650	1.000	1.000	1.000
March 2012	1.000	1.000	1.000	1.000

FIGURE 4.
Slack and surplus values for inefficient depots using short-term variables



The results show that the average efficiency of the Depots 07, 13, 25, and 28 are 0.721, 0.864, 0.960 and 1.000, respectively. There is potential for increased profitability, kilometers per liter, vehicle utilization, and breakdown rate. Depots 07, 13, and 25 are located in heavily-congested areas, resulting in much vehicle idling and waiting time. This could explain poor kilometers per liter and utilization of vehicles in these depots. Further, the increased breakdown rates in Depot 07 could be a vestige of historical vehicle assignments to the depots; the initial lot of vehicles was assigned to operate out of Depot 07, and the typical age of buses in Depot 07 is much higher than those in the other depots.

Sample Size Issues

The efficiency scores computed for each DMU using DEA are sensitive to sampling variations, particularly when small samples are used. It has been reported that DEA analysis typically has an upward bias in efficiency due to dimensionality issues when the sample size is limited compared to the number of inputs and output variables (see Perelman and Santin 2009; Simar 2007; Coelli et al. 2005; Staat 2001; Smith 1997; Banker 1993).

The DEA bootstrap, or smoothed bootstrap, is a combination of the original bootstrap method (Efron 1979) modified with a smoothing parameter (Silverman 1986) and DEA (Charnes et al. 1978) designed to overcome the upward bias in efficiency estimation. Simar and Wilson (1998) managed to estimate bias in the DEA efficiency scores that is due to sampling variations by applying a smoothed bootstrap for generating randomly-sampled efficiency scores that were then used for estimating bootstrapped inputs (input-oriented approach) or outputs (output-oriented approach). Subsequently, the bootstrapped inputs or outputs were introduced to the DEA linear programming models for bias-corrected efficiency scores.

There is a strong suspicion of this upward bias since the number of DMUs in this study is only four. Hence, we sought to estimate the quantity of this upward bias by applying the bootstrap technique. Specifically, we adopted the SW algorithm proposed by Simar and Wilson (1998), in which the bootstrap frontier and the bootstrap efficiency estimates were re-sampled based on a re-sampling of technical efficiencies from the empirical distribution of the original estimates of efficiency. Furthermore, the bootstrap, a replicate of efficiency, is based on the re-sampled data in the same manner as the original estimates were based on the original data.

The efficiency results from the original model and the bootstrapped approach are shown in Table 5. It is observed that the bootstrapping efficiencies are comparatively less that the original DEA efficiency. This confirms the presence of upward bias due to the small sample size. The average bootstrapping efficiencies of Depots 07, 13, 25, and 28 are 0.587, 0.759, 0.853, and 0.999, respectively, compared to the original efficiencies of 0.725, 0.865, 0.960, and 1.000.

TABLE 5.
Results of Bootstrapping DEA for BMTC Premium Service Depots Using Short-Run Variables

Month	Depot-07		Depot-13		Depot-25		Depot-28	
	B	*O*	*B*	*O*	*B*	*O*	*B*	*O*
April 2011	0.572	0.746	0.657	0.704	0.828	1.000	1.000	1.000
May 2011	0.571	0.749	0.668	0.696	0.855	1.000	1.000	1.000
June 2011	0.571	0.740	0.671	0.703	0.862	1.000	1.000	1.000
July 2011	0.568	0.791	0.666	0.740	0.857	0.902	0.993	1.000
August 2011	0.568	0.569	0.653	0.681	0.893	0.902	1.000	1.000
September 2011	0.586	0.717	0.833	1.000	0.856	0.918	1.000	1.000
October 2011	0.562	0.591	0.824	0.858	0.885	0.906	1.000	1.000
November 2011	0.569	0.717	0.858	1.000	0.826	0.995	1.000	1.000
December 2011	0.559	0.714	0.817	1.000	0.831	0.901	1.000	1.000
January 2012	0.567	0.711	0.814	1.000	0.844	1.000	1.000	1.000
February 2012	0.536	0.650	0.845	1.000	0.862	1.000	1.000	1.000
March 2012	0.809	1.000	0.801	1.000	0.834	1.000	0.991	1.000
Average	0.587	0.725	0.759	0.865	0.853	0.960	0.999	1.000

B = bootstrap, O = original

Analysis of Premium Service Routes

The performance of 7 city premium service routes and 11 premium service routes to the airport was studied. The data availability at the service route level was rather restricted. We considered the fleet size and total effective kilometers traveled by all buses as input variables and total revenue generated as the output variable. The analysis was confined to FY 2011/12 from April 2011 to March 2012. Figure 5 shows the premium service routes, and Figure 6 shows the premium service routes to the airport.

FIGURE 5.
Premium service city routes

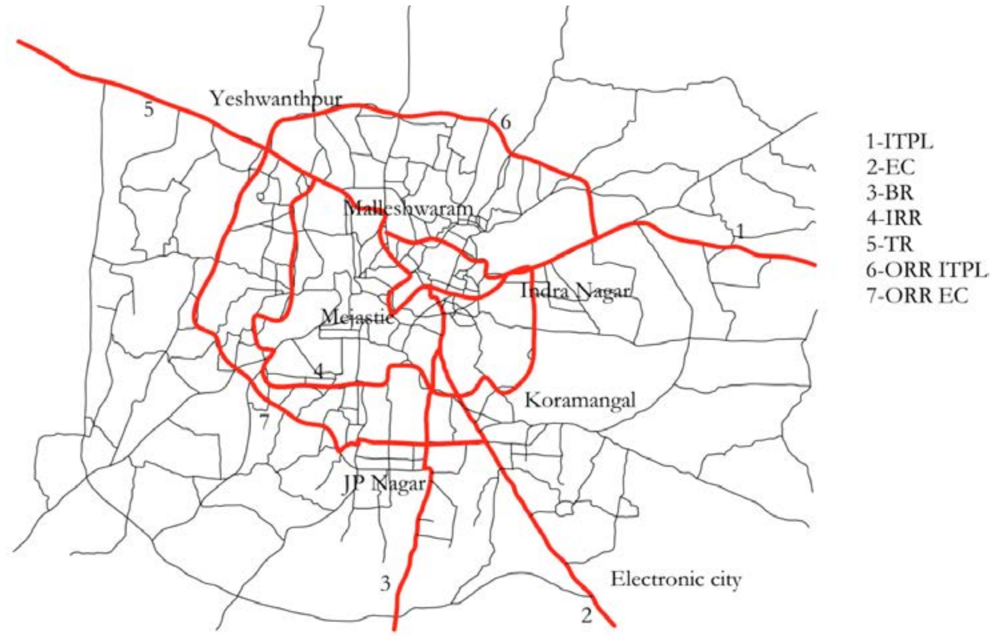
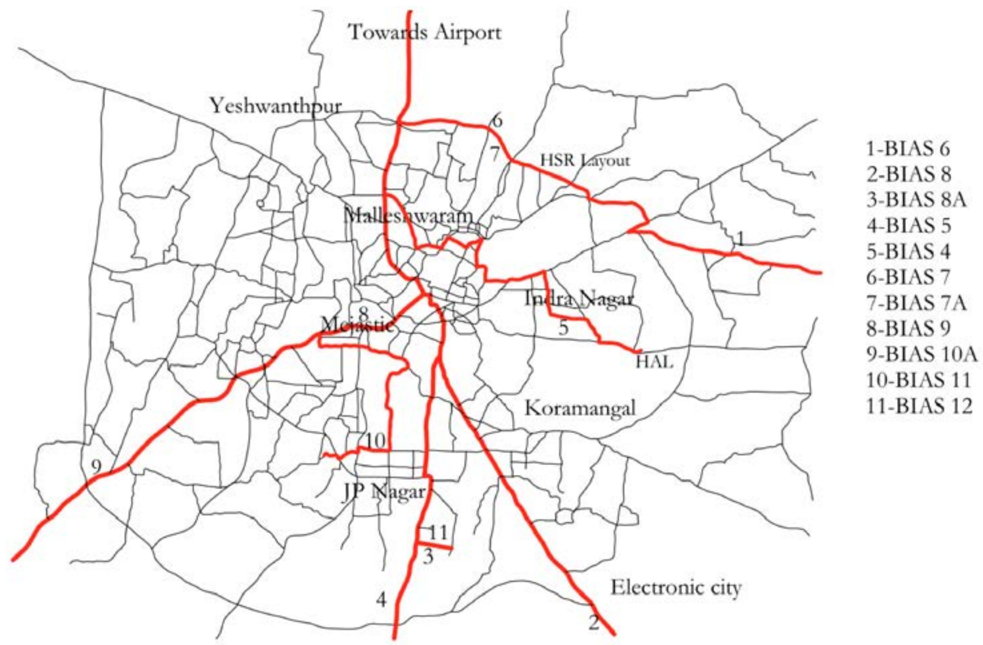


FIGURE 6.
Premium service airport routes



The results of the DEA analysis on these routes are shown Figures 7 and 8. It can be observed from the results shown in Figure 7 that the premium service city routes clusters into two groups; (1) ITPL, EC, BR, IRR, and ORRITPL, which have very high technical efficiencies, in the range of about 95%, and (2) TR and ORREC, which have relatively low technical efficiencies, in the mid-80% range. This could be for the following reasons:

- The Tumkur road corridor is a major small scale industry corridor in Bangalore, and the surrounding residential areas are not economically affluent to demand premium service.

- The areas surrounding the Outer Ring Road–EC are semi-urban in nature in comparison with the Outer Ring Road–ITPL corridor. This might be the reason for the underperformance of the Outer Ring Road–EC route.

FIGURE 7.
Efficiency score of 7 BMTC premium services operated in city routes

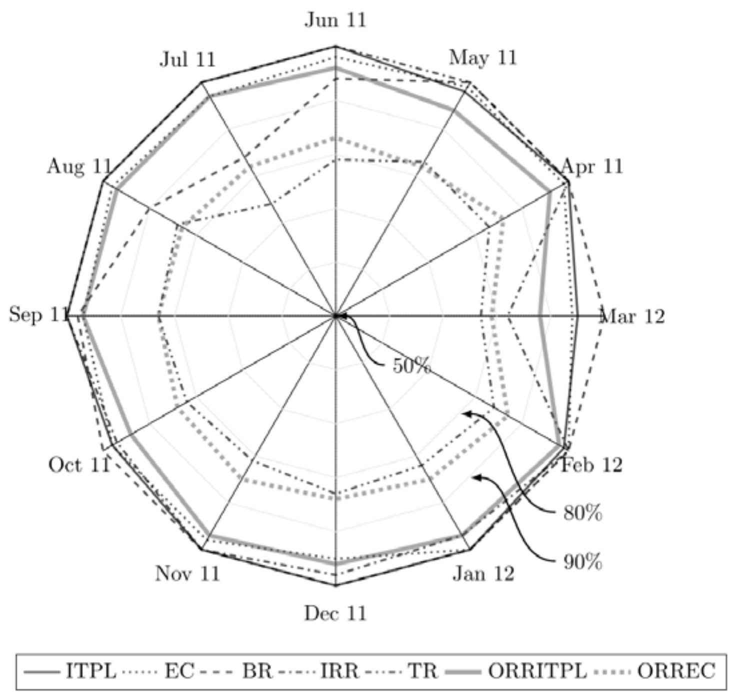
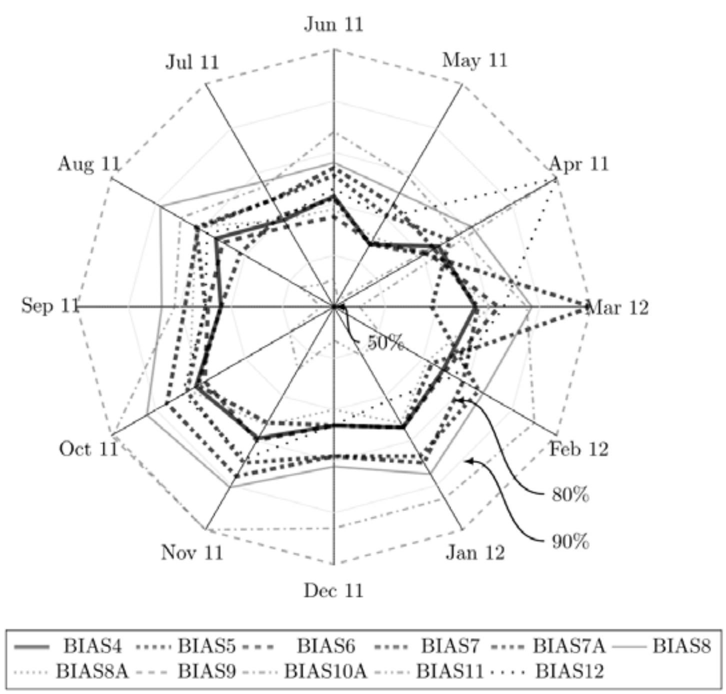


FIGURE 8.
Efficiency score of 11 BMTC premium services operated to airport



The relative performance of these routes also can be viewed from the position of the DMUs in the output standardized input variable space (see Figure 9). The plot for April 2011 data shows that the DMUs ITPL, Bannerghatta Road, and Inner Ring Road form an efficient frontier, in line with the findings of the DEA model. The potential improvement in performance for these routes computed from the slack and surplus in the DEA model is expressed as percentage change from the current levels in Figure 10, which indicates that all the routes have potential for a decrease in fleet size or an increase in revenue. The Tumkur Road and Outer Ring Road–EC routes show opportunities for significant performance improvements by generating additional revenue or by reducing fleet size. The effective kilometers of operation do not seem to provide much potential for improvement.

FIGURE 9.
Efficient frontier for premium city routes

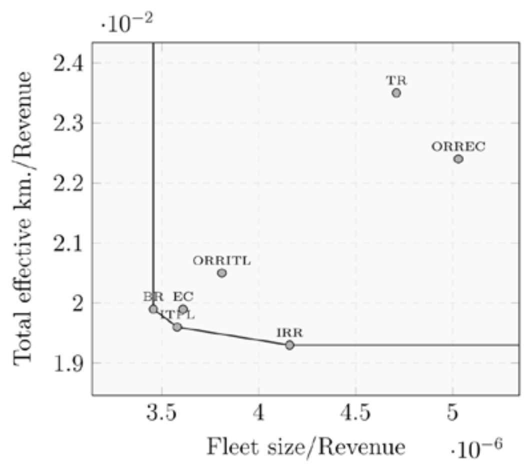
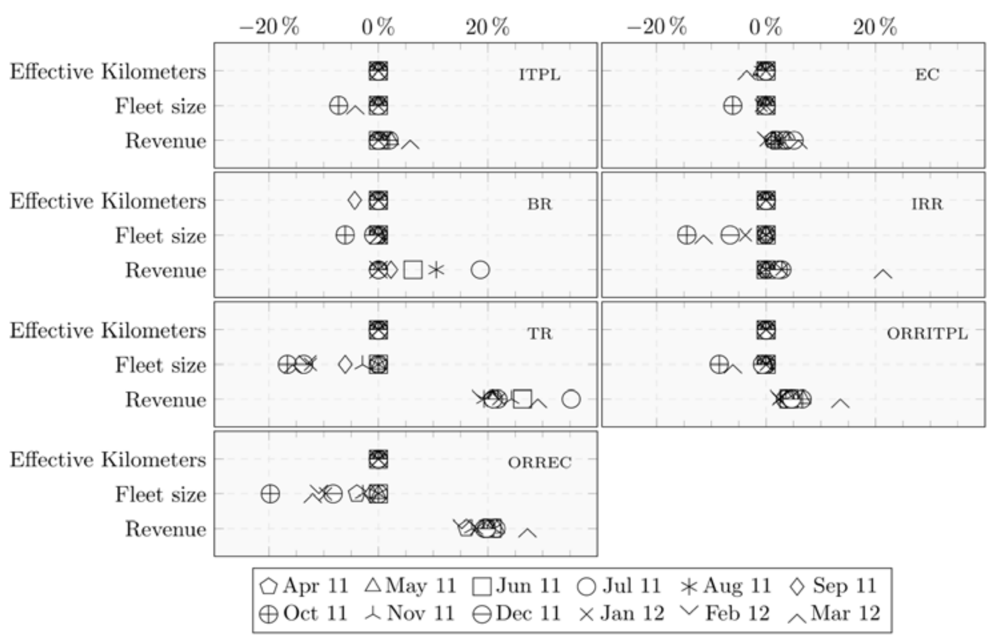
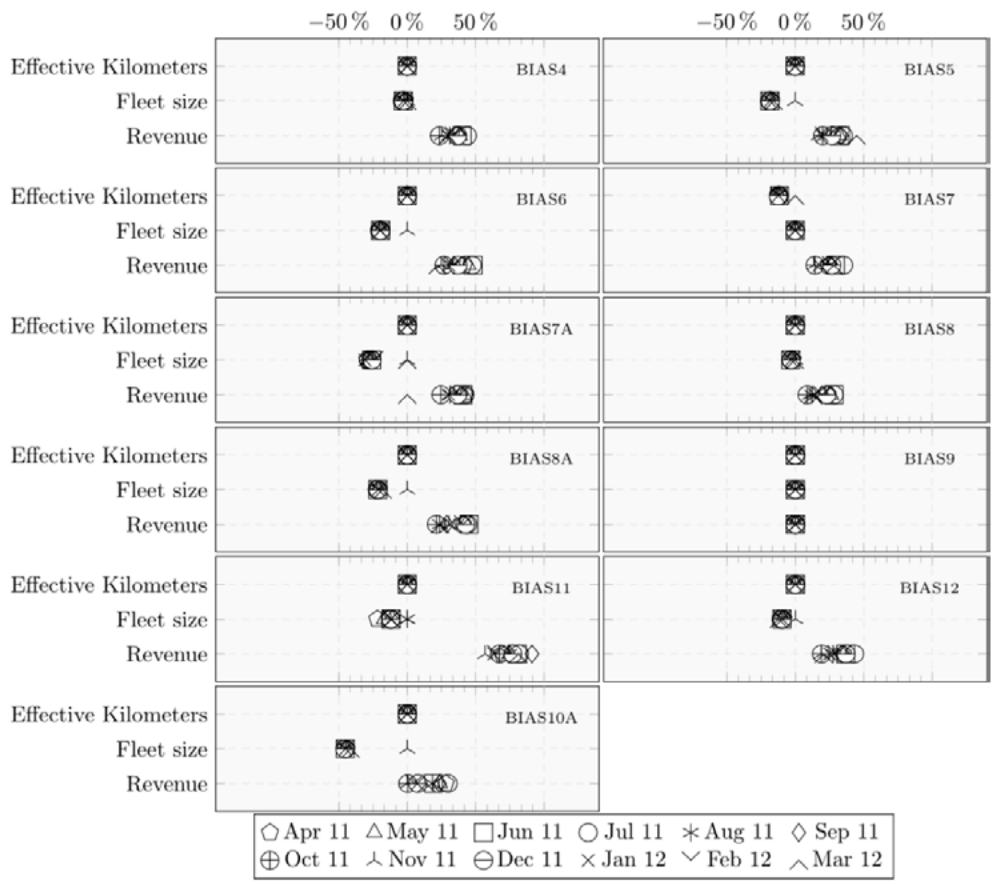


FIGURE 10.
Slack and surplus for inefficient city routes



Similar analysis on the premium service airport routes was conducted; the results are shown in Figure 11, which shows that the BIAS 9 route (Kempegowda bus stand to airport) is the only route with a 100% efficiency score; all other routes show relatively lower efficiency scores.

FIGURE 11.
Slack and surplus for inefficient airport service routes



The main reason for this could be due to the fact that the Kempegowda bus stand is in the city center and is a major transfer hub. Further, BIAS11 (Chikkalasandra bus stand to airport) shows a much lower efficiency, in the 50–60% range, than the other routes, which have efficiencies in the 70–90% range. The BIAS11 route starts from the same area in which Depot 13 is located, which was identified as an inefficient depot in the earlier analysis. A common set of socio-economic factors of the area could be contributing to the inefficiencies.

The other routes that have moderate technical efficiencies (70–90%) operate from different suburbs of Bangalore to the airport, and only people traveling to the airport typically use these services. Also, these services operate around the clock, with lower load factors during the night-time schedules, and they operate with only half the number of seats. The other main reason for the lower efficiency could be related to fares, which are nearly equal to the cost of private transportation modes such as taxis and could be experiencing severe competition from them.

Figure 11 shows the improvement potential for the inefficient BIAS routes expressed as percentage reduction in input or percentage increase in output from the current levels. All the inefficient BIAS routes show significant revenue increase potential compared with the levels achieved in BIAS9 with BIAS11, and as expected, lead the pack with maximum potential improvement. Also, some routes show potential for fleet size reduction.

Conclusions

The main objective of this study was to quantify the performance of premium bus services operated by BMTC. The efficiency scores for different premium service depots and routes using DEA were estimated, and it was found that the average long-term efficiencies of all premium service depot range between 1.00 (for Depots 07, 25, and 28) and 0.917 (Depot 13), with a systemwide average efficiency of 0.97. Similarly, the short-term efficiencies vary—0.725 (Depot 07), 0.865 (Depot 13), 0.960 (Depot 25), and 1.00 (Depot 28). The bootstrapping process for short-term efficiency showed the presence of upward bias in efficiency estimates with low sample sizes. This analysis indicated that the inefficient units have opportunities for improvement in terms of staff productivity, indicating a need to align depot staffing patterns with needs.

The efficiencies of the premium services operated within the city ranged from 1.00 to 0.77, with an average of 0.93 for the 7 service routes. The efficiency values of the 11 premium services operated to the airport ranged from 0.61 to 1.00, with an average of 0.79.

The main finding from this study is that, despite increases in the cost of operation in terms of fuel cost and maintenance cost, the BMTC premium service depots appear to be operating efficiently. At the same time, some of the city and airport routes show potential for improvement. The revenue generated by the various inefficient routes appears to be significantly inadequate, as indicated by the slacks, pointing at the need to rationalize the routes and schedules for a more efficient operation.

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Development of Level-of-Service Criteria based on a Single Measure for BRT in China

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Abstract

Bus rapid transit (BRT) has gained popularity as a cost-effective way of expanding public transit services, and its level of service (LOS) is receiving increasing attention. However, relatively little is known about the precise criteria that can consistently and objectively classify the LOS of BRT into different levels. This paper introduces the measure of "unit delay" to develop BRT LOS criteria, defined as the sum of delays a bus experiences at stops and intersections and on a 100m link. Based on field surveys conducted on BRT in Changzhou, China, we obtained a unit delay data set and established BRT LOS criteria using Fuzzy C-means Clustering. The LOS criteria can be applied for operational, design, and planning analyses for BRT systems. A method to examine the operational conditions in spatial and temporal dimensions and pinpoint the service bottlenecks of a BRT system is presented.

Key words: Level of service criteria, bus rapid transit, unit delay, Fuzzy C-means clustering

Introduction

Bus rapid transit (BRT) combines the efficiency and reliability of rail service with the operating flexibility and lower cost of conventional bus service. Many cities are turning to BRT as a way to cost-effectively expand public transit services to relieve traffic congestion, reduce fuel consumption and carbon emissions, and increase mobility options for the poor (Cervero and Kang 2011). BRT has been implemented throughout Latin America and North America, Europe, Asia, Australia, and, now increasingly, in Africa and India (Deng and Nelson 2011). In China, BRT has expanded faster than in any other regions over the last five years (Fjellstrom 2010). By the end of 2014, BRT was implemented in 19 cities in

China, and its total length has reached 529km (Institute for Transportation & Development Policy 2015).

Level of service (LOS) as a way to quantify service quality of BRT is receiving increasing attention. BRT LOS criteria, which classify the LOS of BRT into several levels, are an effective method to evaluate the service quality of BRT and can provide useful tools for communicating the service quality of BRT to laypersons and decision makers. BRT LOS criteria also can be used for BRT design analysis to allow a new or modified BRT facility to operate at a desired LOS. Typically, analysts can use BRT LOS criteria to determine values for elements such as stop space, berth number, and route number at one stop.

Issues about the planning, design, and passenger-carrying capacity of BRT have been well researched in China (Xu 2007, Mo 2007, Wu 2010, Lu 2011). Researchers outside China focus more on the impacts of BRT on land use, fuel consumption, pollution emissions, and traveler behavior (Zargari and Khan 2002, McDonnell et al. 2008, Mishra et al. 2010, Perk et al. 2010, McDonnell and Zellner 2011, Aiga 2014). However, relatively little academic focus has centered on BRT LOS criteria. Therefore, this study generated scenarios to investigate BRT LOS criteria in China.

First, research progress on LOS criteria of urban streets and public transit are reviewed. This is followed by the introduction of BRT development in China. Next, a research methodology involving measure selection, level number of LOS, theoretical approach for LOS partitioning, and supporting data sources is presented. Finally, BRT LOS criteria are established and their applications are discussed.

Literature Review

The concept of LOS was introduced in the 1965 edition of the *Highway Capacity Manual* (*HCM*), which presented the now-familiar letter-grade system for characterizing the quality of operations on a variety of traffic facilities, from intersections to freeways (Roess et al. 2010). LOS is a quantitative stratification of a performance measure or measures that represent quality of service (TRB 2010). *HCM* defines six levels of service, ranging from A to F, with LOS A representing the best operating conditions from the traveler's perspective and LOS F the worst.

The 2010 edition of *HCM* provides LOS criteria for freeways, multi-lane highways, two-way highways, urban streets, and intersections. BRT is a portion of an urban street; thus, the LOS criteria for urban streets in *HCM* 2010 are introduced below. An urban street right-of-way is shared by four types of travel modes—automobile, pedestrian, bicycle, and transit—and each mode uses its assigned portion of the right-of-way. *HCM* 2010 provides separate LOS criteria for these four modes on urban streets. Through-vehicle travel speed and auto LOS scores are used to characterize automobile LOS. Pedestrian LOS scores and average pedestrian space on a sidewalk are used as measures to classify pedestrian LOS into six levels. LOS scores reported by travelers are used to describe LOS for bicycle and transit modes. The LOS score is the common service quality measure for the four modes on urban streets. Therefore, it can be used to compare the relative quality of service provided to the users of each mode and to estimate the impact of reallocating street right-of-way on each mode's quality of service.

LOS criteria in *HCM* are more suitable for traffic conditions in North America, particularly the United States. Bhuyan and Rao (2010), Mohapatra et al. (2012), Das and Bhuyan (2014) addressed LOS criteria for highly heterogeneous traffic flow on urban streets in India using a clustering algorithm and found that speed thresholds for LOS criteria in India are lower than those mentioned in *HCM*. Historically, *HCM* has used a single performance measure as the basis for defining LOS. Different from this, researchers in China use multiple measures to characterize LOS for urban streets. For example, Xu et al. (2008) proposed LOS criteria for urban streets by considering density, speed, volume-to-capacity ratio, and service flow rate.

BRT is a new form of public transit; LOS criteria of public transit are discussed below. The *Transit Capacity and Quality of Service Manual*, *3rd Edition* (*TCQSM* 2013), provides systematic and detailed introductions to LOS criteria for public transit (TRB 2013). For fixed-route transit service, *TCQSM* 2013 uses two categories of service measures—availability and comfort & convenience—to evaluate service quality. The measures for availability include frequency, service span, and access. The measures for comfort & convenience include passenger load, reliability (on-time performance and headway adherence), and transit-auto travel time ratio. *TCQSM* 2013 also presents LOS criteria (called quality of service tables) for each service measure, which eliminate the LOS letters associated with the transit quality of service measures. Eliminating the letters has allowed LOS criteria to show more or fewer service levels, as appropriate, rather than being forced to fit the levels to the six letters, as before. The selection of thresholds in LOS criteria for service measures represents a collective professional judgment.

Recognizing that transportation planners and engineers generally are comfortable with letter-grade LOS, *TCQSM* 2013 introduced the transit LOS score as the measure of transit quality on urban streets. This measure provides a single transit LOS letter as its output while incorporating most of the factors included in the manual's transit service quality framework. This measure also can be incorporated into an overall evaluation of the service quality provided to all urban street users—transit passengers, pedestrians, bicyclists, and motorists.

The LOS criteria of public transit are characterized by multiple measures in *TCQSM* 2013. The disadvantage of an LOS evaluation system with multiple measures is that it does not allow definite benchmarking of different systems (Xin et al. 2005). Different from the approach adopted in *TCQSM* 2013, Chen (1999) and Xu (2001) developed LOS criteria for exclusive bus lanes based solely on a single measure—delay.

BRT in China

BRT has expanded and evolved in China since the first median bus lanes were introduced in Kunming in 1999. However, with no special BRT buses or pre-board fare collection, and no significantly improved station environment, Kunming is not regarded as a full-fledged BRT system. Beijing was, in 2005, the first full BRT system to open in China, in the sense that it provides high-capacity BRT buses, fare collection at stations rather than on buses, and dedicated bus lanes for most of its length (Fjellstrom 2010).

Information on running ways, stop space, fare collection, ridership, and speed of BRT systems in China is detailed in Table 1. A majority of BRT systems in China use median bus lanes as running ways and on-line stations rather than bus bays for bus stopping. Fare collection is mainly off-board, and passengers pay or swipe at stations. Because of low-floor buses or high platforms, most BRT systems allow level passenger boarding and alighting. BRT ridership among these cities varies greatly, ranging from 600 passengers per hour per direction in Zhoushan to 27,400 passengers per hour per direction in Guangzhou. Peak-hour speeds in city centers also differ, with 39km/h in Zaozhuang compared to about 10km/h in Urumqi.

TABLE 1. Design and Operation Features of BRT in China

City Name	Bus Lane Length (km)	Running Way	Mean Stop Space (m)	Fare Collection	Boarding/ Alighting	Peak Ridership (passengers/ h/ direction)	City Center Peak Speed (km/h)
Beijing	59	Median lane	940	Pre-board	No step	2,750	18–20
Changzhou	51.9	Median lane	900	Pre-board	No step	2,650	19.5
Guangzhou	22.5	Median lane	880	Pre-board	Both	27,400	17–19
Hangzhou	18.8	Median and curbside lane	1100	Pre-board	No step	6,300	18
Zhengzhou	50.3	Median lane	750	Pre-board	No step	7,230	17
Dalian	9	Mainly median lane	1350	Pre-board	No step	6,430	19.3
Jinan	41.6	Median lane	760	Pre-board	No step	2,050	17.5
Hefei	7.2	Median lane	850	Pre-board	Step	3,600	16–18
Changde	18.9	Median lane	820	Pre-board	No step	800	31
Lanzhou	8.6	Median lane	650	Pre-board	No step	6,550	22
Lianyungang	34	Median lane	1210	Pre-board	No step	1,650	18
Xiamen	48.9	Elevated road	1300	Pre-board	No step	8,360	27
Yancheng	16	Median lane	690	Pre-board	No step	1,300	18
Yinchuan	17	Median lane	800	Pre-board	Both	3,600	15
Zaozhuang	33	Median lane	1635	Both	No step	1,400	39
Urumqi	28	Mainly median lane	880	Pre-board	No step	6,950	10–13
Chengdou	28.8	Elevated road	1020	Pre-board	No step	6,650	29
Zhongshan	12.6	Median lane	1000	Pre-board	Step	820	22.7
Zhoushan	23	Curbside lane	2700	Pre-board	No step	600	19

All BRT systems in China use on-line stations.
Source: Bus Rapid Transit Information. *www.worldbrt.net/defaulten.aspx, accessed April 8, 2015.*

To collect data for this research, surveys were conducted on the Changzhou BRT, which opened in January 2008 and currently has two trunk routes, six branch routes, three section routes, and two loop routes. Its operation mode is direct-service operations. The running ways are dedicated median bus lanes that are about 3.75m wide. The system has 58 stations, each about 3m wide and 60m long and spaced roughly 900m apart and located close to intersections. The system has 60 BRT vehicles, most of which are 18m articulated buses. Monitoring facilities are installed throughout system to prevent other vehicles from entering. This system also includes intelligent technologies such as automated vehicle location (AVL), real-time passenger information, and transit signal priority (TSP).

Methodology

Measure Selection for LOS of BRT

BRT is a new type of public transit. Since BRT is located on urban streets, it has the characteristics of both public transit and urban streets. In *HCM*, a single measure is used to define the LOS of urban streets; however, *TCQSM* adopts multiple measures to evaluate LOS of public transit. This paper considered both *HCM* and *TCQSM* when selecting service measures for the LOS of BRT; a single measure to evaluate the LOS of BRT was sought and was selected through identifying the most pressing problems of bus transit in China from multiple service aspects such as availability, reliability, etc.

Availability, economy, comfort & convenience, and reliability are important aspects of bus transit service. At present, the Chinese government attaches great importance to public transit; many bus routes and stops are being planned for Chinese cities, and service times have been extended. Travelers can conveniently access bus service, availability in space and time are not a problem, and bus fares are low and affordable. Reliability is the most significant problem, and it is particularly urgent that it be improved. Late arrivals and departures and unreliable wait and travel times are major weaknesses. Comfort is also a significant problem, with buses too crowded during peak hours and no air conditioning in older buses. Lack of comfort is a derived problem and is exacerbated by unreliability; for example, uneven headways at stops, uncertain bus arrival times, and unreliable travel times all lead to passenger imbalance and crowding on buses. Comfort will be improved with improvements in reliability.

A BRT system includes links, stops, and intersections. Operational conditions on links are relatively unimpeded because of the use of exclusive rights-of-way, but stops and intersections can be traffic bottlenecks in a BRT system, where bus queues and bunching often occur, resulting in bus delays. Although delay of one bus at one stop or intersection may be small, the combined delay of all buses at all stops and intersections can be significant and can result in large economic losses. Accumulated delays at stops, intersections, and links result in unreliability of the entire BRT operation. Therefore, BRT delay—the sum of delays of buses at all stops, intersections, and links within a BRT system—is the appropriate measure of BRT LOS.

Estimation Model for Delay

This study aimed to develop BRT LOS criteria, but the LOS criteria based on BRT delay cannot provide a benchmark for comparing different BRT systems. Therefore, "unit delay" was used to develop BRT LOS criteria. Unit delay in this paper is defined as the sum of delays a bus experiences at stops and intersections and on a 100m link (Note: To compare the LOS of different BRT systems, "link" is a 100m link; the delay on a 100m link equals average delay per 100m link).

A near-side stop is a bus stop immediately prior to an intersection at which buses stop to serve passengers before crossing the intersection. Operational conditions at near-side stops are the worst within the BRT network, as bus queueing and bunching become more severe under the additional interferences of traffic lights at downstream intersections. Bus delays at near-side stops are generated mainly from bus queueing and bunching, and bus delay at near-side stops includes delays at both stops and intersections.

Huo (2013) built a model for bus delay at near-side stops, as shown in Equation (1). This model was validated by data collected from near-side stops on the Changzhou BRT and bus transit in Vancouver, with accuracy of 81.32% and 75.07%, respectively (Huo 2013, Huo 2015). This model was used to calculate the unit delay shown below.

$$D = \begin{cases} \dfrac{P_0\rho^s\rho_s}{\lambda s!(1-\rho_s)^2} + \dfrac{\theta[P_{(n>s)}(1-\frac{1}{s!}+\frac{t_r}{C}) + \sum_{n=2}^{s}\frac{P_n(n!-1)}{n!} + \frac{P_{(n>s)}(s!-1)}{s!} + \frac{(1-P_0)t_r}{C}]}{\lambda} \\ \qquad \times \sqrt{\dfrac{P_0\rho^s\rho_s(1+\rho_s)}{s!(1-\rho_s)^3} - \left(\dfrac{P_0\rho^s\rho_s}{s!(1-\rho_s)^2}\right)^2}, \quad s>1 \\ \dfrac{\rho/\mu}{1-\rho} + \dfrac{\theta(P_{(n>1)}+1-P_0)t_r}{C\lambda}\sqrt{\dfrac{\rho^2-2\rho^4+\rho^5}{(1-\rho)^3}}, \quad s=1 \end{cases} \tag{1}$$

Where, D represents the delay a bus experiences at near-side stop (s/vehicle), Θ indicates the fraction of waiting time variation resulting from buses being blocked from exiting a stop by buses in front and/or by a red light (estimated to be 0.467 based on collected data from Changzhou BRT), λ represents the mean arrival rate (vehicle/s), μ represents the mean service rate (vehicle/s/berth), s represents the berth number at the stop, t_r represents the red time at the downstream intersection (s), C represents the cycle length at the downstream intersection (s), n represents the number of buses included in service and in queue at the stop, $\rho = \lambda/\mu$, $\rho_s = \lambda/(s\mu)$, $P_0 = \left[\sum_{n=0}^{s-1}\frac{\rho^n}{n!} + \frac{\rho^s}{s!(1-\rho_s)}\right]^{-1}$ for $s>1$ and $p_0 = 1-\rho$ for $s=1$, and $P_{(n>s)} = 1-\sum_{n=0}^{s}\frac{\rho^n P_0}{n!}$.

Theoretical Method for LOS Criteria

Defining LOS criteria is a classification problem, and from the literature it was determined that cluster analysis is the most suitable technique for solving this kind of problem (Bhuyan and Rao 2010, Mohapatra et al. 2012, Das and Bhuyan 2014). Fuzzy C-Means clustering (FCM), developed by Dunn in 1973 and improved by Bezdek in 1981, is a cluster analysis method derived from fuzzy logic (Bezdek et al. 1984) that allows a dataset to be grouped into C clusters, with every data point in the dataset belonging to every cluster to a certain degree, which makes the cluster result of FCM closer to reality (Bezdek et al. 1984). Therefore, FCM is the most frequently-used cluster analysis method (Yue et al. 2014). In the study of LOS criteria, Bhuyan and Rao (2010) applied FCM to develop LOS criteria for urban streets in India. Mohapatra et al. (2012) used a hybrid algorithm based on FCM in association with a genetic algorithm (GA) to investigate LOS criteria for urban streets. Cheol and Stephen (2002) applied FCM and other methods to develop real-time inductive-signature-based LOS criteria for a signalized intersection surveillance system. Therefore, based on analysis of literature, this study used FCM to establish BRT LOS criteria.

Level Number Defined

In China, LOS for a roadway facility, such as a freeway or an urban street, is classified into four levels (Xu et al. 2008), which is different from *HCM*'s six levels. BRT is a part of urban streets; thus, the LOS of BRT was defined as four levels in this study, ranging from 1 to 4, with LOS 1 representing the best operating conditions and LOS 4 the worst.

As mentioned, unit delay was used to establish BRT LOS criteria; therefore, BRT LOS criteria were interpreted in the style of Table 2, where D_0 represents unit delay in BRT and d_1, d_2, and d_3 represent unit delay thresholds. Establishing BRT LOS criteria is determining unit delay thresholds for partitioning different levels, i.e., determining the values for d_1, d_2, and d_3 in Table 2.

TABLE 2.
Proposed BRT LOS Criteria

LOS	Unit Delay
1	$D_0 \leq d_1$
2	$d_1 < D_0 \leq d_2$
3	$d_2 < D_0 \leq d_3$
4	$D_0 > d_3$

Unit Delay Data Set Used for BRT LOS Criteria

Unit delay refers to the sum of delays a bus experiences at stops or intersections and on 100m links. Analyzed as above, bus delay at near-side stops includes delays at both stops and intersections. Thus, we used the estimation model for bus delay at near-side stops (Equation [1]) to obtain unit delay data set: 1) determine the variable values in Equation (1), 2) match the values of the variables and form different variable value combinations, 3) calculate the sum of delays at stops and intersections under each variable value combination with Equation (1), and 4) obtain the unit delay data set by adding the delay on a 100m link to the sum of delays at stops and intersections.

The variables in Equation (1) include mean arrival rate, mean service rate, and berth number at a near-side stop and red time and cycle length at downstream intersections. Mean arrival rate is the mean of the number of arrival buses per unit time. Mean service rate is the service capacity of each berth at a stop and is the reciprocal of average service time. Service time is the time that a bus spends at a stop and equals the difference between the time it exits the stop and the time it begins to decelerate.

To gain values for these variables and delay on a 100m link, three types of field surveys were conducted for the Changzhou BRT on April 11 and 12, 2013: 1) mean arrival rate and mean service rate at near-side stops, 2) berth number, red time, and cycle length, and 3) delay on links. For the first type of survey, the two busiest near-side stops were selected, with one surveyor for each stop, who recorded all buses arriving at the stop from 9:00–18:00 and, for each arriving bus, recorded the time when it began to decelerate t_1 and the time when it exited the stop t_2. Values for mean arrival rate were derived by counting the number of arriving buses per hour. Service time for each bus is t_1 minus t_2, and average service time is the mean of service time of all arriving buses per hour. Values for mean service rate were derived by calculating the reciprocal of average service time.

For the second type of survey, 10 near-side stops were randomly selected, with one surveyor to record berth numbers, red times, and cycle lengths. For the third type of survey, 10 links near the selected stops were chosen, with one surveyor to observe bus delay. It is found that buses are almost unimpeded on BRT links due to exclusive rights-of-way, and bus delay on 100m links is approximately 0.5s.

Based on the collected data from the field surveys, the variable values used to produce the unit delay data set were identified, as shown in Table 3. The variable ranges in Table 3 cover as many values as possible in practice and, thus, the unit delay data set is feasible for BRT LOS criteria.

TABLE 3.
Values for Variables in Equation (1)

Variables	Ranges	Step Size	Number
Mean arrival rate (vehicle/h)	20–80	5	13
Mean service rate (vehicle/h/berth)	60–120	10	7
Berth number	2–4	1	3
Red time (s)	60–130	10	8
Cycle length (s)	90–150	10	7

Based on the variable values in Table 3, all the values for all the variables were matched, and different variable value combinations were generated accordingly. The values for mean arrival rate, mean service rate, berth number, red time, and cycle length were 13, 7, 3, 8, and 7, respectively. Therefore, the number of variable value combinations was 15,288 (13×7×3×8×7).

The variable values in Equation (1) were set in the variable value combinations, and the sum of delays a bus experiences at stops and intersections under all the variable value combinations was calculated. Finally, 0.5s (bus delay on a 100m link) was added, and the unit delay data set was obtained, at 15,288.

BRT LOS Criteria Results

Based on the unit delay data set built above, BRT LOS criteria using FCM were established. Cluster numbers in FCM are the four level numbers of BRT LOS. Cluster centers in FCM are median values between adjacent levels of BRT LOS, and thresholds between adjacent levels can be determined on the basis of the median values. Cluster results for unit delay using FCM are shown in Table 4.

TABLE 4.
Cluster Results of Unit Delay using FCM

Category	Cluster Centers of Unit Delay (s)
1	7
2	18
3	37
4	68

By calculating the average values of adjacent cluster centers, the thresholds between adjacent levels of BRT LOS were determined, and BRT LOS criteria were established, as shown in Table 5. Unit delay was less than 13s at LOS 1; when unit delay increased to 28s, BRT LOS deteriorated to LOS 2; when unit delay was between 28s and 53s, it was LOS 3; and when unit delay was more than 53s, it was the worst operating condition, LOS 4. What the four LOS ranges represent from a transit operator perspective are shown in Table 5. (Note: The variables for the unit delay data set were collected from BRT systems in which bus overtaking maneuvers are prohibited; thus, the BRT LOS criteria in Table 5 are suitable only for BRT systems in which bus overtaking maneuvers are prohibited.)

TABLE 5.
BRT LOS Criteria in Changzhou

LOS	Unit Delay (s)	Operator Perspective
1	<13	Slight bus queueing and bunching at a stop and intersection; transit agency does not need to take traffic control actions.
2	13–28	Moderate bus queueing and bunching at a stop and intersection; transit agency needs to arrange traffic police to disperse bus flow during peak hours
3	28–53	Frequent bus queueing and bunching at a stop and intersection; transit agency needs to take action such as adjusting signal timing or increasing berth to transform current BRT
4	>53	Serious bus queueing and bunching at a stop, an intersection, and on a link; government needs to construct new BRT routes to meet passenger demands.

Note: Unit delay refers to the sum of delays a bus experiences continuously at stops and intersections and on a 100m-long link within a BRT system.

Applications

The BRT LOS criteria established above have potential applications for operational, design, and planning analyses for BRT systems.

- Operational analyses review operational conditions (levels of service) of sub-segments within BRT systems and generally are oriented toward current conditions of BRT systems. They aim at identifying operational bottlenecks of BRT systems and providing information for decisions on whether there is a need for improvements to an existing station, link, or facility.
- Design analyses apply the BRT LOS criteria to determine the required physical features that will allow a new or modified BRT to operate at a desired LOS. They are usually targeted at mid- to long-term implementation of BRT systems. Typically, analysts can use BRT LOS criteria to determine such elements as spacing and location of stations, berth number, frequency of bus service, and route number.
- Planning analyses typically focus on future conditions and provide information for decisions on whether there is a need to construct a new BRT and evaluate a series of alternatives.

Further studies are required to develop the methods for all three types of applications. The following presents one method for operational analysis.

A BRT's operational conditions vary in spatial and temporal dimensions; operational conditions differ in different sub-segments and during different time periods. Thus, operational analysis should reflect operating conditions by sub-segment and by time period. Based on this idea, the following method was used to carry out an operational analysis.

First, divide a BRT system into several segments; beginning at a terminal, the sections between two BRT stations are identified as segments, and the division of that segment ends at the next terminal. The division method is illustrated in Figure 1.

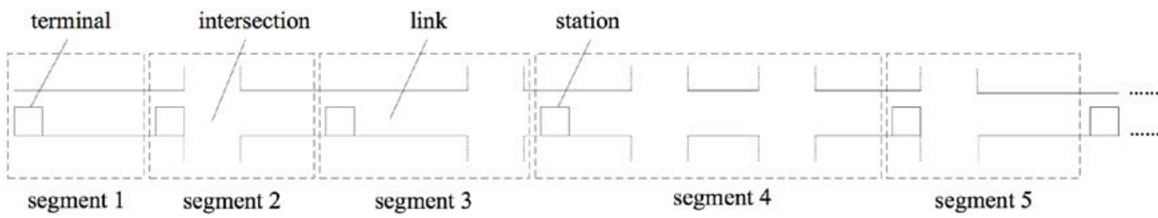

FIGURE 1. Method for dividing BRT into segments

Second, evaluate the operating conditions of each segment during all time periods, e.g., every 15 min, 20 min, 30 min, etc. Table 6 shows the operational analysis for a segment. To complete the operational analysis for a segment, obtain data for the delays a bus experiences on links or at stations and/or intersections in the segment during all time periods; the types of delays can be obtained through field surveys or using existing models. Delays on links are converted into delays on a 100m link; one or more intersections may be included within the segment (as indicated in the division method of segments). If there are no intersections, intersection delay is 0. If there are two or more intersections, intersection delay equals the average delay of multiple intersections. Determine unit delay by adding these delays together. Then, based on the established BRT LOS criteria (Table 5), identify the levels of service for a segment during all time periods.

TABLE 6. Operational Analysis Table for Segment on BRT

Segment number _____			**Link length intersection included: Yes or No**			
Time Periods	**Delay on Links (s)**	**Delay on 100m Link (s)**	**Delay at Station (s)**	**Delay at Intersection (s)**	**Unit Delay for Segment (s)**	**LOS for Segment**
6:00–6:30						
6:30–7:00						
7:00–7:30						
7:30–8:00						
……						
18:30–19:00						
19:00–19:30						
19:30–20:00						

Finally, complete the operational analysis by obtaining the operational analysis results of all the segments. Table 7 shows the operational analysis table for a BRT, which is formed by gathering levels of service and unit delays of all segments during all time periods. The operational conditions by segment and by time period are clear, and the service bottlenecks of the BRT system are obtained.

TABLE 7.
Operational Analysis Table for a BRT System

LOS / Unit Delay (s)							
Segment / Time Period	1	2	3	4	5	6	.....
6:00-6:30							
6:30-7:00							
7:00-7:30							
7:30-8:00							
......							
19:00-19:30							
19:30-20:00							

Conclusions

This study aimed to establish consistent and objective criteria for BRT LOS in China. To make operational conditions comparable across different BRT systems, a new measure of "unit delay"—the sum of delays a bus experiences at stops and intersections and on a 100m link—was proposed to establish BRT LOS criteria. A unit delay data set was obtained by conducting field surveys and based on BRT LOS criteria in Changzhou established using FCM. These BRT LOS criteria can be applied to conduct operational, design, and planning analyses for BRT systems. They also provide a useful tool for communicating operational conditions of BRT to laypersons and non-technical policy makers. Finally, a method for operational analysis that applies BRT LOS criteria to examine operational conditions in spatial and temporal dimensions was presented.

One limitation of this study is that the LOS level number has been pre-determined to be 4, following a tradition of transportation facility LOS classification in China. However, the FCM method has the potential to decide the optimal number of levels on the basis of empirical data analysis. In addition, the BRT LOS criteria are based on objective delays. How to expand to and incorporate passenger perception into consideration remains an open question.

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Impacts of Beijing Bus Rapid Transit on Pre-owned Home Values

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Abstract

Bus Rapid Transit (BRT) has gained increasing popularity worldwide in the last few decades. However, few studies have investigated BRT's impacts on property values in Chinese cities. This research, taking BRT route 1 (BRT1) and BRT route 3 (BRT3) in Beijing as examples, showed that proximity to BRT3 stops is weakly related to pre-owned home prices along the route, whereas BRT1 has induced a significant price premium. For BRT1, the impact is not linear. Specifically, pre-owned home prices for homes within 5–10 minutes' walking distance to BRT stations is 5.35% higher than those located closer to or farther away. The difference between the two routes can be explained by resident income differences and BRT route alignments. For homes very close to the subway route, the impacts of BRT vanish.

Introduction

Bus Rapid Transit (BRT) has gained increasing popularity worldwide in the last few years. Advanced and mature BRT services can be found in many cities in the world, such as Bogotá (Colombia), Curitiba (Brazil), Clermont-Ferrand (France), Orlando (U.S.)., Cleveland (U.S.), Adelaide (Australia), Brisbane (Australia), Osaka (Japan), etc. Historically, BRT has played a more important role in the urban development of developing countries, especially in Latin America. The success of introducing BRT services to these countries mostly stems from the dedicated lanes that offer shorter traveling time compared with traditional bus transit (Vuchic et al. 2014). The Institute for Transportation and Development Policy (ITDP) (Wright and Hook 2007) described BRT as a good alternative public transit mode in terms of relieving traffic congestion, reducing carbon emissions, saving commuting costs, and attracting development along the route. In the United States, the development of BRT projects has been spurred by the Federal Transit Administration's (FTA) BRT initiative (Lee, Miller, and Skinner 2007).

In China, BRT is an emerging idea. The first BRT line in China was built in Beijing in 2006. Since then, many other cities began to consider BRT as an important alternative means of public transit to significantly reduce city infrastructure cost, traffic congestion, and carbon emissions. However, to the authors' knowledge, compared to other public transit modes, few studies have investigated BRT's impacts on surrounding residential property values in Chinese cities.

This research investigated whether the proximity to BRT routes and the surrounding built environments around BRT stops has impacted property values in Beijing. The next section reviews the effect of public transit on property values and several relevant research topics associated with BRT. This is followed by information on sites, data, variables, and methodology applied in this paper. Finally, results from the Hedonic Model are discussed, as are key findings and their implications.

Literature Review

Many studies have investigated the impacts of transit-oriented development (TOD) on surrounding property values and reported positive results (Garrett 2004; McMillen and McDonald 2004; Weinstein et al. 2014; Cervero and Duncan 2004; Haider and Miller 1995; Knaap, Ding, and Hopkins 2001). Of these studies, Chicago's Midway Line showed that the opening of new rail services increased housing prices, with rates of land-value appreciation varying over time (McMillen and McDonald 2004). However, some studies produced the opposite results (Landis, Guhathakurta, and Zhang 1994; Celik and Yankaya 2006). One study in San Francisco found that rail-based TOD had a positive impact on downtown commercial properties but showed no impacts on suburban commercial properties (Cervero and Landis 1997). Although they measured accessibility and nuisance effects, some scholars did not report any positive impacts (Landis, Guhathakurta, and Zhang 1994; Gatzlaff and Smith 1993). Garrett (2004) found that the nuisance impacts on rents were modest and only accessibility, which was measured by distance to the nearest station, was valued, whereas service nuisance, measured by distance to the service corridor, was not significant.

For bus services, it is easy to understand that their impacts on spatial form and land use patterns are limited because, in contrast to many rail systems, it is difficult for buses to provide any appreciable accessibility benefits, and high use of private vehicles makes this benefit negligible (Cervero and Kang 2011). Cao and Hough (2012) found that in North Dakota, buses had no significant impact on land value. The impact was even negative within 200 m of a bus stop.

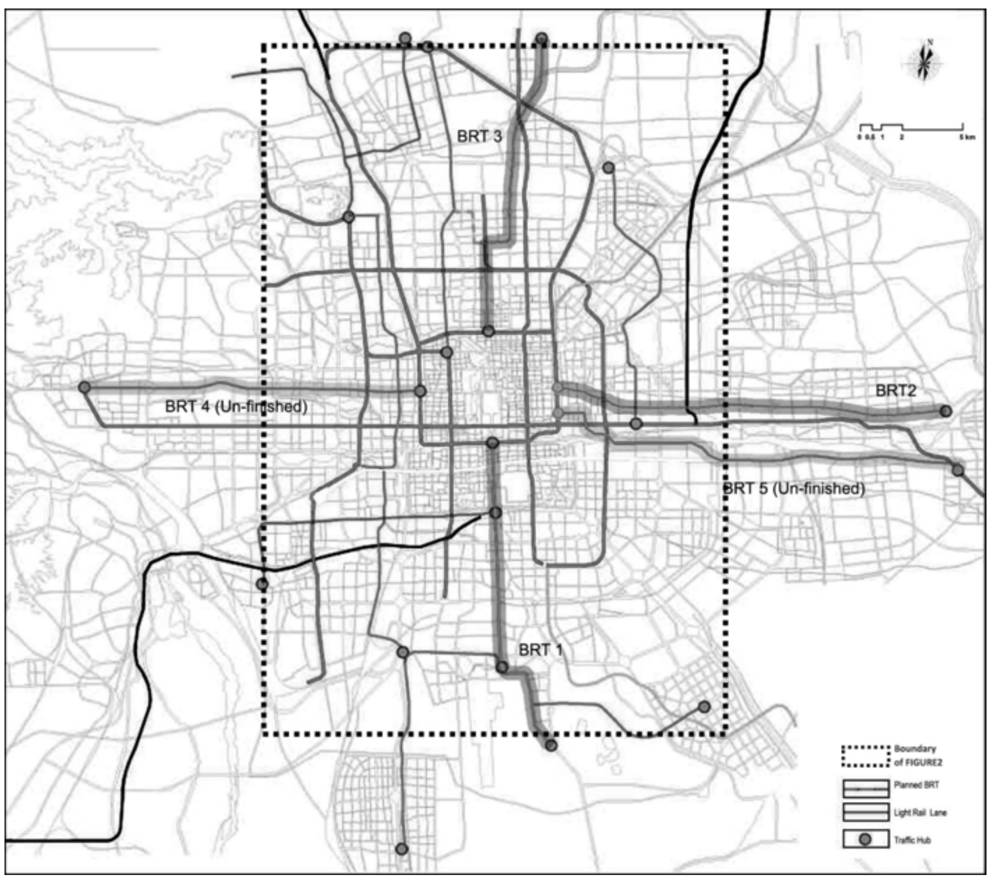
Compared to rail and bus, fewer studies have examined the impact of BRT on properties. Levinson et al. (2002) reported that the land-use benefits of BRT were as significant as LRT in Brisbane. The studies of the BRT system in Bogotá (Rodríguez and Targa 2004) also showed appreciable land value benefits. Rodriguez and Mojica (2008) found that for residences that already had benefited from the service in 2000, housing prices increased, on average, by 15–20%. In addition, Cervero and Kang (2011) found that in Seoul, within 300 m buffers of BRT stops, 10% of the residential house premiums resulted from BRT service. However, for some areas where BRT services were not well-managed or lanes were confined by urban spatial form or local policy, no significant impacts of BRT on land values were observed (Vuchic 2002; Cervero and Duncan 2004).

As the first city in China to build a BRT lane, Beijing has plans to gradually establish a BRT network system to complement the existing light rail system. The main purpose is to connect all major centers within the city limits and provide a good mode for people to visit important suburban centers. Beijing's first BRT was constructed in 2006. Currently, there are four main lines and three branch lines. According to Beijing's BRT Network Plan (2008–2020) (Yang and Xiangzhao 2010), the 1.5 km buffer area surrounding BRT stations within the city center will cover 85% of the total city area, and the 500 m service area will cover 50% of the population within the city center by 2020. Based on the authors' knowledge, few studies have investigated the impacts of BRT on property values in China. Therefore, analyzing the impact of Beijing's BRT system on property values is important, both theoretically and empirically.

Site and Data

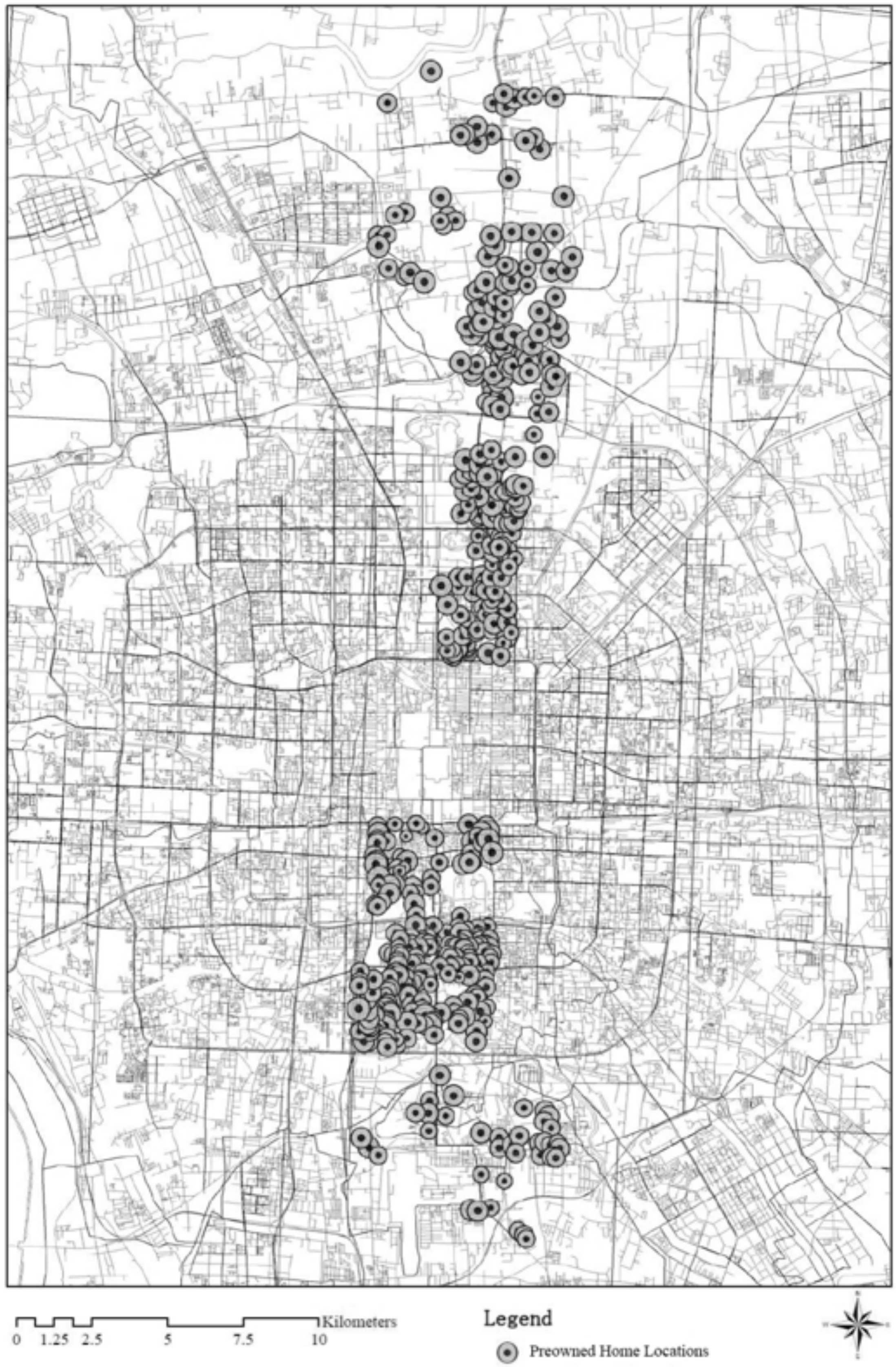
This research focused on Beijing's two earliest routes in operation, BRT route 1 (BRT1) and BRT route 3 (BRT3) (Figure 1). Without complete and instant real estate data from public institutes such as Bogota's Department of Housing Control (DHC), various challenges arise in terms of collecting historical data for the transaction price of a specific property in China. In this research, we collected market prices for second-hand residential properties that were sold between April and May of 2012 from the database of China's largest real estate website, Soufun.com. After removing records with uncertain information, 554 sales records were collected. Among them, 272 records were along BRT1 and 282 were along BRT3 (see Figure 2).

FIGURE 1.
Location of major BRT routes in Beijing



Source: Yang and Xiangzhao 2010

FIGURE 2.
Sample residential sale locations along BRT1 and BRT3, Beijing, April–May 2012



Since this study focused on how BRT influences pre-owned home prices, it is reasonable to include only dwellings close to BRT stations instead of an entire region. According to Munoz-Raskin (2010), pedestrians can bear walking without too much physical burden for no longer than 10 minutes. Knoblauch et al. (1996) showed that people can walk as far as 822 meters within 10 minutes. This research focused on people who can access a BRT station even if they may feel a little bit uncomfortable. Neighborhoods located within a 20-munite walking distance (1,644 meters) from a BRT station were taken into account in this study. Table 1 shows variables and data sources used by this research.

TABLE 1. Variables and Measurements

	Description	Measures
Dependent Variables		
P	Price of second-hand residential properties sold April–May 2012	RMB/m^2 in 2012
Independent Variables		
Dwelling Characteristics		
Dwelling size	Area of dwelling unit (m^2)	m^2 per unit
Gross floor area	Total floor area inside building envelope, including external walls and excluding roof	m^2
Lot area	Total area of lot where building located	m^2
Floor area ratio (FAR)	Ratio of gross floor area to lot area	ratio
Green area ratio (GAR)	Ratio of area of landscape elements to lot area	ratio in 100%
Number of dwelling units per neighborhood	Number of dwelling units per neighborhood	Counts
Dwelling age	2012 minus years (commenced)	Year
Building height	Number of stories	Number of stories
Slab type apartment	Tower apartment: 0 Slab (block) apartment: 1	Category
Finely decorated apartment	Roughcast: 0 (no furniture included, wall and floor roughly painted without wallpaper, carpet or ceramic tile); Fine decorated: 1 (room may have basic furniture, wall finely painted or wallpapered, carpet or ceramic tile included)	Category
Facility Accessibility		
Good accessibility to primary stores	Number of primary stores within 805 m (½ mi)	Counts
Good accessibility to schools	Number of schools within 805 m (½ mi)	Counts
Good accessibility to health care facilities	Number of hospitals or clinics within 805 m (½ mi)	Counts
Distance Attributes		
Distance to city center	Straight distance to city center, Tiananmen Square (m)	m
Distance to nearest subway station	Straight distance to nearest subway station (m)	m
Distance to nearest rapid bus station	Straight distance to nearest rapid bus station (m)	m
Less than 5 min to nearest rapid bus station on foot	Within 5 min walking distance from nearest rapid bus station Yes: 1 No: 0	Category
Less than 10 min but longer than 5 min to nearest rapid bus station on foot	Within 5-10 min walking distance from nearest rapid bus station Yes: 1 No: 0	Category
Longer than 10 min to nearest rapid bus station	Within 10-15 min walking distance from nearest rapid bus station Yes: 1 No: 0	Category

In this study, three types of attributes were considered: dwelling characteristics, facility accessibility, and distance. Descriptive statistics for all variables are shown in Table 2. Two important differences between BRT1 and BRT3 are 1) the average selling price of pre-owned homes along BRT3 was 2,000 RMB (325 USD), which is more expensive than those near the BRT1, and 2) samples along BRT3 were closer to both subway and rapid bus stations but had poor accessibility to primary stores, schools, and hospitals.

TABLE 2. Descriptive Statistics

Variables	Homes along BRT1			Homes along BRT3		
	Mean	*Max*	*Min*	*Mean*	*Max*	*Min*
Continuous Variables						
P (RMB/m^2 in 2012)	24276.00	52933	11391	26015.55	71548	7485
Dwelling size (m^2 per unit)	92.35	370	15	123.52	650	38.0
Gross floor area (m^2)	155,698.50	1,200,000	1342	189,610.60	2,300,000	5,000
Lot area (m^2)	71,449.52	663,000	590	104,829.30	1,040,000	1,000
FAR	2.54	12	0.34	2.71	14	0.2
GAR (%)	31.8	75.0	10	35.2	85.0	16.0
Number of dwelling units per neighborhood	1,406.52	15,800	33	1,594.07	10,000	30
Dwelling age (years)	11.94	50	1	11.29	29	1
Building height (stories)	11.47	33	3	13.87	33	2
Distance to city center (m)	7,357.36	16,043	2,142	10,700.11	22,818	3513
Distance to nearest subway station (m)	1,529.96	7,767	92	935.15	4,597	80
Distance to nearest rapid bus station (m)	1,305.35	2,809	116	937.65	4,004	98
Categorical Variables	**Yes**	**No**		**Yes**	**No**	
Slab type apartment	74.3%	25.7%		64.5%	35.5%	
Fine decorated apartment	76.1%	23.9%		75.9%	24.1%	
Good accessibility to primary stores	54.8%	45.2%		28.7%	71.3%	
Good accessibility to schools	74.6%	25.4%		47.9%	52.1%	
Good accessibility to hospitals	51.5%	48.5%		48.6%	51.4%	
Less than 5 min to nearest rapid bus station on foot	12.5%	87.5%		19.1%	80.9%	
Less than 10 min but longer than 5 min to nearest rapid bus station on foot	15.1%	84.9%		35.1%	64.9%	

Methodology

Hedonic models were employed to capture the impacts of proximity to BRT stations on pre-owned home values. Starting with three model specifications—semi-log, log-log, and Box-Cox—this study applied a log-log form model for the final models because of its better goodness of fit than semi-log and better economic meanings than the Box-Cox model.

A hedonic price model always faces a multi-collinearity issue, especially when it includes several geographic features (Palmquist 1991). In this research, a stepwise regression, an F test, and a likelihood ratio test were applied to determine and remove redundant variables. The model specifications are:

$$\ln \mathbf{P} = \alpha_0 + \sum_I \beta_i \ln \mathbf{DW}_i + \sum_K \delta_k \ln \mathbf{FA}_k + \sum_T \lambda_t \ln \mathbf{DS}_t + \sum_J \gamma_j \mathbf{D}_j + \varepsilon_{robust}$$

Where,

P = pre-owned home price

DW_i = i^{th} variable of Dwelling Characteristics

AC_k = k^{th} variable of Facility Accessibility

DS_t = t^{th} variable of Distance Characteristics

D_j = j^{th} dummy variable

ε_{robust} = heteroscedasticity robust standard error

A hedonic price model assumes that a consumer's preference for each attribute is unsaturated. As stated, BRT can bring accessibility benefits to residents in the vicinity but also may result in problems such as nuisance and unfairness, both of which could have negative impacts on property value. One solution for saturated preference is to apply different dummy variables for specific ranges of distance instead of directly using distance as one variable. In this study, BRT accessibility was measured as 1) straight distance and 2) dummy variables set for specific ranges of distance.

Results

Our research showed that the following factors contributed to higher pre-owned home prices: 1) shorter distance to city center, 2) shorter distance to subway stations, 3) higher green area ratio (GAR), 4) newer property, 5) slab-type, and 6) smaller floor area ratio (FAR). Specifically, distance to the city center was the dominant impact for both BRT1 and BRT3. As shown in Table 3, a decrease of 1% in distance to city center could lead to a decrease of 0.47% in pre-owned home price for BRT1 and 0.65% for BRT3. Also, the pre-owned home price was significantly impacted by proximity to a subway station. An increase of 1% in proximity to a station increased the pre-owned home price by 0.064% for BRT1 and 0.11% for BRT3. The impact of facility accessibility was insignificant. One possible reason might be that, given that Beijing is the capital of China, facilities and other services can cover larger portions of the city compared to other cities in China, meaning that the accessibility to those facilities has relatively little impact on pre-owned home prices in comparison with dwelling characteristics and distance attributes.

TABLE 3.
Summary of Model Estimation

Independent Variables	Homes along BRT1		Homes along BRT3	
	Distance Attributes estimated using:			
	Straight distance	Dummy variables	Straight distance	Dummy variables
Dwelling Characteristics				
Dwelling size (square term)	0.0617***	0.0602***	0.0659***	0.066***
	(5.24)	(5.20)	(4.24)	(4.25)
FAR	-0.0302*	-0.0273*	-0.0775**	-0.0769**
	(-2.55)	(-2.30)	(-3.09)	(-3.07)
GAR	0.0595*	0.0615*	0.237***	0.233***
	(2.00)	(2.15)	(3.35)	(3.32)
Dwelling age	-0.0683***	-0.0671***	-0.133***	-0.133***
	(-4.37)	(-4.42)	(-8.34)	(-8.53)
Slab type apartment	0.0587***	0.0606***	0.09***	0.094***
	(3.33)	(3.49)	(4.09)	(4.30)
Finely decorated apartment			-0.0578*	-0.0577*
			(-2.30)	(-2.30)
Facility Accessibility				
Good accessibility to hospitals			-0.0159***	-0.0157***
			(-3.63)	(-3.63)
Distance Attributes				
Distance to city center	-0.4692***	-0.4719***	-0.6498***	-0.65***
	(-17.96)	(-19.16)	(-19.92)	(-19.88)
Distance to nearest subway station	-0.0647***	-0.0638***	-0.11***	-0.109***
	(-5.50)	(-6.41)	(-5.98)	(-5.88)
Distance to nearest rapid bus station	-0.0183		0.0119	
	(-1.15)		(0.74)	
Less than 5 min to nearest rapid bus station on foot				
Less than 10 min but longer than 5 min to nearest rapid bus station on foot		0.0521**		-0.0244
		(2.37)		(-1.02)
Longer than 10 min to nearest rapid bus station on foot				
Constant				
Constant	14.159***	14.04***	15.58***	15.68***
	(71.54)	(74.3)	(52.86)	(54.52)
N	272	272	282	282
R^2	0.8273	0.8303	0.7453	0.7458
BIC	-358.5	-363.3	-130.1	-130.7
MSE	0.1157	0.1147	0.1732	0.1731
Log-likelihood	204.44	206.84	95.84	96.13

t statistics in parentheses
** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

The model results showed that BRT had different impacts on houses along BRT1 and BRT3. Specifically, for pre-owned homes along BRT1, the prices were positively related to dwelling size, slab type, and GAR and were negatively related to dwelling age, distance to city center, distance to nearest subway station, and FAR. The results agreed with what was expected. Note that the absolute value of the estimate for each factor was smaller in BRT1 (see Table 3). Therefore, the pre-owned home prices along BRT1 were less sensitive to each factor than those along BRT3 in terms of both positive impacts and negative impacts.

For distance measures, straight distance from home to a BRT station was not significant in the model. However, when measured by dummy variables, the results showed that BRT had a significant impact on homes located within 5–10 minutes' walking distance to the nearest BRT station. It confirmed that a saturation point does exist. On average, property values for homes located within 5–10 minutes' walking distance to BRT stations were 5.35% higher than homes located in other zones (exp(0.0521)-1=0.0535).

For homes along BRT3, the number of dwellings in the neighborhood and having a rough-cast apartment also showed negative impacts on property values. The impact of BRT3 on pre-owned home prices was mainly insignificant. Both the F test and the LR test treated the proximity to BRT stations as a redundant variable. The final model showed that the farther away people lived from BRT3, the higher the home prices might be. In summary, unlike BRT1, BRT3 has little to no impact on pre-owned home values.

Conclusion

Overall, Beijing's BRT routes have different impacts on pre-owned home values. BRT1 did contribute to the increase in nearby pre-owned home values; however, the impact was nonlinear. It had a strong impact on properties with good accessibility to BRT1, but not too close. The values of homes located within 5–10 minutes' walking distance to BRT1 stations were 5.35% higher than those located closer to or further away from stations. Different from BRT1, BRT3 almost had no impact on surrounding home values.

The difference can be interpreted as follows:

- As discussed earlier, the average pre-owned home price along BRT3 was about 2,000 RMB higher than those near BRT1 (see Table 2). Studies (Cervero and Kang, 2011) also found that wealthier people were more likely to commute by private vehicle or subway instead of rapid bus. For them, the negative impact of noise and separated lanes taken by rapid buses may override the benefit of good accessibility to rapid bus stations.
- Homes along BRT3 were much closer to existing subway lines than those along BRT1 (Figure 1). Compared to subway, BRT was a much less attractive mode, especially when the city's subway was established much earlier and more comprehensively than the BRT system. All models in this study show that the accessibility to subway stations had a much more significant and more stable impact than accessibility to rapid bus stations. In other words, when subway is available, BRT has no advantages and its impact on home prices nearly vanishes.

This research suffered from data limitation issues. Very limited built environment information was available for the selected samples. Further, cities in China usually do not provide complete and open accessible real estate data for general public. These limitations were major challenges for this research. Future studies need to include more real estate sales data and more detailed built environment characteristics around samples.

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A European Model for Public Transport Authorities in Small and Medium Urban Areas

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Abstract

Public Transport Authorities (PTAs) are well-established in large urban areas. These dedicated authorities act in the public interest to ensure that a well-functioning, integrated transport system operates within their territory. Within Europe, economic pressures and changes in regulation to encourage more competition are providing the catalyst for municipalities/authorities of all sizes to review the structure under which transport is managed and provided in their jurisdictions and to consider the suitability of establishing a PTA. Based on findings from case studies in eight small and medium urban areas across seven European countries, it is clear that although user needs remain at the center of the actions of a PTA, the level of functionality provided by metropolitan PTAs would not be suitable or possible for a PTA in a small- or medium-size urban area. This paper presents a summary model of the functions/responsibilities and guidelines on the organizational structure that are most suitable for PTAs in small and medium urban areas in Europe.

Introduction

Recent legislation in Europe (European Union 2007) is encouraging a more open and competitive market in public transport provision across territories of all sizes (van de Velde 2008). At the same time, there is the growth in demand for more environmentally-friendly transport initiatives (European Commission 2013), with which local authority transport departments historically have little experience. Coupled with a continuing trend for decentralization of various powers from central governments to the local level (see, for example, Zegras et al. 2013), more areas, including smaller cities and surrounding rural areas, are considering restructuring of transport planning and delivery into operating units and controlling bodies or Public Transport Authorities (PTAs) (see, for example, Schuchmann and Papadimitriou 2009).

PTAs are now well-established in large urban areas, and a pan-European organization, European Metropolitan Transport Authorities (EMTA) (http://www.emta.com/), exists to support and transfer best practices among metropolitan transport authorities. EMTA has 27 member cities in which all but one (Vilnius) has a metropolitan area population for which the PTA has responsibility for 1+ million inhabitants. There is no equivalent organization for smaller cities or regions containing fewer than 1 million inhabitants that are considering establishing a PTA. Therefore, this population figure was used to provide a loose definition to distinguish between large urban areas (>1 million) and small/medium urban areas (<1 million).

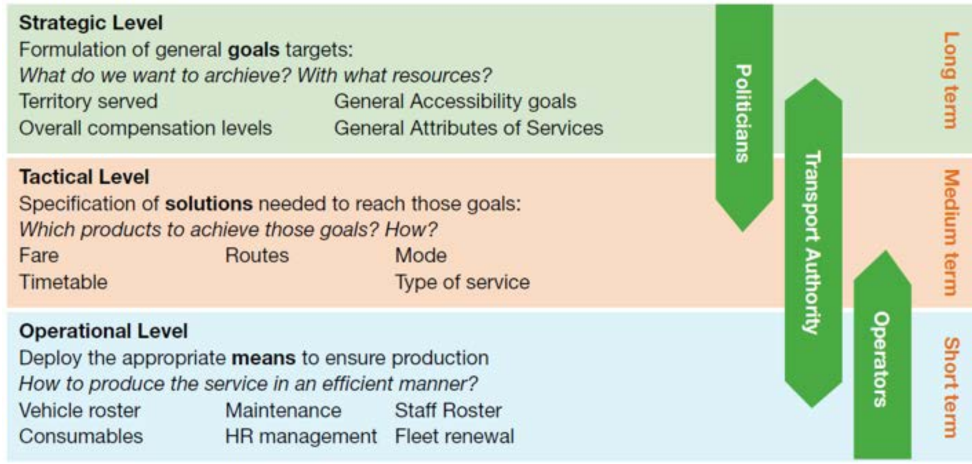
This paper draws on all the activities within the EPTA (European Model for Public Transport Authority) Project, a European Territorial Cooperation project that was active between January 2012 and July 2014. The overall objective of EPTA was the transfer of experience, knowledge, and good practices about PTAs, with particular focus on small and medium urban areas. The paper summarizes the capitalization of the project experiences, resulting in a strategic model and a practical guide with concrete suggestions for effective establishment and management of a PTA in small/medium urban areas.

In describing a model and guidelines for PTAs (also referred to as organizing authorities), it is relevant to first consider the International Association of Public Transport (UITP) definition of what PTAs are or should aim to be: "Organising Authorities are organisations which act in the public interest to ensure a well-functioning, attractive, and integrated transport system. They provide the framework for successful public transport directed at economic, social, and environmental value for citizens and business" (UITP 2009).

As illustrated in Figure 1, a PTA makes the link between political decision-makers and public transport operators, as follows:

- PTAs provide the framework to organize and coordinate different mobility options across a defined geographical area to ensure delivery of efficient, comfortable, and high-quality public transport.
- Whether an operator is public or private, the PTA's role is to act within the public interest to ensure that different modes are well-integrated, affordable, and accessible and to organize this in a manner that complies with strategic level goals and targets set by politicians.
- These strategic-level goals can relate to public transport and accessibility targets but also can be related to policies in related fields such as environment, land use, social inclusion, parking, or traffic planning.
- The transport authority has a set and often limited budget with which to achieve this.

FIGURE 1.
Levels of responsibility in transport provision



Source: UITP 2005

In practice, it is government officers (at either national, regional, or local level) who ensure compliance with strategic goals. The extent to which a PTA should be involved with strategic- and/or operational-level activities varies according to local circumstance but is largely influenced by the scale of the city/area being served. The next section provides guidance on this.

PTA Model in Large Urban Areas

It is now universally recognized that large urban/metropolitan areas benefit from having a PTA and, typically, these follow a decentralized organizational structure that is operated by a dedicated statutory agency (CfIT 2001; Atkins 2007; Masa 2009). Previous studies by EMTA (2003), Finn and Nelson (2004), UITP (2011), and Naniopoulos et al. (2012) have identified the main activities and responsibilities in providing transport services for the public. These have been consolidated within EPTA to form seven main pillars, as shown in Table 1.

TABLE 1. Seven Main Functions of a PTA

1. Regulation	A legal framework gives structure to a PTA to allow it to function in close cooperation with the local government and operators and to carry out the policies made by policy-makers. A legal framework usually defines the options that are open to PTAs to implement. In some cases, it may require some additional legislation to be created to allow the PTA to introduce changes consistent with the regulatory framework for all modes. The framework of activities among stakeholders is strongly linked to the legal framework governing the PTA . *For example, a framework that foresees the presence of structured PTAs gives them strength and authority to allow the organization to meet its objectives.*
2. Planning	The planning function is usually divided into the following categories; Planning Services, Budgeting Resources, and Operatively Designing/Scheduling Services. These activities themselves could be part of the PTA. On a political and administrative level, planning should be linked to and influenced by other public planning activities, such as environment, economics, social, urban, rural, etc. *For example, a PTA can be responsible for planning the entire process, including sourcing resources, budgeting services, and designing/scheduling services, as defined by legal bodies. On the other hand, a PTA can act as an advisory body, providing assistance to stakeholders, such as local bodies, operators, etc.*
3. Tendering / Awarding	The tendering/awarding procedure usually is regulated by law. It is a crucial function in which the operator(s) are chosen and a service contract is awarded. A successful PTA can establish criteria and grounds for fruitful cooperation with operators, based on quality, efficacy, and efficiency. For example, a direct award to an operator does not usually lead to contract optimization. This may be due to local circumstances—lack of competition, etc. A structured tendering process involving all stakeholders can lead to improved services designed to meet the needs of users in the most cost-effective manner.
4. Integration	In planning and awarding services, integration and coordination among different modes and stakeholders (other departments/sectors, such as Health, Education, etc.) that deal with sustainable mobility as a whole represent a strategic objective for delivering inter-modality and co-modality. Of course, the result (efficient integration) can be a benefit for the users and also for the contract, distributed between the PTA and the operator(s). *For example, service integration can improve levels in satisfaction for all users, including those who are rural or urban; older adults and persons with disabilities; commuters; education, health, and social service agencies; leisure establishments; and businesses. Integration between modes can lead to the development of multimodal networks that include bus, train, metro, tram, car-sharing, bike-sharing, taxis/car hire with drivers, and parking management.*
5. Promotion	The promotion of any service is key to its success. Efficient public transport can shift passengers from individual to collective modes and from unsustainable to more efficient and economic modes of transport. Promotion of services can be dealt with at the political or operational levels, particularly within net-cost contracts. *For example, a PTA that has awarded a gross-cost contract has to invest in promotion of services. A PTA has also to invest in promotion if local bodies are deeply interested in its efficacy. A PTA can ignore promotion and include this function in the responsibility of the operator(s) or other organization(s) as part of the tendering process.*
6. Management	Management of services is usually the responsibility of operators (except for PTAs that operate their own services). A transport service contract should contain full understanding of the issues from the PTA, including a good knowledge of the operational activities and meeting the needs of stakeholders. *For example, sometimes PTAs manage services themselves, being owned by local bodies. This usually means that a service contract does not exist. In other cases, it can just own the buses/trains or even maintain them.*
7. Control	Often, the control activity is underestimated. It is important to create trust between the PTA and the stakeholders to ensure that the design and operation of appropriate services meet the needs of users. Clearly-defined standards and operational guidelines are required to allow monitoring of performance so good service can be rewarded and poor service penalized. *For example, the real know-how comes from operating and/or from control. Where a contract is foreseen, an appropriate control structure should be introduced to protect the PTA and users.*

The EPTA Project expanded these seven pillars to identify a larger number of associated key functions or sub-tasks, as shown in Figure 2, in which the inner ring shows the EPTA pillars surrounded by a second ring showing the key sub-tasks or functions in which PTAs can be active. Some of these sub-tasks span more than one pillar. The subtasks shown in Figure 2 combine the tasks and responsibilities of all three actors represented in Figure 1, namely, politicians, transport authorities, and operators.

FIGURE 2.
Model for a PTA with full functionality

Due to the scale of transport provision required in large metropolitan areas, the PTAs in large cities tend to have an active role in all of the sub-tasks identified in the outer ring of Figure 2. The extent of their involvement varies by sub-task and by local circumstances. Metropolitan PTAs are the main responsible body for all tasks associated with tender/award, management of contracts, promotion, and integration pillars. The one exception is service delivery, which is largely the domain of the operators; however, even here, PTAs sometimes act as the operator of certain services (Nash and Bray 2014). An EMTA position paper (EMTA 2003), Preston (2010), and, more recently, findings of the CAPRICE project (2011) stress the importance of a strong integration of transport networks and coordination with policies of land planning and urban development. These sub-tasks, associated with the planning and regulation pillars in Figure 2, increasingly are becoming part of the PTA role in large metropolitan cities.

Example for a Large Metropolitan PTA: London

Transport for London (TfL), the PTA for the Greater London area, has involvement in all the subtasks identified in Figure 2. Its role is to implement the Mayor of London's Transport Strategy (MTS) and manage services across London, for which the Mayor has ultimate responsibility.

TfL delivers in-house the London Underground (LU), the Docklands Light Railway (DLR), the London Overground, and the London Tramlink. It does not deliver London's bus services, but does manage them. There is a competitive tender process for 700 bus service routes in which the terms of service are prescribed in detail (constructive planning), including service routes, frequencies, and fares. Contracts are awarded on a gross-cost basis, which requires significant staff resources for performance monitoring and revenue enforcement through ticket inspectors.

TfL developed a ticketless "contactless" smart card (Oyster card) for payment on any TfL-managed public transport service. Each week, around 57 million journeys are made using Oyster cards, which are used for more than 85% of bus passenger journeys.

TfL also acts as the highway and traffic authority for Greater London, with the following responsibilities:

- Full operational responsibility for the Transport for London Road Network (TLRN), which includes 580km of major roads, which make up 5% of London's roads but carry more than 30% of its traffic.
- Strategic responsibility for coordinating works and ensuring the free flow of traffic (including pedestrians) on the wider Strategic Road Network (SRN), an additional 500km of Borough-maintained A roads.
- Management and maintenance of all of London's 6,000 traffic signals and real-time operational control of the road network through the London Streets Traffic Control Centre (LSTCC).
- Management and operation of the Congestion Charging, Low Emission Zone (LEZ), and Source London schemes, as well as enforcement of decriminalized traffic offenses on the TLRN, including parking, loading, and bus lane regulations.

Operational revenues, including fares and congestion-charge income, account for more than 47% of total funding and amount to approximately £5billion p.a. The remainder of the revenue comes in the form of a central government grant, but this is increasingly being replaced by local taxation (in the form of local business rates and taxes) over which TfL has more control.

The MTS is the principal policy tool through which the Mayor and TfL exercise their responsibilities for the planning, management, and development of transport in London. The development of this strategy has been delegated to TfL although the Mayor retains responsibility for approving consultation documents. TfL was delegated responsibility for undertaking the necessary consultation exercises and impact assessments.

The above illustrates the extent of the tasks for which a large metropolitan PTA has responsibility. However, this level of activity requires significant resources in terms of finance and staffing. TfL employs more than 20,000 staff and annually requires more than £5billion in funds in addition to the operating revenues generated.

PTA Model in Small/Medium Urban Areas

Although the model described in the previous section (and illustrated in Figure 2) may represent the typical situation for a PTA in a very large metropolitan city, the EPTA Project determined that such a level of functionality would not be suitable or possible for a PTA in a small or medium urban area (< 1 million inhabitants). PTAs in some large metropolitan areas have powers devolved to them by legislation, enabling them to set policy specific to their jurisdiction with statutory powers of enforcement and autonomy to raise their own financing to fund services and PTA activities, but smaller cities and surrounding rural areas do not have such powers. The result of this is that there is simply not the expertise and influence at the policy level or the financial resources and manpower at the operational level in a small/medium urban area PTA to take an active role in all the sub-tasks identified in Figure 2.

The development of a PTA model for small/medium urban areas was shaped during the course of the EPTA Project through the transfer of experiences among project partners and local experts at a series of eight workshops and nine training courses and staff exchanges. In addition, several of the PTA model sub-tasks illustrated in Figure 2 have been investigated in more detail within eight feasibility studies by project partners to assess the relevance and importance of these sub-tasks in different operating environments and under differing governance structures. These eight feasibility study sites include:

- Thepta (Greece): "Tendering and Awarding the Bus Transport Services in the City of Thessaloniki"
- Alot (Italy): "Business Plan for a PTA—Awarding the Service"
- SRM Bologna (Italy): "Design and Control of a Public-Transportation Service Contract"
- Brasov (Romania): "Structure and Role of the Brasov Metropolitan PTA"
- Almada (Portugal): "Mobility House of Almada"
- Rogaland (Norway): "Integration and Simplification of the Fare and Ticketing System in Rogaland"
- Razlog (Bulgaria): "Bicycle Sharing System and Car Pooling System"
- Prague Suchdol (Czech Rep): "Establishing More and Better Consultation with Local Partners and the Public"

Analysis of these feasibility studies revealed that, despite the studies having very different aims and environments in which they were examined, a number of key findings emerged:

1. The level of involvement by the PTA needs to be based on the scale of the operation. PTA involvement has a resource and time cost associated with it. What works in big cities often is not appropriate or possible in small towns and medium-size cities. In general, the larger the population covered, the more functions the PTA can take responsibility for.
2. Contract design and award are key to PTAs of any size. This is the area in which PTAs have the power to influence who operates the services and the way in which

operators act, which has a bearing on quality and levels of service, expectations for supply of service performance data, and levels of integration with other operators and other modes. It dictates the operator requirements for service monitoring and for supporting integration action that the PTA may implement. The type of contract can influence the marketing strategy and approach of an operator—e.g., net cost contracts place the onus on the operator to attract passengers, which tends to result in operators providing innovative and well-marketed services. (For more detailed information and advice on implementation, see the EPTA online training module on Contract Design and Award at http://www.eptaproject.eu/training/on-line-training/on-line-training-tool-contractaward/.)

3. Large metropolitan PTAs are inclined to have a hands-on approach to service monitoring and promotion activities rather than delegating these tasks to operators. Medium and small cities, on the other hand, do not have the resources to dedicate significant manpower to service promotions and monitoring of services and, instead, tend to focus on approval and supervision of operator-led monitoring of services and on activities related to integration among operators, modes, and sectors. (For more detailed information and advice on implementation, see the EPTA online training module on Monitoring and Incentives at http://www.eptaproject.eu/training/on-line-training/monitoring/.)

4. Large metropolitan cities take an active role in policy forming to ensure that policies in land planning and urban development are integrated with transport. They also are integral to the planning of transport infrastructure investments that impact on their area (e.g., airport, rail, and road-building initiatives). Medium- and small-city PTAs have little or no input into these matters, as their planning is undertaken at a higher level (often national or regional government) and is paid for through national or local government funding. It is vital that there is better communication and integration between the PTA and these external departments at the planning stage. The EPTA Project identified the need for a more formalized mechanism by which local needs and concerns can be more strongly represented in the policy and planning process. This is relevant not only to medium- and small-city PTAs having a voice in regional or national policy and planning, but also for single municipalities within a large metropolitan city being able to feed into higher-level policy making and planning that impacts their citizens. The recommendation from EPTA is that a policy- and strategic-level planning committee be constituted that provides the platform for coordination and cooperation between local municipalities, PTAs, and metropolitan/regional government. The committee should include PTA representatives, national/regional government decision-makers/politicians, locally-elected politicians, and local government officers, as well as specialist groups of experts (e.g., university, third sector, etc.) to advise and feed into the planning and decision process to help ensure that local interests are being represented without political bias.

5. The policy- and strategic-level planning committee (as detailed above) could also preside over financing and fundraising/spending decisions. This makes it more plausible to adopt local funding strategies such as local levies on fuel sales and employment or local sales taxes. These provide a democratic and locally-accountable

means of raising funding for public transport. The presence of locally-elected representatives on the committee will ensure that local citizen preferences are upheld and could result in a more flexible and locally-focused funding stream that enables PTAs to better respond to the needs of their people rather than being restricted by national or regional funding constraints. (For more detailed information and advice on implementation, see the EPTA online training module on Funding at http://www.eptaproject.eu/training/on-line-training/funding/.)

Based on the above findings and recommendations from the EPTA Project, Figure 3 illustrates the PTA model for a small rural to medium urban area.

FIGURE 3. Model for PTA in medium or small city

PTA Structure in Small/Medium Urban Areas

The findings from the EPTA Project suggest that the most cost-effective PTA structure for small and medium cities appears to be that of a decentralized agency that is contracted/commissioned by the regional or national government. The primary focus, then, is to provide approval and supervision of services and to facilitate/enforce integration among operators, modes, and sectors.

If the model of Figure 3 is adopted, including the formation of a policy and strategic planning committee, then the PTA can operate as an independent organization with the following advantages:

- Local financing and funding become possible.
- User needs remain at the center of the actions of the PTA.
- The focus on a more limited set of functions allows more expertise in these functions to be developed by employees, ensuring effective control of performance of the contract of transportation services to high-quality standards.
- Many of the risks of providing services and resources required for service data collection and promoting services are borne by the operators.
- Labor-related issues associated with in-house service provision are displaced to the contracted operator, which often has more flexibility in dealing with/avoiding such issues.

The biggest advantage of the above approach is that the cost of PTA provision can be relatively modest since the staffing levels are much lower than those required for a large-city PTA, in which involvement in service design, monitoring, and promotion is generally much greater. The agency approach also allows for flexibility in staffing when required, as it is easier to appoint additional staff on a temporary or short-term basis than if a relatively small municipality were to appoint staff directly. The establishment of a policy and strategic planning committee also removes the need for the PTA to have a top-heavy management structure of locally-elected politicians, since they sit on the committee alongside the PTA representatives rather than on a PTA board of directors.

All the above contributes to a very lightweight staffing structure while remaining responsive to peaks in activity/workloads. This results in a low-cost solution to forming a PTA, which is a critical requirement in small and medium cities.

Examples of PTA structure and functions/responsibilities are provided below for three EPTA project partners: SRM Bologna, the proposed Brasov Metropolitan Area PTA, and the proposed PTA for the Razlog region.

Example for a Medium City PTA: Bologna, Italy

SRM (Reti e Mobilità Srl) is the agency that acts as the PTA for the Province of Bologna, serving a population of almost 1 million across 60 municipalities. It is a joint-stock company whose capital is entirely publicly-owned by the Municipality and Province of Bologna and was established in 2003 when several functions of public interest were delegated to it from local governmental bodies in the field of public transport.

The budget to fund the public transport services delivered totals 96M Euros per annum, with more than 80% of this provided by the Regional Government (Emilia-Romagna Region in the case of SRM) based on parameters such as total public transport km per year, etc. The remaining funding comes from local bodies. SRM manage the budget and controls the main assets necessary to provide public transport services. With this budget, it has complete control of the tender and award process and funds the local operators on the basis of a contract for service. Management and control of contracts also are tasks delegated to SRM. SRM has some role in promotion of service integration, but strategic functions such as planning and setting fare levels are retained by local municipalities and the Province of Bologna; policy/regulation is mainly set by the Regional government. As a result, SRM has a very light staffing structure, employing only nine persons. The budget for this is provided from a 0.5% cut of the Regional PT Funding (360,000 Euro per year) plus around 400,000 Euro per year from rent relating to transport infrastructure.

In the recent months, SRM has tendered for and been awarded the management of on-street parking on behalf of the Municipality of Bologna. As a result, an additional two staff will be appointed. This illustrates the flexibility and ability to respond to additional opportunities offered by the agency approach to PTA delivery in small and medium cities.

Proposal for a Medium City PTA: Brasov, Romania

The Brasov Metropolitan Area PTA was established as a reaction to the highly-unregulated manner in which transport services are provided in the Brasov City Region (approximately 450,000 inhabitants in a relatively compact area). The PTA was developed during the EPTA Project and has gained from European best practices identified both within and outside the EPTA partnership.

The PTA for the Brasov Metropolitan Area is basically an NGO agency of local public bodies. This structure is in line with the Romanian legislative framework and, for the first time, allows small communities and local authorities to be involved in organizing the public transport system in and around their local community. A newly-formed Association for the Sustainable Development of Public Transport Brasov was established in 2013 and includes the 15 communities in the metropolitan area together with the Brasov Metropolitan Agency PTA. This association will make strategic decisions on policy/regulation and planning. The initial approach is for the Brasov PTA to tackle a limited set of functions such as tendering/awarding and control with inputs to planning and regulation through the Association for the Sustainable Development of Public Transport Brasov; other functions will be integrated into the PTA model as the organization grows and a favorable local critical mass is in place.

The permanent staffing structure for the PTA will be small (4–8 full-time employees); specialists can be hired temporarily for specific tasks when necessary. Given the reduced staff structure, a large part of the responsibility for monitoring of the service contracts will be transferred to selected operators. The PTA will establish procedures for monitoring and will verify compliance and collect monitoring process data. To compensate for the small PTA staff, it will be desirable, where possible, to use ICT technology, especially for service-monitoring purposes.

The annual budget for the proposed PTA is around 157,000 Euro, but a minimal budget would allow functioning of the PTA with only 100,000 Euro/year.

Proposal for a PTA in a Small Town and Surrounding Region: Razlog, Bulgaria

The Municipality of Razlog, located in southwest Bulgaria, includes a small population (21,709) with centers in the towns of Razlog (12,852) and Banska (3,000). The region is a mountain tourism destination characterized by the rapid growth of ski resorts on the fringes of the towns and large fluctuations in seasonal employment. A rail link and intercity coach services pass through the region, but the only current form of local public transport operating within the municipality is a limited bus service. The low and variable demand for transport makes all but the most socially-essential bus routes unaffordable.

Regulation, strategic planning, and funding for transport are controlled at the national government level. Currently, the Municipality is responsible for procurement of the essential local bus lines. It also coordinates the routes regarding the needs of the different public transport users, and special routes and timetables are prepared for student transportation. It is clear that the Municipality can continue to provide this minimum level of transport service without the need to establish a PTA; however, seasonal demands for transport are not being adequately met. Although tourists can afford to use taxis, there is a need to accommodate more transport demands of the local population. Furthermore, to support business growth, especially in the tourism sector, additional transport options are required for lower-paid workers to access the main employment sites.

A culture of informal carpooling exists in the region and, due to the flat geography and relatively short distances between the main settlements and employment centers, there is potential for greater amounts of cycling. As a result, a PTA will be established to plan, implement, and manage a shared public bicycle system and coordinate a formalized carpooling service, including promotion measures for both. Although this could be established as a section within the municipality, increasing the staffing capacity to provide these services cannot be justified due to the seasonal nature of the demand. Therefore, it was considered more advantageous to establish a specialized NGO to act as a PTA agency to handle the operation of the system in cooperation with the Municipality of Razlog. The PTA will not require funds from the Municipal budget and will seek to develop funding partnerships with local businesses and through formation of public/private partnerships for construction of elements of the bike-share system. Given the local circumstances and limited staff resources, it was felt that the PTA agency would be better able to mobilize the support of all stakeholders to build and maintain a wide, active transport and carpooling system. Once the active travel measures become established, there is the possibility for the procurement and management of public transport services to migrate to PTA agency control.

The need for and roles of a PTA in an environment such as Razlog Municipality are different from that of a medium-to-large city. The greater focus on "soft" transport measures is moving out of the traditional focus of PTAs (providing public transport services) into the wider domain of providing alternatives to private car use.

Conclusions

This paper provides strategic guidance on the structure and functions of a PTA for small to medium urban areas. This provides a useful tool for policy decision-makers and stakeholders to follow when considering setting up and/or managing a PTA in their territory. The key guidelines are summarized below.

Guidelines for PTA Functions

User needs remain at the center of the actions of a PTA, but the level of functionality provided by metropolitan PTAs would not be suitable or possible for a PTA in a small or medium urban area. Figure 3 presented the model for a PTA in small and medium urban areas, and the main elements of this model are the following:

- Contract design and award are key to PTAs of any size.
- Thereafter, the primary focus of a PTA is to provide approval and supervision of services and to facilitate/enforce integration among operators, modes, and sectors.
- The PTA delegates to operators the resource-intensive daily activities (service delivery, monitoring, and promotion).
- The focus on a more limited set of functions (in comparison to Metropolitan PTAs) allows more expertise in these functions to be developed by PTA staff, ensuring effective control of performance of the contract for transportation services to high-quality standards.
- Many of the risks of providing services and resources required for service data collection and promoting services are borne by the operators. Labor-related issues also are displaced to the contracted supplier.
- Integration should remain a core element of PTA activity in small and medium cities.
- Local needs and concerns should be more strongly represented in the policy and planning process through formation of a policy and strategic planning committee, enabling formal inputs from the PTA and local stakeholders to planning and regulation/policy decisions.

Guidelines for PTA Structure

The most cost-effective PTA structure for small/medium cities appears to be that of a decentralized agency that is contracted/commissioned by the regional or national government. The PTA can operate as an independent organization with the following advantages:

- Local financing and funding become possible.
- The cost of PTA provision can be relatively modest since the staffing levels are much lower than those required for a large-city PTA in which involvement in service design, monitoring, and promotion is generally much greater.
- The agency approach also allows for flexibility in staffing when required, as it is easier to appoint additional staff on a temporary or short-term basis than if a relatively small municipality were to appoint staff directly.

- Formation of a policy and strategic planning committee removes the need for the PTA to have a top-heavy management structure; locally-elected politicians can sit on the committee rather than on the PTA board of directors.

The result is a very lightweight staffing structure that remains responsive to peaks in activity/workloads, which provides a low-cost solution to forming a PTA and is essential in small/medium cities.

The focus of this paper is firmly based on European experience, but it is likely that the general principles of the model being proposed have relevance to small/medium urban areas outside Europe. In the United States, public transit agencies typically provide similar functions to those identified in Figure 2; in some cases, they are part of city government and in others they are independent public agencies. Typically, they provide the majority of their primary services in-house and do not contract them out (Booz Allen Hamilton 2011). However, U.S.-focused research (Iseki 2008) points towards the increasing efficiency of smaller transit agencies as their level of contracting increases. Therefore, it is likely that the European model proposed for small/medium cities (based on contracting operations and monitoring) illustrated in Figure 3 will also have relevance in the U.S.

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Mind the Gap: Perceptions of Passenger Aggression and Train Car Supervision in a Commuter Rail System

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Abstract

Negative perceptions about the safety of a commuter rail system can act as a barrier to using public transportation. When operational issues increase rider tension (i.e., crowding or worsening on-time performance), or the management capabilities of conductors and law enforcement personnel are called into question, an upsurge in passenger-on-passenger aggression may occur. In turn, riders concerned about their safety may retreat to personal vehicles or other forms of "less risky" transit, such as express buses. Modifying an interstitial estimation process, this study presents a new method of identifying where rider concerns about public safety concentrate. Using the commuter rail system of Los Angeles as a case study, specific inbound and outbound trip segments were found to exhibit different problems. Raw scores identify segments in need of greater train car supervision, and these segments differ from where discontented riders congregate (requiring customer service outreach). Tailored responses, focused on a few segments, stand to improve perceptions of safety and, ultimately, may increase ridership.

Introduction

The use of public transportation has widely-recognized benefits at many levels. Public transit reduces traffic congestion, which increases public interest in the provision of convenient and affordable mass transit services. This issue is of special concern in the Los Angeles metropolitan area, which was considered to have the worst commute in the United States in 2007 based on pollution levels, time spent in rush-hour traffic, and number of per-capita fatal car accidents (Forbes 2007).[1] In 2011, the advocacy group Transportation for America ranked this region the second-worst in the country regarding the accessibility of public transit for older adults.[2]

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[1] http://www.forbes.com/2007/07/23/health-commute-pollution-forbeslife-cx_avd_0724commute.html (accessed August 8, 2014).

[2] http://t4america.org/docs/SeniorsMobilityCrisis.pdf (accessed August 8, 2014).

However, people take advantage of public transportation services only when systems run efficiently and are perceived to be safe. Studies in the U.S. and overseas (New York, Washington DC, London, Stockholm, etc.) have shown that transit crime affects all large systems, reducing the number of passengers, creating service disruptions and decreasing revenue (Clarke, Belanger and Eastman 1996; LaVigne 1996; Crime Concern 2002; Newton 2004; Ceccato 2013). Interestingly, the results of these studies show that crime does not happen evenly across the system; it concentrates on specific lines, segments, and stations.

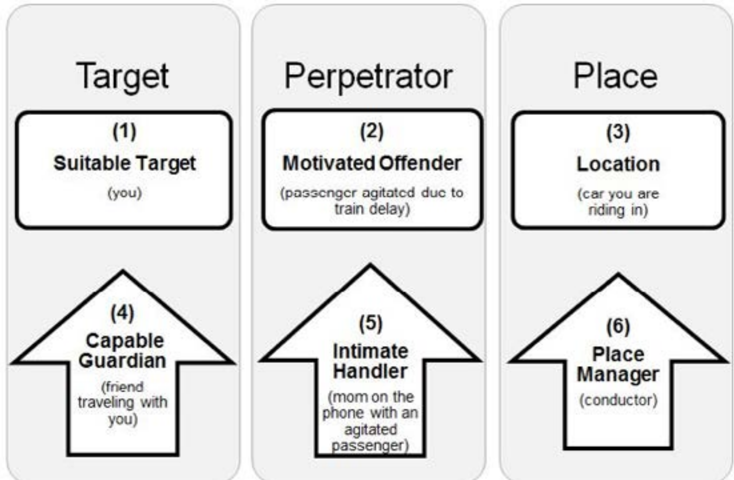
Existing research on perceptions of safety in public transportation explores issues such as whether fear of crime is affected by experiences of victimization (Feltes 2003; Crime Concern 2002, 2004); which factors influence perceptions of safety when using public transportation (Currie, Delbosc, and Mahmoud 2013); and the use of social media to study those perceptions (Collins, Hasan, and Ukkusuri 2013). The questions of exactly where incidents that generate perceptions of unsafety occur, and in what parts of the system riders feel more fearful, remain unanswered.

Our study addresses these questions by employing a unique method, as described below, for estimating where and when public safety problems occur and where discontent accumulates among the ridership of the Los Angeles Commuter Rail system, Metrolink. We begin by considering the role place managers play in ensuring train car safety and the importance of pinpointing where incidents occur and concentrate in the system. This section is followed by a brief description of Metrolink. Then, we explain the estimation process and the results. To conclude, we discuss the implications of this work and offer a few suggestions about how to address public safety concerns.

Transit Crime and Public Safety Issues

Many criminologists argue that crime and public safety issues emerge when opportunity abounds. Illustrated in Figure 1, the conditions that generate opportunities can be reduced to six essential factors (Felson, 2006). Crime occurs when (1) a suitable target and (2) motivated offender encounter each other, (3) converging in time and space, in the absence of protective agents. Protective agents watching over the possible targets are called (4) capable guardians and those keeping an eye on possible offenders are described as (5) intimate handlers. By some accounts the most critical protective agent is the one monitoring the place where convergence occurs, these are (6) place managers. Place managers are critical to public safety as they have the authority to control behavior in their assigned area, either by proactively working to prevent crime or responding to issues as they unfold. Conductors are important place managers because they have access to resources. For instance, they can call for sheriff support and they can fine or eject riders that behave badly. Ejecting riders temporarily suspends their privilege to travel on the system, and this can act as an effective deterrent. However, as research demonstrates (e.g., LaVigne 1996; Ceccato 2013), motivated offenders must perceive that this response is a certain consequence of bad behavior and that conductors and their law enforcement counterparts will act with celerity.

FIGURE 1.
Routine Activities Theory



One of the challenges unique to transportation research is determining where an incident occurs during a journey. Reporting mechanisms generally record the train number, date, and time and, on rare occasions, the origin and destination stations of the parties involved; missing is the exact location of where an issue occurred. Moreover, since the train may be in motion when an issue transpires, it is not entirely certain how much of the trip is affected by the incident. This means that since people board at each station while the train is en route, an incident may continue with a new batch of riders—unsuspecting riders, not having witnessed the beginning of the incident, may be caught off-guard.

Fortunately, this problem of geographic imprecision received a great deal of attention, and an aoristic procedure was adopted to address it (e.g., Ashby and Bowers 2013; Newton 2004; Ratcliffe 2002). Applied to crime and public safety, aoristic techniques estimate the time at which incidents are likely to have occurred at specific locations. Recast as an "interstitial" estimation process (Newton, Partridge, and Gill 2014), with information about the line, time of day, origin, and destination, it is possible to calculate the probability that an event occurred at any point of the complainant's journey. By summing these probabilities for all reported incidents, it is possible to generate a sense of when and where events are likely to concentrate.

Metrolink

Metrolink[3] is a regional commuter rail service operated by the Southern California Regional Rail Authority (SCRRA). It is the third-largest commuter rail agency in the United States based on its 512-mile directional route network and the seventh-largest based on annual ridership. Metrolink operates 7 lines across 6 counties and serves 55 stations, most of which are located in different cities. At various locations, the system connects with Amtrak, light rail, and bus services. Metrolink equipment includes 55 locomotives and 184 coaches with an average passenger capacity of 150 passengers and 90 cab cars with a capacity of approximately 101–130 passengers. Although Metrolink operates throughout a region that contains close to 20 million people, it recorded an average weekday rider-

[3] A map of the system is available at http://www.metrolinktrains.com/pdfs/MetrolinkMap.pdf.

ship of only 40,795 boardings during the second quarter of FY 2013–2014. Passenger trips average 38 miles, and 65% of riders commute to/from work (Metrolink 2014).

Trains are staffed with a conductor and an engineer subcontracted from Amtrak, who are supervised by Metrolink compliance officers. If a public safety issue arises at any point in the journey or on a platform, the responsible agency is the L.A. County Sheriff's Department. Issues occurring at a station or in a parking facility fall under the domain of the City's contracted private security or law enforcement agency, as each city maintains its own stations. Sometimes Metrolink security officers and Customer Engagement Representatives (CERs) are deployed to stations to ensure safe boarding of trains during peak ridership or to assist with service disruptions and bus bridges.

Goals of the Current Study

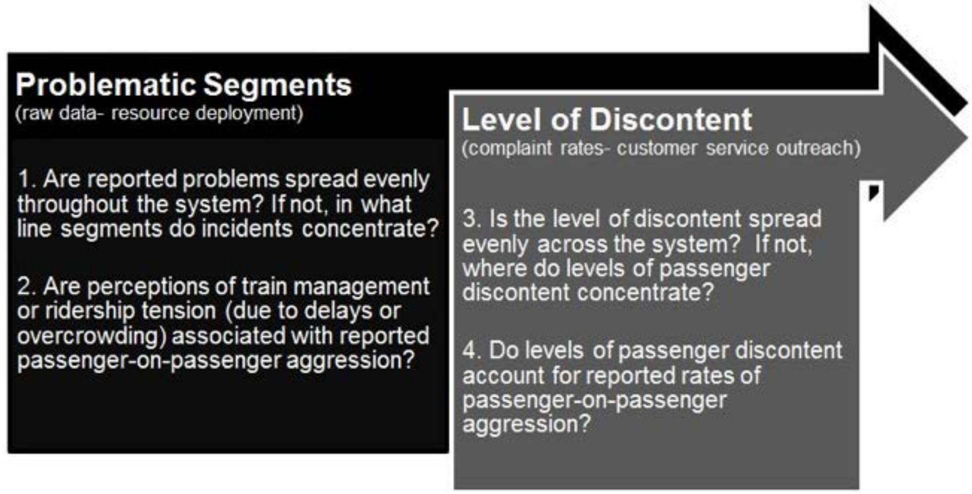
With such a large service area, ensuring effective place management along all routes is a significant operational challenge for Metrolink. The goal of this study was to identify the segments (portions of the train line between stations) that pose the greatest perceived public safety risk.

Not everyone voices their opinions, and reporting systems rarely capture all information necessary for problem identification and diagnosis. For instance, estimates suggest that, at the most, 1 in 5 people and, at the least, 1 in 20 riders actually notify transit services of problems encountered while en route (Vavra 1997). Recordkeeping by conductors and law enforcement officers capture some concerns, but much activity goes unobserved. When information is available, complainants are often vague about where and when incidents occurred. Thus, with such a large gap in information, alternative methodologies are needed to estimate the concerns of riders.

When analyzing crime and public safety issues, it is important to consider both the volume of activity occurring at specific locations and the rate of occurrence based on the number of people accessing the system. Each calculation tells us something unique about the situation. Tabulating the volume of incidents occurring on each trip segment indicates where problems concentrate (raw scores). This is useful for knowing where to aim interventions for maximum impact. However, travel segments servicing a disproportionate level of worried passengers reveal parts of the system where the ridership feels more vulnerable. These complaint rates suggest where the customer service department and marketing team can focus outreach efforts to address safety concerns that, if resolved, may increase ridership.[4] Figure 2 outlines the four research questions that drive this study.

[4] An example illustrates the need for both calculations. If we analyze two trip segments (A→B and B→C), we might see that in the first one there were 5 incidents and in the second one there were 20 incidents. The volume of problems would indicate that the second leg is more problematic. But if we account for ridership (10 people traveling the first leg and 400 traveling the second), we would find that concern about those incidents is much higher on the first segment (A→B), as it is being reported at much higher rates.

FIGURE 2.
Research questions



Methods

Data

Complaint information from August 1, 2009, to December 31, 2012, was extracted from an archive maintained by the Customer Engagement Department of Metrolink. Although many communication channels exist, this archive captures only formal correspondence—email, letters, and phone calls. Each issue raised is recorded, and a single customer contact can include multiple complaints and/or commendations. As outlined in Table 1, four categories of complaints were used—Rider Tension (including On-Time Performance and Crowding complaints), perceptions of train car Supervision (which indicates perceived quality of place management), and Passenger-on-Passenger Aggression (dependent variable).

TABLE 1.
Description of Customer Complaints about Incidents Occurring while Onboard or during Boarding/Alighting

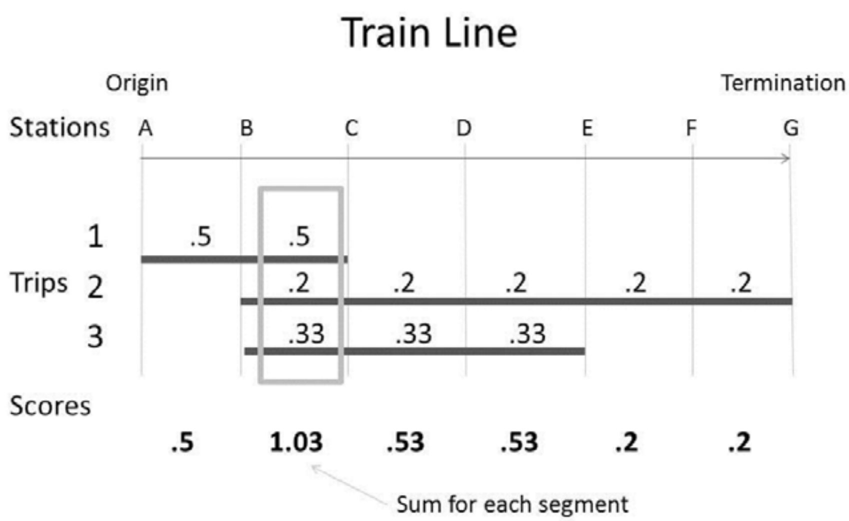
Category	Description	Total Issues	Included in Study	% Lost
Rider Tension: On-Time Performance (OTP)	Concerns about delays and disruptions to regular service (excluding planned maintenance)	1,574	1,423	9.6
Rider Tension: Crowding	Statements about inability to find seating, and congestion in vestibules and stairs (e.g., too many bicycles or luggage blocking movement)	99	82	17.2
Supervision	Statements about a conductor or sheriff not enforcing rules, behaving inappropriately, being aggressive, or failing to respond to a request	497	455	8.5
Passenger-on-Passenger Aggression	Victimization or witnessing aggressive behavior by a passenger on another rider, including assaults, verbal threats, defiance, and disorderly conduct	192	163	15.1

Note: Only formal complaints (email, letters, or phone) are included; tweets and Facebook posts are not. Cases were lost due to missing information about origin or destination of trip.

Interstitial Estimation Technique

Interstitial estimation (Newton et al. 2014), as depicted in Figure 3, provides a method for determining where problems are likely to have occurred given where a person got on the train and at what station he/she departed. For example, a rider writes in to complain about an issue occurring during a trip (Trip 1). In this instance, the trip involves two segments (between stations), and we estimate that it is equally likely that the incident occurred during the first segment as the second. A value of 0.5 (probability) is assigned to each segment. A second incident is reported by someone boarding at station B and traveling to the end of the line. The likelihood that the incident occurred on any segment is 1/5 segments or 0.2. The third reported issue involved a person traveling three segments, and the probability of the incident occurring on any one segment is 1/3 or 0.33. By summing all probabilities for each segment, we arrive at a total estimated probability of issues occurring for each segment of a line. Separate estimates were generated for inbound (toward L.A. Union Station or Riverside Station) and outbound travel. These values are used to weight the transportation network.

FIGURE 3.
Trip segment estimation process



Calculating Rates

The process described above provides the estimated number of incidents (raw estimate) per segment. It does not take into consideration the number of passengers that typically ride the line. To convert the raw estimates into rates per 1,000 passengers,[5] we divided the estimated probability of problems by the number of riders per segment. To calculate the number of riders on each segment, we used the number of boardings per station and the number of riders per line during peak travel. This process is outlined in Figures 4(a) and 4(b).

[5] Using the industry standard of 100,000 riders was not feasible given the low level of ridership.

FIGURE 4(a).
Calculating percent of boardings for each station, per line and by direction traveled

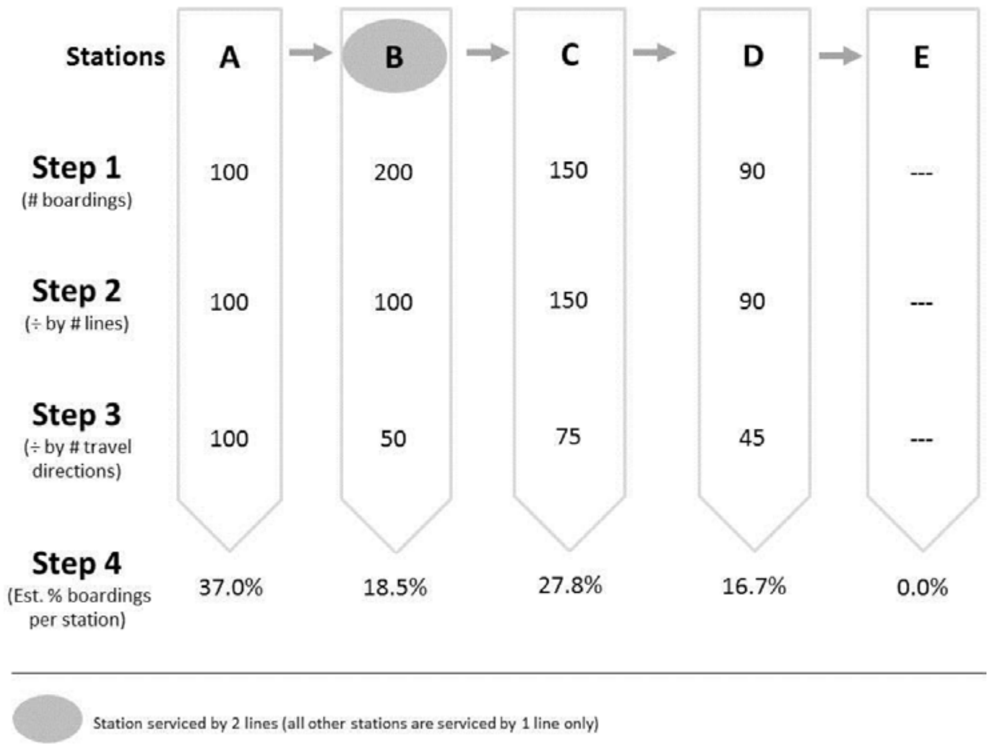
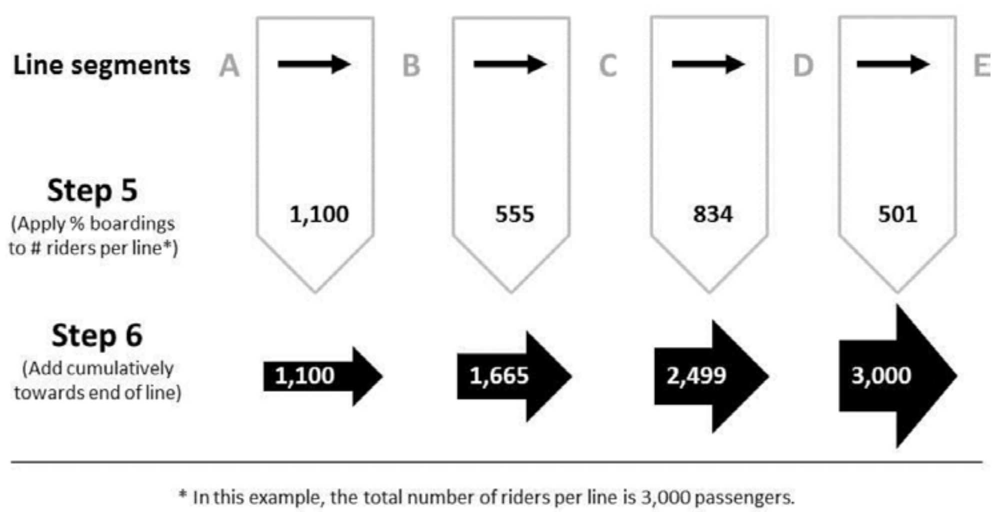


FIGURE 4(b).
Process used to estimate ridership, per trip segment

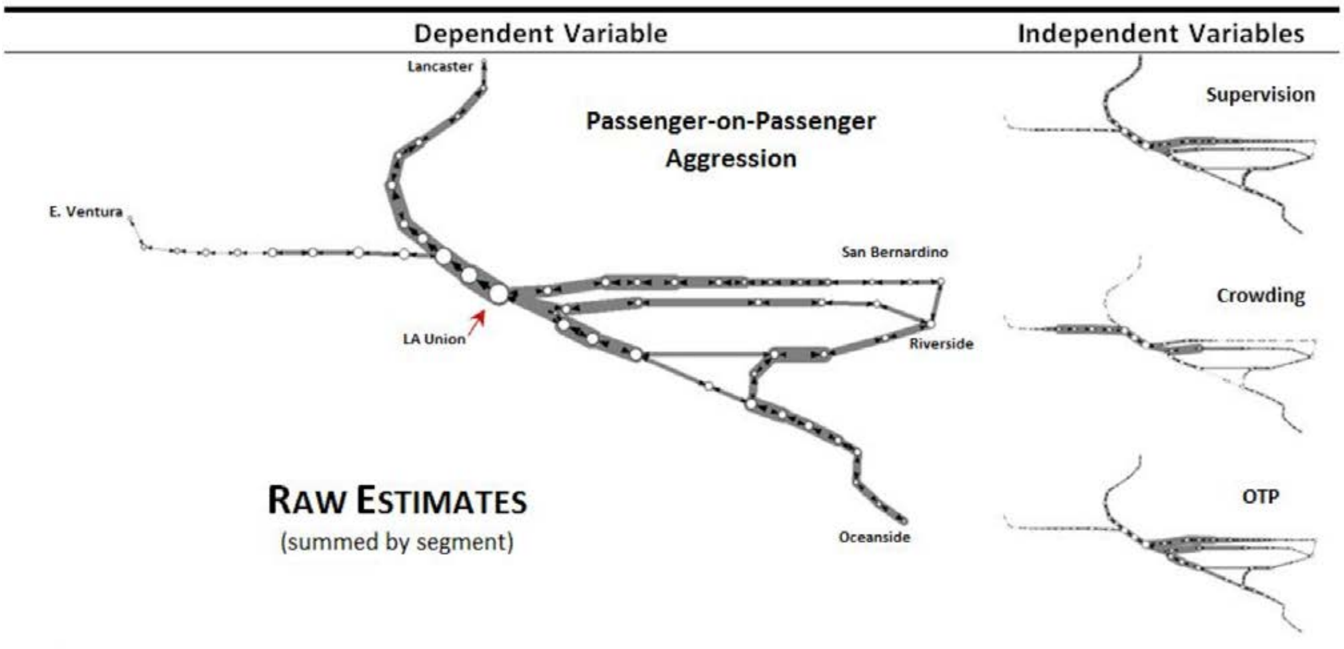


We began Step 1 with the total number of boardings at each station. This count of passengers entering the system was divided by the number of lines servicing the station (Step 2) and the number of travel directions of each line at each station (Step 3). This estimated the number of passengers entering each line in each of the travel directions (inbound or outbound). The end of line station was not included, as passengers would only be able to get off the train, not on it. The first part of the calculation resulted in the percent of boardings for each station (Step 4) per line and by direction traveled.

The second part of the calculation generated an estimate of ridership per trip segment. In Step 5, the percent of boardings per station was applied to the total number of riders per line and direction traveled. Finally, the estimated ridership per segment was obtained by adding the number of riders cumulatively toward the end of the line (Step 6).

Results

Figure 5(a) illustrates the transit network as it reflects customer complaints. Thicker line widths indicate a greater probability of issues that generate complaints. Arrowheads indicate the travel direction. Recall that raw scores tell us where problem behavior is likely to occur (Figure 5[a]) and rates suggest where greater proportions of discontented riders concentrate (Figure 5[b]).



Note: Station symbols vary in size to reflect a statistic called betweenness centrality. Bigger symbols identify stations that are more central to the flow of passengers throughout the entire system (across different lines).

FIGURE 5(a). Visualization of trip segment values for customer complaints, raw estimates

Figure 5(a) shows that reports of passenger-on-passenger aggression concentrate in and around the center of the system (LA Union Station), on the Antelope Valley line (Lancaster–LA Union Station), and the Inland Empire-Orange County line (San Bernardino–Oceanside). The center of the system and the segments close to it accumulate most of the complaints for OTP, crowding, and train car supervision.

Standardized values (Figure 5[b]) suggest that aggression disproportionately concerns riders mostly at the beginning of the Ventura County Line (East Ventura) and on the Inland Empire–Orange County line. These same segments display higher rates of complaints about train car supervision and crowding, while levels of discontent about on-time performance seem to affect the Riverside and 91 lines as well. The high volume of complaints in the center of the system displayed in Figure 5(a) does not correspond with a high level of concern among the passengers (Figure 5[b]), as it is also the part of the system where most riders concentrate.

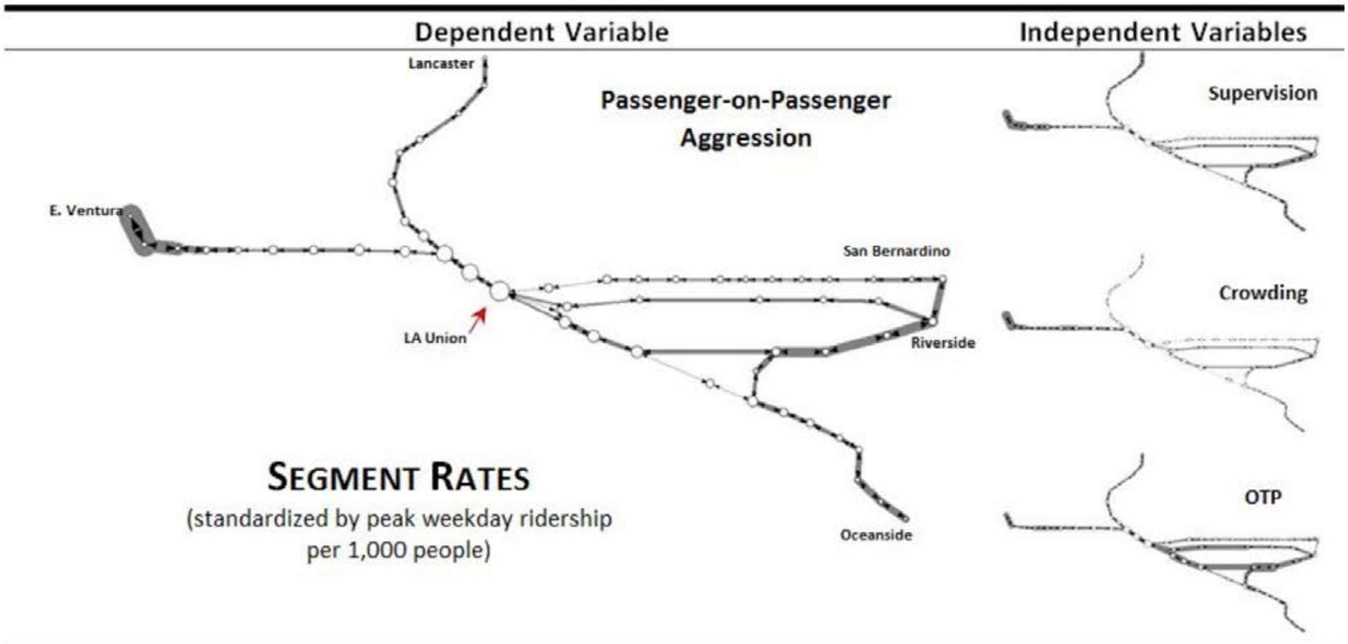


FIGURE 5(b). Visualization of trip segment values for customer complaints, segment rates

The patterns suggested in Figure 5 are further detailed in Table 2. Spearman's Rho coefficients suggest that irrespective of the direction of travel, the prevalence of aggression complaints is correlated with OTP complaints and perceptions of poor train car supervision. However, when we are interested in finding out the segments with higher rates of aggression complaints, poor supervision is the primary correlate for inbound travel. Outbound, a greater proportion of riders who see public safety problems are comingling (or the same complainants may report several issues) with those perceiving crowdedness and problems with on-time-performance.

TABLE 2.
Correlations between Customer Complaint Categories by Trip Segments

		P-on-P Aggression	On-time Performance	Crowded	Supervision
Raw Estimates	Passenger-on-Passenger Aggression		0.850[a]	0.227	0.804[a]
	On-time Performance	0.778[a]		0.453[a]	0.814[a]
	Crowded	0.338[a]	0.413[a]		0.170
	Supervision	0.753[a]	0.783[a]	0.172	
Rate per 1,000 People	Passenger-on-Passenger Aggression		0.456[a]	0.622[a]	0.722[a]
	On-time Performance	0.794[a]		0.587[a]	0.378[a]
	Crowded	0.773[a]	0.551[a]		0.596[a]
	Supervision	0.773[a]	0.819[a]	0.628[a]	

Shaded cells indicate outbound travel, and white cells indicate inbound travel.
[a] p<.001; N = 72; the significance of these Spearman Rho's coefficients was established with a non-parametric bootstrapping procedure (n= 1,000 samples).

Correlations tell only part of the story. Turning to the regression estimates reported in Table 3, it becomes clear that on-time performance is more than three times more important in predicting the number of passenger-on-passenger incidents of aggression (raw values) during inbound travel than all other factors. On the outbound journey, high numbers of reported passenger aggression can be accounted for by complaints about conductors and security (our measure of train car supervision).

TABLE 3. Customer Complaint Categories Regressed on Passenger-on-Passenger Aggression

		Raw Estimates		Rate per 1,000 People	
		β	*Sig.*	β	*Sig.*
Inbound Travel	On-time Performance	0.724	0.000	-0.066	0.310
	Crowded	-0.112	0.072	0.355	0.000
	Supervision	0.218	0.051	0.647	0.000
	F	91.305[a]		92.913[a]	
	Adjusted R^2	0.792		0.795	
Outbound Travel	On-time Performance	0.068	0.744	0.279	0.000
	Crowded	0.295	0.002	0.792	0.000
	Supervision	0.570	0.006	-0.011	0.859
	F	25.049[a]		302.558[a]	
	Adjusted R^2	0.504		0.927	

N= 72 trip segments; 1,000 bootstrap samples were used to test these effects and generate corresponding 95% confidence intervals (available upon request).

[a] $p < 0.001$.

Interestingly, the rate of passenger-on-passenger aggression exhibits opposite patterns. Greater concern about passenger aggression corresponds with complaints about inadequate supervision (inbound) and crowdedness (outbound). This means that, regardless of where the incidents actually accumulate, the proportion of passengers reporting on aggression is linked to concerns about supervision on the way to work and about crowded trains on the return journey. More research is needed to fully understand how crowd sentiment (the aggregated perceptions of passengers) interacts with fear of violence.

Discussion

The onboard climate is more than simply the temperature. Passengers expect not only a reliable, clean, and comfortable environment, but also a safe one. Experiencing or witnessing an altercation while riding on a train is an upsetting event that contaminates the onboard climate and affects passenger impressions of that specific trip, and of the system as a whole.

More than 60% of Metrolink riders commute to work. When traveling on a train, passengers find themselves in an enclosed setting. Over time, passengers commuting on a regular basis come to know, perhaps only by sight, the others with whom they typically travel. When passenger-on-passenger aggression occurs, the effects of the incident will linger among the crowd. Conflict builds. Declining OTP will increase anxiety and stress among passengers, which in turn, may generate more arguments among passengers.

After a long day, a crowded train seems to have that same impact on riders. In both cases, concern about car management is associated with significantly higher levels of aggression. If a conductor is perceived to be unable to handle an issue, trust in the ability of Metrolink to maintain the rules and keep riders safe is called into question, because conductors are the most immediate place managers of train cars. This significantly affects the willingness of people to take public transportation (e.g., Newton 2004; Ceccato 2013).

Tailored responses, focused on asserting stronger train car management in a few problematic segments, stands to improve perceptions of safety and, ultimately, increase ridership. In this research, we looked at safety concerns from two perspectives:

- On one hand, identifying the segments with the higher volume of incidents shows where aggression is actually happening.
    - In the short term, directing security personnel and law enforcement to the specific segments with higher volume of aggressions (which are mostly located in and around the center of the system) could reduce the total number of aggressive incidents happening in the system.
    - Long term, the causes of those incidents must be identified and addressed.
- On the other hand, complaint rates show where passengers are most concerned about aggression, even if the total number of incidents in those locations is low. If a car is full of passengers, a small argument occurring on one end will have little effect on riders sitting 20 rows away. However, if the car is relatively empty, as is often the case toward the end of the line, the effects of one small fight between passengers is magnified. Fear and concern may escalate if help is not forthcoming from the conductor.
    - In the short term, many strategies can be deployed to enhance relations between car managers (conductors) and riders. For example, conductors can be strategically placed to be visible and available at the end of line stations; placards can be posted and flyers distributed to inform passengers about who to call for safety concerns; special promotions distributed by conductors (e.g., giving away pins, special event trip tickets, or other materials) can be used to foster positive interactions with riders.
    - Long term, it is advisable to implement a new approach to train car management on affected segments. Additionally, sustained outreach to disaffected riders through social media and other mechanisms may help to turn complainants into advocates who will attract other riders by sharing positive assessments of their public transit experience.

This is just the beginning of the analysis of this problem which, while providing a good understanding of the Metrolink system through passenger eyes (their complaints) raises new questions. Future research should include direct measures of incidents of aggression and of perceived safety, using crime data and passenger surveys, respectively. Agencies such as Metrolink should consider keeping track of alternative sources of information such as social media (Facebook, Twitter, YouTube, etc.) and building analytic capabilities of these data into their systems. This information could then be matched to more reliable sources of data.

Given the complexity of the system, other variables and units of analysis (stations) should be included in future analyses: measures of specific place management at each station, how many jurisdictions overlap at each segment, the number of systems coinciding at each point of the system (Amtrak, bus, subway), etc.

Light rail and bus service connections provide Metrolink passengers with many multimodal public transit service options, and this significantly increases the mobility of riders. Generally, these multimodal linkages also extend the impact that perceptions of safety and efficiency of Metrolink have on public transit systems. Reducing the number of problems and feelings of unsafety will very likely increase ridership across the whole system.

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Well-to-Wheel Analysis of Electric and Hydrogen Light Rail

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Abstract

The application of renewable energy technologies to rail transit should be evaluated on a comprehensive energy pathway efficiency basis to ensure that the renewable energy technology is truly beneficial. One such method is the well-to-wheel analysis method, which combines the energy efficiencies of each component of the energy pathway into a single energy efficiency value. The focus of this paper is on well-to-wheel analysis of electric and hydrogen light rail. The inefficiencies of the hydrogen train's power plant and hydrogen production process are apparent in the hydrogen train's well-to-wheel efficiency value of 16.6–19.6%. The electric train, due to improved pathway efficiencies, uses substantially less feedstock energy with a well-to-wheel efficiency value of 25.3%. While this result is specific to Charlotte, North Carolina, the electric train efficiency is influenced by the main source of electricity production—it is 24.6% in Cleveland, Ohio (coal heavy) and 50.3% in Portland, Oregon (hydroelectric heavy).

Key words: Light rail, electricity, hydrogen fuel, well-to-wheel analysis

Introduction

Rail in the United States is in the midst of a revival for both freight and passenger rail. The revival and stricter air quality standards prompted research into the application of renewable energies for railroad traction. Hydrogen fuel cells are becoming more cost-competitive with conventional power sources and maintain key advantages such as zero-emissions, little wayside infrastructure, and an abundance of hydrogen in the environment. Passenger rail, especially intra-city rail, in the United States is largely electrified, but hydrogen fuel cells would enable passenger trains more autonomy and a reduction of wayside infrastructure and maintenance costs. To evaluate the application of hydrogen fuel cells to light rail, it is useful to compare the well-to-wheel energy efficiency of the various traction power systems. A well-to-wheel analysis considers the energy efficiency of each step in the energy change and power production component. A well-to-wheel analysis of a concept hydrogen light rail train has not been researched previously. This paper focuses on well-to-wheel analysis of hydrogen light rail transit system and compares it with an electric light rail system.

The motivation for using hydrogen as an energy carrier is two-fold. There are substantial potential benefits, both environmentally and economically, in using hydrogen as an energy carrier. Hydrogen is an energy carrier, which is a very important distinction when considering hydrogen as a fuel source. To use hydrogen for power generation, energy input is required to make hydrogen useful. Various feedstocks, primarily fossil fuels, are responsible for imbuing hydrogen with energy. The use of a renewable feedstock, such as wind or hydroelectric energy, permits hydrogen to be an entirely emission-free energy source. Hydrogen is also a very common element and is not geographically concentrated like fossil fuels. Hydrogen could revolutionize the energy market by shifting the pricing power to consumers rather than suppliers.

Conversely, hydrogen as an energy carrier for most applications is redundant. For hydrogen to be a worthwhile energy carrier, it should be produced by renewable energy. In this case, the renewable energy is already in the form of an energy carrier, electricity. Further transformation of the renewable energy into stored chemical energy adds complexities that require energy. The energy requirements to produce, package, distribute, store, and transfer hydrogen are not small. Well-to-tank analysis, which evaluates the energy consumption of the entire production pathway, indicates that approximately 0.35–0.40 units of energy are expended for every unit of hydrogen energy available. Alternatively, electricity only requires 0.1 units of energy for each unit of electricity produced (Hoffrichter 2013; Bossel and Eliasson 2003).

For these reasons, hydrogen as an energy carrier in most conventional stationary applications is inappropriate. Electricity is a far more logical and efficient energy carrier in stationary applications. Hydrogen's niche as an energy carrier is limited to roles that require mobility and zero emissions at the point-of-use. In this arena, batteries are much more common and widely available. Batteries, however, suffer from their own drawbacks: they have notoriously poor life cycles, low energy density per unit mass, and lengthy recharge times. Hydrogen offers the advantage of an improved life cycle and energy density and refill time comparable to liquid fossil fuels.

Literature Review

Hydrogen as an energy carrier for rail applications is relatively novel. Like other transport applications of hydrogen fuel cells, it is beginning to gain more recognition and plausibility. Research surrounding hydrogen as an energy carrier for rail applications has been conducted with simulations and real-world demonstrations. To date, hydrogen has been successfully implemented in a variety of rail applications, and practical feasibility has been demonstrated for intercity passenger rail through the use of simulations.

One of the earliest hydrogen-powered rail vehicles was designed as a mining locomotive. The project, under the management of "Vehicle Projects," was motivated by the mining industries' need for a zero-emission, safe, powerful, and productive locomotive (Miller and Barnes 2002). Like indoor utility vehicles, mining locomotives operate in environments that require several safety considerations. Mining locomotives are mostly associated with coal and, as a result, have strict health and safety standards to satisfy. Diesel-electric locomotives are inappropriate for mining applications because of the emissions at the point-of-use, and battery-powered locomotives are impractical because of their lack of productivity (Miller and Barnes 2002). Hydrogen fuel cells were seen as an opportunity to satisfy the mining regulations while allowing mines to operate productively without exorbitant costs.

Beyond utility-related projects, hydrogen also has been tested for use in a variety of other rail applications. Another hydrogen retrofit project involved a Burlington Northern Santa Fe switcher locomotive. Switcher locomotives are used for train assembly, often in rail yards and, as a result, operate a rigorous duty cycle. "Vehicle Projects" managed the project that converted an existing diesel-electric switcher locomotive to a hydrogen-hybrid locomotive. The hydrogen-hybrid weighs 127 tonnes, is able to produce 250 kW of continuous power, and has transient power greater than one mW. The motivation for this retrofit was the need to reduce rail yard emissions (particularly at seaports), reduce emissions at point-of-use, create a mobile power source for disaster relief and military applications, and reduce foreign energy reliance. For a switcher locomotive, up to 90% of operating time may be spent idling, so emission-free power generation can substantially reduce unnecessary emissions (Miller et al. 2007).

Simulations of a diesel-electric commuter line in the United Kingdom demonstrated the ability of a hydrogen-powered and hydrogen-hybrid train to operate the route with greater efficiency and less greenhouse gas emissions. The increase in volume and weight considered could be accommodated on the train model used for simulation. It was concluded that hydrogen is a technically feasible propulsion system for trains (Hoffrichter 2013). The route studied by Hoffrichter (2013) had low passenger volume and was uneconomical to electrify but would still need to meet stricter emission standards in the future. In this instance, the use of hydrogen as the prime mover is suggested to be more economical than electrification and is able to achieve zero point-of-use emissions.

The first hydrogen-hybrid propulsion system for rail transit began operation in the island nation of Aruba in December 2012 (altenergymag.com 2013). Owing to abundant and reliable wind energy, the streetcars of Aruba's capital, Oranjestad, are powered by 100% clean and renewable energy. The streetcars use a combination of power generation from on-board batteries and hydrogen fuel cells. The hybrid nature of the streetcars allows the system to improve its energy efficiency through regenerative braking. The fuel cell serves to augment the batteries during high power output and when the battery is close to depletion. In total, the hybrid system is far more efficient than any other fossil-fueled propulsion system and retains the autonomous, catenary-free characteristics of diesel-electric trains.

A method used in previous studies to evaluate the full energy pathway efficiency is the well-to-wheel analysis, which is separated into a well-to-tank and tank-to-wheel portions (TIAX LLC 2007). For rail, this method has been used to compare the energy efficiency and emission production of different propulsion systems (Hoffrichter 2013). The energy efficiency is a function of the efficiency of the supply chain of energy and the vehicle's drive train. This analysis determines how much energy from the well, or initial extraction of the fuel from nature, is required to provide one unit of energy at the wheel. The emission analysis determines the amount of greenhouse gas emissions associated with the entire pathway of the energy from the well to the wheel (TIAX LLC 2007).

Methodology

A description of methodology adopted in this research is discussed in this section.

Study Model

This study is based on existing characteristics associated with the Blue Line Extension in Charlotte, North Carolina, the Blue Line Extension rolling stock, and a concept hydrogen light rail train. The Blue Line Extension is a 9.3-mile-long urban light rail line with 11 stops. The Siemens S70, a light rail vehicle in the United States, is the rolling stock for the Blue Line Extension. Normal operation on the line includes a three-car consist with 7.5-minute headways. The selection of the light rail in Charlotte for the study context has clear implications on the results, and the results will certainly vary for different study contexts.

Well-to-Wheel Analysis

To complete the well-to-wheel analysis, a basic model of a hydrogen light rail train was necessary. Since hydrogen light rail trains do not exist currently, a concept hydrogen light rail train was developed from existing technologies. The well-to-wheel analysis was, therefore, limited by the assumptions made in developing the concept hydrogen light rail train, although the assumptions are considered to be conservative and realistic.

Based on previous research and development of hydrogen locomotives, several components are necessary to conceptually design a hydrogen light rail train using a conventional light rail train as a base model. A hydrogen light rail train differs from a conventional light rail train in its propulsion system, energy carrier storage system, energy carrier transport system, and energy carrier production system. The concept designs for the hydrogen light rail train are guided by current hydrogen production, hydrogen storage, and hydrogen fuel cells. Each system is based on products that are available for consumer purchase at the time of this writing (August 2014).

The efficiency factors, used to track the energy throughout the entire energy pathway, are based upon a chemical fuel's heating value (U.S. Department of Energy 2012). Each chemical fuel has two heating values—a lower heating value (LHV) and a higher heating value (HHV). The LHV is also referred to as the net calorific value because it accounts for the heat released during the combustion of the fuel less the latent heat of vaporization of water (U.S. Department of Energy 2012). The HHV, or gross energy, takes into account the latent heat of vaporization of water. The HHV is a more complete measure of heat because it includes heat stored in the form of water vapor. However, when computing the energy inputs required based on efficiency factors, the LHV is recommended because it represents the energy available for work (Clarke Energy 2013). For this reason, efficiency factors are given in terms of the LHV.

Hydrogen Production and Transport

Natural gas reforming is currently the most efficient, cost-effective, and common method to produce hydrogen (Alternative Fuels Data Center 2014). Initially, a synthesis gas is formed as a product of natural gas reacting with high temperature steam. The synthesis gas is composed of hydrogen, carbon monoxide, and trace amounts of carbon dioxide. Next, the carbon monoxide can be used in a second reaction involving water, which produces additional hydrogen and carbon dioxide (Alternative Fuels Data Center 2014). The two reactions that serve as the basis of natural gas steam reforming are shown as Equation 1 and Equation 2 (Air Products 2013).

$$CH_4 + H_2O \rightarrow 3H_2 + CO \text{ (methane reforming)} \qquad \text{Equation (1)}$$

$$CO + H_2O \rightarrow H_2 + CO_2 \text{ (water gas shift)} \qquad \text{Equation (2)}$$

The well-to-wheel emission analysis is dependent on the energy mix, or the method by which the energy is produced. In the case of hydrogen and electricity, both are an energy carrier, and thus, require a source of energy. Duke Energy supplies electricity in Charlotte (the location of choice for the concept hydrogen and electric light rail train to operate), and the energy mix for North Carolina in shown in Table 1. Hydrogen may be produced in a variety of methods, but for the purpose of this research, the most successful method of production was steam-methane reforming (SMR). Distributed SMR, specifically, was chosen as the hydrogen production method.

TABLE 1.
Energy Mix by Energy Carrier

Feedstock	Contribution to Electricity Generation[1]	Gaseous Hydrogen Production via SMR[2]
Coal	38.5%	3.2%[3]
Nuclear	31.9%	2.7%[3]
Natural gas	24.5%	93.7%[4]
Hydroelectric	2.5%	0.2%[3]
Other renewables	2.6%	0.2%[3]

[1] U.S. Energy Information Administration 2014.
[2] Elgowainy, Han, and Zhu 2013.
[3] Used to generate electricity necessary for SMR.
[4] 91.7% (SMR), 2.0% (electricity generation).

SMR may be small-scale or large-scale, which allows hydrogen to be produced on-site or off-site, respectively. If produced off-site at a large industrial SMR plant, the hydrogen must be transported to the final destination, usually by truck or pipeline. Until hydrogen becomes a widely-used energy carrier, distributed SMR plants are the most cost-effective method of hydrogen production (Ogden 2002). Distributed SMR plants can be located near the point of use and integrated into the refueling infrastructure. The downside to distributed SMR is the reduced energy efficiency, compared to centralized SMR. As a result, the use of a distributed SMR for analysis is a conservative assumption. Currently, hydrogen can be produced in a more efficient way than distributed SMR, but the transportation logistics are not realistic. By choosing distributed SMR, the most common method of hydrogen production is used and the logistical challenge of hydrogen transport is avoided. In the authors' opinion, distributed SMR is most likely to be designed as the hydrogen production and transportation mode if a hydrogen light rail system were to be implemented at the time of this writing (August 2014). The efficiency factors for a distributed SMR plant are used for the well-to-wheel emission analysis.

Based on the energy mix for North Carolina electricity, a weighted efficiency factor that incorporates the LHV efficiency factor for energy generation, the LHV efficiency factor for the recovery and transport of the energy was computed. In computing a total weighted LHV efficiency for the recovery, transport, and generation of North Carolina electricity, the well-to-wheel emission analysis is simplified. Table 2 shows the formulation of the weighted LHV efficiency factor.

TABLE 2.
Total Weighted LHV Efficiency for North Carolina Electricity Feedstock: Recovery, Transport, and Generation

Feedstock	Electricity Mix[1]	LHV Generation Efficiency[2]	LHV Recovery and Transport Efficiency[2]	Weighted Score
Coal	38.5%	36%	99%	13.7%
Nuclear	31.9%	34%	95%	10.3%
Natural gas	24.5%	51%	95%	11.9%
Hydroelectric	2.5%	90%	-	2.2%
Other renewables	2.6%	35%	-	0.9%
Total LHV Efficiency for Electricity Generation				**39.0%**

[1] U.S. Energy Information Administration 2014.
[2] Hoffrichter 2013.

The weighted score in Table 2 is a function of the electricity mix, generation efficiency, and recovery and transport efficiency. The purpose in computing a weighted score is to produce a single efficiency value that takes into account the respective efficiencies of each of the energy sources. The method to compute the weighted score is outlined in Equation 3.

$$\sum_{i=0}^{n} \boldsymbol{EM_n} * \boldsymbol{GE_n} * \boldsymbol{RT_n} \text{(Weighted Score)} \qquad \text{Equation (3)}$$

where, EM_n is the electricity mix of the n^{th} energy source in percentage, GE_n is the LHV generation efficiency of the n^{th} energy source in percentage, and RT_n is the LHV recovery and transport efficiency of the n^{th} energy source in percentage.

The weighted LHV efficiency for the hydrogen feedstock is computed similarly and summarized in Table 3. The weighted efficiency factor for electricity feedstock and hydrogen feedstock, as seen in Tables 2 and 3, are clearly a function of the feedstock mix. The feedstock mix is specific to the North Carolina study context and the distributed SMR hydrogen production method. Consequently, locations with a higher coal or nuclear share than North Carolina are likely to have a reduced electricity feedstock efficiency factor. Likewise, hydrogen production methods such as coal-powered electrolysis would reduce the feedstock efficiency factor for hydrogen production. The assumptions made in this study are specific to the study context, but may easily be varied under different scenarios.

TABLE 3.
Total Weighted LHV Efficiency for Hydrogen Feedstock: Recovery, Transport, and Generation

Feedstock	Hydrogen Feedstock Mix[1]	LHV Generation Efficiency[2]	LHV Recovery and Transport Efficiency[2]	Weighted Score
Coal	3.2%	36%	99%	1.1%
Nuclear	2.7%	34%	95%	0.9%
Natural gas	93.7%	51%	95%	45.4%
Hydroelectric	0.2%	90%	-	0.2%
Other renewables	0.2%	35%	-	0.1%
Total LHV Efficiency for Hydrogen Feedstock				**47.7%**

[1] Elgowainy, Han, and Zhu 2013.
[2] Hoffrichter 2013.

Hydrogen Storage

Hydrogen storage as a gas, although less concentrated on a volume basis, is preferred in the transport industry because of minimal weight. For rail, where storage of fuel is not strictly limited by volume or weight, gas storage of hydrogen is acceptable. For transport applications, gaseous hydrogen storage is usually 350-bar or 700-bar, with the preference being 700-bar vessels. In particular, Type IV vessels are most applicable to the transport application. Type IV vessels are characterized by a polymeric liner fully wrapped with a fiber-resin composite with a port built into the structure of the vessel (Barral and Barthelemy 2006). Type IV vessels can withstand very high pressures without adding considerable weight.

For a given quantity of hydrogen, composite tanks have the advantage of less volume and less weight. The trend for the automotive industry, the chief promoter of hydrogen storage research, is 700-bar composite tanks (Bakker 2010). The drawback in pressurizing a gas is the loss of energy content due to the pressurization. As a result, more energy is required to fill a 4 kg 700-bar composite vessel compared to a 4 kg 200-bar standard vessel. Compared to a 350-bar vessel, a 700-bar vessel requires approximately 10–12% additional compression energy (Sirosh 2013; Mao 2010). The volumetric increase, 55%, exceeds the additional compression energy by such an extent that the additional energy loss is worthwhile (Mao 2010).

Since hydrogen's energy content per unit of volume is a fraction of conventional liquid fossil fuels, such high pressures are required to minimize the volume requirements of the storage system and maximize the range of the vehicle. The characteristics of a modern 700-bar vessel for hydrogen are listed in Table 4. These characteristics are the basis for the hydrogen storage component design.

TABLE 4.
Parameters of a Type IV 700-bar Hydrogen Vessel

Parameter	Value
Useable storage capacity	5.6 kg H_2
Gravimetric capacity	4.2%
Gravimetric density[1]	33.3 kWh/kg
Vessel weight with 5.6 kg H_2	112 kg
Volumetric capacity	26.3 kg H_2/m^3
Vessel volume	0.22 m^3 (7.77 ft^3)
Storage cost	$18.7/kWh

[1] SUSY 2012.
Source: Argonne National Laboratory 2010

Hydrogen Propulsion System

Regardless of the production method of hydrogen, it may be used in a fuel cell to produce energy. There are other methods of producing energy from hydrogen, such as internal combustion engines, but their energy efficiency is unable to match that of fuel cells (U.S. Department of Energy 2014). Perhaps the most common fuel cell today is the polymer electrolyte membrane (PEM) fuel cell. PEM fuel cells are made up of three distinct parts—the anode, the electrolyte, and the cathode, which create energy from hydrogen and oxygen. As hydrogen enters the fuel cell, on the anode side, the hydrogen molecule is oxidized. The polymer electrolyte membrane that separates the anode from the cathode is permeable for hydrogen cations, but not electrons. The electrons flow to an external circuit, which is how electrical current is produced by the fuel cell.

The polymer exchange membrane is preferred in vehicle prototypes due to its ability to be sufficiently efficient at low operating temperatures (Bakker 2011). More than 80% of fuel cells in production in 2013 were PEM fuel cells (Barbir 2013). The hydrogen fuel cell system design is based on currently available commercial technology. Ballard Power Systems, Inc., is a leading fuel cell manufacturer that produces fuel cells for a variety of applications. The Ballard FCVelocity-HD6 fuel cell, which is designed for bus applications, was chosen as the model for the concept design of the fuel cell system because it is a leading commercial technology for bus applications, which is transferable to railway applications. The operating and physical characteristics of this technology are listed in Table 5. Fuel cells marketed for specific applications, such as mobile or telecom applications, are generally interchangeable with alternative uses (Hoffrichter 2013). The selection of the Ballard FCVelocity-HD6 fuel cell, originally intended for bus applications, is appropriate given sufficient power output. Just as battery technology is generally interchangeable among applications, fuel cells may be interchangeable given an appropriate bundle design (fuel cell unit power output and number of units). The manufacturer lists the fuel cell efficiency as 60–71%; therefore, a conservative case and optimistic case were employed in the well-to-wheel analysis.

TABLE 5.
Parameters of Ballard FCVelocity-HD6 Fuel Cell

Parameter	Value
Power rating	150 kW
DC voltage	230–800V
Maximum current	320A
Weight	404 kg
Volume	23.3 ft^3
Fuel consumption	1.3–2.5 g/s
Fuel cell efficiency	60–71% LHV
Lifetime	12,000 hours

Source: Ballard Power Systems, Inc., 2012

Results

The remaining efficiency factors consider energy losses through the locomotive drive train and the transmission of electricity for electric trains. The energy chain and the respective efficiency factors for the existing electric S70 and the concept hydrogen train are shown in Tables 6 and 7. Neither table includes improved efficiency due to regenerative braking, as that is figured separately and is based on physical characteristics of the journey. However, a hydrogen-hybrid propulsion system may offer greater regenerative braking efficiency than an electric propulsion system. Regenerative braking for an electric train captures approximately 57.6% of energy available to be regenerated (80% of total is captured due to blended braking, 90% due to traction efficiency, and 80% available for use because of receptive catenary) (International Union of Railways 2002). A hydrogen-hybrid train would have a similar 80% efficiency factor for blended braking and 90% traction efficiency but would not be constrained by unreceptive catenary. As a result, a hydrogen-hybrid could close the well-to-wheel efficiency gap that separates electric and hydrogen propulsion systems by a factor that is a function of catenary receptivity.

TABLE 6.
Well-to-Wheel Efficiency Factors Using LHV for Electric Train

Well-to-Tank (Well-to-Pantograph)	**LHV Efficiency**
Energy at source	100%
Weighted efficiency of North Carolina electricity mix[1]	39.0%
Grid transmission[2]	94%
Catenary transmission[3]	92.5%
Total well-to-tank (well-to-pantograph)	33.9%
Tank-to-Wheel (Pantograph-to-Wheel)	**LHV Efficiency**
Feed cable[3]	95%
Transformer[3]	95%
Control system and electronics[3]	97.5%
Electric motors[3]	95%
Transmission[3]	96%
Traction auxiliaries[4]	93%
Total tank-to-wheel (pantograph-to-wheel)	74.6%
Total Well-to-Wheel	**25.3%**

[1] Computed previously in Table 2.
[2] U.S. Energy Information Administration 2014.
[3] Hoffrichter 2013.
[4] Computed from assumed auxiliary load of 35 kW, Traction Auxiliaries Efficiency = (1 – (35 kW * 0.7406 hours)/375 kWh).

TABLE 7.
Well-to-Wheel Efficiency Factors Using LHV for Hydrogen Train

Well-to-Tank	**LHV Efficiency**
Energy at source	100%
Weighted efficiency of feedstock (91.7% natural gas and 8.3% electricity)[1]	47.7%
Steam methane reforming (H_2 production and compression)[2]	71.4%
Total well-to-tank	34.0%
Tank-to-Wheel	**LHV Efficiency**
Fuel cell power plant[3]	60–71%
Electric motors[4]	92%
Transmission[4]	95%
Motor auxiliaries[4]	99%
Traction auxiliaries[5]	93.72%
Total tank-to-wheel	48.7–57.6%
Total Well-to-Wheel	**16.6–19.6%**

[1] Computed previously in Table 3.
[2] Inclusive of compression efficiency (Elgowainy, Han and Zhu 2013).
[3] Efficiency of Ballard FCVelocity-HD6, 60–71% LHV (Ballard Power Systems Inc 2012).
[4] Hoffrichter 2013.
[5] Computed from assumed auxiliary load of 35 kW, Traction Auxiliaries Efficiency = (1 – (35 kW * 0.74 hours)/411 kWh). No negligible difference between hydrogen and hydrogen-hybrid.

The LHV efficiency factors not associated with hydrogen technology are sourced from existing literature and are not specific to the S70 rolling stock or a hydrogen-powered light rail vehicle. Hydrogen production is assumed to be via a distributed SMR; therefore, an efficiency factor for pipeline or trucking transportation is omitted in Table 7.

By comparing the well-to-wheel efficiency chart for electric and hydrogen trains, the differences are apparent. For the well-to-tank, both propulsion technologies have a nearly identical efficiency factor of 34%. The feedstock energy production efficiency for hydrogen is greater than that of electricity because of the large share of natural gas that is required for SMR. As the electricity mix transitions away from coal-produced power in the coming years, the difference in feedstock energy production efficiency will decrease. To make up for this loss in feedstock efficiency superiority, the hydrogen production method has room to improve. Regardless of the hydrogen-to-electricity conversion method (electrolysis or SMR), advances in technology will improve hydrogen production efficiency and make hydrogen power more competitive with electricity. Feedstock energy production for both electric and hydrogen propulsion systems will advance in parallel; hydrogen's additional chemical conversion (H_2 to H_2O) has room for improvement.

Technological advances in electrolysis or SMR will enable hydrogen-powered technologies to close the efficiency gap with electric propulsion. The hydrogen and electric trains tank-to-wheel is nearly comparable albeit one major difference. The efficiency of the energy pathway for a hydrogen train is severely limited by the efficiency of a fuel cell. This, unlike hydrogen production methods, cannot be substituted by alternatives and, therefore, is dependent on technological advancements. In total, the efficiency superiority of an electric train is clearly demonstrated with current technology, but hydrogen and hydrogen-hybrid trains will close the gap in the coming years and may make the technology a more viable alternative.

Conclusions

The results presented in this paper are presumed to be representative of hypothetical hydrogen-powered light rail trains for operation in Charlotte, North Carolina. Since hydrogen-powered light rail trains are not in use in the United States, several assumptions were made that have significant implications on the results. The well-to-wheel analysis is dependent on the assumed energy production methods and is specific to the study area of North Carolina. True operating characteristics and efficiency values may differ from what is presented, but the magnitude of difference is not expected to be large. Consequently, the research is useful in demonstrating the relative performance of hydrogen-powered trains with electric-powered trains.

The hydrogen fuel cell used in this research touts impressive 60–71% fuel cell efficiency, which only a few years ago would be a great feat. However, without accounting for any additional losses, such as traction auxiliaries, the overall vehicle efficiency of a hydrogen train is already less than that of an electric train. Until improvements are made in hydrogen fuel cell efficiency, hydrogen power must compete in feedstock generation. The feedstock generation and hydrogen generation gives hydrogen-power flexibility to reduce overall energy demand and energy emissions.

From an energy demand perspective, the energy at the wheels of the hydrogen train balloons by 502% (or 410% for the optimistic case) to the required feedstock energy. These values far exceed the 295% increase in energy demand from the wheels to the well for an electric train. A hydrogen train will not reduce energy consumption of light rail operations based on current technologies. Two processes restrict the hydrogen train energy pathways—the production and compression of hydrogen and the production of current in the fuel cell. Improvement in the efficiency of the fuel cell power plant can reduce energy demand and emission production. Additionally, replacing SMR with electrolysis that is powered by renewable energy removes the efficiency factor and emission production. The total well-to-wheel efficiency could improve from 16.6% (or 19.6% for the optimistic case) to a value comparable to the electric train's 25.3% well-to-wheel efficiency.

Feedstock efficiency is a sizable portion of the well-to-tank analysis and has an effect on the overall results. The results presented here are not applicable to all cities, but may be easily interpreted to a different context. Light rail in Cleveland, Ohio, for example, is powered by an electricity mix with a 64% coal share. The difference in electricity mix between Ohio and North Carolina, all else equal, results in an overall well-to-wheel efficiency of 24.6% and 25.3%, respectively. Alternatively, a city with a more favorable electricity mix, such as Portland, Oregon, has the opposite effect on the overall well-to-wheel efficiency. Oregon's electricity comprises a 72% hydroelectric share, which nearly doubles North Carolina's electric train well-to-wheel efficiency factor to 50.3%. For settings where the electricity mix is primarily composed of coal, electric light rail systems compound the energy inefficiency while settings with large hydroelectric shares take advantage of the hydroelectric energy efficiency.

The well-to-wheel analysis is just one part of a variety of analysis methods that provide decision-makers and planners sufficient information necessary to make objective decisions. The objective in using new power technologies for light rail, such as hydrogen power, should be sufficiently analyzed to ensure that it is met. Often, hydrogen power is presented as a green technology and, therefore, should perform well in a well-to-wheel analysis. The well-to-wheel analysis specifically provides insight into system efficiencies. Obviously, the current hydrogen power technologies assumed for this study do not meet the current technology standard (electric catenary). However, a litany of other technology assumptions and evaluation metrics could be made that would impact the results.

The well-to-wheel analysis results demonstrate the critical importance of hydrogen production and fuel cell technology development. These two areas represent the greatest potential for energy efficiency gain for hydrogen-powered trains. The efficiency of fuel cell is improving as research and development finds improved methods, which will bode well for hydrogen power in the future. Hydrogen production methods also have some potential efficiency gains, but the greatest asset associated with hydrogen production is the flexibility.

An evaluator or planner could impact the results by changing the hydrogen production method. For this study, decentralized SMR hydrogen production was assumed because it is currently the most practical production method for a case study in North Carolina. However, different objectives may yield different scenarios. For example, water electrolysis may be more appropriate in a situation in which surplus renewable energy is available. In this case, lower efficiency values may be tolerated for the expected reduction in emissions. Most importantly, the underlying objective should guide the design of new applications of technology.

There may be practical limitations to the adoption of renewable energy technology in rail transit, such as the maximization of usable floor space for passengers. A hydrogen-powered light rail (e.g., Charlotte's Blue Line Extension, operating a 3-car consist for 20.5 hours per day) would require approximately 1,391 ft^3 of volume (in general, space) for 25 fuel cells and 125 hydrogen storage vessels (Washing 2014). This volume requirement is nearly identical to the estimated volume for the diesel-electric articulated railcar's power module and excess roof volume of 1,329 ft^3 (Hoffrichter 2013). The difference in usable passenger space between a hydrogen and diesel-electric passenger train is expected to be negligible. On the other hand, an electric light rail is without an on-board power plant, which reduces the amount of available space for hydrogen technology. However, the nearly 1,400 ft^3 of necessary volume for hydrogen fuel cells and storage vessels for a three-car consist could certainly be added to the roof of the light rail, without significant changes to the overall size. A Siemens S70 with a three-car consist is approximately 280 feet long, which would only require a frontal cross section area increase of 5 ft^2 to accommodate the hydrogen-related volume needs (Washing 2014). The light rail manufacturer, however, would most certainly meet such design challenges in the event that a market for hydrogen light rail develops.

Economics are always an important part of the adoption of new technologies, which is another avenue for hydrogen power to surpass current technologies. While the hydrogen-powered light rail train does not demonstrate energy efficiency superiority over electric catenary under the made assumptions, other decision criteria, such as emissions and economics, may prove to be more important criteria. As always, the objective of the application should determine the course of action.

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Geographical Applications of Performance Measures for Transit Network Directness

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Abstract

This research developed a geographical presentation method to show which areas of the city need to be improved in terms of the directness of transit service using two measures, Degree of Competitiveness and Degree of Circuity, which were developed in the first author's previous research. In this research, the directness of transit networks in five cities in Korea was analyzed and compared as an example and demonstrated geographically. The results show that although more populated cities are likely to provide more direct transit service than less populated cities, population density affects the transit network directness more. Also, this research showed that there is a strong relationship between transit network directness and transit ridership. As a result of this research, transit agencies can have a better visual understanding of their transit network directness and can improve transit network configuration where transit network directness is poor.

Key words: Transit network, performance measures, GIS, directness, circuity

Introduction

Transit network design is the foundation for efficient transit operation and planning. However, designing an efficient transit network is always difficult and requires considerable effort. To realistically improve a transit network, many transit agencies rely on evaluation measures. Measures to determine transit operation show how to diagnose current transit operations and make future planning more efficient. For these reasons, setting and developing measures are always important for transit agencies. Measures used for transit planning and operation are related to transit users, transit agencies, and society, as shown in Table 1 (TCRP 2003).

TABLE 1.
Transit Performance Measures

Point of View	Category	Performance Measure Examples	
Customer (Quality of Service)	Travel Time	• Transit-auto travel time	• Transfer time
	Availability	• Service coverage • Service denials	• Frequency • Hours of service
	Service Delivery	• Reliability • Comfort	• Passenger environment • Customer satisfaction
	Safety & Security	• Vehicle accident rate • Passenger accident rate	• Crime rate • Percent of vehicles with safety devices
Agency	Maintenance & Construction	• Road calls • Fleet cleaning	• Spare ratio • Construction impact
	Economic	• Ridership • Fleet maintenance performance	• Cost efficiency • Cost effectiveness
	Transit Impact	• Community economic impact • Employment impact	• Environmental impact • Mobility
Vehicle/Driver	Capacity	• Vehicle capacity • Volume-to-capacity ratio	• Roadway capacity
	Travel Time	• Delay	• System speed

Lee (2008) extensively researched the various kinds of measures for transit-auto travel time because they can show the competitiveness of a transit service, which eventually greatly affects ridership and revenue, as indicated in many studies (McGillivray 1970; Cambridge Systematics and Economic Development Research Group 1999; Fan and Machemehl 2004; Racca and Ratledge 2004). Lee's previous research discussed and developed comparative measures to diagnose current planning and operation in more efficient ways. Since travelers compare the available travel modes for their trips using travel times and costs, measures that show the relationship between auto travel time and transit travel time are very useful and show the competitiveness of a transit service. Measures that compare current transit networks and potential shortest travel-time transit networks also were developed. If the size of demand is large enough to provide high frequency for any route, this comparison reveals how much a transit network potentially can be improved. However, this previous research used only one hypothetical network and its data to demonstrate the methodology.

In this research, to analyze transit network directness efficiently, a geographical presentation method for transit network directness was developed based on the previously-developed measures to define competitiveness and directness of a transit network. Then, five major cities in Korea were analyzed using a geographical presentation method. GIS applications for transit performance analysis (Ramirez and Seneviratne 1996; Berkow 2009; Bertini and El-Geneidy 2003) have been gaining popularity and are believed to be very useful.

Literature Review

Transit Network Configuration

Transit network configuration is one of the most important components in determining the level of service for passengers and is the key to operational efficiency. Numerous studies have been conducted using optimization techniques, including Lee (1998), Pattinak et al. (1998), and Lee and Vuchic (2005). Guiharire and Hao (2008) summarized the related studies extensively. However, optimizing transit network configuration always has been a difficult task for the transit industry, in part, due to the complexity of designing transit network configuration. Because of this complexity, most transit networks have been designed based on intuition and experience. Another difficulty is in changing a current network configuration. Although recent studies have shown how to optimize a transit network, it is difficult for transit agencies to complete changes all at once; it is recommended that modest changes in scheduling or the transit network be explored, rather than drastically changing the transit network configuration. Once a transit network is designed, user travel time cannot be improved drastically through other changes.

Relationship between Routing and Scheduling

Total transit travel time is computed as the sum of travel time components. Routing and scheduling are the major factors determining these components, although there are many considerations. Routing determines in-transit travel time and access/egress time (by station location) and also determines whether transfers are required for certain trips. Scheduling is closely related to waiting time and transfer time, if there is a transfer. Without scheduling information, average waiting time is half of the headway, assuming that passengers arrive uniformly at stations. Although waiting time with scheduling information does not have a definitive relationship with headway, unlike waiting time without scheduling information, it clearly moves in the same direction as headway.

Although the difficulty of coordinating routing and scheduling often results in their separate planning processes, routing and scheduling should be considered together. The relationship between routing and scheduling comes from the scheduling process. Scheduling is affected by many concerns, such as maximum policy headway and fleet size. However, the most important input for the scheduling process is demand size, because more frequencies usually are provided for the heavy-demand routes. To prevent overcrowding, frequency should be linearly related with demand. This means that demand for a certain route determines its frequency (Vuchic et al. 1976; Cedar and Israeli 1998).

Depending on routing, demand for a route is basically determined by (1) the number of riders picked up by the route, assuming fixed transit demand, and (2) in-vehicle travel time. The more efficient a transit route is, the larger the share transit can have from the general demand for the trip. For these reasons, although routing and scheduling are separate and different processes, routing affects and generally determines scheduling.

Under fixed transit demand, a route collects more riders if it is circuitous, resulting in higher frequency and shorter headway. However, there is a trade-off with circuitous routing—even though it can provide shorter waiting time due to a shorter headway, it requires longer in-transit travel. Increasing directness results in shorter in-transit travel time under the assumption of a single mode, but it requires more routes and lower frequency for each route due to less demand for each route. Lower frequency results in longer headway and, eventually, longer waiting time.

Transportation Network Circuity

Previous research defined and analyzed the transportation network circuity by means of geography. Circuity was defined as the ratio of the shortest network distance over Euclidean distance between origin and destination (Barthlemy 2011). Newell (1980) found that the average circuity on a road network was around 1.2, and Ballou et al. (2002) estimated the travel distance through the several countries. However, there has been no research to compare auto network circuity and transit network circuity based on a given road network.

Demand Size and Circuity of the Transit Network

The overall shape of transit network configuration typically can be classified in three ways (Lee 2006): directly-connected networks with a larger number of routes, networks with a smaller number of routes that are circuitous, and networks that require transfers due to fewer directly-connected routes. Demand size is a primary consideration in determining the type of transit network. When demand is low, providing many routes with direct connection is not efficient because the frequency of each route would be low, resulting in longer waiting times. Direct connection is a better choice when demand is sufficient, because networks still can provide short headway with many direct routes.

Transit networks with transfers share characteristics with transit networks that have circuitous routes. Frequencies of those networks are higher than those of directly-connected networks due to the smaller number of routes, but in-vehicle travel time is still short due to the direct connection. However, transfer time exists in total travel time. If a network has fewer circuitous routes, waiting time would be shorter due to the higher frequency, but in-vehicle travel time would be longer due to circuitous routing.

Transit Score

The website www.walkscore.com provides information related to walk scores (walkability) and transit scores (transit friendliness) at neighborhood levels (Walk Score 2014). According to the site, a transit score is a patented measure of how well a location is served by public transit and is based on data released in a standard format by public transit agencies. To calculate a transit score, a "usefulness" value is assigned to nearby transit routes based on frequency, type of route (rail, bus, etc.), and distance to the nearest stop on the route. The "usefulness" of all nearby routes is summed and normalized to a score of 0–100. Although this site rates accessibility to transit service, it does not address how competitive transit service is in terms of travel time versus auto travel time. A transit score may be related to access time and waiting time, but not to the in-vehicle travel time to a destination, which is usually the largest part of total transit travel time.

Methodology

Measures for Transit Network Directness

In Lee's previous research (2008), two comparative measures were developed—Degree of Competitiveness (DOCO) and Degree of Circuity (DOCI)—which compare the performance of auto and transit and evaluate potential transit network performance. The main comparison in this research is travel time. DOCO is a comparison between auto and transit travel times and shows how transit service is competitive with auto for each origin-destination trip. DOCI measures how much the transit service or network configuration can be improved; in general, if transit ridership increases, the optimality of the transit network becomes higher with more direct connections between origin-destination pairs (Lee 1998). DOCI indicates how circuitous a current transit network is compared to a hypothetical transit network with the possible shortest connections, which provides the shortest in-vehicle transit travel time.

Although it is simple to estimate auto travel time, estimating transit travel time is more complex because of its various travel time components. Transit users generally consider travel time as total transit travel time and in-vehicle transit travel time. Total transit travel time includes waiting time and complete door-to-door travel time (or station-to-station travel time for a simpler computation). Waiting time can be determined by many other considerations in addition to demand size. When a headway is long and schedule information is provided, waiting time may not be estimated from headway and frequency. As a result, travel time can be distorted by the length of waiting time when the transit network is evaluated. In-vehicle transit travel time, which excludes waiting time, is transit travel time after boarding. This measure excludes waiting time, which is stochastic among all the components of travel times, so it could represent the transit network configuration better than total transit travel time. However, in-transit travel time does not include the relationship between routing and scheduling and may not represent the overall performance of the transit system. (Access and egress times are also part of a transit trip and total transit travel time, but they are excluded from this paper for simplicity.)

Auto travel time and transit travel time are compared as the Degree of Competitiveness. DOCO is a measure designed to show how much additional travel time the transit network requires when compared to auto travel time. If transit travel time is identical to auto travel time, its DOCO is zero.

As stated earlier, there are two types of competitiveness that can be considered with the two different kinds of transit travel time—Total Travel Time Degree of Competitiveness (TTTDOCO) and In-Vehicle Travel Time Degree of Competitiveness (ITTDOCO). TTTDOCO compares door-to-door travel times of auto and transit and shows how competitive the transit system is. ITTDOCO compares the in-vehicle travel time of auto and transit; since waiting time is not included in the comparison and auto travel follows the shortest paths, ITTDOCO shows how direct the transit network configuration is. Equations 1 and 2 show the TTTDOCO and ITTDOCO, respectively, for an individual user or a certain origin-destination.

$$\text{Individual TTTDOCO } [\%] = 100 \cdot \frac{\Delta t_{ij}^{T1} + t_{ij}^{t} + p_{ij}}{\min t_{ij}^{a}} \quad [1]$$

$$\text{Individual ITTDOCO } [\%] = 100 \cdot \frac{\Delta t_{ij}^{i1} + t_{ij}^{t} + p_{ij}}{\min t_{ij}^{a}} \quad [2]$$

Where,

Δt_{ij}^{T1} = additional total travel time (difference between real total travel time of transit and shortest travel time of auto) from i to j

Δt_{ij}^{i1} = additional in-vehicle travel time (difference between real in-vehicle travel time of transit and shortest travel time of auto) from i to j

t_{ij}^{t} = transfer time from i to j

p_{ij} = transfer penalty from i to j

$\min t_{ij}^{a}$ = auto shortest path travel time from i to j

DOCI shows how much additional travel time is required by the current transit network compared to the directly-connected hypothetical transit network. This is due to the indirect connection of the current transit network. There are two types of DOCI. Total Travel Time Degree of Circuity (TTTDOCI) compares the real door-to-door (precisely, station-to-station in this example) travel times of the current transit system and the potential minimum transit travel time. This assumes that the potential minimum transit travel time is estimated with no waiting time and the shortest connected in-vehicle travel time. TTTDOCI shows how much the transit system ultimately can be improved. In-vehicle Travel Time Degree of Circuity (ITTDOCI) compares the current in-vehicle travel time of transit and potential shortest in-vehicle travel time. Since potential shortest in-travel time comes from the directly-connected transit network and waiting time is not included in the comparison, ITTDOCI shows how direct the transit network configuration is. Equations 3 and 4 show the TTTDOCI and ITTDOCI, respectively, for an individual user or a certain origin-destination.

$$\text{Individual TTTDOCI [\%]} = 100 \cdot \frac{\Delta t_{ij}^{T2} + t_{ij}^{t} + p_{ij}}{\min t_{ij}^{i}} \qquad [3]$$

$$\text{Individual ITTDOCI [\%]} = 100 \cdot \frac{\Delta t_{ij}^{i2} + t_{ij}^{t} + p_{ij}}{\min t_{ij}^{i}} \qquad [4]$$

Where,

Δt_{ij}^{T2} = additional total travel time (difference between real total travel time of transit and total travel time of potential transit shortest path) from i to j

Δt_{ij}^{i2} = additional in-vehicle travel time (difference between real in-vehicle travel time of transit and in-vehicle travel time of potential transit shortest path) from i to j

t_{ij}^{t} = transfer time from i to j

p_{ij} = transfer penalty from i to j

t_{ij}^{i} = in-vehicle travel time of potential transit shortest path from i to j

Two DOCOs and two DOCIs can be presented for each origin-destination trip, as shown in the equations and for the whole network.

For estimating measures for the entire network, simple average and weighted average can be used based on different ways to consider demand. Simple average does not consider zone-to-zone demand. Without consideration of the demand size, these measures represent competitiveness or circuity of the transit network with the same weight for each origin-destination. Equations 5 and 6 show two simple DOCO for the total travel time and in-vehicle travel time. Equations 7 and 8 show simple DOCI. In the equations, $n(n\text{-}1)$ is used instead of n^2 as the denominator for the simple average because it is assumed that there are no intra-zonal trips.

$$\text{Simple average TTTDOCO [\%]} = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{individual(TTTDOCO)_{ij}}{n(n-1)} \qquad [5]$$

$$\text{Simple average ITTDOCO [\%]} = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{individual(ITTDOCO)_{ij}}{n(n-1)} \qquad [6]$$

$$\text{Simple average TTTDOCI [\%]} = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{individual(TTTDOCI)_{ij}}{n(n-1)} \qquad [7]$$

$$\text{Simple average ITTDOCI [\%]} = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{individual(ITTDOCI)_{ij}}{n(n-1)} \qquad [8]$$

Weighted average considers each zone-to-zone demand size. The weighted average shows how efficiently the transit network is designed to meet the demand and how well the transit network provides better service to an origin-destination with higher demand. This is shown in Equations 9 through 12.

$$\text{Weighted average TTTDOCO [\%]} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(ITTDOCO)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}} \qquad [9]$$

$$\text{Weighted average ITTDOCO [\%]} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(TTTDOCI)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}} \qquad [10]$$

$$\text{Weighted average TTTDOCI [\%]} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(ITTDOCI)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}} \qquad [11]$$

$$\text{Weighted average ITTDOC [\%]} = 100 \cdot \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(TTTDOCO)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}} \qquad [12]$$

Where n = number of zones and D_{ij} = demand from zone i to zone j.

Travel Time Estimation for Auto and Transit

The inputs defined in Equations 1–12 are necessary to estimate the DOCO and DOCI. Those inputs—demand size, link travel time, and transfer time—can be obtained easily. However, the real travel time of auto and transit and the potential shortest travel time of transit should be found and computed through route choice algorithms.

Auto travel time assumes that users find the shortest auto travel paths. With this assumption, auto travel time can be estimated using the shortest path algorithm. This theory is well-known and has been developed by many scholars, including Moore (1957), Dijkstra (1959), and Dantzig (1966). This shortest path algorithm provides the shortest path with a given fixed travel time. In reality, link travel time varies with traffic volume, and this shortest path algorithm may not be adequate; however, estimating real travel time with real travel demand is very complicated and difficult.

To estimate the transit travel time in this research, Optimal Strategy by Spiess and Florian (1989) was chosen as the transit route choice model, which is popularly used for transit assignment.

As discussed previously, comparison of an auto network and a transit network may not successfully show the effectiveness of the current transit network because transit link travel time and auto link travel time are different. Although this comparison can show how competitive a transit service is, the comparison does not show how much the current transit system can be improved. To determine how much the current transit network can be improved, comparison with the potential transit shortest paths may be more adequate. The potential transit shortest path can be found by using the auto shortest path algorithm with transit link travel time instead of auto link travel time. This is the hypothetical transit path, assuming that transit does not have fixed routes and can go anywhere with the shortest path.

Geographical Presentation of Transit Network Directness

From each zone, the simple average and the weighted average of measures to all other zones can be presented geographically and can provide a good geographical guideline of which areas need to be improved in terms of the directness of the transit service.

Data and Modeling

This analysis uses origin-destination data and road network data from the Korea Transportation Database (KTDB). However, KTDB's Transportation Analysis Zone (TAZ) is too large for analyzing the transit network system, so a smaller-size zone was created for this study based on census data. Transit operation data, including average speed and average headway of all available public transportation including metro rail system, regional express bus, regular bus, and small local bus systems, came from databases provided by the local governments, Korea Railroad (KoRail), Seoul Metropolitan Rapid Transit Corporation, and local bus companies of the analyzed cities. A transfer penalty was assumed as 20% of transfer waiting time, which is a conventional default value for analysis in Korea as well as a default value at TransCad. Modeling and computation of travel times were done using TransCAD.

Example and Analysis

Five cities in Korea—Seoul, Busan, Suwon, Seongnam, and Uijeongbu—were chosen for the analysis. Seoul is the largest city in Korea, and Busan is the second largest. Suwon, Seongnam, and Uijeongbu are mid-size cities near metropolitan Seoul. City characteristics are shown is in Table 2, and zones and transit networks for the analysis are shown in Figure 1.

TABLE 2.
Characteristics of Cities in Analysis (2011)

Characteristic	Seoul	Busan	Suwon	Seongnam	Uijeongbu
Population (million prs)	10.25	3.55	1.09	0.98	0.43
Area (Km^2)	605.25	765.64	121.01	141.74	81.59
Population density (prs/Km^2)	16,935	4,637	9,008	6,914	5,270
Bus passenger per day (million prs/day)	5.58	1.53	0.85	0.55	0.21
Subway passenger per day (million prs/day)	6.35	0.96	0.24	0.23	0.07
Transit demand density (prs/Km^2)	19,710	3,252	9,008	5,503	3,432
Transit demand/population	1.16	0.70	1.00	0.80	0.65
Number of zones	2,088	1,070	682	448	160
Number of bus routes	435	271	114	56	72
Number of subway routes	9	4	1	2	2

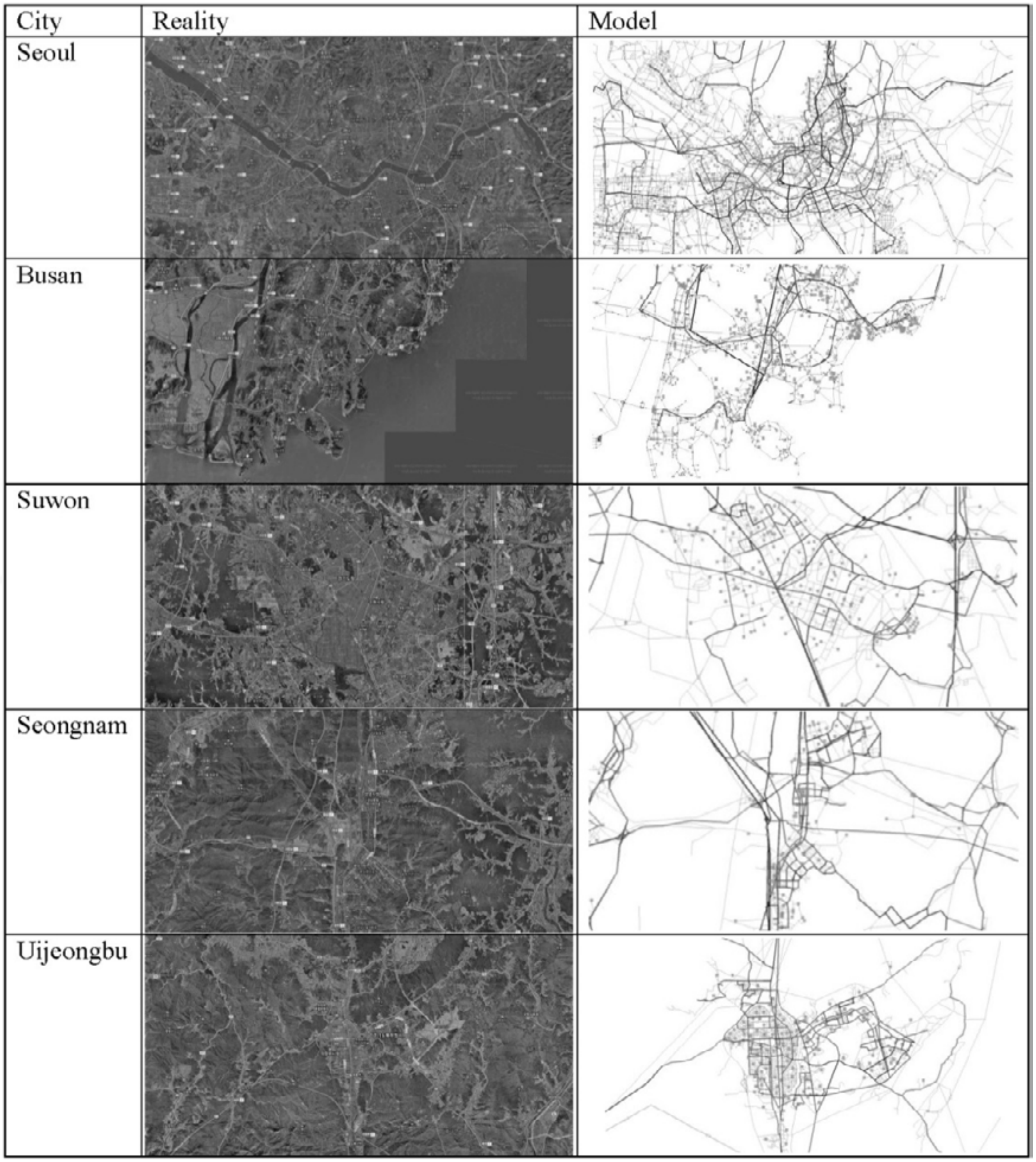


FIGURE 1. Modeling zones and transit networks of cities in analysis

Table 3 shows the results of the computed measures for the five cities. Seoul's values are the average of its 2,088 zones, and Busan's values are the average of its 1,070 zones. Each zone's value is the average of the values from that zone (origin) to all other zones (destinations).

TABLE 3.
Summary of Transit Directness Measures

Measure	Simple	Weighted	Simple	Weighted	Simple	Weighted
	Seoul		*Busan*		*Suwon*	
TTTDOCO	197%	186%	268%	267%	221%	210%
ITTDOCO	145%	136%	202%	199%	162%	155%
TTTDOCI	110%	101%	152%	150%	125%	112%
ITTDOCI	75%	66%	103%	99%	86%	74%
	Seongnam		*Uijeongbu*			
TTTDOCO	290%	278%	336%	333%		
ITTDOCO	213%	200%	254%	252%		
TTTDOCI	163%	147%	187%	182%		
ITTDOCI	112%	97%	128%	126%		

TTTDOCO = Total Travel Time Degree of Competitiveness, ITTDOCO = In-vehicle Travel Time Degree of Competitiveness, TTTDOCI = Total Travel Time Degree of Circuity, ITTDOCI = In-vehicle Travel Time Degree of Circuity

Assuming that transit networks are not direct, DOCI is always more than 0%. Assuming that auto travel is faster than transit travel because of shorter access and egress time and no waiting time, DOCO is always higher than DOCI. Also, a transit route with higher demand has a better chance of being direct, and weighted averages are always lower than simple averages. Table 3 shows that the results meet all of these assumptions as well as general common sense.

In good transit network design, weighted measures should be lower than simple measures because heavily-demanded trips are designed to be more direct. In Table 3, it is noticeable that the difference between simple measures and weighted measures for Busan and Uijeongbu are minimal compared to the other cities, meaning that transit networks in Busan and Uijeongbu are not properly designed for heavy demand.

In Table 3, the average additional travel time by transit (weighted) in Seoul is 186% more than auto travel time and the average transit travel time with the current Seoul transit system is 66% more than that of a potential ideal transit network. The measures for Seoul are lower than those for the other cities because Seoul is highest in population density and has more transit demand; as a result, Seoul can provide a more direct transit network than the other smaller cities. If a transit network is designed properly, a city with more demand is likely to have a more direct transit network. However, that may not occur in all cities. As shown in Table 4, although Busan is the second largest city in population, because its area is largest, its population density is lowest (#5). However, because of its relatively high ranking in transit network directness (#3), Busan's ratio for transit demand/population is #4, which is better than Uijeongbu's, although Busan's transit demand density is still the lowest (#5).

TABLE 4.
Rankings of Cities for Analysis Measures (2011)

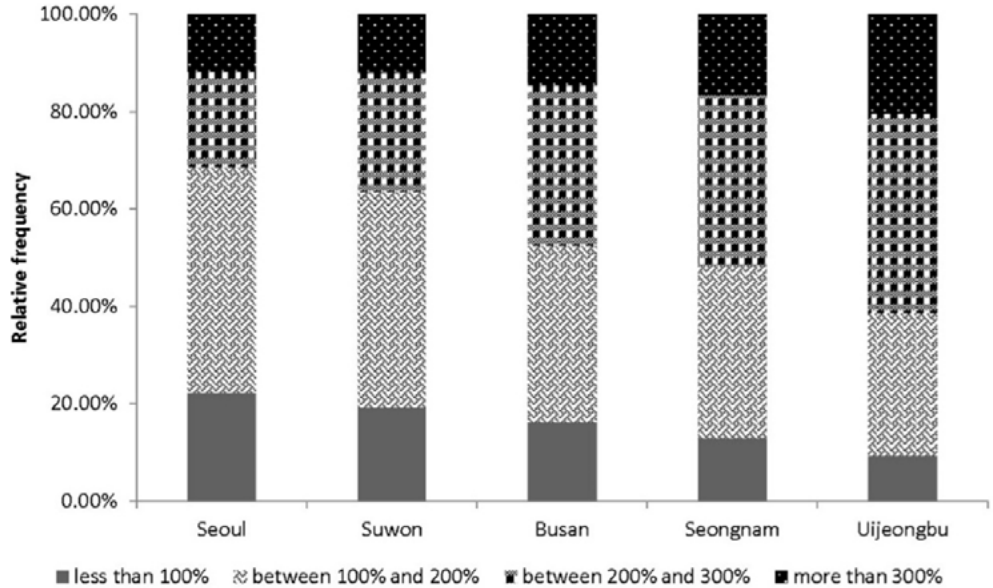
	Seoul	Busan	Suwon	Seongnam	Uijeongbu
Population	1	2	3	4	5
Area	2	1	4	3	5
Population density	1	5	2	3	4
Transit demand density	1	5	2	3	4
Transit demand/population	1	4	2	3	5
Number of bus route	1	2	3	5	4
Transit directness measures	1	3/4	2	4/3	5

Although Uijeongbu is the smallest of the five cities in terms of population, because of its small area, population density ranks fourth and the number of bus routes is relatively high for the area size and population size (especially compared to Seongnam). However, all of Uijeongbu's measures are worse than all the other cities', including Seongnam's, meaning that the transit network for Uijeongbu is unnecessarily indirect compared to other cities. In addition to Busan, all the other cities show a good correlation among population density, transit demand density, and transit network directness, which shows that transit network directness can be a very strong measure for transit ridership.

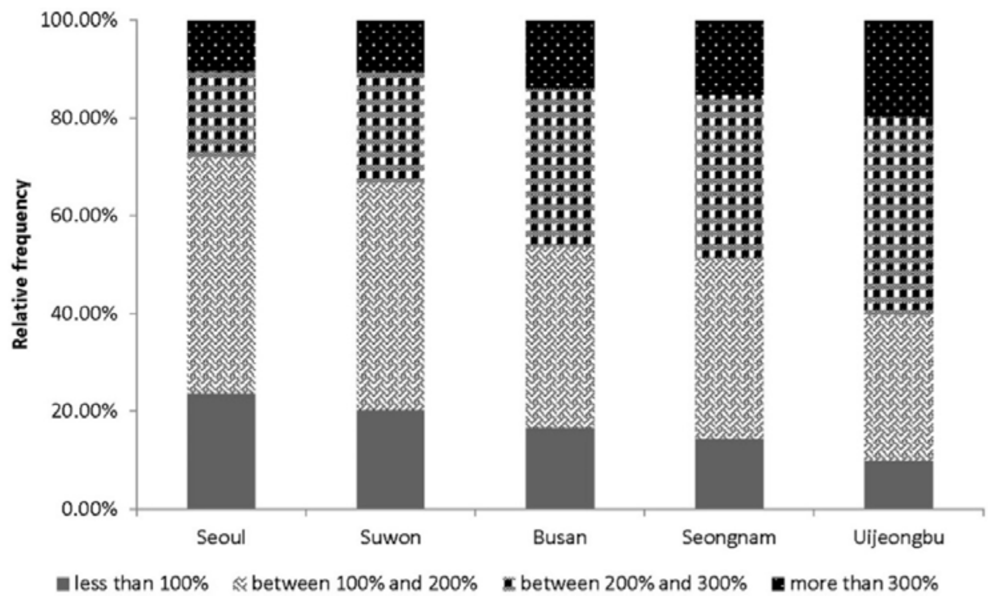
In Figure 2, the averages in Table 3 were broken down to show the composition of the zones for each additional travel time category, indicating the percentage of zones with relatively competitive and direct service and the percentage of zones with relatively indirect and uncompetitive service. Figure 2 shows that all cities have proper compositions. A city that has a lower average value of measures, such as Seoul, has more zones of lower values of measures, and a city that has a higher average value of measures, such as Uijeongbu, has more zones of higher value of measures. Figures 3 and 4 show the spatial distribution of measures for each city. These figures clearly show which zones have circuitous transit service visually. As expected, central business district (CBD) areas enjoy more direct service to other zones than do outside areas. These figures provide a good geographical guideline of which areas need to be improved in terms of transit service.

FIGURE 2.

Frequencies of zones as percentages for transit directness measures



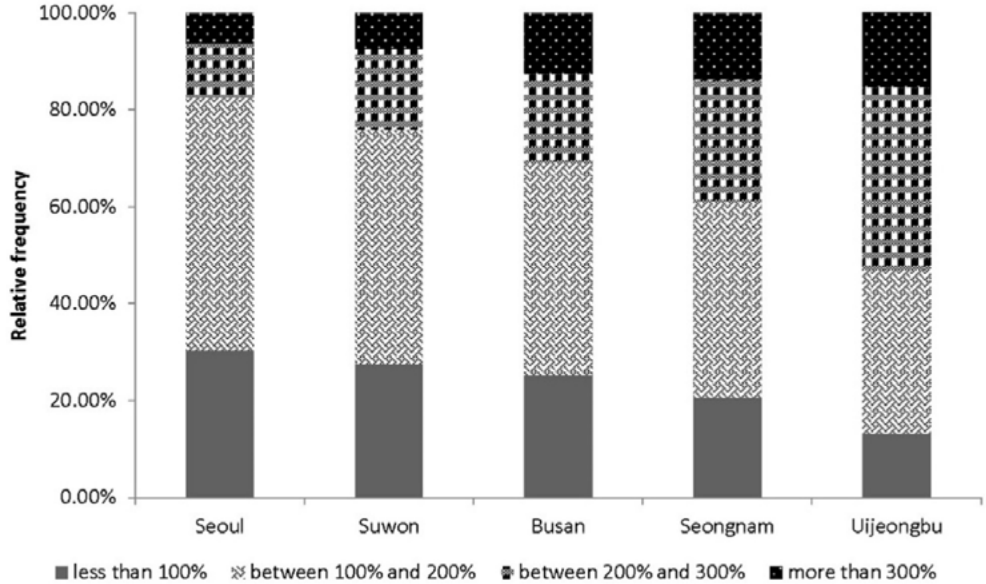
(a) Simple Average TTTDOCO



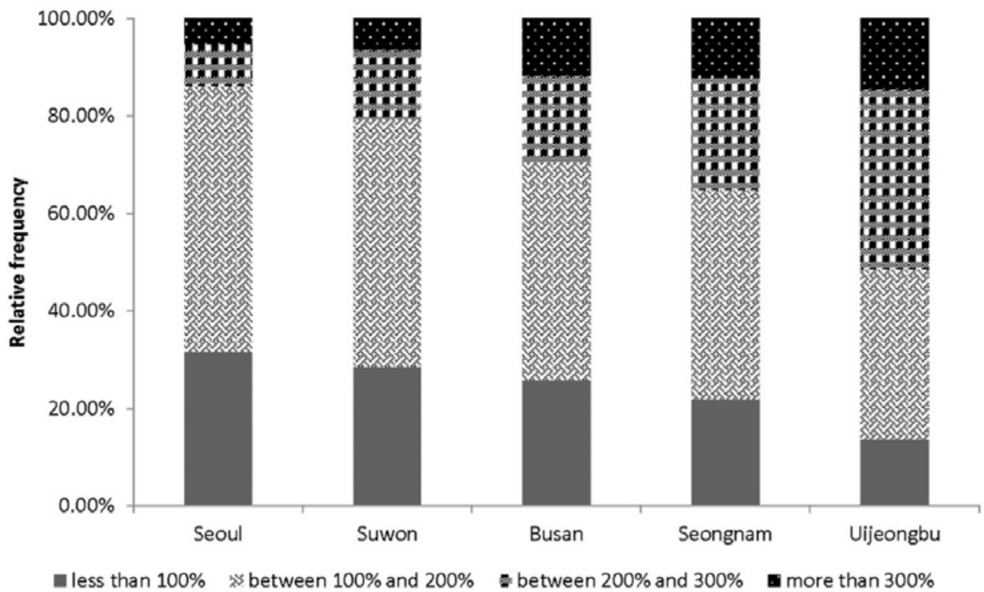
(b) Weighted Average TTTDOCO

FIGURE 2. (cont'd.)

Frequencies of zones as percentages for transit directness measures

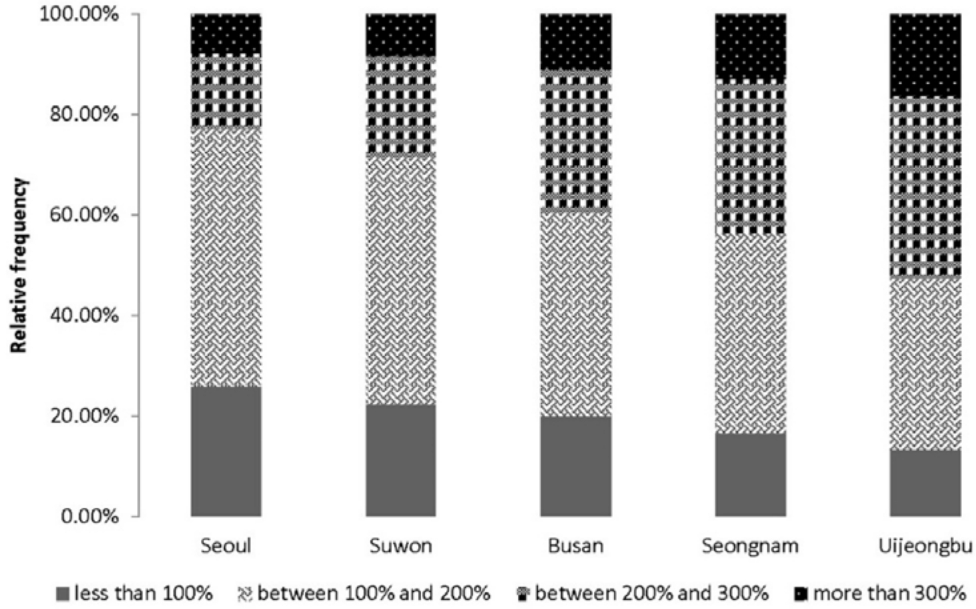


(c) Simple Average ITTDOCO

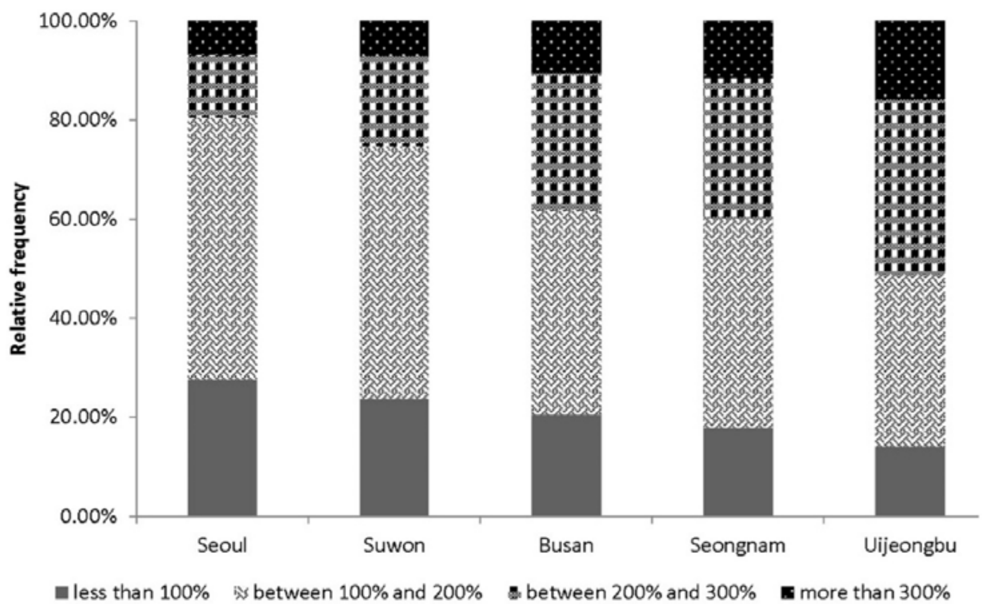


(d) Weighted Average ITTDOCO

FIGURE 2. (cont'd.)
Frequencies of zones as percentages for transit directness measures

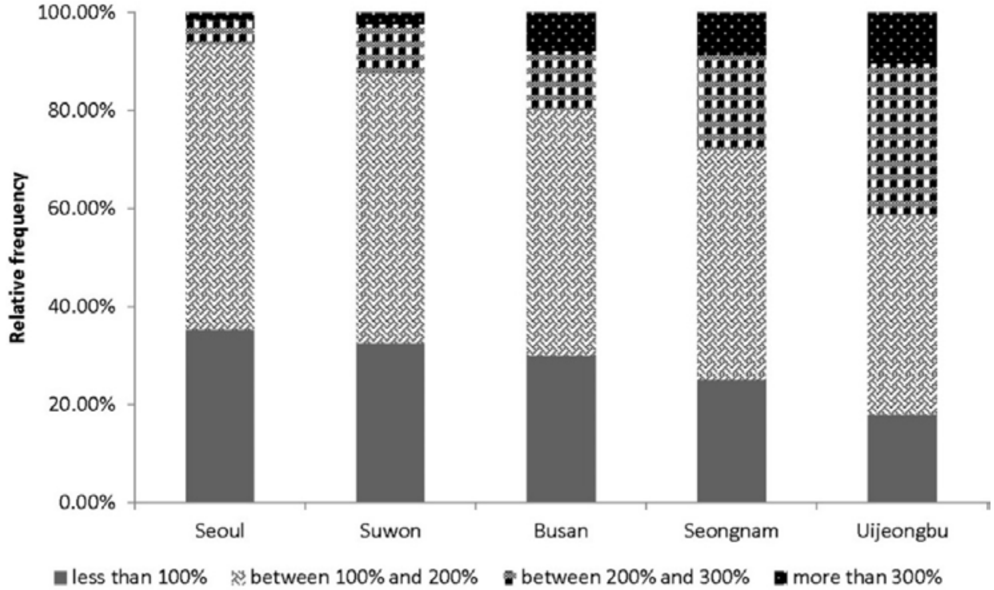


(e) Simple Average TTTDOCI

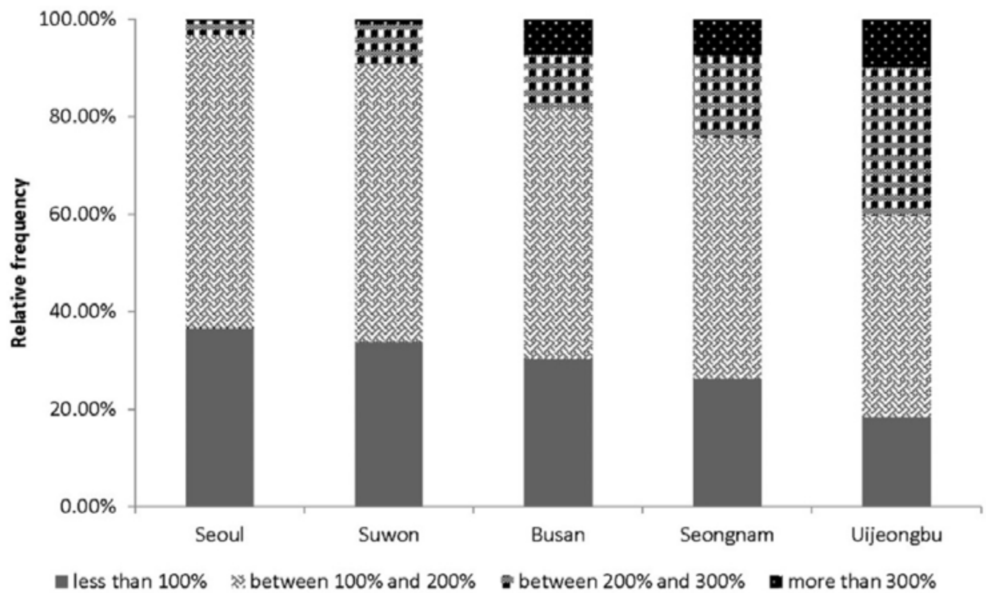


(f) Weighted Average TTTDOCI

FIGURE 2. (cont'd.)
Frequencies of zones as percentages for transit directness measures



(g) Simple Average ITTDOCI



(h) Weighted Average ITTDOCI

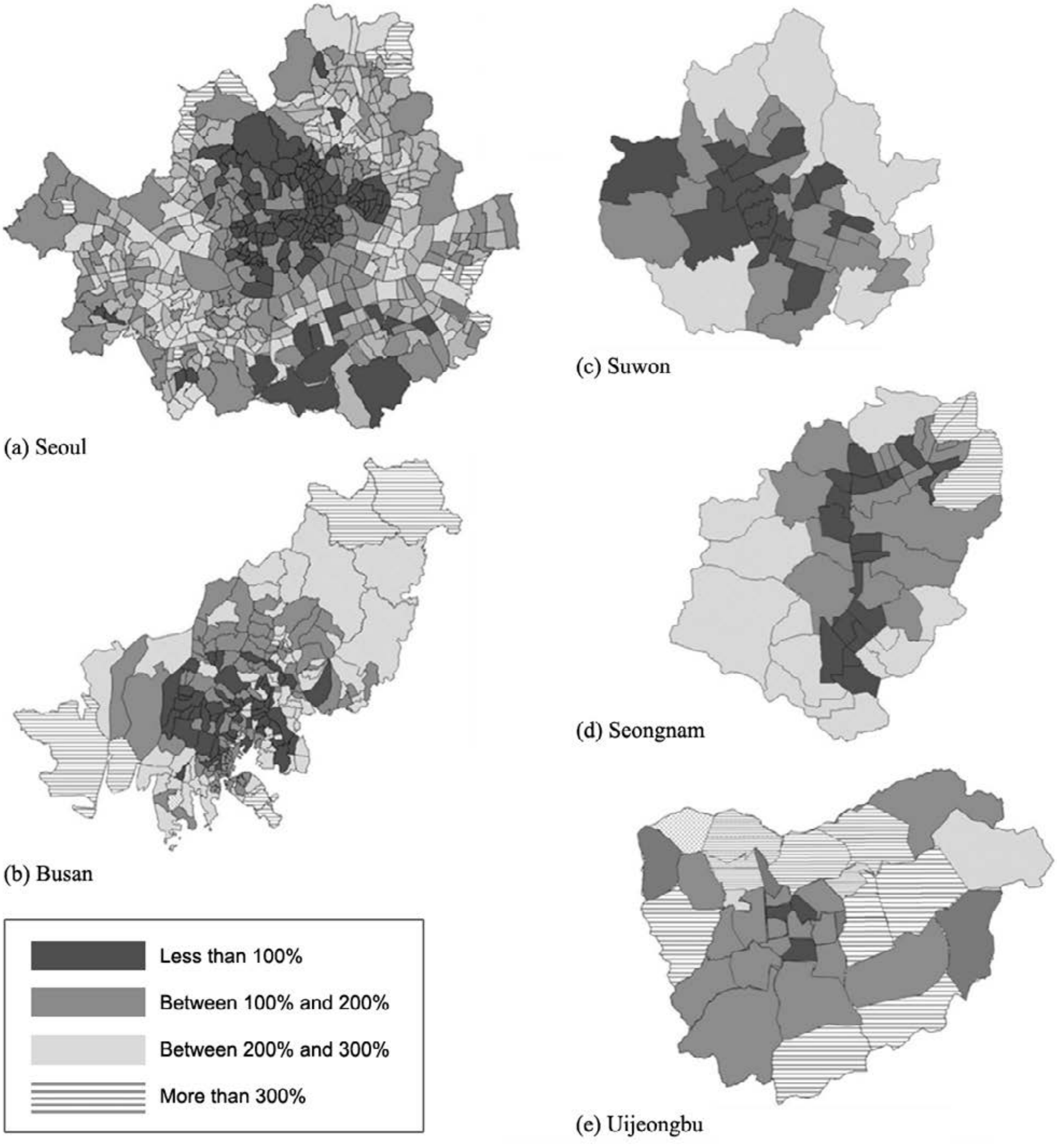


FIGURE 3. Spatial Distribution of TTTDOCO for Each City

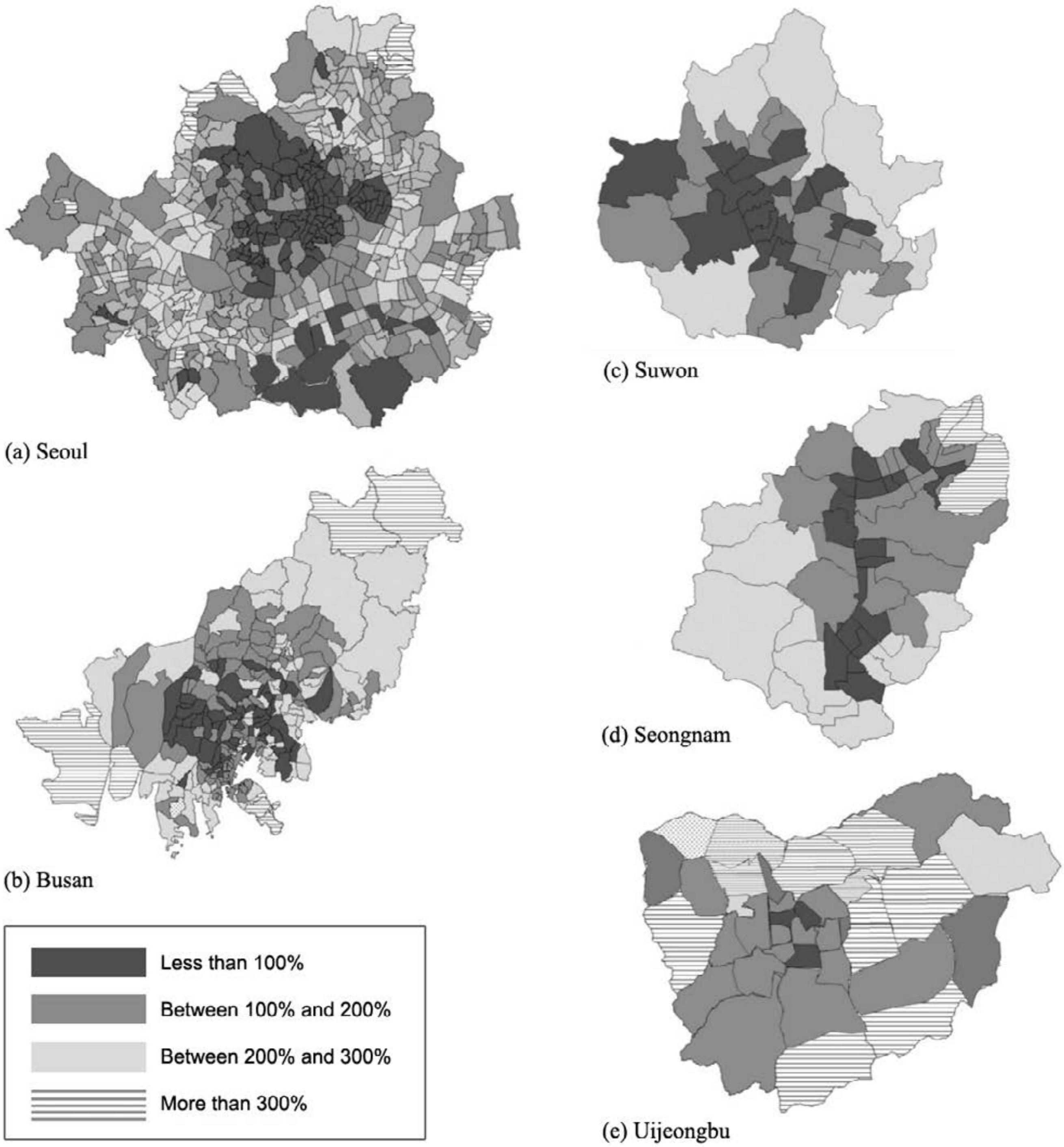


FIGURE 4. Spatial Distribution of TTTDOCI for Each City

Conclusion

Using Lee's previously-developed measures to indicate the competitiveness and indirectness of a transit system (2008), this paper evaluated the transit network of five major cities in Korea and developed a geographical presentation method.

The shape of a transit network is usually affected by demand size; similarly, the shape of a transit network also affects transit demand size. Therefore, the relationship between the shape of a transit network and demand size is complicated but is worth investigating. Indeed, many other factors affect transit demand, so it may not be appropriate to connect transit network directness and transit demand size. However, as discussed, transit travel time is an important factor for mode choice, so it is still meaningful to find the relationship between transit demand size and transit network directness.

Although the results of the analysis and geographical presentation are for five specific cities, the developed methodology can be used to analyze any cities and their transit networks. Transit agencies can have a better visual understanding of their transit network directness and can improve transit network configuration where transit network directness is poor.

The analysis of the five cities shows some meaningful results that may be generalized and used for other cities as well. First, most transit ridership (transit demand/population) depends on transit network directness. Second, to attract more transit riders, the weighted averages of the transit network directness measures should be meaningfully lower than the simple averages of the transit network directness. That means transit routes must be more direct where large transit demands exist. Third, a transit network is more direct in cities with higher population densities.

This research provided valuable illustrations (Figures 2–4) of transit network directness. Figures 3 and 4 show the spatial distribution of zones that have different categories of transit service in terms of competitiveness and directness. From those figures, it is clear that Busan provides very poor service in the outer part of the city, and no zone in Suwon has more than 300% of additional travel time by transit. These figures show which areas should be improved in terms of directness of transit service.

The measures and concepts discussed in this paper rely on the first author's previous research, but this paper systematically structures and mathematically develops them in detail so they can be useful for transit network design and planning. Indeed, this analysis provides a good guideline to evaluate which cities need to improve their transit network to provide more direct service and also provides a good geographical guideline of which areas need to be improved in terms of the directness of the transit service, although transit network directness may result from many other concerns, such as social issues, politics, topology, and the original transit network that the existing users are used to.

For future research, if many different cities with good transit networks are analyzed using these measures, it will be possible to provide a guideline for proper transit network directness for cities of different size. Also, the relationship between transit network directness and land use patterns or topology will be worth investigating.

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A Scientometric Analysis of Public Transport Research

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Abstract

Public transport research involves a lot of disciplinary and interdisciplinary research applying methods, techniques, and technologies to investigate, regulate, and advance public transport. The importance of research in this area has led to a huge amount of publications in recent years. In this study, we conducted a comprehensive scientometric analysis of related literature published in 2009–2013 to empirically explore the consistence, focus areas, and key contributors of public transport research from a meta-perspective, providing novel insights into publication patterns, major topics, research impact, and productivity by focusing on short-term developments. As such, the results of this study provide a novel perspective on public transport research and may help achieving an overview on important characteristics.

Keywords: Public transport, public transport research, scientometric analysis, scientometrics, keyword cluster analysis.

Introduction

Public transport, as a mode of transportation moving people from one place to another by publicly-used forms of conveyance (Levinson et al. 2015), plays an essential role not only for providing sustainable transport forms (Krygsman et al. 2004) and serving the urban and inter-urban travel needs of those who are dependent on efficient transport means, but also for supporting social equity principles (Webster and Bly 1982). The performance of local public transport in terms of accessibility, safety, and efficiency not only affects inhabitants day by day, but also influences the destination satisfaction of visitors such as business travelers and tourists (Thompson and Schofield 2007). Further, the quality of public transport as well as the interplay between different inter-urban and urban transportation systems, including car and bike sharing systems, become increasingly important not only in our modern society, but also in developing countries (Sohail et al. 2006). Public transport demand is stimulated by social and economic conditions (e.g., city population, income, car ownership, land use) as well as by direct demand factors such as fares and service quality (Webster and Bly 1982). Against this backdrop, public transport research consists of a range of research activities to understand, regulate, and advance public transport from several perspectives and under certain circumstances. Consequently, the field involves not only disciplinary research, but also requires interdisciplinary and even transdisciplinary research to tackle current and future challenges, meaning that scholars from different subjects and practitioners share their experiences and perspectives in collaborative works to study the subject in its wider context, such as the interplay with technical, economic, social, and information technology-related aspects. Challenges include those related to planning and operations, information management, regulations, traffic congestion, safety and security, energy consumption, and health issues in urban environments.

Given the considerable number of research contributions in recent years, reflecting the international scope of transport research and the growing number of people researching in transport (Banister 2014), it is essential to investigate the current state of public transport. The huge growth in publications require an overseeable entry point on a meta level to better explore specific aspects in greater depth in a next step, which is especially important for new researchers aiming to become experts in the field (Banister 2014). This entry point can be provided by a scientometric analysis of public transport research, which extends, on a higher level, common public transport-related reviews on specific topics.

Scientometrics refers to quantitative studies and methods to measure and analyze science from a meta-perspective (Van Raan 1996; Schwarze et al. 2012). Scientometric studies can support the development and improvement of an academic discipline (Lewis et al. 2007; Straub 2006) by serving as a vital basis for defining and debating future research agendas (Serenko and Bontis 2004). Assuming that scientific activities are reflected through scientific publications, scientometric studies apply empirical measures to analyze scientific output of a specific field. A scientometric analysis can give some indication of research activities in general, such as with respect to research outlets, research impact, co-citations, influential countries/affiliations/authors, and development of key topics. For further reading, see, e.g., Hood and Wilson (2001), Leydesdorff (2002), Leydesdorff and Schank (2008), Van Raan (1996), Straub (2006), and Voß and Zhao (2005). Going further, scientometrics, as an evaluation tool of science, increasingly impacts the resource distribution of research institutions (Voß and Zhao 2005) and can be used to analyze how research is funded. While evaluating science has a long tradition in many fields, we identified an absence of scientometric studies in the area of public transport research.

In this paper, we present a comprehensive scientometric analysis that empirically explores publications related to public transport covered by Elsevier's Scopus database from 2009 to 2013. Although it might be interesting to extend the timeframe, we intended to focus on the past five years to better reflect recent developments rather than biasing implications with long-term developments. The latter may be considered in future research. For the analysis of short-term developments, we aimed to comprehensively cover publications that are available in Scopus for that timeframe to provide empirical insights on public transport research in general. In total, we investigated 7,868 publications. With our study, we aimed to explore general patterns on how research is conducted and conveyed within the community as well as what key contributing and influencing forces are serving the current and future development of public transport research. Our scientometric analysis was structured according to these research questions. By applying scientometric means to the body of publications, we provided extensive insights into publishing patterns (e.g., academic disciplines, contributing countries, number of authors, and distribution of outlets) and analyzed frequent keywords as well as keyword co-occurrences to identify widely-discussed topics and current trends. Finally, we explored the application of Lotka's law, which describes a frequency distribution of scientific productivity widely applied in scientometric studies.

Generally, this paper presents novel insights from a meta-perspective. Due to limitations of space, this study does not intend to give an overview of public transport in general (for further reading, the reader is referred to, e.g., Larson and Odoni 1981; Ceder 2007; White 2008; Levinson et al. 2015, together with some of those contributions to the field exemplified in the appendix that follows). To the best of our knowledge, this is the first scientometric analysis in the field of public transport research.

The remainder of this paper is organized as follows. The next section briefly describes the methodology and methods being applied. Then, publishing patterns are investigated and further analyzed to understand the consistence of the research area. Key topics as well as dependencies between topics of public transport research are observed by analyzing top keywords and keyword clusters, and the impact and productivity of public transport research is examined. The results from applying Lotka's law to our observations are also presented, and, finally, a conclusion and ideas for further research are given.

Research Methodology

Several steps were necessary to retrieve scientometric findings from a selection of publications. This scientometric analysis intended to explore a large number of peer-reviewed publications published in the years 2009–2013 in, or at least strongly related to, the field of public transport research. We chose a period of five years to focus primarily on recent publications. A comprehensive and accurate collection of corresponding publications builds a foundation to gain empirical evidence for supporting the meta-scientific findings. The methodology basically encompassed the phases of data collection, data cleansing, data processing, and proofreading, further explained in the following.

Data Collection and Cleansing

For the collection of bibliographic data, we used Elsevier's Scopus, which provides advanced functionality to export structured data, including citations and bibliographic data as well as abstracts, keywords, and references based on a search query. A comprehensive collection of structured data on publications builds the basis for semi-automatic data processing activities and minimizes extremely cost- and labor-intensive manual processing (Heilig and Voß 2014; Serenko and Bontis 2004). The reason for choosing Scopus is that it provides decisive advantages over other bibliographic databases such as Thomas Reuter's Web of Science (WoS). In addition to advanced export functionality and more frequent updates, Scopus covers more than twice as many publications from the area of public transport research (see Table 1). In comparison, WoS covers only 53% of the transport-related journals that are indexed by Scopus and does not provide any additional journals that are not already covered by Scopus (see Appendix A). The numbers also indicate a constant increase of publications, which was recently discussed in Banister (2014). Although Google Scholar stands out in its coverage of citation counts, it does not provide means to export structured bibliographic data. Nevertheless, we manually incorporated citation counts from Google Scholar to provide a more accurate picture on top publication citation patterns (see Appendix B). A limitation of using bibliography databases is, however, that it can take a while until new publications are indexed.

TABLE 1. Number of Publications per Year

Database	2009	2010	2011	2012	2013	Overall
Scopus	1,269	1,318	1,618	1,745	1,918	7,868
ISI WoS	654	646	673	764	801	3,538

To retrieve a comprehensive amount of publications, a generic search query is used based on empirical observations during our study. We used the terms **public transport*, *public transit*, *mass transit*, and *urban transport** in the fields Title, Abstract, Keywords, and Source Title (title of the publication outlet). The asterisk represents a wildcard character so that other terms such as *urban transportation* also are considered. As we also obtained some non-related publications from fields such as biochemistry and medicine (mainly due to the term *mass transit*), we further refined the search query by specifying superior research disciplines, including engineering, geography and environmental science, material science, energy, decision sciences, mathematics, computer science, business and economics, and social sciences. The search query found 8,087 data records in the period from 2009 to 2013 (as of May 19, 2014). Then, a cleansing method detected and removed inaccurate data records (e.g., unspecified authors/title, double entries, etc.). The final selection of data records represents a selection of 7,868 publications containing 160,132 references and 22,247 unique keywords. Note that one keyword refers to a complete entry in the keywords list such as that *public transport*, for example, is considered as one keyword, which also applies for acronyms. Only 91.85% of those publications had a non-empty bibliography, resulting in an average of 22.16 references per article (median value of 16 references). Most publications, at an average 92.18%, are written in English. A small percentage, 4.68%, are published in Chinese (i.e., Mandarin) where the metadata can be processed in English.

Data Processing

Besides rather general classification and aggregation methods, we applied scientometric methods from the literature to measure research productivity and impact. Further, we implemented methods to analyze keywords and keyword clusters.

Research Productivity

Research productivity is measured predominantly by the aggregated number of publications of an individual author, a specific affiliation, and/or of a certain publication outlet. Different approaches are used in the literature to measure research productivity: straight count, author position, and equal credit (Holsapple et al. 1994; Serenko and Bontis 2004). The straight count method assigns a score of 1 to each of the co-authors of a publication and, thus, does not discriminate among authors. Although this might be reasonable for alphabetically-ordered author lists, the method undervalues the productivity of single-author papers and favors individual co-authors of multi-author papers in which the main contributor is the first author. In contrast, the author position method assigns higher scores to anterior authors (Howard et al. 1987). The consideration of the author's position, however, might lead to erroneous results when author lists are ordered alphabetically. The equal credit method compensates those errors by scoring individual authors based on the reciprocal of the number of authors. Consequently, the productivity of individual authors decreases by each additional author. In this study, we focused on the equal credit method, as it involves the least tradeoff and error-proneness.

Research Impact

The research impact was measured based on the citations of publications. We calculated the individual citations of journals, conferences, affiliations, and authors as well as the Normalized Citation Impact Index (NCII), which takes into account the longevity of publications (Serenko and Bontis 2004). Note that we considered all citations for measuring impact, not only those retrieved from publications within our selection.

Keyword and Keyword Cluster Analysis

To analyze current focus areas, trends and the interrelation of certain keywords in the field of public transport, we implemented a method for counting all occurrences and co-occurrences of keywords. While the latter involves a huge amount of comparative operations to identify and count common combinations of keywords, a simple count method as used to retrieve top keywords.

Proofreading

To ensure the correctness of the scientometric findings, semi-automatic reviews were conducted to find and correct inconsistencies. These inconsistencies might result from a non-standard specification of certain metadata or missing identification numbers. For instance, the author's affiliation description might occur in different forms and may require careful checking to determine if identical authors are merged correctly; otherwise, related data must be merged manually.

Analysis of Publishing Patterns

To begin, we analyzed the overall consistence of public transport research in terms of publishing patterns. First, we identified major scientific disciplines mainly responsible for the progress in this area of research. Then, we identified contributing countries and investigated publishing patterns on the document level. This involved an analysis of the co-authorship distribution, distribution of document types, referencing patterns, and the number of publications per publication outlet to partially understand how research is produced and conveyed within the community.

Academic Disciplines

To better understand the consistence of public transport research, it is essential to analyze the distribution of main contributing academic disciplines. Thereby, some implications on dominant disciplines can be derived in general. Note that Scopus assigns each publication to at least one academic discipline, i.e., subject area (Scopus 2012). The range of subject areas is limited and not specifically related to the area of public transport. Due to these limitations, we extend the analysis of subject areas by specifically analyzing keywords presented in a later section.

The results in Table 2 reveal some interesting patterns. While it is not surprising that most of the research activities stem from social sciences and engineering, the high percentage of computer science-related research demonstrates the importance of information and communication technology (ICT) and information systems in public transport nowadays. Further, the environmental impact of public transport systems increasingly is being investigated, leading to research on eco-friendly fuel and vehicle alternatives, traffic control, and other measures for reducing harmful air pollution. This requires more research on the interface between public transport and other disciplines such as computer science and environmental science.

TABLE 2.
Academic Disciplines Related to Public Transport

Academic Discipline	Avg. (%)
Social Sciences	32.86
Engineering	28.46
Computer Science	13.35
Environmental Science	8.07
Decision Sciences	4.94
Mathematics	3.53
Business, Management, and Accounting	3.17
Economics, Econometrics, and Finance	2.77
Energy	2.25
Materials Science	0.60

The small percentage of research from mathematics and decision sciences, which plays an essential role in the planning and operation of public transport systems and related structures (such as for route design, timetable development, and crew scheduling; see e.g., Ceder 2007; Kroon et al. 2009; Levinson et al. 2015), can be explained by the fact that more than one academic discipline can be assigned to one publication. Further note that the small share of economics-related research does not mean that research is not based on economics, but that related publications often are not, or not only, labeled as pure economics research papers. As the field involves a lot of interdisciplinary research, theories and methods from the field of mathematics and decision sciences often are combined with engineering and computer science research activities. The same applies for studies focusing on public transport aspects from a business and economics perspective—for instance, in the context of infrastructure investments, which is also related to engineering research (e.g., civil engineering). The concentration of research activities of the various academic disciplines also is reflected in the results of the keyword and keyword cluster analysis described later, in which important topics and interrelations between topics are explored.

Contributing Countries

Next, we analyzed the distribution of contributing countries. To consider the impact of contributions, we separately investigated the main contributing countries of publications that are cited at least 10 times by other publications. Table 3 lists the top contributing countries of both selections with a contribution frequency *f* of at least 1.00%. The numbers indicate that most of the publications are published by scholars from China (18.82%), followed by a large portion of publications from the United States and the United Kingdom. Note that we do not distinguish whether an author is a native or, for instance, a visiting scholar publishing with an affiliation in the respective country. The numbers demonstrate that most research contributions are from countries with a relatively large share of public transport. Some of them are facing serious transport problems, such as those related to traffic congestion (see, e.g., Vickerman 2000). Nevertheless, we must consider that some countries, such as the United States, United Kingdom, Germany, and China, are generally top research contributors in rather fundamental topics important for their development due to their leading role in the global economy and technological progress, as also demonstrated in other scientometric studies (see e.g., Heilig and Voß 2014). Taking into account the number of citations, we observe that authors from the United States (21.84%) have published most of widely-recognized publications.

TABLE 3.
Contributing Countries

Rank	Country	*f* (%)*	Rank	Country	*f* (%)**
1	China	18.82	1	United States	21.84
2	United States	14.85	2	United Kingdom	28.35
3	United Kingdom	5.66	3	China	7.07
4	Australia	4.60	4	Italy	6.42
5	Germany	3.99	5	Australia	6.00
6	Canada	3.67	6	Canada	4.93
7	Italy	3.58	6	Germany	4.93
8	Spain	3.50	8	Spain	4.50
9	France	3.43	9	Netherlands	3.64
10	Japan	2.52	10	France	3.21
11	Netherlands	2.03	10	Sweden	3.21
12	India	1.91	12	Belgium	2.36
13	Sweden	1.69	13	Greece	1.71
14	Belgium	1.67	13	Switzerland	1.71
15	Taiwan	1.40	13	Japan	1.71
16	South Korea	1.32	16	Chile	1.50
17	Portugal	1.26	17	Taiwan	1.28
18	Switzerland	1.24	17	Hong Kong	1.28
19	Austria	1.20	17	Brazil	1.28
20	Brazil	1.10	20	Portugal	1.07
Total		79.45	Total		88.01

**All publications*
***Publication citations ≥ 10*

Co-Authorship Distribution

By analyzing the co-authorship distribution, we observed that the number of co-authors per publication (f) lies between 1 and 3 for almost three-quarters of all publications n, as shown in the last column of Table 4. A relatively high percentage, at an average 22.06% of publications, is published by a single author. Although a high number of authors might indicate that collaboration may have some advantages over research by individual researchers, for instance, due to the high degree of interdisciplinarity in the field, the numbers demonstrate that public transport research often is very specialized and concerns individual issues, for instance, based on certain conditions in an area of interest. The high percentage of single-authored works underlines these findings. By analyzing co-authorship distribution for multiple time-periods, however, we identified a decline of single-authored publications and a general increase of publications that are published by more than three authors. One of the main reasons is the growing demand for integrative approaches to further advance public transport, requiring interdisciplinary and transdisciplinary research collaborations.

TABLE 4.
Co-Authorship Distribution

# of Authors	2009 (%)	2010 (%)	2011 (%)	2012 (%)	2013 (%)	Overall (%)
1	26.48	24.45	23.99	18.31	17.08	22.06
2	27.11	30.13	27.98	27.32	27.41	27.99
3	23.72	22.94	25.46	26.87	25.70	24.94
4	13.87	13.55	13.65	16.09	16.41	14.71
5	5.28	4.39	5.29	6.39	7.68	5.81
6	1.81	2.50	2.09	2.51	3.06	2.39
7	0.95	1.21	0.80	1.37	1.40	1.15
> 7	0.79	0.83	0.74	1.14	1.25	0.95
n	1,269	1,318	1,618	1,745	1,918	7,868

Publication Outlet

The conscious selection of an appropriate publication outlet often impacts the visibility and citations of publications. Therefore, we explored the distribution of publication outlets to identify the preferences of the community in terms of sharing and conveying knowledge. In Table 5, the numbers show that most of the publications, average 54.39%, are published as a journal paper. An increasing pressure to publish and the growing competition among journals and conferences further contribute to a growing number of publications per year (Banister 2014), leading to a discussion on different publishing strategies of authors and editors as well as on the quality impact (see, e.g., Faria and Goel 2010).

TABLE 5.
Number of Publications by Document Type

Outlet	2009 (%)	2010 (%)	2011 (%)	2012 (%)	2013 (%)	Overall (%)
Article	51.22	55.39	51.55	56.68	57.14	54.39
Conference paper	42.63	38.85	40.17	38.28	36.97	39.38
Review	1.73	1.06	2.16	2.35	1.88	1.84
Short survey	2.52	1.59	1.11	0.74	0.16	1.23
Article in press	-	0.08	0.06	0.46	2.50	0.62
Other	1.89	3.03	4.94	1.49	1.36	2.54
n	1,269	1,318	1,618	1,745	1,918	7,868

The numbers of journal and conference papers lie close together, and the distribution seems to be stable for the period 2009–2013. Although in some fields conference publications are preferred, such as in computer science (Vardi 2009), the main reason for scholars to choose a journal is that their work naturally gains superior consideration, in particular if the journal has a high impact factor or a good reputation (Banister 2014). Apart from that, some scholars may prefer to get quick feedback and to present and discuss current progress to an (international) audience of researchers in the same field for which a dedicated conference would be a better choice. In the field of public transport, we see that both alternatives are frequently used to convey knowledge and insights of research activities.

Referencing Patterns

Next, we analyzed reference patterns of journal and conference papers having a non-empty bibliography. From a scientometric perspective, referencing patterns are essential to understand to what extent existing works build the basis for research progress. In this context, "efficient" means that a publication has a high impact and, thus, largely contributes to the existing knowledge basis. For this purpose, we compared the median (MED) of references per publication with the number of citations. We chose the median as it represents a robust statistic. Generally, we distinguished between journal and conference papers, as depicted in Table 6. A table row describes the median number of references MED depending on the minimum number of citations that a group of publications *n* receives. For example, the median number of references of a journal paper that is cited by 25–49 other publications is 36; the median of a journal that is cited by 1–4 other publications is 27.

TABLE 6.
Referencing Patterns

Min. Citations	n (Conference)	MED	n (Journal)	MED
0	2959	9	4019	24
1	489	12	2329	27
5	75	19	798	29
10	23	26	325	33
25	1	28	61	36
50			9	40
100			1	148

The numbers show a general pattern: a publication retrieves more citations the more publications it cites. Indeed, the coverage of important works is generally recognized as a significant indicator for the impact of publications (Straub 2006). By comparing journal and conference referencing patterns, we observed that journal papers contain more references in general, mainly for the simple reason that the page limits for conference papers often are more restrictive forcing scholars to cut some references.

Keyword and Keyword Cluster Analysis

After analyzing some general publishing patterns, a keyword analysis was conducted to gain deeper insights into important topics, current trends, and relationships between topics reflected by keyword clusters. This supports a better understanding of focus research activities. Generally, keywords are used to abstractly summarize and classify the content of a scientific publication. By aggregating the occurrence of keywords in consecutive time periods, it is possible to identify research trends. Implicit relationships between topics can be identified by analyzing co-occurrences of keywords. For gaining these insights, we implemented methods to aggregate unique keyword occurrences and occurrences of keyword clusters with different lengths. Based on the large bibliographic data basis, we extracted 22,247 unique keywords and analyzed top keywords in the area of public transport. A ranking of keywords with a high frequency (f greater than or equal to 50) is shown in Table 7, indicating the importance of certain topics, challenges, methodologies, and technologies frequently discussed in the last five years. At a glance, important topics can be identified, such as reflected by the keywords *accessibility*, *traffic congestion*, *bus rapid transit*, *sustainable transport*, and *mobility*. Plenty of research activities aim to find sustainable solutions for related challenges currently faced in particular by urban/metropolitan areas.

TABLE 7.
Top Keywords ($f \geq 50$)

Rank	Keyword	f	Rank	Keyword	f
1	transportation	336	30	climate change	66
2	accessibility	158	30	vehicles	66
3	traffic congestion	156	33	urban development	64
4	optimization	145	33	mode choice	64
5	urban planning	141	35	transportation policy	63
6	transportation planning	135	36	bus	61
7	sustainable development	132	37	decision making	60
8	transportation system	127	37	genetic algorithm	60
9	mobility	116	37	united kingdom	60
10	traffic management	110	40	economics	59
11	sustainability	105	40	travel behavior	59
11	urban traffic	105	40	bus rapid transit	59
13	buses	103	43	commuting	58
14	urban areas	102	43	intelligent transportation systems	58
15	land use	99	45	intelligent systems	56
15	light rail transit	99	46	GPS	55
17	China	98	46	public transportation systems	55
18	travel time	97	46	evaluation	55
19	GIS	88	46	transport policy	55
19	planning	88	50	traffic engineering	54
21	transport	87	50	transportation development	54
22	United States	86	52	public transport systems	53
23	research	79	52	computer simulation	53
24	bus transportation	78	54	people movers	52
25	simulation	76	55	sustainable transport	51
26	traffic control	74	55	bus transport	51
27	motor transportation	69	57	walking	50
28	metropolitan area	67	57	surveys	50
28	transport planning	67	57	urban area	50
30	design	66			

This includes activities in designing *transport policies* and involves *urban and transport planning* as well as *urban development* based on *surveys*, *optimization*, and *simulation* studies with regards to transport *economics*, efficiency, and environmental impacts. Moreover, the keyword ranking demonstrates a focus of research on certain transport modalities such as *buses* and *light rail* vehicles. We further see that the top three contributing countries appear in the ranking of top keywords. This confirms that research on public transport often is related to certain countries with a relatively large share of public transport often facing severe challenges of implementing and advancing their public transport systems, as demonstrated by the ranking of top contributing countries. We also can see the strong influence of transportation research in general due to its implication on public transport (e.g., regarding infrastructure and safety aspects) as well as due to the impact of public transport on transportation in general (e.g., regarding sustainable transportation planning and development). Moreover, the importance of innovative technologies and information systems is confirmed, reflected by the keywords *GIS* (geographic information system), *traffic control*, and *intelligent transportation systems* (ITS). This further explains the essential role of computer science-related research, or, in general terms, the importance of interdisciplinary research in the field of public transport. By analyzing the occurrence of some particular keywords per year, it is possible to identify some current trends, for example, related to the focus on sustainability and transport vehicle technologies, expressed by the keywords *sustainability*, *bus rapid transit*, and *electric vehicles*. These exemplary research trends are depicted in Table 8.

TABLE 8.
Keyword Trends

Keyword	2009	2010	2011	2012	2013
sustainability	7	11	23	21	36
bus rapid transit	6	10	10	11	18
electric vehicles	5	6	2	12	16

Topic coherence can be observed by analyzing keyword co-occurrences. We used the term *keyword cluster* to describe a group of a certain number of keywords that co-occur frequently. As mentioned previously, a method was implemented to investigate the occurrence of all possible keyword combinations of different length by a pairwise comparison of respective keyword clusters. As some keywords refer to the superordinate area (e.g., *transportation*, *public transportation*, *mass transit*, *urban transport*, etc.), we excluded these keywords for the keyword cluster analysis to gain meaningful results. In the following, we present the results of the keyword cluster analysis for keyword cluster with two elements (Table 9) and three elements (Table 10).

TABLE 9.
Top Keyword Cluster of Length 2 ($f \geq 15$)

Rank	Keyword Cluster		*f*
1	buses	bus transportation	27
2	cost effectiveness	multimodal transportation	21
2	Europe	Eurasia	21
4	transportation system	transportation planning	20
4	urban planning	United States	20
6	traffic management	traffic congestion	19
6	mass transit systems	light rail transit	19
8	intelligent systems	intelligent transportation systems	18
8	roads and streets	motor transportation	18
8	transportation system	traffic congestion	18
11	gas emissions	greenhouse gases	17
11	transportation planning	united states	17
11	urban planning	sustainable development	17
11	automation	people movers	17
11	transportation development	transportation system	17
16	mobility	accessibility	15
16	railroad transportation	railroads	15
16	rapid transit	light rail transit	15
16	transportation system	transportation	15
16	urban transportation systems	transportation	15
16	urban planning	urban development	15

While some keyword clusters only contain word synonyms (e.g., *gas emissions* and *greenhouse gases*), some keyword clusters expose multiple interesting interrelations, such as between *multimodal transportation* and *cost effectiveness*, which reflects the impact of public transport as a part of transportation in general. Some keyword clusters further reveal the coherence between fundamental topics, such as that *transportation planning* is related to *transportation infrastructure* and *transportation development* as well as to *transportation safety* and *road transport*. Consequently, the keyword cluster analysis provides the data for creating a topic network, which consists of nodes (representing topics) and edges (representing the relationship between topics). An extension of the keyword analysis would be the application of text mining methods based on the content of the publication (e.g., a simple word count). As computational time exponentially grows by increasing the number of publications to be analyzed, it would be beneficial to implement the method as a MapReduce algorithm to count words in publications in a parallel fashion to measure their importance (see, e.g., Akritidis and Bozanis 2012; Agrawal et al. 2011; Dean and Ghemawat 2008).

TABLE 10. Top Keyword Cluster of Length 3 ($f \geq 5$)

Rank	Keyword Cluster			*f*
1	buses	bus transportation	bus stop	10
2	bus transport	transportation system	railway transport	9
3	people movers	light rail transit	automation	8
3	gas emissions	greenhouse gases	global warming	8
3	bus services	bus transportation	buses	8
3	carbon dioxide emissions	carbon dioxide	global warming	8
3	people movers	airports	international airport	8
3	bus terminals	bus stop	bus transportation	8
9	traffic congestion	motor transportation	roads and streets	7
9	automotive engineering	commercial vehicles	automobiles	7
9	road network	motor transportation	roads and streets	7
12	traffic control	motor transportation	road network	6
12	highway administration	motor transportation	roads and streets	6
12	bus transport	transportation system	transportation development	6
12	emission control	gas emissions	greenhouse gases	6
12	buses	bus transportation	travel time	6
12	buses	bus terminals	bus stop	6
18	urban development	metropolitan area	urban planning	5
18	public transportation networks	transportation routes	algorithms	5
18	traffic management	transportation system	traffic congestion	5
18	highway traffic control	intelligent transportation systems	intelligent systems	5
18	buses	bus transportation	traffic congestion	5
18	bus rapid transit	light rail transit	rapid transit	5
18	population densities	population statistics	economics	5
18	railway transport	transportation system	transportation development	5
18	traffic management	roads and streets	motor transportation	5
18	transportation planning	transportation infrastructure	transportation development	5
18	bus stop	arrival time	bus transportation	5
18	road transport	traffic congestion	traffic management	5
18	buses	bus transportation	bus route	5
18	transportation safety	transportation planning	road transport	5
18	bus transport	railway transport	transportation development	5

Citation Patterns

After providing some insights into publishing patterns, current topics, and related trends, we evaluated the impact of contributions by applying scientometric means. A widely-accepted indicator for measuring the impact in a field of research is the number of citations a contribution receives. As the time a publication is available has a significant influence on its citations, we used both aggregated citations and NCII. The NCII makes citations of publications comparable by taking into account the longevity of each publication, which refers to the number of years the publication has been in print (Heilig and Voß 2014; Serenko and Bontis 2004), as shown in equation (1). A paper published in 2009, for instance, has a publication longevity of five years. Citations of the first year fully count for the calculation.

$$NCII = \frac{number\ of\ citations\ per\ publication}{publication\ longevity\ (in\ years)} \quad (1)$$

Overall Citation Patterns

First, we analyzed the distribution and impact of publications in general. The numbers in Table 11 reveal some important patterns. The time significance is reflected by the contrary trend of citations concerning the number of publications. Generally, an increase of the average NCII per publication can be observed for the first two years. In contrast, the results show a declining trend of the average NCII per publication between 2011 and 2013 and a strong decrease in 2013. One of the main reasons for a lower average NCII in 2012 and 2013 is that a lot of works citing those publications still are not covered in Scopus. Nevertheless, we observed that the standard deviation of the numbers from the average NCII per publication over time between 2009 and 2012, which is 0.06 from a mean of 0.67, is not significant. Consequently, we observed that the distribution of citations is evenly distributed.

TABLE 11.
Overall Citation Pattern

Year	2009	2010	2011	2012	2013
Number of publications	1,269	1,318	1,618	1,745	1,918
Number of citations	4,066	3,860	3,370	2,118	756
Longevity (in years)	5	4	3	2	1
Overall NCII	813.20	965.00	1,123.33	1,059.00	756.00
Avg. NCII/publication	0.64	0.73	0.69	0.61	0.39

Outlet Citation Patterns

As shown previously, the large number of journal papers suggests that the scientific community in the field of public transport publishes mostly in journals. By analyzing the distribution of citations with regard to different publication outlets, the reason for the superior role of journal papers becomes obvious. Although conference papers account for only 8.52% of the overall citations on average, journal papers have a huge scientific impact, accounting for 86.99% of the overall citations.

TABLE 12.
Outlet Citation Patterns

Outlet	2009 (%)	2010 (%)	2011 (%)	2012 (%)	2013 (%)	Overall (%)
Journal paper	85.19	87.44	84.54	87.58	90.21	86.99
Conference paper	9.99	9.79	9.26	8.55	5.03	8.52
Review	4.01	1.66	5.58	3.45	4.76	3.89
Other	0.81	1.11	0.62	0.42	-	0.59
Number of citations	**4,066**	**3,860**	**3,370**	**2,118**	**756**	**14,170**

Journal Citations

Due to the superior role of journal papers and their scientific impact, a ranking of top-cited journals (see Table 13) has been generated to reflect the impact of specific journals. While n is the number of publications related to public transport, n_{all} reflects the number of all articles published by the respective journal within the defined time period to demonstrate the concentration of public transport research in those journals. Furthermore, we attached a column with the Impact Factor (IF) and 5-year IF from the 2013 *Journal Citation Reports* (JCR). The IF and 5-year IF calculate the average number of citations per publication based on the preceding two and five years, respectively. However, some of the top cited journals are not covered by the JCR, such as *Public Transport* and *Research in Transportation Economics*.

Publication Citation Patterns

As a further step, we measured the impact of individual publications and generated a ranking of top publications in the area of public transport research (see Appendix B; note that not all articles in the ranking are referenced in the bibliography). For this purpose, the NCII and the total count of citations f for each publication is calculated. An additional column, R_f, includes the ranking by the total count of citations. Publications with a high citation number and a relatively low NCII are attached in the end of the ranking, ordered by f. Moreover, we added citation information of Google Scholar f^G (as of August 26, 2014) and a respective ranking R_{fG}. We observe that important topics, identified with the keyword analysis, are represented in the titles of top publications. The ranking further provides an overview on important literature in the area of public transport.

TABLE 13. Top Cited Journals ($f \geq 75$)

Rank	ISSN	Journal	Publisher	*f*	n	n_{all}	IF (2 y)	IF (5 y)
1	0965-8564	Transportation Research Part A: Policy and Practice	Elsevier	978	137	522	2.525	2.855
2	0967-070X	Transport Policy	Elsevier	813	175	473	1.718	2.084
3	0966-6923	Journal of Transport Geography	Elsevier	747	146	758	2.214	2.768
4	0968-090X	Transportation Research Part C: Emerging Technologies	Elsevier	530	86	591	2.006	2.433
5	0191-2615	Transportation Research Part B: Methodological	Elsevier	402	67	547	3.894	4.439
6	0361-1981	Transportation Research Record	TRB	380	225	4608	0.442	0.636
7	0049-4488	Transportation	Springer	280	81	280	1.617	2.061
8	1361-9209	Transportation Research Part D: Transport and Environment	Elsevier	265	53	469	1.626	1.626
9	1866-749X	Public Transport	Springer	210	65	73	-	-
10	0733-9488	Journal of Urban Planning and Development	ASCE	204	56	196	0.931	0.900
11	0301-4215	Energy Policy	Elsevier	176	31	4257	2.696	3.402
12	1366-5545	Transportation Research Part E: Logistics and Transportation Review	Elsevier	169	21	484	2.193	2.943
13	0308-518X	Environment and Planning A	Pion Ltd.	158	23	996	1.694	2.485
14	0733-947X	Journal of Transportation Engineering	ASCE	150	68	668	0.877	1.073
15	1556-8318	International Journal of Sustainable Transportation	T&F	149	31	120	1.447	1.505
16	0013-936X	Environmental Science & Technology	ACS	133	8	-	5.481	6.277
17	0264-2751	Cities	Elsevier	132	32	455	1.836	2.055
18	0739-8859	Research in Transportation Economics	Elsevier	114	73	262	-	-
19	0144-1647	Transport Reviews	T&F	100	25	225	1.551	2.310
20	0042-0980	Urban Studies	SAGE	98	20	1172	1.330	1.961
21	0360-5442	Energy	Elsevier	96	8	3343	4.159	4.465
22	0048-9697	Science of the Total Environment	Elsevier	94	17	5169	3.163	3.906
23	0094-1190	Journal of Urban Economics	Elsevier	91	8	262	1.888	3.277
24	1570-6672	Journal of Transportation Systems Engineering and Information Technology	Elsevier	84	105	274	-	-
25	1567-7141	European Journal of Transport and Infrastructure Research	TU Delft	77	14	118	1.023	1.132
26	0304-3894	Journal of Hazardous Materials	Elsevier	75	5	7514	4.331	5.123
26	1524-9050	IEEE Transactions on Intelligent Transportation Systems	IEEE	75	18	755	2.472	2.935

n = number of publications
n_{all} = number of all articles published by the respective journal within the defined time period
IF = Impact Factor
TRB = Transportation Research Board
ASCE = American Society of Civil Engineers
ACS = American Chemical Society
T&F = Taylor & Francis

Author Citation Patterns

The impact of individual authors can be derived from the number of citations of co-authored publications. In Table 14, a ranking of top authors based on their individual citations is provided. The top three cited authors are Robert Cervero (University of California, Berkeley), Fred Mannering (Purdue University), and Dominique Lord (Texas A&M University). We further observed that most of the top researchers are from the United States. Note that name changes (e.g., after marriage) are not considered and may have implications for the ranking.

TABLE 14. Top Cited Authors ($f \geq 70$)

Rank	Name	Affiliation	Country	n	NCII	*f*
1	Cervero, Robert	University of California, Berkeley	United States	15	41.433	175
2	Mannering, Fred	Purdue University	United States	3	40.167	158
3	Lord, Dominique	Texas A&M University	United States	2	38.500	154
4	Kennedy, Chris	University of Toronto	United States	8	33.083	142
5	Currie, Graham	Monash University	Australia	30	36.367	132
6	Pucher, John	Rutgers University	United States	7	45.000	127
7	Phdungsilp, Aumnad	Dhurakij Pundit University	Thailand	2	24.250	114
8	Dell'Olio, Luigi	University of Cantabria	Spain	12	33.167	104
9	Ibeas, Angel	University of Cantabria	Spain	10	28.767	100
10	Steinberger, Julia	University of Klagenfurt	Austria	1	17.000	85
10	Pataki, Diane	University of California, Irvine	United States	1	17.000	85
10	Méndez, Gara Villalba	Autonomous University of Barcelona	Spain	1	17.000	85
10	Gasson, Barrie	University of Cape Town	South Africa	1	17.000	85
10	Hansen, Yvonne	University of Cape Town	South Africa	1	17.000	85
10	Ramaswami, Anu	University of Colorado Denver	United States	1	17.000	85
10	Hillman, Tim	University of Colorado Denver	United States	1	17.000	85
17	Burinskiene, Marija	Vilnius Gediminas Technical University	Lithuania	5	16.867	83
18	Hensher, David	University of Sydney	Australia	23	28.333	80
19	Karlaftis, Matthew	National Technical University of Athens	Greece	11	20.233	76
20	Gomez, Luis Fernando	Foundacion FES Social	Colombia	1	15.000	75
20	Jacoby, Enrique	Pan-American Health Organization	United States	1	15.000	75
20	Sarmiento, Olga L.	University of Los Andes	Colombia	1	15.000	75
20	Neiman, Andrea	University of Illinois, Chicago	United States	1	15.000	75
20	Daganzo, Carlo F.	University of California, Berkeley	United States	6	26,333	75
25	Li, Jianqiu	Tsinghua University	China	6	21.483	70

n = number of publications

Affiliation Citation Patterns

Finally, the performance of research institutions in terms of citations was evaluated. The NCII is calculated based on the citations of authors belonging to the affiliation at the time of publication. In the ranking of the top 30 affiliations in Table 15, we see that the University of Toronto, the University of California, Berkeley, and Monash University are the leading research institutions in the field of public transport. Most of the influential affiliations are from the United States confirming the results given in an earlier section.

TABLE 15.
Top Research Institutions (NCII ≥ 40.00)

Rank	Affiliation	Country	NCII
1	University of Toronto	Canada	92.45
2	University of California, Berkeley	United States	87.70
3	Monash University	Australia	76.23
4	University of Sydney	Australia	71.18
5	Tsinghua University	China	65.43
6	Rutgers University	United States	56.73
7	Karlstad University	Sweden	53.37
8	University of Melbourne	Australia	52.83
9	University of Hong Kong	China	50.85
10	Beijing Jiaotong University	China	49.80
11	Texas A&M University	United States	49.03
12	University of Minnesota	United States	48.63
13	Delft University of Technology	Netherlands	46.02
14	Purdue University	United States	44.17
15	Queensland University of Technology	Australia	44.00
16	University of Leeds	United Kingdom	41.62

Research Productivity

The scientometric measurement of research productivity is just as important as analyzing citation patterns for the evaluation of science from a meta-perspective. The overall research productivity is an important indicator for the development of a field of research. It reflects the number of publications individuals contribute to the overall knowledge base within a specific time frame.

Individual Research Productivity

First, we focused on the individual productivity of scholars by using the equal credit method, as discussed earlier. Table 16 provides a ranking of the top 20 scholars in terms of research productivity based on the overall number of co-authored publications, n. The top three scholars are Corrine Mulley (University of Sydney), Graham Currie (Monash University), and Avishai Ceder (University of Auckland). Graham Currie is also one of the most cited authors (Rank = 5, see Table 14). Most of the top contributors are from institutions located in China, which confirms the results of the contributing countries analysis given in an earlier section. As an extension of that section, we see that mostly the high productivity of a handful of scholars located in Australia contribute to the overall productivity. Moreover, we see that only one scholar from the United Kingdom, John Nelson

(University of Aberdeen), is in the top 20 of highly-productive scholars. Consequently, the high overall productivity of institutions located in the United Kingdom (see Table 3) must be generated by a large number of scholars carrying out research in the field.

TABLE 16. Top Individual Productivity (Equal Credit Method)

Rank	Author	Affiliation	Country	n	Score
1	Mulley, Corinne	University of Sydney	Australia	34	15.23
2	Currie, Graham	Monash University	Australia	30	12.43
3	Ceder, Avishai	University of Auckland	New Zealand	24	11.83
4	Cervero, Robert	University of California, Berkeley	United States	15	8.87
5	Hensher, David	University of Sydney	Australia	23	8.82
6	Chen, Yanyan	Beijing Jiaotong University	China	23	8.20
7	Zhang, Guo-wu	Beijing Jiaotong University	China	9	8.20
8	Kumar, Ashok	University of Toledo	United States	17	7.75
9	El-Geneidy, Ahmed	McGill University	Canada	18	7.07
10	Nelson, John	University of Aberdeen	United Kingdom	17	6.27
11	Delbosc, Alexa	Monash University	Australia	14	6.08
12	Wang, Wei	Southeast University	China	21	5.75
13	Kadiyala, Akhil	University of Toledo	United States	12	5.25
14	Yang, Xiaoguang	Tongji University	China	18	5.15
15	Karlaftis, Matthew G.	National Technical University of Athens	Greece	11	5.08
16	Chen, Xuewu	Southeast University	China	14	4.90
17	Gordon, Cameron	University of Canberra	Australia	7	4.75
18	Tirachini, Alejandro	University of Sydney	Australia	13	4.70
19	Chen, Yu-yi	Beijing University of Technology	China	12	4.37
20	Jin, Wen-zhou	South China University of Technology	China	11	4.25

Lotka's Law

We extended the analysis on research productivity by exploring the overall productivity distribution patterns of all authors being active in the field of public transport. This helps not only to understand the structure of this field, but also enables a comparison with other fields and an estimation of future research productivity. For this, prior scientometric studies tested the application of Lotka's law (Serenko and Bontis 2004), which describes a frequency distribution of scientific productivity in a certain field of research. According to Alfred J. Lotka, the proportional relationship between the number of scholars accounting for p publications is about $1/p^{\alpha}$, where $\alpha = 2$ (Coile 1977). On basis of these observations, the theoretical relationship between the number of publications p and the proportional number of all authors making p contributions $f(p)$ is expressed by equation (2):

$$f(p) = {}^{C}/_{p^{\alpha}} \qquad (2)$$

where α and C are non-negative constants to be determined from the observations and p = 1, 2, 3, 4, etc. The constant C corresponds to the number of authors who have contributed to the field only once, as in Serenko and Bontis (2004). The start and end point of the time period of investigation are arbitrary as a matter of principle (Wagner-Döbler and Berg 1995).

According to Pao (1986), the Lotka distribution is independent on the period of time investigated. To test the application of Lotka's law, an optimal value of α must be found that fits the distribution of observations. This value can be used to verify Lotka's law and to predict an approximate number of authors contributing a certain frequency of publications (Kretschmer and Rousseau 2001; Serenko and Bontis 2004). Therefore, we calculated the optimal value for α minimizing the sum of absolute errors. By this, we found an α value of 2.62, which is considerably higher than the theoretical α proposed by Lotka (α = 2), but not exceptional regarding other scientometric studies. As discussed in Serenko and Bontis (2004), prior scientometric studies in other fields obtained different values for α within the ranges of 1.5 to 3 (Bonnevie 2003), 1.95 to 3.26 (Chung and Cox 1990), and 2.21 to 2.46 (Cocosila et al. 2011).

The reason for the higher value of α in the area of public transport is that approximately 78.98% of contributors have published only one publication, whereas Lotka assumed that approximately 60% of contributors have a single publication (Coile 1977). This phenomenon can be explained by the fact that scholars often collaborate with practitioners whose primary concern is to explain and solve specific problems rather than producing extensive research on a variety of problems. Thus, those non-academics tend to publish less frequently than academics. Further, note that selecting a certain time period in the development of a scientific area has effects on the frequency distribution, as it generally depends on the individual behavior of authors and on the inflow of new authors (Wagner-Döbler and Berg 1995).

Furthermore, the inequality of the frequency with which scholars are able to contribute has roots in the Matthew Effect (Wagner-Döbler and Berg 1995) and the related theory of cumulative advantage proposed by Price (1976). That is, more eminent scholars are given more credit and are repeatedly rewarded by other scientists. A good reputation promotes the collection of research funds and cultivates co-authored publications with other scholars aiming to collaborate. In Appendix C, we compared the domain-specific optimal value α as well as the aggregated error with the theoretical α proposed by Lotka (α = 2). By analyzing the coefficient of determination (R2), we observe that both the predictions for α = 2 and α = 2.62 fit well to the observed number of authors ($R^2_{\alpha=2,\ \alpha=2.62} \geq 0.99$). Of course, R^2 is improved by finding the optimal value for α as the aggregated error decreases. Consequently, we demonstrated that Lotka's law can be used to predict the number of authors that contribute p = 1, 2, 3, 4, etc. publications.

Conclusion

In this study, we conducted a scientometric analysis of public transport research based on a large bibliographic data basis of respective contributions, published in the period from 2009 to 2013. With the empirical findings of this scientometric analysis, we provide novel insights into a range of publishing patterns. The results indicate that most contributions are produced in the United States, China, and the United Kingdom and that mostly social science, engineering, and computer science disciplines are involved. Regarding co-authorship, we see a trend towards multi-authorship contributions to better address interdisciplinary research challenges. Knowledge is conveyed primarily through journal papers, which gain superior consideration in comparison with conference papers. Further, we observe current research topics and trends as well as relationships between topics by analyzing keywords and keyword clusters.

The results demonstrate the role of research in designing public transport policies and planning based on surveys, optimization, and simulation studies that consider economic, efficiency, and environmental factors. In addition, the importance of innovative ICT solutions and information systems for public transport is reflected. The concentration of topics and trends can be compared with current and future challenges for elucidating research gaps. In general, we see a trend and major research efforts to better integrate different problems and research disciplines in the area of public transport, allowing for system-wide improvement and innovations based on interdisciplinary and even transdisciplinary research activities.

By applying scientometric methods, we further present valuable rankings on current driving forces in terms of research productivity and impact, respectively, as well as on research outlets and topics. The intention of this study was to provide a novel meta-perspective on public transport research that extend common review papers and further helps scholars and practitioners to get a quick overview on important aspects. Consequently, our results may help steer individual projects, extend research collaborations, and select a proper publication outlet, to name a few benefits.

Finally, we conducted an experiment to verify the satisfaction of Lotka's law, showing that the distribution of productivity can be compared to several other research areas as our results show that the theoretical distribution fits to the observed data. Methodologically, the empirical findings demonstrate the strength of a scientometric analysis to extensively investigate a field of interest. As demonstrated, the results of the scientometric analysis are not only valuable for discussing and defining future research agendas in the area of public transport. Technically, the semi-automated process of assessing a large amount of publications makes it possible to easily obtain a comprehensive overview of a particular research area. This, in contrast, cannot be achieved by a structured literature review to that degree. Therefore, the study represents a good starting point for academics and practitioners to identify the sources and concentration of the existing knowledge base.

For further research, the temporal scope of our scientometric analysis could be expanded to explore long-term developments in the area of public transport. In methodological terms, we intend to investigate network structures among authors as well as the relationship between topics and authors. A respective visual representation would help to see at a glance pivotal elements and their connections to each other. By exploring those connections, we aim to measure and explain their potential impact on the structure and development of public transport research from different perspectives, for instance, by exploring the effect of maintaining a high level of collaboration or networking in scientific circles on research productivity and citations of individual authors.

Another interesting aspect for further research is the analysis of collaboration structures between academics and professionals to explore how public transport research is influenced by practice. More importantly, the analysis of network structures may help to observe the lack of research or collaboration such as by identifying missing connections (e.g., between topics), as shown in Schwarze et al. (2012). Technically, we intend to further improve the applied data processing methods to further reduce manual proofreading activities by means of data mining techniques and accuracy metrics. In this regard, we aim to apply MapReduce algorithms to parallelize computations to reduce computation time.

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Appendix A

TABLE 17.
Comparison of Journal Coverage of Scopus (2015) and WoS (2015)

ISSN	Journal Title	WoS
18245463	Advances in Transportation Studies	-
08669546	Archives of Transport (active until 2012)	-
2213624X	Case Studies on Transport Policy	-
22120122	Economics of Transportation	-
15677141	European Journal of Transport and Infrastructure Research	X
18253997	European Transport - Trasporti Europei	-
18670717	European Transport Research Review	-
19391390	IEEE Intelligent Transportation Systems Magazine	X
15249050	IEEE Transactions on Intelligent Transportation Systems	X
20429738	IET Electrical Systems in Transportation	-
1751956X	IET Intelligent Transport Systems	X
18688659	International Journal of Intelligent Transportation Systems Research	-
17566517	International Journal of Shipping and Transport Logistics	X
15568318	International Journal of Sustainable Transportation	X
03918440	International Journal of Transport Economics	-
10096744	Journal of Transportation Systems Engineering and Information Technology	-
01976729	Journal of Advanced Transportation	X
15472450	Journal of Intelligent Transportation Systems	X
2095087X	Journal of Modern Transportation	-
1077291X	Journal of Public Transportation	X
22109706	Journal of Rail Transport Planning and Management	-
09696997	Journal of Air Transport Management	X
16711637	Journal of Traffic and Transportation Engineering	-
22141405	Journal of Transport and Health	X
19387849	Journal of Transport and Land Use	-
00225258	Journal of Transport Economics and Policy	X
09666923	Journal of Transport Geography	X
00225266	Journal of Transport History	-
0733947X	Journal of Transportation Engineering	X
19439962	Journal of Transportation Safety and Security	-
19387741	Journal of Transportation Security	-
15706672	Journal of Transportation Systems Engineering and Information Technology	-
18744478	Open Transportation Journal	-
03037800	Periodica Polytechnica Transportation Engineering	-
16137159	Public Transport	-
1016796X	Public Transport International (active until 2012)	-
22105395	Research in Transportation Business and Management	-
07398859	Research in Transportation Economics	X
10375783	Road and Transport Research	X

ISSN	Journal Title	WoS
23275626	SAE International Journal of Transportation Safety	-
0360859X	Special Report - National Research Council, Transportation Research Board	-
00404748	Texas Transportation Researcher	-
16484142	Transport	X
14076160	Transport and Telecommunication	-
0967070X	Transport Policy	X
18960596	Transport Problems	-
01441647	Transport Reviews	X
00494488	Transportation	X
22143912	Transportation Geotechnics	-
00411612	Transportation Journal	X
19427867	Transportation Letters	X
03081060	Transportation Planning and Technology	X
09658564	Transportation Research Part A: Policy and Practice	X
01912615	Transportation Research Part B: Methodological	X
13619209	Transportation Research Part D: Transport and Environment	X
13665545	Transportation Research Part E: Logistics and Transportation Review	X
13698478	Transportation Research Part F: Traffic Psychology and Behaviour	X
03611981	Transportation Research Record	X
00411655	Transportation Science	X
18128602	Transportmetrica (active until 2012)	X
23249935	Transportmetrica A: Transport Science	X
21680566	Transportmetrica B	X
17494729	World Review of Intermodal Transportation Research	-
10062823	Journal of Wuhan University of Technology (Transportation Science and Engineering)	-

Appendix B

TABLE 18.
Top Publications (by NCII)

Rank	R_f	R_{fG}	Publication	NCII	f	f^G
1	1	1	Lord D., Mannering F. (2010) The statistical analysis of crash- frequency data: A review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice, 44(5): 291-305.	38.50	154	294
2	2	3	Kennedy C., Steinberger J., Gasson B., Hansen Y., Hillman T., Havranek M., Pataki D., Phdungsilp A., Ramaswami A., Mendez G.V. (2009) Greenhouse gas emissions from global cities. Environmental Science and Technology, 43(19): 7297-7302.	17.00	85	178
2	4	2	Glaeser E.L., Kahn M.E. (2010) The greenness of cities: Carbon dioxide emissions and urban development. Journal of Urban Economics, 67(3): 404-418.	17.00	68	286

Rank	R_f	R_{fG}	Publication	NCII	f	f^G
4	9	26	Wang W., Zhang W., Guo H., Bubb H., Ikeuchi K. (2011) A safety-based approaching behavioral model with various driving characteristics. Transportation Research Part C: Emerging Technologies, 19(6): 1202-1214.	16.67	50	72
5	154	60	Giles-Corti B., Bull F., Knuiman M., McCormack G., Van Niel K., Timperio A., Christian H., Foster S., Divitini M., Middleton N., Boru B. (2013) The influence of urban design on neighborhood walking following residential relocation: Longitudinal results from the RESIDE study. Social Science and Medicine, 77(1): 20-30.	16.00	16	36
6	5	16	Rakopoulos D.C., Rakopoulos C.D., Hountalas D.T., Kakaras E.C., Giakoumis E.G., Papagiannakis R.G. (2010) Investigation of the performance and emissions of bus engine operating on butanol/diesel fuel blends. Fuel, 89(10): 2781-2790.	15.75	63	90
7	12	6	Pucher J., Buehler R., Seinen M. (2011) Bicycling renaissance in North America? An update and re-appraisal of cycling trends and policies. Transportation Research Part A: Policy and Practice, 45(6): 451-475.	15.33	51	97
8	3	4	Cervero R., Sarmiento O.L., Jacoby E., Gomez L.F., Neiman A. (2009) Influences of built environments on walking and cycling: Lessons from Bogotá. International Journal of Sustainable Transportation, 3(4): 203-226.	15.00	38	57
9	6	24	Chen X., Xia X., Zhao Y., Zhang P. (2010) Heavy metal concentrations in roadside soils and correlation with urban traffic in Beijing, China. Journal of Hazardous Materials, 181(1-3): 640-646.	14.50	34	141
9	54	29	Blocken B., Janssen W.D., van Hoo T. (2012) CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus. Environmental Modelling and Software, 30: 15-34.	14.50	29	61
11	14	20	Daganzo C.F., Gayah V.V., Gonzales E.J. (2011) Macroscopic relations of urban traffic variables: Bifurcations, multivaluedness and instability. Transportation Research Part B: Methodological, 45(1): 278-288.	13.67	16	86
11	14	19	Geroliminis N., Sun J. (2011) Properties of a well-defined macro- scopic fundamental diagram for urban traffic. Transportation Research Part B: Methodological, 45 (3): 605-617.	13.67	41	87
13	8	15	Bissell D. (2010) Passenger mobilities: Affective atmospheres and the sociality of public transport. Environment and Planning D: Society and Space, 28(2): 270-289.	12.75	51	97
14	21	30	Wu Y., Wang R., Zhou Y., Lin B., Fu L., He K., Hao J. (2011) On-road vehicle emission control in Beijing: Past, present, and future. Environmental Science and Technology, 45(1): 147-153.	12.67	38	57
15	30	8	Duranton G., Turner M.A. (2011) The fundamental law of road congestion: Evidence from US cities. American Economic Review, 101(6): 2616-2652.	11.33	34	141

Rank	R_f	R_{fG}	Publication	NCII	f	f^G
16	32	56	Dell'Olio L., Ibeas A., Cecin P. (2011) The quality of service desired by public transport users. Transport Policy, 18(1): 217-227.	11.00	33	53
16	32	56	Li Z., Chen C., Wang K. (2011) Cloud computing for agent-based urban transportation systems. IEEE Intelligent Systems, 26(1): 73-79.	11.00	33	53
16	305	62	Redman L., Friman M., Garling T., Hartig T. (2013) Quality attributes of public transport that attract car users: A research review. Transport Policy, 25: 119-127.	11.00	11	23
19	7	9	Eliasson J., Hultkrantz L., Nerhagen L., Rosqvist L.S. (2009) The Stockholm congestion - charging trial 2006: Overview of effects. Transportation Research Part A: Policy and Practice, 43(3): 240-250.	10.80	54	125
20	99	61	Abou-Zeid M., Witter R., Bierlaire M., Kaufmann V., Ben-Akiva M. (2012) Happiness and travel mode switching: Findings from a Swiss public transportation experiment. Transport Policy, 19(1): 93-104.	10.00	20	28
20	344	64	Camacho T.D., Foth M., Rakotonirainy A. (2013) Pervasive technology and public transport: Opportunities beyond telematics. IEEE Pervasive Computing, 12(1): 18-25.	10.00	10	12
22	10	30	Jakimavicius M., Burinskiene M. (2009) A GIS and multi-criteria- based analysis and ranking of transportation zones of Vilnius city. Technological and Economic Development of Economy, 15(1): 39- 48.	9.80	49	57
22	10	13	Crainic T.G., Gendreau M., Potvin J.-Y. (2009) Intelligent freight-transportation systems: Assessment and the contribution of operations research. Transportation Research Part C: Emerging Technologies, 17(6): 541-557.	9.80	49	109
24	18	10	Santos G., Behrendt H., Teytelboym A. (2010) Part II: Policy instruments for sustainable road transport. Research in Transportation Economics, 28(1): 46-91.	9.75	39	116
25	50	28	Angel S., Parent J., Civco D.L., Blei A., Potere D. (2011) The dimensions of global urban expansion: Estimates and projections for all countries, 2000-2050. Progress in Planning, 75(2): 53-107.	9.67	29	70
26	57	58	Eboli L., Mazzulla G. (2011) A methodology for evaluating transit service quality based on subjective and objective measures from the passenger's point of view. Transport Policy, 18(1): 172-181.	9.33	28	51
27	23	6	Shaheen S., Guzman S., Zhang H. (2010) Bikesharing in Europe, the Americas, and Asia. Transportation Research Record, 2143: 159-167.	9.25	37	152
27	23	12	Thiagarajan A., Biagioni J., Gerlich T., Eriksson J. (2010) Cooperative transit tracking using smart-phones. In: Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys 2010), 85-98, ACM.	9.25	37	110
29	114	63	Yu B., Yang Z.-Z., Jin P.-H., Wu S.-H., Yao B.-Z. (2012) Transit route network design-maximizing direct and transfer demand density. Transportation Research Part C: Emerging Technologies, 22: 58-75.	9.00	18	22

Rank	R_f	R_{fG}	Publication	NCII	f	f^G
29	59	59	Awasthi A., Chauhan S.S. (2011) Using AHP and Dempster-Shafer theory for evaluating sustainable transport solutions. Environmental Modelling and Software, 26(6): 787-796.	9.00	27	45
29	61	16	Lin J.-R., Yang Ta-Hui T.-H. (2011) Strategic design of public bicycle sharing systems with service level constraints. Transportation Research Part E: Logistics and Transportation Review, 47(2): 284-294.	9.00	27	90
(36)	13	7	Crainic T.G., Ricciardi N., Storchi G. (2009) Models for evaluating and planning city logistics systems. Transportation Science, 43(4): 432-454.	8.60	43	144
(41)	14	22	Feng K., Hubacek K., Guan D. (2009) Lifestyles, technology and CO2 emissions in China: A regional comparative analysis. Ecological Economics, 69(1): 145-154.	8.20	41	78
(48)	17	30	Middleton J. (2009) "Stepping in time": Walking, time, and space in the city. Environment and Planning A, 41(8): 1943-1961.	8.00	40	57
(49)	18	23	Vandenbulcke G., Steenberghen T., Thomas I. (2009) Mapping accessibility in Belgium: a tool for land-use and transport planning? Journal of Transport Geography, 17(1): 39-53.	7.80	39	77
(49)	18	21	Coveney J., O'Dwyer L.A. (2009) Effects of mobility and location on food access. Health and Place, 15(1): 45-55.	7.80	39	85
(55)	21	14	Cao X.J., Mokhtarian P.L., Handy S.L. (2009) The relationship between the built environment and non-work travel: A case study of Northern California. Transportation Research Part A: Policy and Practice, 43(5): 548-559.	7.60	38	108
(57)	23	11	Ewing R., Dumbaugh E. (2009) The built environment and traffic safety: A review of empirical evidence. Journal of Planning Literature, 23(4): 347-367.	7.40	37	112
(57)	23	18	Wang D., Chai Y. (2009) The jobs-housing relationship and commuting in Beijing, China: the legacy of Danwei. Journal of Transport Geography, 17(1): 30-38.	7.40	37	88
(23)	27	27	Currie G. (2010) Quantifying spatial gaps in public transport supply based on social needs. Journal of Transport Geography, 18(1): 31-41.	8.75	35	71
(67)	28	25	Von Ferber C., Holovatch T., Holovatch Y., Palchykov V. (2009) Public transport networks: Empirical analysis and modeling. European Physical Journal B, 68(2): 261-275.	7.00	35	73
(23)	28	32	Hu X., Chang S., Li J., Qin Y. (2010) Energy for sustainable road transportation in China: Challenges, initiatives and policy implications. Energy, 35(11): 4289-4301.	8.75	35	54

Appendix C

TABLE 19.
Lotka's Law – Frequency Distribution of Contributions by Author

No. of Publications	No. of Authors	Predicted Number of Authors (α = 2)	Difference Observed - Predicted (α = 2)	Predicted Number of Authors (α = 2.62)	Difference Observed - Predicted (α = 2.62)
1	7,653	7,653.00	0.00	7,653.00	0.00
2	1,282	1,913.25	631.25	1,244.90	37.10
3	366	850.33	484.33	430.30	64.30
4	162	478.31	316.31	202.50	40.50
5	90	306.12	216.12	112.86	22.86
6	46	212.58	166.58	70.00	24.00
7	26	156.18	130.18	46.74	20.74
8	18	119.58	101.58	32.94	14.94
9	11	94.48	83.48	24.19	13.19
10	7	76.53	69.53	18.36	11.36
11	9	63.25	54.25	14.30	5.30
12	2	53.15	51.15	11.39	9.39
13	2	45.28	43.28	9.23	7.23
14	2	39.05	37.05	7.60	5.60
15	3	34.01	31.01	6.35	3.35
16	3	29.89	26.89	5.36	2.36
17	1	26.48	25.48	4.57	3.57
18	1	23.62	22.62	3.94	2.94
19	1	21.20	20.20	3.42	2.42
21	3	17.35	14.35	2.63	0.37
28	1	9.76	8.76	1.24	0.24
31	1	7.96	6.96	0.95	0.05
Total	9,690	12,231.38	2,541.38	9,906.75	291.81
				R^2 (α = 2.00)	0.99001
				R^2 (α = 2.62)	0.99987

About the Authors

Leonard Heilig (*leonard.heilig@uni-hamburg.de*) holds a B.Sc. from the University of Münster (Germany) and an M.Sc. from the University of Hamburg (Germany) in Information Systems. Currently, he holds a position at the Institute of Information Systems at the University of Hamburg. He spent some time at the University of St Andrews (Scotland, UK) focusing on security management, web technologies, and software engineering. Practical experiences include work at companies such as Adobe, Airbus Group Innovations, and Beiersdorf Shared Services. His current interest focuses on business-oriented cloud computing.

Prof. Dr. Stefan Voß (*stefan.voss@uni-hamburg.de*) is director of the Institute of Information Systems at the University of Hamburg. In addition to being professor in Hamburg, he holds a visiting position at the PUCV in Valparaiso, Chile. Previous positions include full professor and head of the department of Business Administration, Information Systems and Information Management at the University of Technology Braunschweig (Germany) from 1995 to 2002. He holds degrees in Mathematics (diploma) and Economics from the University of Hamburg and a Ph.D. and the habilitation from the University of Technology Darmstadt. His current research interests are in quantitative/information systems approaches to supply chain management and logistics, including applications in maritime shipping, public mass transit, and telecommunications. He is author and co-author of several books and numerous papers in various journals and serves as editor of *Netnomics* and *Public Transport*.

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