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Planning for Pedestrian Flows in Rail Rapid Transit Stations: Lessons from the State of Current Knowledge and Practice

Carole Turley Voulgaris, Anastasia Loukaitou-Sideris, and Brian D. Taylor, FAICP
Institute of Transportation Studies, UCLA

Abstract

Decades of research have contributed to the development of standards and models to guide pedestrian-friendly transit station designs, although it is not at all clear from the literature how these tools are collectively used in practice. To address this, we interviewed 15 experts in transit station design. Based on the themes identified in these interviews, we conducted an online census of all 16 transit agencies in North America with rapid rail transit systems with below-grade stations. We found that although standards and codes are most likely to guide design decisions, the three types of tools (published standards, deterministic models, and microsimulation models) are as likely to complement as substitute for one another. We recommend that such analytical models of passenger flow should consider explicitly how practitioners employ them in practice to better link future refinements to the more “pedestrian” world of engineering and design practice.

Introduction

The question of why people choose to travel by private car rather than by public transit is of major concern to transportation planners and transit operators. For some would-be riders reluctant to wade through congested rail transit stations, the answer might be summed up by the words of Yogi Berra: “Nobody goes there anymore. It’s too crowded” (Berra 2010, 9).

Good design can alleviate passenger crowding, thereby improving passenger safety, increasing system capacity, and possibly increasing transit ridership. The purpose of this paper is to identify the approaches North American rail transit operators take to analyzing and designing for passenger crowding at below-grade rail transit stations and offer suggestions for more effective utilization of such tools.
The Evolution of Pedestrian Flow Analysis

Beginning in the 1950s, engineers began to develop formulas based on empirical observation to describe pedestrian flows (Hankin and Wright 1958):

\[ v = S \times D \]  

(1)

where, \( v \) is pedestrian flow per foot width (p/ft/min), \( S \) is walking speed (ft/min), and \( D \) is pedestrian density (p/ft\(^2\)).

\[ v = S / M \]  

(2)

where \( v \) is pedestrian flow per foot width (p/ft/min), \( S \) is walking speed (ft/min), and \( M \) is pedestrian space (ft\(^2\)/p).

In the half-century since Hankin and Wright’s initial work on this topic, other researchers have observed a similar relationship between pedestrian speeds and pedestrian density, although they each observed different maximum pedestrian densities, as summarized in a review and meta-analysis by Weidmann (1992). The most influential of these studies was conducted by John Fruin and incorporated into his highly-cited manual, *Pedestrian Planning and Design* (Fruin 1971).

The simple relationships described by Equations 1 and 2 and illustrated in Figure 1 can be applied to determine the appropriate widths of transit station elements such as passageways, doorways, stairways, and platforms. The current edition of the *Transit Capacity and Quality of Service Manual* (Kittleson & Associates et al. 2003), also referred to as TCRP 100, recommends such a design methodology, where the designer may consider the station area as comprising distinct elements that can be segmented to determine the appropriate sizes for each element, based on anticipated passenger volumes.

The deterministic methodology described in TCRP 100 (Kittleson & Associates, Inc et al. 2003) is relatively straightforward to implement—the analysis can be done using simple spreadsheet calculations—and adequately describes pedestrian flows in simple stations under uncongested conditions. However, its applicability to more complex and crowded conditions is more likely problematic.
Beginning in the late 1980s, researchers began to explore the application of increasingly powerful computing technology to simulate the movement of crowds of individual pedestrians without aggregating them into average flows (Gipps and Marksjö 1985). With computers becoming more powerful and widespread, microsimulation became a more feasible way to evaluate pedestrian (and motor vehicle traffic) flows in complex environments and understand crowd dynamics.

Over the past several decades, researchers have developed models to simulate pedestrian movement at the microscopic (or individual pedestrian) level (Gipps and Marksjö 1985; Helbing and Molnár 1995; Blue and Adler 2001; Løvás 1994). These models are the basis for commercially-available pedestrian modeling software packages such as VISSIM (Fellendorf and Vortisch 2010) and Legion (Castle et al. 2011). Although there is a substantial body of literature on solutions to the technical and computational problems associated with accurately portraying the movement of pedestrians (Jia, Yang, and Tang 2009; Ishaque and Noland 2009; Johansson, Helbing, and Shukla 2007; Peacock, Kuligowski, and Averill 2011), very little has been written about whether these increasingly-sophisticated microsimulation models actually are used by transit operators and station designers to inform their design work beyond what is available from deterministic analysis.

Whereas pedestrian flow analysis, whether deterministic and macroscopic or stochastic and microscopic, can guide the design of transit stations, established standards and codes can play a more important role in station design, since they often trump the findings of microscopic or macroscopic models—usually by requiring more space for pedestrians than called for by models of passenger flows (Kittleson & Associates, Inc. et al. 2003). Two sets of standards that are particularly relevant to station design are the Americans with Disabilities Act (ADA) (108th Congress 1990) and the Standard for Fixed Guideway Transit Systems published by the National Fire Protection Association, also referred to as NFPA 130 (NFPA 2014).

These standards focusing on the needs of passengers with disabilities and facilitating evacuations under peak conditions frequently determine the size of platforms and other station elements. Nevertheless, such standards typically define only minimums; they do not define maximums, nor do they define all aspects of platforms, queueing areas, and stairs. In such cases, other standards, rules of thumb, deterministic, and microsimulation models may come into play. Under what circumstances are these models employed? That is the subject of our analysis below.

**Research Methodology**

To determine whether existing standards and analysis methodologies are adequate for the design of new transit stations, we must first understand how and whether station designers actually use these tools. Specifically, we ask two questions: Does reliance on standards and codes complement or supplant rigorous analysis of pedestrian flows? Is microsimulation a complement to or substitute for deterministic, macroscopic analysis?
To answer these questions, we conducted in-depth, semi-structured interviews with 15 experts in transit station design, including architects, engineers, and transit planners in North America. The experts were identified based on referrals from experienced transit professionals and included consultants as well as agency staff, many of whom had worked in both contexts. Interviews were conducted by telephone, recorded, and transcribed. After compiling the interview transcripts, we carefully reviewed them to identify recurring themes, issues, and considerations in transit station planning for pedestrians.

Based on the themes identified through these expert interviews, we prepared an online survey of planners, designers, engineers, or managers at all 16 transit agencies in the United States and Canada that have below-grade rail transit stations. We contacteded representatives from each transit agency by email to invite them to complete the survey. In the event of non-response, we followed up with a telephone call to ask our initial contacts to complete the survey or to identify another person within their agency who would be able to complete it. In most cases, one respondent from each agency completed the survey. At two agencies, New York City Metropolitan Transportation Authority and Bay Area Rapid Transit, two people from each agency completed the survey. Although 18 respondents would be a relatively small sample if we were attempting to generalize about a larger population, this was not the case here, as our survey was something of a census, since every transit operator in the United States and Canada with underground rail transit stations was represented. Since the survey questions (in contrast to our interviews), for the most part, were factual rather than perceptual, responses should—in theory—be consistent among respondents from the same agency. Thus, there would have been only minimal value gained from increasing the sample size to have more respondents from each agency, particularly since the universe of U.S. and Canadian underground heavy-rail operators already was fully represented.

We limited our survey sample to include only those agencies with underground stations, although in all cases these systems operate at- or above-ground stations in their systems as well. As such, the techniques we discuss are applicable to all rail rapid transit stations (those serving systems with fully-controlled tracks), whether the stations are underground, at grade, or elevated. Many regional rail and light rail transit stations are similar to underground rail rapid transit stations, so our findings likely are applicable to such systems as well.

Because the interviews presented primarily the viewpoints of transit station planning and design consultants (since consultants were over-represented among the interviewees and many of the interviewees who currently work for public transit agencies also had experience working as consultants), the survey helped to balance the viewpoints of both consultants and agency staff.

1 In one instance, the expert was not available for a phone interview and answered the interview questions by email.
The study included seven tasks—(1) determining the number of fare collection machines and gates, (2) selecting locations of fare collection machines and gates, (3) selecting type of fare collection machines and gates, (4) determining the number of vertical circulation (stairs, escalators, elevators) elements, (5) selecting locations for vertical circulation elements, (6) selecting the type of vertical circulation elements, and (7) determining sizes for waiting and walking areas—and survey respondents were asked to select one or more of the following methods or tools they used in the design of the most recent new station with which they were personally involved:

- published standards and codes
- deterministic spreadsheet analysis
- microsimulation software

Respondents also were asked to indicate whether their design interventions were intended to correct for problems observed at other stations in their system, to be consistent with other stations in the system, or to incorporate best practices observed in other transit systems.

Results
Our findings are presented below, first from the expert interviews and then from the transit agency survey. The survey was created based on common themes that emerged from the interviews with all 15 interviewees, even though not all interviewees are directly quoted in the discussion below.

Expert Interviews
We begin first with the relative roles played by published standards, deterministic models, and microsimulation models in the analysis of pedestrian flows at transit stations.

Published Standards
Both consultants and agency staff mentioned the conservative nature of existing standards and codes, noting that adherence to existing standards can render detailed analysis of pedestrian flows moot because the standards often mandate more circulation space than would be called for by an analysis of anticipated passenger volumes. As a staff member at one transit operator put it:

A lot of that kind of technical work is embedded in standards associated with the design. So, as long as you follow the standards, typically you have enough ... entrance capacity to satisfy safety requirements associated with transit stations. So whether you have enough entrances and exits to satisfy the pedestrian flow and circulation space, those are typically handled through the standards we have in place. (Interviewee #1)

Another consultant also explained that station design depends on criteria other than passenger volumes and that when these other criteria are met, the design often will be more than adequate to accommodate anticipated passenger volumes:
It depends on the volume, but … there should be other factors that are going to govern the size of the facilities. You have to have an agency that understands the minimum of two escalators and then, in some cases, you need to have three in case you have to take one out for maintenance, which you will…. You often will have more capacity just by the fact of redundancy and maintenance requirements that you are going to need for normal operations and normal growth. (Interviewee #2)

This idea of standards serving a dual purpose—for example, that standards intended to allow for emergency evacuation also serve the purpose of ensuring adequate circulation space for comfortable day-to-day passenger flows— also is reflected in the attitudes expressed towards ADA standards. The same consultant said:

A lot of the things you do for ADA actually help all passengers or a large percentage of passengers, such as people with bikes or luggage or carriages. (Interviewee #2)

In discussing how the practice of transit station design has changed over the years, consultants referred to an increasing reliance on, and stringency of, standards and codes. One referred to the increasing role of ADA standards:

ADA has changed the way we handle pedestrians over the last 20 years. So we’re a lot more cognizant of pedestrian safety and needs of access than we were just 20 years ago. (Interviewee #3)

A second consultant referred to the nearly universal adoption of NFPA 130 (NFPA 2014) as a positive development that improves station safety, although its requirements might be unnecessarily conservative in some cases:

NFPA 130 is being embraced as the guideline; I don’t think just in this country … systems all around the world are following these guidelines, which I think is good—a little bit over-designed, but people will be safe. (Interviewee #4)

On the other hand, some experts expressed concern that the generic, one-size-fits-all nature of some standards can fail to account for station-specific contexts.

Although adherence to standards such as ADA (108th Congress 1990) and NFPA 130 (NFPA 2014) may have added benefits beyond the purposes those standards are intended to serve, they are written to serve particular purposes, and the adoption of standards to meet these purposes may cause the neglect of other goals. One expert mentioned that the lack of a specific standard for passenger comfort might lead to neglect of this consideration or confusion regarding how to address it through station design:

There tends to be a gap between the fire- and life-safety egress standards that might tell you one thing about what the minimum design safety factor might be and, at the other end of the spectrum, for the comfortable and desirable walking and vertical circulation environment. I think there’s still a fair bit of murkiness for what tools are appropriate, what level of analysis is needed. (Interviewee #5)
Deterministic Models
We also asked the experts interviewed about the use of deterministic analyses, which can be done using spreadsheets, and microsimulation analyses, which require specialized software. Such models can be used to determine space needs for passenger movement and queueing and to ensure that designs meet adopted standards or design issues not accounted for in standards.

Some experts mentioned that the methodologies for much of the pedestrian flow analysis for transit stations have changed very little over the past decades. One referenced the continuing relevance of John Fruin’s guidelines (Fruin 1971):

Surprisingly, a lot of what we do right now with pedestrian flow, the basic theory is from John Fruin; his book is called Pedestrian Planning and Design. He was a New York City Port Authority employee; this book was published ... in the 70s ... and most of the stuff that he has in there are the guidelines that are still used today.... All his guidelines for level of service in pedestrian corridors, stairs, escalators, are still used as a basis. (Interviewee #7)

A major advantage of spreadsheet models is their simplicity and cost-effectiveness compared to microsimulation models. Whereas an agency may need to hire consultants to conduct microsimulation analysis, deterministic models can be created and run in-house. However, one consultant gave an example to emphasize that deterministic models can be adapted to be as complex as circumstances require. If used appropriately, he argued, they can be as informative as microsimulation models:

We did a bunch of surveys of route choice, and about 95% of people are using the same facilities day in and day out.... So, while the spreadsheet models were more deterministic, if you had enough data from surveys, a transportation transit architect could determine pretty confidently the majority of paths that would be taken through the facility.... You are really designing it and analyzing it for the normal disruptions that occur with enough regularity that you have to plan for, so there are a lot of safety factors built in. (Interviewee #2)

Microsimulation Models
As discussed above, many experts find deterministic spreadsheet analysis of passenger flows to be adequate for many station designs. Some, in fact, were skeptical that sophisticated microsimulation added much value beyond what could be gained through deterministic analysis. A staff member at one agency explained that she saw the value of microsimulation primarily in terms of visualization and communication rather than the analytical insight they offered. According to one consultant, the sophistication of microsimulation modes could even be a disadvantage, when reliance on sophisticated software packages supplants and inhibits analysts’ or designers’ intuition and expertise:

There’s a couple of new generation models, which, I’m afraid, it’s gotten [to be] a little too much of a black box.... I think we’ve gotten models with some aspects that are very sophisticated, but they also dumb down some other components like the path choice.... Some of the people that are running this model don’t know how to interpret this information. So my concern is that
as the models have become more technically and graphically sophisticated, the people operating them don’t really understand what’s going on inside them and don’t have a good underlying understanding of what the outcome is telling them. So they are just letting the machine … whatever comes out, that’s it…. I’m finding [that] the understanding of the fundamental principles in the interpretation of the results is a real problem. (Interviewee #2)

This observation may point to a pattern in which increasingly sophisticated models are now available to analysts who may not have sufficient expertise in basic principles of pedestrian flows and station design to be able to adequately interpret or apply the insights that could be gained from the model. If, as Interviewee #2 suggests, complex and increasingly sophisticated microsimulation models are used primarily, not as analytical tools, but as visualization tools for policymakers and the general public, then agencies may be greatly underutilizing the potential power of these models, and the benefit they do receive may not justify the cost.

A number of experts referred to the high cost of microsimulation models. One consultant explained why microsimulation was not typically used for station retrofits:

- There are very sophisticated pedestrian flow modeling and pedestrian simulation modeling tools that are available, but they’re going to be quite costly in the context of a retrofit to a station. (Interviewee #5)

Another consultant further explained that the costs of running a microsimulation model go beyond simply the software license or the consultant fee, and such costs may be justified only in particular situations. In spite of these drawbacks, experts mentioned that microsimulation models allow analysts to test a variety of different designs under a variety of different conditions.

**Demand Forecasts**

Regardless of which techniques are used to analyze pedestrian flows, the analyst must begin with an accurate assessment of anticipated passenger volumes. One agency staff member explained that a model ultimately is only as good as its input data:

- The bottom line is, the … model is only as good as the information that’s being put in there…. The model is as subjective as the … person … saying the data is accurate. And that’s somewhat frustrating … if you really need some sort of an objective analysis. (Interviewee #8)

One consultant referred to the fact that inflated ridership forecasts may be used to justify a rail project and emphasized the importance of verifying all assumptions used for ridership forecasts before applying those forecasts to station design:

- Sometime ridership forecasts are high just to justify the pursuit of the project…. But I know when I see some numbers, and the numbers look high, I can tell that’s going to be a problem before I run any analysis. So ridership forecasts have to be as exact as possible…. I trust them, but when I see those that are really high I say, “Well, let’s get into the numbers a little bit.” So it’s important—it’s important to do it right. (Interviewee #4)
Survey Results
To complement the interviews of the experts, we also conducted a survey of transit operators in the United States and Canada to better understand how transit station passenger queueing and flow design decisions play out in actual practice.

Table 1 lists several design tasks and indicates how commonly standards and codes, deterministic spreadsheet analysis, and microsimulation software are used for each task. Respondents were asked to select all methods that applied to each design task. For some tasks, multiple tools were applied; for others, none of the three tools was applied (for instance, design decisions simply could be made to maintain consistency with other stations). Thus, the row totals in Table 1 do not necessarily sum to 100%.

<table>
<thead>
<tr>
<th>Design Task</th>
<th>Method or Tool Applied to Design</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Standards and Codes</td>
</tr>
<tr>
<td>Determining number of fare collection machines and gates</td>
<td>9 (60%)</td>
</tr>
<tr>
<td>Selecting locations of fare collection machines and gates</td>
<td>7 (47%)</td>
</tr>
<tr>
<td>Selecting type of fare collection machines and gates</td>
<td>4 (27%)</td>
</tr>
<tr>
<td>Determining number of vertical circulation elements</td>
<td>9 (60%)</td>
</tr>
<tr>
<td>Selecting locations for vertical circulation elements</td>
<td>11 (73%)</td>
</tr>
<tr>
<td>Selecting type of vertical circulation elements</td>
<td>10 (67%)</td>
</tr>
<tr>
<td>Determining sizes for waiting and walking areas</td>
<td>11 (73%)</td>
</tr>
<tr>
<td>Some aspects of station design</td>
<td>12 (80%)</td>
</tr>
</tbody>
</table>

As shown in the bottom row of Table 1, 12 (80%) of the 16 surveyed agencies reported that at least some aspects of the design for the most recently-designed station in their system were based on published standards and codes. One of the 16 respondents skipped the question because (s)he was not personally involved in the design of any recent stations. Of the three remaining agencies reporting that none of their design tasks were based on published standards and codes, two reported using deterministic spreadsheet analysis as a basis for design. One reported not using any type of quantitative analysis as a basis for design, indicating instead that all design tasks were based on consistency with existing stations in the system.

Table 2 shows that use of published standards does not obviate the perceived need for further quantitative analysis using deterministic spreadsheet or microsimulation models. Agencies that use standards and codes as a basis for a design task are about as likely to use microsimulation and/or deterministic analysis for that task as those that do not use standards and codes as a basis—although neither is employed routinely.
### TABLE 2.
Number of Transit Agencies Reporting Using Deterministic and Microsimulation Analyses in Addition to Published Standards and Codes for Various Station Design Tasks

<table>
<thead>
<tr>
<th>Design Task</th>
<th>Deterministic Spreadsheet Analysis</th>
<th>Microsimulation Software Analysis</th>
<th>Both</th>
<th>Neither</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>When published standards or codes are used</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Determining number of fare collection machines and gates</td>
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<td>1</td>
<td>1</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Selecting locations of fare collection machines and gates</td>
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<td>0</td>
<td>1</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Selecting type of fare collection machines and gates</td>
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<td>1</td>
<td>0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Determining number of vertical circulation elements</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Selecting locations for vertical circulation elements</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Selecting type of vertical circulation elements</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Determining sizes for waiting and walking areas</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2</td>
<td>5</td>
<td>9</td>
<td>5</td>
<td>34</td>
</tr>
<tr>
<td><strong>Percent</strong></td>
<td>3%</td>
<td>8%</td>
<td>15%</td>
<td>74%</td>
<td>100%</td>
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<tr>
<td><strong>When published standards or codes are not used</strong></td>
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<td></td>
<td></td>
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<td>0</td>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
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<td>6</td>
<td>8</td>
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<tr>
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<td>0</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Selecting locations for vertical circulation elements</td>
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<td>0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
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<tr>
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<td>0</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>34</td>
<td>44</td>
</tr>
<tr>
<td><strong>Percent</strong></td>
<td>12%</td>
<td>2%</td>
<td>9%</td>
<td>77%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Regardless of use of standards and codes</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
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<td>7</td>
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</tr>
<tr>
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<td>75%</td>
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</tbody>
</table>
Based on the interviews, in which transit station design experts explained the advantages and disadvantages of microsimulation relative to deterministic analyses, we might expect these two types of analysis to be substitutes for one another. However, Table 2 suggests that this is not the case. For a given design task, agencies are about as likely to use both microsimulation and deterministic analyses than either type of analysis alone. This suggests that microsimulation and deterministic analyses are used as complements as often as substitutes.

**Complementarity of Analysis Tools**

Ultimately, the question of whether to base a particular analysis task on published standards and codes, deterministic analysis, or microsimulation analysis depends on the questions the analyst seeks to answer. Table 3 lists some potential questions that may be associated with a particular design, as well as the most appropriate analysis tool to answer each question. It also is possible that the size of pedestrian flows and the level of station complexity may influence the choice of analysis tools, with more sophisticated techniques being used for major-volume stations such as major transfer points or stations serving special events. Unfortunately, our survey was not designed to differentiate among station categories, and we cannot confirm this hypothesis.

### Table 3. Appropriate Analytical Tools to Answer Particular Questions

<table>
<thead>
<tr>
<th>Question</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does the proposed design meet code requirements?</td>
<td>Analysis described in relevant code</td>
</tr>
<tr>
<td>How much space is needed to accommodate at a particular station element</td>
<td>Deterministic spreadsheet analysis</td>
</tr>
<tr>
<td>(e.g., width of platforms or corridors, number of doorways or fare gates)</td>
<td></td>
</tr>
<tr>
<td>How and where do passenger flows transition from one element to another,</td>
<td>Microsimulation analysis</td>
</tr>
<tr>
<td>and how do individual elements interact with one another?</td>
<td></td>
</tr>
<tr>
<td>How do streams of pedestrians in opposing directions interact with one</td>
<td>Microsimulation analysis</td>
</tr>
<tr>
<td>another?</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion and Recommendations**

The results of our expert interviews and subsequent operator survey suggest that agencies rely primarily on published standards and codes in the design of pedestrian circulation elements in rail rapid transit stations. Moreover, deterministic spreadsheet models and microsimulation models are as likely to complement as to substitute for one another as bases for station design.

Given our focus on how these various approaches are applied in practice, and given the enormous variability in the objectives and constraints of heavy rail station design, it is not possible in this research to answer the question of what approach agencies ought to take in analyzing pedestrian flows. We have, however, documented the use of these three distinct approaches in current planning and design practice, as well as the views about their relative merits from interviews of transit station design experts. Our review of the literature, expert interviews, and survey of transit agencies collectively allow us to

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2 Thanks to an anonymous reviewer for making this point.
both draw conclusions about the state of transit station design for passenger queueing and flows and offer some recommendations for best practice.

**Short Term**

In the short term, agencies can begin each analytical exercise by clearly defining the question that the analysis seeks to address and selecting a modeling or analytical approach that can appropriately answer that question, as suggested in Table 3.

Stations are components of larger systems that interact with and are influenced by both the rail network and the neighborhood surrounding each station. Therefore, an additional short-term practice that can improve pedestrian queueing and flow analysis is to use information about current and anticipated land uses and travel flow patterns adjacent to the station to determine the most common origins and destinations of passenger flows at different times of the day and week and at special events.

Transit operators also can establish processes and systems that encourage coordination and knowledge-sharing among consultants and agency staff, as well as among analysts, planners, and designers. Such coordination can improve the relevance of the analysis by giving analysts a better understanding of the question being asked and empowering them to select the most appropriate tools in response. It also can have designers ask analysts the right questions. To the extent that designers and decision-makers see analysis as a “black box,” they are less able to apply the information it provides to their decision-making.

**Long Term**

In the long term, the literature review, interviews, and survey results suggest that transit agencies occasionally should examine the requirements published in various standards and codes to determine how well they apply to the extant circumstances. In cases in which existing standards are very conservative, such that they result in stations that are consistently over-designed with respect to all other passenger queuing and flow parameters, transit agency staff may choose to either accept the additional margin of safety (and expense) that the codes provide or argue that the standards and codes need not be adhered to (where they are not bound into regulatory code) or that the standards and codes ought to be relaxed in light of changing circumstances (where they are bound into administrative law).

On the other hand, in cases in which existing standards and codes are found to be inadequate with respect to passenger comfort or safety, transit agency staff may choose to codify their own, more demanding standards to ensure that passenger needs and safety will be met consistently.

At present, given the generally conservative requirements of published standards and codes, most agencies do not see a need for, or an added value from, the added cost of sophisticated analysis techniques. As government agencies and professional organizations continue to develop and refine standards and codes, they should do so in ways that encourage the use of available analytical tools to adapt guidelines to the local context, as appropriate. There also may be opportunities to use microsimulation models to verify and refine deterministic models and vice versa, although our research suggests that this is rarely done.
Finally, transit agencies occasionally should reexamine the assumptions that are routinely used for passenger queuing and flow analysis to determine if they continue to adequately describe the characteristics of their riders and particular stations. These assumptions may not change significantly from year to year, but they may drift enough over a decade to require some adjustment. In the end, the choice of particular analytical tools and strategies for accommodating passenger flows should depend on the specific issues that exist at a station and transit system.

Acknowledgment

This research was funded by the Federal Transit Administration (FTA) through a contract with Mineta Transportation Institute, and the authors are grateful for this support. Any errors or omissions are the responsibility of the authors and not FTA. Our thanks to the many experts interviewed and surveyed for this study; this work would not have been possible without their generous time and assistance. UCLA students Brady Collins and Lisa Berglund assisted in conducting and transcribing the expert interviews, and Casey Osborn assisted with the online survey of transit operators.

References


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Evaluating the Regional Benefit/Cost Ratio for Transit State of Good Repair Investments

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UN-HABITAT

David Vautin
Metropolitan Transportation Commission (San Francisco Bay Area)

Abstract

Should transit operators focus scarce funding on maintaining current systems in a state of good repair (SGR), or on expanding transit systems? Prior to this analysis, user impacts of transit SGR had not been systematically calculated. This study develops a new methodology for assessing the impacts of SGR on ridership, vehicle miles traveled, travel times and costs, and public health and safety. This is done for the 25 major transit systems in the nine-county San Francisco Bay Area. Moreover, the study uses a methodology parallel to that used to assess transit system expansion in the Bay Area and, therefore, is able to compare the benefit/cost ratios of transit expansion vs. transit SGR on an even footing. Results indicate regional benefit/cost ratios of close to 3 for transit SGR, with diminishing returns at higher funding levels. This is similar to the benefit/cost ratio of the average transit expansion project.

Background

In the San Francisco Bay Area and cities throughout the United States, there is an ongoing debate about the best use of transit funding. Some argue that maintaining current assets in a state of good repair (SGR) should take priority over expanding transit systems. Others argue that cities and regions need to continue expanding their transit network to enable modal shift in underserved communities, a strategy that can come at the expense of system preservation without an influx of additional funds.

The nine-county San Francisco Bay Area metropolitan planning organization—known as the Metropolitan Transportation Commission (MTC)—completes a rigorous performance assessment for expansion projects and operational improvement projects as part of the regional planning process (Metropolitan Transportation Commission 2013). Projects proposed for inclusion in the regional transportation plan (RTP) are
evaluated for their cost-effectiveness using a model-based methodology to calculate a benefit/cost (B/C) ratio. However, this methodology has been used only to examine the benefits of expansion projects and operational changes; there is no existing methodology to assess user and regional benefits of transit SGR. In fact, there has never been published research quantitatively linking transit SGR with ridership, a key component in a regional benefit/cost assessment.

This study defines a new methodology to link transit state of good repair with impacts on ridership and regional benefits as a whole, piloting this methodology with the 25 major transit systems in the San Francisco Bay Area. The results of this analysis provide a benefit/cost ratio for transit SGR funding. This ratio can be compared on an equal footing with the B/C ratio transit expansion projects assessed as part of the most recent Regional Transportation Plan (RTP), “Plan Bay Area.”

**Literature Review**

Efforts to quantify benefits of transit state of good repair generally have stopped short of linking asset condition with user impacts or ridership. It has been demonstrated that poorly-maintained transit systems can experience large ridership reductions based on the experience of rail systems in New York, Chicago, and Philadelphia in the 1970s and 1980s (Deakin et al. 2012). However, these studies do not systematically quantify the relationship between SGR spending and user benefits. Furthermore, the link between transit asset management and user impacts has yet to be modeled using a regional travel demand model to understand systemwide and multimodal impacts beyond riders.

A study by the U.S. Government Accountability Office finds that, although transit agencies sometimes track SGR backlog and on-time service, none of the agencies link SGR to future ridership. The report suggests that understanding the implications of SGR on ridership could help transit agencies optimize their asset management strategies (U.S. GAO 2013).

Another recent report by the Transit Cooperative Research Program, *State of Good Repair: Prioritizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit* (TCRP Report 157), includes a comprehensive literature review of transit asset management practices. The report finds that programs across the country generally rely upon asset ages to determine predicted condition and replacement needs. The only system currently tying asset condition to user impacts is the London Underground. Unfortunately, this methodology has not yet been published (Transportation Research Board 2012).

Perhaps the most powerful and widely-used transit asset management software is the Federal Transit Administration’s (FTA) Transit Economic Requirements Model (TERM) and its counterpart for local- and regional-level analysis, TERM-Lite. However, as highlighted by a broad review of TERM by Cohen (2014), the software tracks asset age without linking it to system performance or public benefits. Cohen proposes that a useful addition to TERM’s capabilities would develop and use a model to quantitatively link failures to total passenger delay, building upon the TCRP 157 framework.
There are two exceptions to the dearth of studies linking transit SGR and user impacts. One is a 2012 regional impacts study examining SGR investments into the San Francisco Bay Area’s heavy rail system known as BART (Deakin et al. 2012). The study estimates user impacts based on some broad assumptions that are very problematic; however, the report includes useful data from focus group interviews, which found that travel times and costs are the primary factors in transit mode choice. Only non-riders noted that crime, cleanliness, and noise would deter them from taking BART, indicating that deterioration of these elements would likely have small impacts on ridership.

The other study that links transit SGR with broad impacts in a recent study of the Southern Pennsylvania Transportation Authority (SEPTA) (Voith, Angelides, and Ozimek 2013). Results of econometric modeling indicate that completely eliminating SEPTA would increase costs to travelers by $488 million annually, cause externalities associated with higher automobile usage, reduce public revenues and property values, and trigger the loss of 60,000 jobs. Importantly, the authors note that they examine the extreme case of complete transit elimination partly because they do not have the means to simulate the incremental reduction in services that would result from a less-than-full capital shortfall: “A concrete analysis of economic impacts associated with underfunding SEPTA’s capital needs would require a direct connection between the extent to which the capital shortfall will result in reduced transit services, then use those specific changes in service patterns to model the impact on ridership and congestion” (p. 15). The current study fills this gap.

Our study builds upon existing research by quantifying the linkages between asset ages, failure rates, delay, ridership, and broader regional impacts for 25 of the Bay Area’s transit systems. We focused on delay as the primary operational impact of transit asset failure based on the results of the BART focus group interviews. We assumed that transit operators will hold ticket prices constant in various SGR scenarios. While passenger experiences of comfort, cleanliness, and safety may have an impact on travel behavior, Cohen notes that there is a lack of analytical procedures for relating asset age to passenger comfort (Cohen 2014). In the present study, we were able to answer Cohen’s call to link transit asset management best practices with user impacts. We believe this gives the best and most detailed estimation yet of the regional impacts of funding for transit state of good repair.

**Methodology**

To predict regional benefits for transit SGR funding scenarios, we calculated travel delays associated with aging transit assets and used those as inputs into the Bay Area’s regional activity-based travel model (Travel Model One) in the form of in-vehicle and

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1 The study assumes that an SGR funding shortfall affects all asset categories equally, whereas, in reality, funding sources and operators prioritize assets for funding based on their impact on system operations. Second, the authors predict ridership reductions directly corresponding with projected decreases in train capacity (assuming older trains have declining availability) and reduce predicted ridership further due to delays and discomfort. However, because BART trains generally are not currently full to capacity, capacity reductions likely will not translate directly into ridership reductions. Additionally, the study does not specify formulas for translating asset age into reported delays and asset failures.
out-of-vehicle travel times. We focused on travel time instead of cost or safety for the following reasons: (1) the cost of transit to users is determined by operators and not directly dependent upon SGR maintenance funding, and (2) safety risks generally are dealt with by instituting slow zones or removing assets from operation, actions that counted as a “failure” in our model and thus contribute to delays (Cohen 2014).

Travel Model One simulates travel behavior for a typical workday. In this context, we could not simulate location-specific failures that occur less than once daily. Additionally the Bay Area’s Regional Transit Capital Inventory (RTCI), which tracks all transit assets, does not yet contain locational information. For these reasons, we calculated average delay (based on probability) occurring when the average asset (by type) in the average location fails for each operator and mode. We then added this expected delay to all of the operator’s routes of that mode. This effectively served a proxy for system reliability due to the level of system maintenance. Figure 1 summarizes the approach taken to link funding scenarios, travel times, and regional benefits.

**FIGURE 1.** Pathway between funding scenarios and benefit calculations for transit SGR

**Step 1: Link Funding Scenarios with Asset Conditions using TERM-Lite Model**

MTC’s RTCI is used in conjunction with TERM-Lite to help prioritize the allocation of funding to be used for maintenance, rehab, and replacement of transit assets. Under a given funding scenario or a backlog target for a future year, the TERM-Lite model can calculate the age of each transit asset in the RTCI for a future year. We used TERM-Lite to approximate the replacements made by system operators in each year to predict asset ages in year 2040.

Each SGR funding scenario was compared to a baseline of current conditions. This led to cases in which both benefits and costs were negative (i.e., cases of spending less than is necessary to achieve baseline conditions and getting fewer benefits). Benefit/cost ratios for such degradation scenarios can be seen as representing the cost-effectiveness of moving from a funding level below baseline to the baseline funding level.
Step 2 (Vehicles): Link Vehicle Ages with Failure Rates and Energy Costs Using TCRP’s Vehicle Model

TCRP’s Vehicle Model (Transportation Research Board 2012) provides an equation for linking a vehicle’s lifetime miles with energy costs per vehicle mile. We used this equation to predict energy consumption costs in 2040 based on vehicle ages. To do this, we estimated lifetime mileage based on age using a constant for average annual mileage by operator and asset. Base-year energy costs per mile for 2040 were calculated using standard MTC projections for year 2040. Then, the TCRP model was applied to each transit vehicle in the RTCI. Average energy costs per mile for each operator and vehicle were then used to calculate total projected energy costs for each operator in 2040, drawing upon outputs from Travel Model One, which show how many miles are traveled by each transit operator in 2040. The difference between total scenario energy costs and baseline scenario energy costs for each operator was subtracted from the benefits side of the benefit/cost ratio. This reflects additional energy costs due to aging vehicles in a given scenario.

TCRP’s Vehicle Model also provides an equation for linking bus and train ages with road calls or vehicle failures per mile. We used this equation with data on base-year failures by operator and mode previously collected by MTC and the age of each vehicle in year 2040 under each scenario to get each vehicle’s failures per mile in 2040.

Step 2 (Non-Vehicle Assets): Link Non-Vehicle Asset Ages with Failure Rates Using TCRP’s Age-Based Model

TCRP’s Age-Based Model uses a Weibull distribution to calculate the probability of failure based on the age of nonvehicle transit assets. The TCRP report also provides shape and scale parameters based on national data for a range of asset types. Although there are 127 specific asset types listed in the TCRP report, we modeled only a subset which we believe will cause delay when failure occurs. These include guideway assets (31 categories, including tracks, viaducts, crossovers, tunnels, fills, and ballasts), systems assets (15 categories, including train controls, catenary, and signal systems), and electrification assets (8 categories, including third rails, power cables, and substations).

Step 3 (Vehicles): Link Per Mile Failure Rates with Travel Delays

TCRP Report 157 recommends using the following equation to calculate passenger delay per road call or vehicle failure:

\[
PDR = H \left( \frac{PM}{VM} + \frac{RT \cdot PT}{VH} \right)
\]

where,

\(PDR\) = passenger delay per road call

\(H\) = headway in minutes

\(PM\) = passenger miles

\(VM\) = revenue vehicle miles

\(RT\) = recovery time

\(PT\) = passenger trips

\(VH\) = revenue vehicle hours
Data on passenger miles, vehicle miles, headways, and boardings for each operator were taken from Travel Model One’s baseline 2040 projections. Equation 1 assumes that passengers on the failing vehicle and those waiting for the failing vehicle will be picked up by the next scheduled vehicle and, therefore, their delay is equal to headways. The average number of passengers on the bus or train is \( \frac{PM}{VM} \). The number of people waiting for the broken vehicle along the route until a replacement bus or train takes over is \( \frac{RT^*PT}{VH} \). This second calculation is problematic for MTC’s data since the number of buses and trains running likely is not distributed evenly throughout a day’s worth of revenue vehicle hours. To account for this, we substituted equation 2 to calculate the number of people waiting for the failed vehicle. For this analysis, we assumed that recovery miles (the number of miles before another bus takes over the route) were equivalent to one-half the operator’s average route length, but further research could improve this assumption.

\[
PWV = \left( \frac{PT}{VM} \right) * MR
\]  

where,

\( PWV \) = passengers waiting for the failed vehicle  
\( MR \) = recovery miles (miles before another bus takes over the route)

An added component of delay can occur in the case of rail failures when a failed train is blocking the passage of other trains. There is no TCRP equation to quantify this, so we used our own. If the average time to remove a blocking train is less than headways, there will be no delay arising from waiting behind a stalled train because the train will be cleared before the next train gets there. If this is not the case, equations 3, 4, and 5 can be used.

\[
DWBT = AWT * \left( \frac{PM}{VM} \right)
\]  
\[
AWT = \frac{\sum_{i=1}^{NT} \left( \frac{TC}{H} \right) - i}{NT} * H
\]  
\[
NT = \text{RoundDown} \left( \frac{TC}{H} \right)
\]  

where,

\( DWBT \) = delay from waiting behind stalled trains  
\( AWT \) = average wait time in headways for trains stuck behind stalled train  
\( i \) = each additional train  
\( TC \) = average time it takes to clear tracks  
\( NT \) = the number of trains that are delayed due to a stalled train ahead
In equation 5, we rounded down the number of headways that pass during the time it takes to clear the tracks, because an additional train reaches the delay point only every full headway. The average time it takes to clear the tracks was information gathered from individual rail operators.

Another adaptation we made to TCRP’s model of vehicle delay was to differentiate between two types of expected delay, which we call Type 1 Expected Delay and Type 2 Expected Delay. Expected delay is the chance of experiencing a failure multiplied by the delay that arises when a failure occurs. Expected delay is what we used as an input into Travel Model One.

Type 1 Expected Delay adds to in-vehicle travel time and was calculated per mile. Type 2 Expected Delay adds to out-of-vehicle travel time and was calculated per boarding. Both of these delay types were easily inserted into Travel Model One by adding a script to adjust skims and headways.

To calculate the two types of expected delay, we combined parts of the previous equations:

\[ T_{1ED}(V) = RM \left( DWBT + \left( H \cdot \frac{PM}{PM} \right) \right) \]
\[ T_{2ED}(V) = \frac{(H\cdotPWV) + (RM\cdotVM\cdot300)}{PT\cdot300} \]

where,

- \( T_{1ED}(V) \) = Type 1 Expected Delay from vehicle failures
- \( RM \) = road calls per mile from Step 2 above
- \( T_{2ED}(V) \) = Type 2 Expected Delay from vehicle failures
- \( PBDV \) = per boarding delay from vehicle failures (type 2 delay)

In equation 7, the numerator is composed of total passenger delay per boarding \((H \cdot PWV)\) and the expected number of annual failures \((RM \cdot PM \cdot 300)\). This total annual delay is per annual boarding \((PT \cdot 300)\). Miles and boardings were annualized using 300 instead of 365 to represent the fact that travel on weekends is expected to be less than travel on the typical weekday modeled by Travel Model One. This is consistent with other assessments used by MTC.

We adjusted equations 6 and 7 to cap the wait time on vehicles, behind stalled vehicles, and waiting for a failed vehicle at 30 minutes, since some average headways are longer than that. We assumed that after 30 minutes, a delayed passenger will either choose another mode (in some cases a replacement bus sent by the operator) to get to his/her destination or decide not to take the trip. Thus, we replace \( H \) with \( \text{Min}(H, 30) \) in both equations.

**Step 3 (Non-Vehicle Assets): Link Probability of Failure with Travel Delays Using a New Operator-Informed Model**

For non-vehicle assets such as fixed guideways, train control systems, and electrification elements, there is no established model for translating non-vehicle transit asset failures...
into travel time delays. Based on discussions with BART and Caltrain staff, we developed a set of equations to quantify Type 1 and Type 2 Expected Delay, which is associated with the age of non-vehicle assets.

When a non-vehicle asset fails, three groups of riders potentially are affected: (1) those on vehicles affected by slow zones, (2) those on vehicles that have been stopped and cannot proceed until a non-vehicle failure has been addressed, and (3) those waiting to board a vehicle that has been stopped. Due to the potential for long repair times, we capped the wait time for groups (2) and (3) at 30 minutes, assuming that they will either switch modes or cancel their trip.

Type 1 Expected Delay includes delay experienced by riders affected by slow zones and by riders riding in a vehicle that has been stopped. Delay experienced by people waiting for a stopped vehicle contributes to Type 2 Expected Delay. Expected delay for those on trains affected by slow zones can be calculated using the following equations:

\[ SZD = PF \times \left( \frac{NT \times MD}{VM \times 300} \right) \] (8)

\[ NT = \text{RoundDown} \left( \frac{(TR - \frac{1}{2}H)}{H} \right) \times LA \] (9)

where,

- \( SZD \) = expected delay arising from slow zones
- \( PF \) = probability of failure in 2040 (from Step 2 above)
- \( MD \) = minutes of delay to the train caused by slow zone
- \( TR \) = time until repair or replacement of the failed asset in minutes
- \( LA \) = average number of lines affected by failure

Equation 9 assumes the average train is half a headway away from the location of the non-vehicle asset at the time it fails. Average minutes of delay resulting from a slow zone (MD), average time until repair or replacement (TR), and average number of lines affected by asset failure (LA) is information specific to each non-vehicle asset type and operator. Rough estimates were developed in consultation with operators based on each Bay Area rail system's unique characteristics; future efforts should collect and use statistical data on the real-world operational impacts of failures to supplement our baseline assumptions.

Expected delay for passengers on trains that must stop until a non-vehicle asset is repaired or replaced can be calculated using equation 10. This is similar to the calculation for expected delay due to a slow zone (equation 8).

\[ STD = PF \times \left( \frac{NT \times \left( \frac{TR}{2} \right)}{VM \times 300} \right) \] (10)

where,

- \( STD \) = expected delay from being on a stopped train due to a non-vehicle asset failure ahead
Equation 10 assumes that the average train has to wait half the total time it takes to repair or replace the asset. We capped TR/2 at 30 minutes, assuming that if a vehicle is stopped beyond that time, people will off-board and choose a different route.

As stated above, Type 1 Expected Delay for non-vehicle assets (arising per mile, experienced in-vehicle) is the sum of expected delay arising from slow zones (equation 8) and expected delay arising from having to wait in a vehicle while a non-vehicle asset is repaired or replaced (equation 10).

\[
T1\text{ED} (NV) = SZD + STD
\]  

(11)

where,

\[T1\text{ED} (NV) = \text{Type 1 Expected Delay from non-vehicle asset failures}\]

Type 2 Expected Delay (arising per boarding, experienced out-of-vehicle) is associated with waiting for vehicles that have been stopped until a failed asset is repaired or replaced. Type 2 Expected Delay can be calculated using equation 12.

\[
T2\text{ED} (NV) = PF \cdot \frac{WT \cdot WN}{WB \cdot 300}
\]

(12)

\[
WT = TR - \left( \frac{1}{2} H \right)
\]

(13)

\[
WN = BM \cdot \left( \frac{1}{2} ARL \right) \cdot \min (NT, DT)
\]

(14)

\[
DT = LA \left( \frac{MOD}{H} \right)
\]

(15)

where,

\[WT = \text{additional out-of-vehicle wait time when a vehicle is stopped by a non-vehicle asset failure}\]

\[WN = \text{number of passengers waiting to board a vehicle stopped by a non-vehicle asset failure}\]

\[WB = \text{average weekday boardings}\]

\[BM = \text{average boardings per mile}\]

\[ARL = \text{average route length}\]

\[DT = \text{number of trains passing through affected area in one day}\]

\[NT = \text{number of trains affected by failure (equation 9)}\]

\[MOD = \text{minutes of operation daily (for example, this is 1080 minutes if trains run from 6 AM to 12 AM)}\]

We capped WT at 30 minutes. We estimated the number of lines affected by failure for each asset type (LA) based on the number of lines using the average section of track for each operator and whether a failure of the specific asset type would affect travel in one or both directions.
One other assumption was that operators spend the needed funding to get failed assets back into service. Because the cost of such emergency repairs is not already factored into the cost side of the B/C equation (which is based on the scenario's funding level), it must be added in once it is known which assets are likely to fail. To do this, we assumed that the cost of emergency repair or replacement is roughly equal to the value of the asset. We then multiplied the probability of failure by the value of each asset and added that to the cost side of the B/C equation.

After calculating the two types of expected delay for both vehicle and non-vehicle assets, we added them together to get for each operator a total amount of in-vehicle delay per mile (Type 1 Expected Delay) and a total amount of out-of-vehicle delay per boarding (Type 2 Expected Delay). These totals are used as inputs in Travel Model One.

**Step 4: Link Travel and Wait Time Delays to Benefits Using Travel Model One**

To input delays into Travel Model One, we manually adjusted in-vehicle and out-of-vehicle travel time skims. Type 1 Expected Delay was added to the in-vehicle travel time skims based on the distance traveled on each operator and mode. Type 2 Expected Delay was added to the out-of-vehicle time skims based on the number of boardings for each operator between each set of travel zones. Once transit travel time skims were adjusted, these new times influenced all travel choices made within the model, including auto ownership, activity choice, destination choice, mode choice, and route choice. Results of Travel Model One scenarios included miles traveled by mode, travel times, and travel costs. When compared to the baseline model run, these results can be used to calculate the full set of benefits included in the standard B/C assessment. These benefits are based on the outputs of Travel Model One and include collisions, air pollution, noise, active transportation, travel costs, and travel times. Each benefit is valuated based on previous research by MTC and detailed in the “Plan Bay Area Draft Performance Assessment Report” (Metropolitan Transportation Commission 2013).

**Results**

**Scenarios and Costs**

We assessed two regional funding scenarios in comparison to a baseline scenario: a zero funding (0F) scenario and a zero regional funding (0RF) scenario. The baseline scenario is defined as the funding required to maintain the current transit capital backlog until the year 2040. The 0F scenario examines conditions in 2040 if assets are allowed to degrade without any SGR investment. The 0RF scenario—approximately 40% of the baseline scenario funding—examines the consequences of cutting all regional funding to transit SGR so that the only funds available are from FTA, bridge tolls, sales taxes, and bonds.

We intended to examine an additional scenario where transit backlog is completely paid down by 2040; however, the difference in delays between the baseline scenario and the improvement scenario was negligible. This is due to the fact that MTC’s version of TERM-Lite prioritizes timely replacement of the assets most linked with delay in part by using a Transit Capital Priorities (TCP) score. This score also is used in regional funding decisions and places highest priority on replacement of revenue vehicles, which have the
greatest capacity to create delay. While the baseline scenario includes enough funding
for timely replacement of revenue vehicles, in a zero backlog scenario, the region is able
to pay for timely replacement of all assets, including those that are not directly linked to
delay (stations and facilities). Although these assets likely have an impact on passenger
comfort and ridership, previous research has suggested that this impact is secondary to
that of delay (Deakin et al. 2012).

The costs of the baseline scenario are $27 billion over the 28-year planning period
in 2013 dollars. The 0RF scenario spends $11 billion in the same period. Expected
emergency replacement costs for assets that fail in the 0RF scenario is $1.1 billion in
comparison with baseline. Emergency replacements beyond baseline total $1.2 billion in
the 0F scenario. Total costs for each scenario include the cost savings from decreasing
SGR funding and cost expenditures on emergency replacements. Final costs for each
scenario in comparison to baseline are -$617 million annually for the 0RF scenario and
-$1,011 million annually for the 0F scenario.

Benefits
To assess benefits, we compared the outputs of Travel Model One under baseline, 0RF,
and 0F scenarios. We used travel model outputs to calculate the following benefits
experienced by the region’s population in 2040: travel time savings for all modes; travel
cost savings related to driving, auto ownership, and parking; air pollution reduction
including PM2.5, CO2, and other pollutants; reductions in fatalities, injuries, and
property damage due to collisions; active transport health benefits; and noise reduction.
These benefits are monetized according to the values in Table 9 of the “Plan Bay Area
Draft Performance Assessment Report” (Metropolitan Transportation Commission
2013).

Lower spending on transit SGR is linked with greater in-vehicle and out-of-vehicle
delays. These delays cause a shift away from transit to driving, causing increased VMT.
Transit ridership region-wide declined from 2.16 million daily trips to 2 million trips in
the 0RF scenario and to 1.8 million trips in the 0F scenario. BART and Caltrain, the two
largest rail systems in the Bay Area, experienced the largest decreases in ridership, likely
due to the age of those systems’ assets today and the other modal options available to
the riders they tend to attract. Both transit delays and the negative externalities from
increased VMT (including congestion, pollution, and collisions) are reflected in the total
regional benefits. Table 1 shows the breakdown of regional benefits, with the greatest
impacts coming from travel times.
When we compared the total benefits and funding levels in Table 1, we found a B/C ratio of 2.8 for moving between a zero funding and baseline scenario. We found a B/C ratio of 2.6 for moving between a scenario with zero regional funding and a baseline scenario. These ratios demonstrate diminishing returns to SGR investment. This is to be expected when operators prioritize replacement of assets linked to the greatest user benefits.

### Conclusions

We found that current SGR funding levels compared to scenarios where funding is reduced generates a benefit/cost ratio of between 2.6 and 2.8 over the 28-year planning period, which is a very conservative estimate. “Plan Bay Area Draft Performance Assessment” (Metropolitan Transportation Commission 2013), which uses a parallel methodology to assess new transit infrastructure projects, found that transit efficiency projects, such as frequency and speed enhancements to existing transit services, generate an average benefit/cost ratio of 1.4 when weighted by size. Transit expansion projects, such as rail extensions and bus rapid transit corridors, generate an average benefit/cost ratio of 2.8 when weighted by size. From these numbers, we can conclude that SGR funding should, indeed, be a high-ranking regional priority.

The benefit/cost ratio here is for all 25 transit systems together. However, SGR funding likely has much higher benefits for systems with higher ridership.

Whereas it is clear that current funding levels for transit SGR have societal benefits that far exceed their costs, the change in delays and slope of the benefit/cost curve along different funding scenarios indicate diminishing returns. This implies that, at some point, increasing funding for transit SGR is not economically efficient. Testing more scenarios would help to indicate where this point lies. Our inability to show travel time benefits when moving from current funding levels to a state of zero backlog suggests that it is possible that the Bay Area has either reached or exceeded this point. Additionally, the lack of delay resulting from current funding and prioritization algorithms also indicates

---

**TABLE 1.**

Regional Impacts Compared to Baseline Scenario

<table>
<thead>
<tr>
<th></th>
<th>Zero Regional Funding</th>
<th>Zero Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Funding Levels (annually, million $)</td>
<td>-617</td>
<td>-1,011</td>
</tr>
<tr>
<td>Average delay per boarding (min)</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Average delay per mile (min)</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>VMT (annually, million)</td>
<td>655</td>
<td>1,324</td>
</tr>
<tr>
<td>Ridership (daily trips on transit)</td>
<td>-160,000</td>
<td>-360,000</td>
</tr>
<tr>
<td>Air pollutant reduction benefits (2040, million $)</td>
<td>-28</td>
<td>-56</td>
</tr>
<tr>
<td>Collisions, active transport, &amp; noise benefits (2040, million $)</td>
<td>-114</td>
<td>-244</td>
</tr>
<tr>
<td>Travel cost benefits (2040, million $)</td>
<td>-474</td>
<td>-1,012</td>
</tr>
<tr>
<td>Travel time benefits (2040, million $)</td>
<td>-1,004</td>
<td>-1,493</td>
</tr>
<tr>
<td>Total benefits (2040, million $)</td>
<td>-1,620</td>
<td>-2,806</td>
</tr>
<tr>
<td>Benefit/cost ratio</td>
<td>2.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>
that transit operators already are maximizing benefits to society through their judicious use of limited funding.

**Recommendations and Future Research**

Based on this research, it is recommended that transit operators in the Bay Area continue to prioritize vehicles and other high-impact assets for SGR funding, because this prioritization mitigates the majority of delays associated with baseline funding as compared to fully-funded SGR. It also is recommended that MTC as a regional agency continues to fund transit SGR, given the fairly high B/C ratio of regional funding (2.6). However, it is recommended that additional funding for transit be used for expansion rather than SGR, because the benefits of SGR funding rapidly diminish at levels higher than the current baseline.

Future research should expand to other regions within the United States and worldwide. Bay Area research on SGR should increase in specificity, comparing the benefits of SGR funding for different transit systems within the Bay Area. Additionally, future research should begin to address the limitations of the current study. Specifically, these limitations include our inability to model the impact of degradation for a large set of assets not directly linked with delay, such as stations and facilities. These non-operational impacts, such as user comfort or perceived security, certainly affect modal choice decisions. Finally, future research should confirm estimates of failure recovery times, rail lines affected by non-vehicle asset failures, slow zone speed restrictions, and additional delay to excessive failures and staff constraints in very degraded scenarios.

**References**


About the Authors

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Comparative Appraisal of Metro Stations in Delhi Using Data Envelopment Analysis in a Multimodal Context

Mansha Swami, Manoranjan Parida
IIT–Roorkee

Abstract

Urban public transit is a critical component for sustainable urban development and is crucial to multisector expansion of a developing economy. Continuous monitoring of infrastructure performance and assessment of its effectiveness are required to continually improve service quality. The urban agglomeration of Delhi, India, was studied for the efficacy of its multimodal urban public transit system. The toolkit used was Data Envelopment Analysis (DEA), a linear optimization technique that estimates relative efficiencies of its decision making units (DMUs) for a multitude of inputs and outputs. The study area includes the Red and Yellow lines of the Delhi Metro network. Commuter-based questionnaires were used to collect 1,328 valid responses about demographic, travel time, and quality perception parameters, which were analyzed, and relative rankings of the DMUs were evaluated. The efficiency was analyzed according to the Red and Yellow lines divided into seven corridor segments and individual stations. Results revealed efficiency scores and inefficiency slacks for which improvement strategies are proposed.

Keywords: Data Envelopment Analysis, Decision Making Units, DMU, slack values, projected values, multimodal transit, efficiency evaluation

Introduction

The urbanscape of developing countries is struggling with the ever-emerging demands of growing population and infrastructure. With economic growth, the responsibility of a city increases in delivery of services to its citizens. The deterioration in Indian public transport is more prevalent in metropolitan cities, in which the increase in the number of motorized vehicles is huge. Delhi constitutes nearly 7% of all motor vehicles in India but accommodates only 1.4% of the Indian population (Singh 2005). The population of Delhi is approximately 16.8 million (Census of India 2011). The multimodal urban transit
Comparative Appraisal of Metro Stations in Delhi Using Data Envelopment Analysis in a Multimodal Context

System in Delhi was studied in a comprehensive manner in this paper, and the Delhi Metro, the line haul mode in this system, was the emphasis in this study.

A multimodal urban transit system essentially comprises four main elements: access leg, egress leg, line haul leg, and transfer stages. Multimodal transportation clearly identifies the stage-based nature of public transport (Krygsman et al. 2001). A terminal plays a vital role in a trip. When two or more modes are used in a trip in which at least one mode is a conventional public transport mode, the trip is called a multimodal trip. The structure of a multimodal trip is as illustrated in Figure 1.

**FIGURE 1.**
Structure of a multimodal trip

In most cases, egress has a disadvantage over the availability of personal modes at the destination end. Transfer among different transportation modes may take place in a smaller area to enhance transfer efficiency, as time and cost consumed will become less (Sun et al. 2007). Sun et al. (2007) conducted a study in which transit terminal assessment was carried out under the influence of parameters such as transfer area, operating expense, number of staff, capacity of bus, total number of transfer passengers, transfer safety, and transfer time taken. In this study, the importance of carrying out a multimodal efficiency analysis using a metro station as a focal point was more consolidated.

Waiting times are a component of travel time delay along with transfer times in most multimodal trips. According to van Oort et al. (2009), if the services of a transit mode are being performed adequately, then waiting time is equal to half the headway time. This applies to short headways, and, in the case of longer headways, the passenger is likely to arrive closer to the scheduled time. Also, they discussed that vehicles and drivers of public transit units, owing to their dynamic characteristics, cause delays and congestion, thereby reducing service regularity, which the traveler perceives as a longer waiting time compared to the expected times.
The attractiveness of transfers may not be a hurdle if transfers are easy and provide access to the entire public transport network (Maxwell 2003). Also, better integrating the costs of transfers will result in increased attractiveness (Hidalgo 2009). Comfort and safety are other attributes that should influence passenger decisions (Atkins 1990; Kumar et al. 2011; Guo and Wilson 2011).

In the present scenario for a city such as Delhi, instead of increasing the number of modes, the city needs to manage the current modes in congruence with each other to yield better system efficiency and patronage. Two major aspects that need to be understood before starting an evaluation or assessment study on a urban public transport system are determining the factors that dissuade and influence passengers traveling on public transport (Naveen Eluru et al. 2012). Attributes such as travel time, waiting time, number of transfers, walking time, income, and gender play key roles in this selection. In a factor analysis study done on the attributes of importance, results yielded that information services play a key role. The other important factor was street service, which includes transfer convenience, bus frequency, level of service, reliability of service, and well-planned routes (Sharfuddin et al. 2000).

Another study proposed the definitive difference between planned and unplanned transfers, including five attributes—network integration, integrated physical connection of transfers, integrated time transfer, information integration, and fare ticket integration (Chowdhury and Ceder 2013). It was observed from this study that commuters had more willingness to use transfer-based routes when these five attributes are better aligned to the planned alignment. Smart et al. (2009) studied transit stop performance from the perspective of the operating agency instead of the user. When a transit operating agency has full control of the premises of a transit station or stop, it is more likely to better influence the attributes concerning operational requirements (Vuchic and Kikuchi 1974).

**Study Methodology**

**Identification of Study Area**

Delhi, the capital of India, has many public transportation modes. The Delhi Metro is a very widely distributed network with an extensive multimodal urban public transit system. The route map of the Delhi Metro is shown in Figure 2.
The Delhi Metro was launched in 2002 with two successfully-operating phases. With Phase 3 in the works, and Phase 4 to begin operating in the next decade, the Delhi Metro will be more extensive and distributed than ever, which will increase the connectivity of the city. To identify best practices for replication in the upcoming phases, this study assessed the proximity and overall interconnectivity of the metropolitan area by conducting a comprehensive evaluation of various resource units and performance indicators of the existing system. The study methodology is shown in Figure 3.
Concept of DEA-based Efficiency

Data Envelopment Analysis (DEA) is a performance measurement technique that uses a comparative analysis methodology. It was developed in 1978 by Charnes, Cooper and Rhodes to aid the evaluation of various organizations. Karlaftis (2003) used it to conduct an efficiency analysis of transit companies, and Zhenlin et al. (2012) conducted a comprehensive efficiency evaluation of the Beijing intelligent traffic management system based on super-DEA that used 15 inputs and 23 outputs for 10 Decision Making Units (DMUs) for a macro level study correlating the influence of various urban transport indicators.

Epstein and Henderson (1989) concluded that all variables that are included in the model have an equal opportunity to influence the calculated efficiency. Here, DEA has advantages over traditional efficiency calculations. The efficiencies of public transportation subunits were calculated for the Chicago Transit Authority (Barnum et al. 2007), and Saxena Punitha et al. (2010) conducted a study to measure the efficiencies of Indian public road transit using DEA with input variables such as fleet size, total staff, and fuel consumption and output parameters such as passenger kilometers and seat kilometers for 26 DMUs.

DEA compares different DMUs, which are often the resource units for a system. In the present study, DMUs were the metro stations of the Delhi Metro system. An output unit is usually a performance attribute to be judged, and the inputs and outputs are

*FIGURE 3. Study methodology flowchart*
Compared on the basis of correlation between the two in terms of the impact of inputs on outputs. Then, their comparative efficiencies are compared, and best practice units are identified. Also, DEA identifies slacks in the resource and output units and determines their projected values. The slack values for metro station performance can be helpful in determining the cause of their poor or good performance.

In the DEA model, the concept of efficiency is technical efficiency, which is the basic concept of relative efficiency that is determined through comparison with the most efficient unit. The relative efficiency ($\eta$) typically is represented in the mathematical form in Equation 1. In this case, the unit is the Metro station and, in place of weight of inputs, we used the values of the input parameters. $y_{rj}$ and $X_{ij}$ are the projected values obtained for various Metro stations from the analysis for different sets.

$$\eta_j = \frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}}$$  \hspace{1cm} (1)

$\eta_j$ = relative efficiency of unit j  
$v_i$ = weight of Input i  
$u_r$ = weight of Output r  
$y_{rj}$ = the quantity of Output r for unit j  
$x_{ij}$ = the quantity of Input i for unit j  
$j = 1, 2, 3 \ldots n$  
$n$ = number of units

This technique can be used to assess the existing system and further enhance the service quality by identifying the gaps and is based on linear programming methodology. The ratios are apt for calculation of efficiency in the case of a single input and output. However, for multiple inputs and/or outputs, scenario relative weights of each of the resource and performance entities need to be considered.

**DEA Software**

A multi-stage DEA model was used, which is capable of handling a multitude of inputs and outputs. In the present analysis, however, only multiple inputs were considered. The outputs in each of the six objective sets were single outputs. The number of inputs varied for each set of objectives.

Also, the multi-stage DEA analysis was done in output-oriented mode, which focuses on expansion of output to achieve scores. This study used constant returns to scale (CRS), meaning that outputs were modified in the same proportion as inputs. In this study, infrastructural components of the system were constant even if the operational parameters or the outputs were changed; therefore, the constant returns to scale are preferred here.

The DEAP software allowed for the creation of lists of inputs and outputs of Metro stations in Notepad and then was incorporated into the model requirements separately in an instruction file format (.ins) (see Figure 4). The result can be obtained in a Notepad file that can be conveniently converted to Excel.
DEA Inputs and Outputs

As in a previous study in Cosenza, Italy (Eboli et al. 2009), the parameters considered for the performance study included route characteristics, service characteristics, service reliability, comfort, cleanliness, fare, information, safety and security, customer service, personnel, and environmental factors. The definitions of parameters used in the framing of the inputs and their respective outputs in this study are shown in Table 1. The parameters Interconnectivity Convenience ($I_C$) and Service Time Ratio (STR) were conceptualized specifically for this analysis.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>Level of Service</td>
<td>Ratio of OVTT to IVTT; the larger the ratio, the less attractive the public transport.</td>
</tr>
<tr>
<td>IR</td>
<td>Interconnectivity Ratio</td>
<td>Ratio of access + egress time to total trip travel time.</td>
</tr>
<tr>
<td>IVTT</td>
<td>In-Vehicle Travel Time</td>
<td>Time spent in main public transport mode in line-haul stage.</td>
</tr>
<tr>
<td>$I_C$</td>
<td>Interconnectivity Convenience</td>
<td>Percentage of IVTT spent in access + egress, expressed in %.</td>
</tr>
<tr>
<td>PWI</td>
<td>Passenger Waiting Index</td>
<td>Ratio of mean passenger waiting time to frequency of transport service. Close to 0 is not possible.</td>
</tr>
<tr>
<td>RI</td>
<td>Running Index</td>
<td>Ratio of total service time (IVTT+OVTT) to total travel time. As RI increases, system efficiency decreases. For passenger satisfaction, value can be fixed between 0.15 and 0.75.</td>
</tr>
<tr>
<td>OVTT</td>
<td>Out-of-Vehicle Travel Time</td>
<td>Time spent traveling in other modes for access/egress apart from main line-haul mode.</td>
</tr>
<tr>
<td>TTR</td>
<td>Travel Time Ratio</td>
<td>Ratio of travel time by public transport to travel time by personal mode such as cars between a particular origin and destination</td>
</tr>
<tr>
<td>TTT</td>
<td>Total Travel Time</td>
<td>Sum of IVTT, OVTT, transfer time, and wait time.</td>
</tr>
<tr>
<td>STR</td>
<td>Service Time Ratio</td>
<td>Ratio of penalty time (wait time + transfer time) to TTT.</td>
</tr>
<tr>
<td>Penalty</td>
<td>Sum of waiting time and transfer time.</td>
<td></td>
</tr>
</tbody>
</table>
The parameters in Table 1 were assimilated into interrelated groups to form sets with multiple inputs and single outputs. The interrelationship between outputs and inputs was based on a cause-effect relationship. For example, in Set 1, the ridership on a line is likely to be affected by operation timing, roundtrip distance coverage, and number of stations, which indicates how many areas on the route have access to the line. In the current study, the sections were limited to six combinations. These sets were then analyzed using DEAP software to determine the relative efficiencies of the DMUs, which, in four of the six cases, were corridors of the Yellow and Red lines separated into seven parts; in two sets, the DMUs were the individual stations of the Red and Yellow lines. Table 2 shows the inputs and outputs in their respective sets.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Inputs</th>
<th>Units</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Line Performance</td>
<td>Operation Time</td>
<td>min</td>
<td>Ridership on Line</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Round Trip Distance</td>
<td>k</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of Metro Stations in Line</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Operational Efficiency of</td>
<td>Operating Speed</td>
<td>kmph</td>
<td>Interconnectivity Ratio (IR)</td>
</tr>
<tr>
<td></td>
<td>Line</td>
<td>Frequency</td>
<td>min</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Access/Egress Time</td>
<td>min</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Spatial Efficiency of Line</td>
<td>Total Travel Time (TTT)</td>
<td>min</td>
<td>Interconnectivity Convenience (I_C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Customer Perception Score on Access</td>
<td>index</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>and Egress</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Availability of Feeder in Area</td>
<td>#</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Travel Time Ratio (TTR)</td>
<td>ratio</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Proximal Efficiency</td>
<td>Total Transfer Time (TTRT)</td>
<td>min</td>
<td>Access+Egress Time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Wait Time (TWT)</td>
<td>min</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>In-Vehicle Travel Time (IVTT)</td>
<td>min</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Information and Safety</td>
<td>Security Score</td>
<td>index</td>
<td>Overall Customer Perception of Multimodal Transport System</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>Information Score</td>
<td>index</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Multimodal Efficiency</td>
<td>Passenger Waiting Index (PWI)</td>
<td>ratio</td>
<td>Level of Service (LOS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Running Index (RI)</td>
<td>ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interconnectivity Ratio (IR)</td>
<td>ratio</td>
<td></td>
</tr>
</tbody>
</table>

Line performance gives the comparative performances of the seven segments on a broader perspective. Operational efficiency of the line takes into account operational performance of the segments. Spatial efficiency considers the connectivity in a spatial context. Proximal efficiency compares catchment area access and egress availability. Information and safety efficiency evaluates facilities for safety and the quality of information provided to passengers. Multimodal efficiency checks the performance in context and coordination with the other modes of the urban public transportation system that a passenger uses in his/her journey from door of origin to door of destination.
**DEA Results and Interpretations**

The six possible combinations of analysis are discussed below.

**Delhi Metro Corridor Performance**

The input and output data for this evaluation were collected from Delhi Metro Rail Corporation (DMRC). The data and results of this set are shown in the Tables 3 and 4.

**TABLE 3.**

<table>
<thead>
<tr>
<th>Delhi Metro Corridors</th>
<th>Line</th>
<th>Operation Time (hrs)</th>
<th>Round Trip Distance (km)</th>
<th>Number of Metro Stations</th>
<th>Ridership on Line (August 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jahangirpuri to Kashmere Gate</td>
<td>Yellow</td>
<td>17.5</td>
<td>21.8</td>
<td>9</td>
<td>288,975</td>
</tr>
<tr>
<td>Chandni Chowk to Central Secretariat</td>
<td>Yellow</td>
<td>17.5</td>
<td>13.6</td>
<td>6</td>
<td>276,789</td>
</tr>
<tr>
<td>Udyog Bhawan to Saket</td>
<td>Yellow</td>
<td>17.5</td>
<td>24.6</td>
<td>9</td>
<td>205,434</td>
</tr>
<tr>
<td>Qutub Minar to Huda City Center</td>
<td>Yellow</td>
<td>17.5</td>
<td>29.0</td>
<td>10</td>
<td>191,230</td>
</tr>
<tr>
<td>Rithala to Kanhaiya Nagar</td>
<td>Red</td>
<td>18</td>
<td>17.2</td>
<td>8</td>
<td>153,429</td>
</tr>
<tr>
<td>Inderlok to Kashmere Gate</td>
<td>Red</td>
<td>18</td>
<td>12.6</td>
<td>6</td>
<td>103,110</td>
</tr>
<tr>
<td>Shastri Park to Dilshad Garden</td>
<td>Red</td>
<td>18</td>
<td>15.0</td>
<td>7</td>
<td>125,649</td>
</tr>
</tbody>
</table>

As shown in Table 4, the most technically-efficient corridors among the seven are the Jahangirpuri to Kashmere Gate corridor and Chandni Chowk to Central Secretariat (column 2). Both of these corridors are integral parts of the Yellow line. Results of the overall line performance efficiency test revealed the presence of negative slacks (column 6) for several input parameters in projected values, indicating that these corridors could improve their services in relevant domains. Figure 6 is a graphical comparison of the efficiency scores and ranks of corridor performance.

**TABLE 4.**

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>Jahangirpuri to Kashmere Gate</td>
<td>1.000</td>
<td>1</td>
<td>288,975</td>
<td>288,975,000</td>
<td>1</td>
<td>0.0</td>
<td>17.500</td>
</tr>
<tr>
<td>Yellow</td>
<td>Chandni Chowk to Central Secretariat</td>
<td>1.000</td>
<td>2</td>
<td>276,789</td>
<td>276,789,000</td>
<td>1</td>
<td>0.0</td>
<td>17.500</td>
</tr>
<tr>
<td>Yellow</td>
<td>Udyog Bhawan to Saket</td>
<td>0.711</td>
<td>3</td>
<td>205,434</td>
<td>288,975,000</td>
<td>1</td>
<td>0.0</td>
<td>17.500</td>
</tr>
<tr>
<td>Yellow</td>
<td>Qutub Minar to Huda City Center</td>
<td>0.662</td>
<td>4</td>
<td>191,230</td>
<td>288,975,000</td>
<td>1</td>
<td>0.0</td>
<td>17.500</td>
</tr>
</tbody>
</table>
Comparative Appraisal of Metro Stations in Delhi Using Data Envelopment Analysis in a Multimodal Context

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>Rithala to Kanhaiya Nagar</td>
<td>0.530</td>
<td>5</td>
<td>153,429</td>
<td>289,469.000</td>
<td>1</td>
<td>0.0</td>
<td>18,000</td>
<td>136040</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>0.0</td>
<td>17,200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>0.065</td>
<td>7,346</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>Inderlok to Kashmere Gate</td>
<td>0.402</td>
<td>7</td>
<td>103,110</td>
<td>256,436.868</td>
<td>1</td>
<td>1.787</td>
<td>16,213</td>
<td>153,326.868</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>0.0</td>
<td>12,600</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>0.441</td>
<td>5,559</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>Shastri Park to Dilshad Garden</td>
<td>0.439</td>
<td>6</td>
<td>125,649</td>
<td>286,200.339</td>
<td>1</td>
<td>0.0</td>
<td>18,000</td>
<td>160,551.339</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>0.0</td>
<td>15,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>0.459</td>
<td>6,541</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 6.**
Efficiency scores of corridor performance for Delhi Metro
Table 5 shows the summarized observations and recommended strategies for performance enhancement of the study corridors.

**TABLE 5. Strategies for Enhancement of Corridor Performance Efficiency**

<table>
<thead>
<tr>
<th>Corridor Details</th>
<th>Observation and Interpretation</th>
<th>Improvement Strategies</th>
</tr>
</thead>
</table>
| Udyog Bhawan to Saket                                 | Slack of (-2.8) in Input 2; implies that current round trip distance for this corridor is more than it can effectively handle. | • Expand operation hours.  
• Introduce new Metro station in existing corridor. |
| Quatb Minar to Huda City Center                        | Slack of (-7.2) in Input 2 and 3; implies that round trip distance and operating hours are reasons for inefficiency. | • Increase number of Metro stations connecting New Delhi and Gurgaon.  
• With many passengers traveling to CBD from Ghitarini, Arjangarh, Chattarpur, suburbs, etc., need to increase operating times in evening to make it easier to travel back home. |
| Rithala to Kanhaiya Nagar & Shastri Park to Dilshad Garden | Negative slacks for Input 3. | • Need more intermediate Metro stations. |
| Inderlok to Kashmere Gate                              | Negative slack for operating hours input due to CBD attracting huge workforce from suburban areas. Also negative slack for Input 3. | • Increase operating hours.  
• Need more intermediate Metro stations. |

Overall, the line performance efficiency of all seven corridors can be summarized as the need for stations at shorter distances to increase the accessibility of commuters. Once the accessibility issue is addressed, the timing of service can be stretched, especially in the evening hours, to enhance efficiency and promote ridership. None of the outputs show a negative difference with projected values, which implies that ridership values do not indicate any overloading and have a scope that can be further improved within the available infrastructure.

**Operational Efficiency of Corridor**

Table 6 show the inputs and outputs for the operational efficiency of the seven line corridors of the DMRC. In this analysis, the interconnectivity ratio is taken as the performance output. Inputs 1 and 2 of this set were collected from DMRC, and Input 3 was calculated from the commuter survey data, primarily from the 1,450 respondents. Filtering of the data led to the removal of 122 responses; the remaining 1,328 were considered fit for analysis.
TABLE 6. Inputs and Outputs for Operational Efficiency of Corridor

<table>
<thead>
<tr>
<th>Delhi Metro corridors</th>
<th>Line</th>
<th>Operating Speed (kmph)</th>
<th>Frequency</th>
<th>Access/ Egress Time</th>
<th>Interconnectivity Ratio I,</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jahangirpuri to Kashmere Gate</td>
<td>Yellow</td>
<td>29</td>
<td>2.9</td>
<td>21.838</td>
<td>0.301</td>
</tr>
<tr>
<td>Chandni Chowk to Central Secretariat</td>
<td>Yellow</td>
<td>30</td>
<td>3</td>
<td>20.129</td>
<td>0.322</td>
</tr>
<tr>
<td>Udyog Bhawan to Saket</td>
<td>Yellow</td>
<td>33</td>
<td>2.8</td>
<td>20.398</td>
<td>0.297</td>
</tr>
<tr>
<td>Qutub Minar to Huda City Center</td>
<td>Yellow</td>
<td>31</td>
<td>2.8</td>
<td>22.602</td>
<td>0.269</td>
</tr>
<tr>
<td>Rithala to Kanhaiya Nagar</td>
<td>Red</td>
<td>30</td>
<td>4</td>
<td>19.944</td>
<td>0.273</td>
</tr>
<tr>
<td>Inderlok to Kashmere Gate</td>
<td>Red</td>
<td>32.5</td>
<td>4</td>
<td>19.500</td>
<td>0.318</td>
</tr>
<tr>
<td>Shastri Park to Dilshad Garden</td>
<td>Red</td>
<td>33</td>
<td>4</td>
<td>21.056</td>
<td>0.324</td>
</tr>
</tbody>
</table>

Figure 7 is a graphical comparison of the efficiency scores and ranks for operational efficiency.

FIGURE 7.
Operational efficiency scores and ranks of corridors

Possible solutions for enhancement and the analysis results of the operational efficiency of corridors are shown in Table 7.
TABLE 7.
Strategies for Enhancement of Operational Efficiency of Corridor

<table>
<thead>
<tr>
<th>Corridor Details</th>
<th>Observation and Interpretation</th>
<th>Improvement Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandni Chowk to Central Secretariat and Inderlok to Kashmere Gate</td>
<td>Technically efficiency scores are 1 = efficient stations.</td>
<td>• These two corridors are the best performing among seven corridors.</td>
</tr>
<tr>
<td>Jahangirpuri to Kashmere Gate</td>
<td>Slack value of (-2.380) for Input 3. Access and egress times to this station are more, making this corridor inefficient.</td>
<td>• Extend corridor; has been proposed by DMRC in Phase 3 until Badli in Yellow line beyond Jahangirpuri; expected to enhance efficiency.</td>
</tr>
<tr>
<td>Udyog Bhawan to Saket and Qutab Minar to Huda City Center</td>
<td>Big negative slacks for Inputs 1 and 3; implies that operating speed is less and access/egress times are more than desired.</td>
<td>• Operating speed for these corridors needs to be increased. Huda City Center is terminal station facing access and egress problems, as passengers are coming from distances far from planned catchment area. Qutab Minar was terminal station extended to Huda City Center. Station not well connected to nearby areas; feeder or IPT connectivity needs to be enhanced for these two stations areas.</td>
</tr>
<tr>
<td>Rithala to Kanhaiya Nagar and Shastri Park to Dilshad Garden</td>
<td>Slack of (-0.940) and (-0.347) for Input 2 = frequency of arrival of consecutive Metro trains in these corridors is less.</td>
<td>• Frequency for these corridors can be increased. Increase in number of coaches will increase capacity and may increase efficiency.</td>
</tr>
</tbody>
</table>

The operational efficiency of the seven line corridors reveals that speed and frequency of the Delhi Metro need to be augmented. Also, Metro extension phases related to the growing city size need to be planned in advance to counter the problem of excessive access and egress distances at terminal stations.

Spatial Efficiency of Corridor

This section evaluates efficiency on a spatial basis. Inputs 1, 2, and 4 were calculated from the 1,328 responses. Input 3 was observed at various stations during the survey collection visits and recorded separately. Table 8 shows the data for the spatial efficiencies of the seven corridors.
TABLE 8. Inputs and Outputs for Spatial Efficiency of Corridor

<table>
<thead>
<tr>
<th>Delhi Metro Corridors</th>
<th>Line</th>
<th>Total Travel Time</th>
<th>Customer Perception on Access/ Egress</th>
<th>Availability of Feeder in Area</th>
<th>Travel Time Ratio</th>
<th>Interconnectivity Convenience Ic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Input 1</td>
<td>Input 2</td>
<td>Input 3</td>
<td>Input 4</td>
<td></td>
</tr>
<tr>
<td>Jahangirpuri to Kashmere Gate</td>
<td>Yellow</td>
<td>72.493</td>
<td>9.045</td>
<td>0.111</td>
<td>2.085</td>
<td>0.663</td>
</tr>
<tr>
<td>Chandni Chowk to Central Secretariat</td>
<td>Yellow</td>
<td>62.600</td>
<td>8.508</td>
<td>0.001</td>
<td>2.213</td>
<td>0.722</td>
</tr>
<tr>
<td>Udyog Bhawan to Saket</td>
<td>Yellow</td>
<td>68.644</td>
<td>8.694</td>
<td>0.333</td>
<td>2.278</td>
<td>0.628</td>
</tr>
<tr>
<td>Qutub Minar to Huda City Center</td>
<td>Yellow</td>
<td>83.884</td>
<td>8.780</td>
<td>0.001</td>
<td>2.501</td>
<td>0.514</td>
</tr>
<tr>
<td>Rithala to Kanhaiya Nagar</td>
<td>Red</td>
<td>72.944</td>
<td>7.827</td>
<td>0.375</td>
<td>2.552</td>
<td>0.570</td>
</tr>
<tr>
<td>Inderlok to Kashmere Gate</td>
<td>Red</td>
<td>61.297</td>
<td>8.035</td>
<td>0.001</td>
<td>2.087</td>
<td>0.782</td>
</tr>
<tr>
<td>Shastri Park to Dilshad Garden</td>
<td>Red</td>
<td>65.000</td>
<td>8.459</td>
<td>0.143</td>
<td>2.094</td>
<td>0.777</td>
</tr>
</tbody>
</table>

Figure 8 is a graphical comparison of the efficiency scores and ranks for spatial efficiency, and Table 9 includes remarks on the analysis of the spatial efficiency of corridors.

FIGURE 8.
Spatial efficiency scores and ranks of corridors
TABLE 9. Strategies for Enhancement of Spatial Efficiency of Corridor

<table>
<thead>
<tr>
<th>Corridor Details</th>
<th>Observation and Interpretation</th>
<th>Improvement Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jahangirpuri to Kashmere Gate and Shastri Park to Dilshad Garden</td>
<td>Negative slacks for Inputs 1, 2, 3. Big slack value for (-11.255) for total travel time; indicates that total travel time is more than desirable on these corridors.</td>
<td>• Since total travel time is a function of speed and corridor distance, these can be enhanced in this case. • Additional feeder connectivity required to increase interconnectivity convenience for passengers. • Jahangirpuri (terminal station) has poor access/egress facilities, which increases total travel time on this corridor.</td>
</tr>
<tr>
<td>Chandni Chowk to Central Secretariat and Qutab Minar to Huda City Center</td>
<td>Negative slacks for Inputs 1, 2, 4; suggests that total travel time, customer perception of access and egress, and travel time ratio of these corridors are problem areas. Big slack (-22.587) in Qutab Minar to Huda City Center corridor, indicates bigger portion of access and egress in total travel time.</td>
<td>• Huda City Center (terminal station) contributes to access/egress times more than IVTT, which eventually affects travel time ratio. More temporal delay discourages passengers to use public transit. Good integration from near and far areas required to increase proximal connectivity to terminal stations.</td>
</tr>
<tr>
<td>Udyog Bhawan to Saket &amp; Rithala to Kanhaiya Nagar</td>
<td>Total travel time, travel time ratio, and availability of feeder in area are problem elements.</td>
<td>• Rithala (terminal station) contributes to increased total travel time. • Customer perception on access and egress good, indicates that IVTT hampers perception instead of OVTT. This means that speed and frequency of corridor needs to be enhanced.</td>
</tr>
<tr>
<td>Shastri Park to Dilshad Garden</td>
<td>Slack values for Inputs 1, 2, 3.</td>
<td>• Dilshad Garden (terminal station) requires feeder service augmentation.</td>
</tr>
</tbody>
</table>

Spatial line efficiency results indicate that terminal stations have a common issue of increased access/egress time and, therefore, reduced interconnectivity convenience. The output projected values reveal a scope for improvement in the interconnectivity convenience of commuters. The ease of access/egress facilities and time savings in the intermodal or multimodal transfer process of the Metro terminals should be considered for enhancement to make these corridors more efficient spatially.

**Proximal Efficiency**

There are 34 Metro stations on the Yellow line and 21 on the Red line, with one common station, Kashmere Gate. Proximal efficiency compared the different stations for ease of accessibility that each of these stations provides in its respective catchment areas. The output parameter is the sum of total time taken for accessing and egressing the line haul mode. Inputs 1, 2, and 3 were calculated from the data acquired from the primary commuter travel time survey.

The common station Kashmere Gate is also an interstate bus transfer terminal (ISBT) and has been developed as a multimodal interchange hub by DMRC and DIMTS (Delhi Integrated Multimodal Transit System Limited). Kashmere Gate, along with G.T.B. Nagar and Ghittorini on the Yellow line and Pulbangash on the Red line, are best-practice stations in terms of proximal connectivity for commuters. Figure 9 shows the comparison of efficiency scores and ranks of proximal efficiency.
Strategies to improve the proximal efficiency of stations are presented in Table 10.

**TABLE 10.** Strategies for Enhancement of Proximal Efficiency of Corridor

<table>
<thead>
<tr>
<th>Station Details</th>
<th>Observation and Interpretation</th>
<th>Improvement Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow Line: Chawri Bazaar, NDLS, Central Secretariat, INA, Saket, Chattarpur, Sultanpur, Guru Dronacharya, M. G. Road</td>
<td>Waiting times on platform and transfer time are longer. IVTT is a reason for inefficiency.</td>
<td>• For heavily residential areas, station area design needs to be improved to reduce walking in transfer areas and increase frequency and speed to reduce IVTT. • For commercial zones, footfall in peak hours is more, so transfer procedure needs to be augmented, which may require additional safety check counters and turnstiles to cater to large crowds. • For interchange stations, transfer area reduction between two modes can help efficiency. • Additional baggage check counter for luggage carried by intercity travelers can save time in security check process. Travelators could be provided to facilitate interchange process between modes. • Medium- to high-density mixed-use suburban areas may increase patronage if transfer facilities in peak hours are augmented. • In busy CBD areas with major work/education destinations, number of coaches in peak hours needs to be increased to cater to larger number of passengers.</td>
</tr>
<tr>
<td>Red Line: Rithala, Kohat Enclave, Netaji Subhash Place, Kanhaiya Nagar, Inderlok, Pratap Nagar, Tis Hazari, Seelampur, Mansarover Park, Jhilmi, Dilshad Garden</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Udyog Bhawan, Pitampura, Huda City Centre, Qutub Minar, Rohini West</td>
<td>Very poor performance.</td>
<td>• Availability of feeder and IPT modes needs to be promoted for these stations.</td>
</tr>
</tbody>
</table>
Information and Safety Efficiency

Customer perception in the context of the information and security infrastructure available at the Metro stations was used as input in this section. Further, an overall customer perception score was calculated using the primary data collected in the customer perception questionnaire. The customer perception score was used as the output in this set. Figure 10 is a graphical comparison of efficiency scores and ranks for information and safety efficiency.

![Bar chart showing efficiency scores](image)

**FIGURE 10.** Information and security scores of corridors

This set covered the safety and information aspect of travel in a multimodal transit environment. Results show that the efficiency of the 54 stations related to safety and information is better and that the station areas are comparatively considered safer according to customer perception. Also, an ample number of billboards and station premises signage ensures that commuters are well informed. The stations exhibiting the best practices in this segment were Race Course and Chawri Bazaar of the Yellow line; the stations that require improvement are Mansarovar Park, Shahadra, Pratap Nagar, Adarsh Nagar and Model Town.
**Multimodal Efficiency**

In the multimodal efficiency calculation, the overall contribution of the seven line haul corridors individually was considered. The data for the entire trip of an individual (in these cases, multimodal trips) was used for evaluation. Table 11 shows the objective data of this set. The performance parameter considered was the level of service of these corridors calculated from the primary data. The inputs were calculated from the responses of commuter travel time data. Figure 11 is a graphical comparison of efficiency scores and ranks for multimodal efficiency. Strategies for improving multimodal efficiency are shown in Table 12.

### TABLE 11.

<table>
<thead>
<tr>
<th>Delhi Metro Corridors</th>
<th>Line</th>
<th>Passenger Waiting Index (PWI)</th>
<th>Service Time Ratio (STR)</th>
<th>Interconnectivity Ratio (IR)</th>
<th>Level of Service (LOS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jahangirpuri to Kashmere Gate</td>
<td>Yellow</td>
<td>2.011</td>
<td>0.222</td>
<td>0.301</td>
<td>0.714</td>
</tr>
<tr>
<td>Chandni Chowk to Central Secretariat</td>
<td>Yellow</td>
<td>1.829</td>
<td>0.244</td>
<td>0.322</td>
<td>0.699</td>
</tr>
<tr>
<td>Udyog Bhawan to Saket</td>
<td>Yellow</td>
<td>2.062</td>
<td>0.222</td>
<td>0.297</td>
<td>0.645</td>
</tr>
<tr>
<td>Qutub Minar to Huda City Center</td>
<td>Yellow</td>
<td>2.179</td>
<td>0.191</td>
<td>0.269</td>
<td>0.545</td>
</tr>
<tr>
<td>Rithala to Kanhaiya Nagar</td>
<td>Red</td>
<td>1.713</td>
<td>0.239</td>
<td>0.273</td>
<td>0.587</td>
</tr>
<tr>
<td>Inderlok to Kashmere Gate</td>
<td>Red</td>
<td>1.601</td>
<td>0.269</td>
<td>0.318</td>
<td>0.796</td>
</tr>
<tr>
<td>Shastri Park to Dilshad Garden</td>
<td>Red</td>
<td>1.675</td>
<td>0.260</td>
<td>0.324</td>
<td>0.775</td>
</tr>
</tbody>
</table>

Figure 11. Multimodal efficiency scores and ranks of corridors.
TABLE 12.
Strategies for Improving Multimodal Efficiency of Corridors

<table>
<thead>
<tr>
<th>Corridor Details</th>
<th>Observation and Interpretation</th>
<th>Improvement Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jahangirpuri to Kashmere Gate &amp; Inderlok to Kashmere Gate</td>
<td>Technically efficient.</td>
<td>Better performance in context to multimodal integration.</td>
</tr>
<tr>
<td>Shastri Park to Dilshad Garden &amp; Chandni Chowk to Central Secretariat</td>
<td>Inefficiency linked to $I_p$ input.</td>
<td>Affects overall LOS, is a measure of proximity so improvement in access/egress facilities should improve OVTT values.</td>
</tr>
<tr>
<td>Udyog Bhawan to Saket</td>
<td>PWI more than desired.</td>
<td>Demand supply gap in capacity for transfer and travel need to be addressed.</td>
</tr>
<tr>
<td>Rithal to Kanhaiya Nagar</td>
<td>Negative slacks for Inputs 1 &amp; 2. Waiting time and service time ratio are weak links.</td>
<td>Terminal station proximal connectivity needs to be addressed at Rithala. Phase 3: no extension proposed beyond Rithala on Red line.</td>
</tr>
<tr>
<td>Qutab Minar to HudaCity Center</td>
<td>PWI more than desired. $I_p$ value shows negative slack.</td>
<td>Feeder and IPT connectivity need to be strengthened. Wait times are more due to terminal stations at both ends; needs better proximal connectivity.</td>
</tr>
</tbody>
</table>

Here again, none of the outputs portray a negative slack with their projected values, which indicates that to make the Yellow and Red lines more multimodal-friendly and enhance the efficacy of multimodality, much work needs to be done. The output values show a tremendous scope for improvement in this set.

The comparative summary of various input and output evaluation sets at the corridor level are illustrated in Figure 12. As can be seen, of the seven corridors compared, three corridors need significant improvement in all aspects.
Conclusion
The results of the efficiency analysis carried out on operational, spatial, proximal, and corridor performance and information, security, and overall multimodal efficiency attributes of the major line haul mode of Delhi revealed collective and individual characteristics of the entire system as well as gaps in performance. Each station has its own set of dynamic attributes and, for each station, a different approach is needed to enhance its contribution towards the multimodal fabric of the system. The following conclusions were drawn from the present study.

1. DEA is an effective technique to compare the relative efficiencies of DMUs using a multitude of inputs and outputs to assess a multimodal public transit system.

2. DEA analysis not only provides technical efficiencies after comparing DMUs but also provides target values for inputs and outputs of all other DMUs to achieve the efficiency equivalent of the best-performing DMU. Also, DEA analysis provides specific slack values, which makes it easy to determine the weak and strong links of the DMUs in the system.

3. Among the corridors, Jahangirpuri to Kashmere Gate on the Yellow line and Inderlok to Kashmere Gate on the Red line emerged as the best-performing corridors in the relative efficiency analysis. Qutab Minar to Huda City Center was the worst-performing corridor.
4. Among individual stations, efficient stations include Kashmere Gate, which is common to both lines; on the Yellow Line, G.T.B. Nagar, Rajiv Chowk, Malviya Nagar, and Ghitorini emerged as the better-performing stations; and on the Red line, Pulbangash and Welcome Station performed better.

5. The corridors that have terminal stations indicate several access/egress distance issues. This is mainly because people from areas out of catchment of the terminal stations come from distant areas to use Metro services. This calls for an extension of lines or very strong and efficient feeder connectivity to the areas beyond the last station for better interconnectivity.

6. The stations in Central Delhi and the CBD areas should concentrate on reducing passenger waiting times and transfer times. This can be done by using travelators on interchange stations, introducing parking areas that are internally connected with the stations, installing turnstiles to reduce queue times, etc.

7. The suburban areas from which large numbers of commuters move to the CBD or to prominent work and education centers are less efficient in terms of operational hours, especially at night, resulting in longer transfer time delays. Passengers could travel more from the suburbs if timing was extended at night.

8. Access and egress legs emerged as the weakest links of all the corridors and individual stations in the study. This is due to poor connectivity and poor scheduling of connecting modes. Organized routes and enhancement of feeder connectivity are required on a large scale along the Yellow and Red line routes of Delhi Metro.

9. Transfer areas could be designed or infrastructurally augmented to promote fast transfers for a large number of passengers simultaneously. More staff could be deployed for peak hours, or more parking can be provided for stations with larger footfalls.

References


Comparative Appraisal of Metro Stations in Delhi Using Data Envelopment Analysis in a Multimodal Context


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Model for Measuring Passenger Satisfaction and Assessing Mass Transit Quality

Ivana Olivková, Ph.D.
VŠB – Technical University of Ostrava

Abstract

This paper presents a detailed description and explanation of the model for measuring passenger satisfaction and assessing the quality of mass transit. The basis of this model is the assessment of a mixed set of mass transit quality criteria, both quantitative and qualitative in nature. The model was applied in an actual case study of the mass transit system in Ostrava as an assessment of transportation passenger satisfaction. The paper presents the results of the model's application and includes an analysis of the results of the survey using SWOT analysis. The conclusion assesses the benefits and practical application possibilities of the model for measuring passenger satisfaction and mass transit quality. Some of the primary advantages of the model include the option of presenting basic survey results. In combining the values of satisfaction and importance for the individual criteria or groups thereof, it is possible to formulate conclusions on the necessity of further actions by the carrier.

Introduction

The role of the mass transit system is to secure a city's transportation requirements at the required qualitative level. The quality of the mass transit system plays a significant role primarily in relation to the utilization of private automobile transport. Currently, private automobile transport in urban areas is problematic in its spatial requirements, increasing the number of traffic accidents and decreasing traffic flow speed, which is also reflected in the travel speed of mass transit transportation.

The only solution that can help encourage decreased use of private automobiles in urban areas is a high level of quality of passenger transportation. Although passenger transportation can be secured essentially without major issue from a quantitative aspect, user demands increase primarily in terms of quality. This is why the quality requirement for mass transit carrier services remains one of the goals of transportation policies in the Czech Republic (Ministry of Transport CR 2014).
The issues involved in the assessment and measurement of the quality of services in the Czech Republic have begun to be reflected in many areas, and transportation is no exception. For quite some time, the concept of quality applied only to tangible products; usage in the service sectors is a relatively new notion (Hayes 1998; Hill, Roche, and Allen 2003; Nenadál et al. 2004). (This applies not only to the countries of Central and Eastern Europe, but to all other member countries of the European Community as well.) Issues related to quality began to be applied in transportation later than in other service sectors (European Standard EN 13816 2002; European Standard EN 15140 2006). The reason is that quality (which has always been customer-centric) was not at the forefront of interest during the era of monopolized state carriers.

The United States was the first to take advantage of the practical applications of the theory of service quality in public transportation. According to TCRP Report 47 (Transportation Research Board 1999), which was led by a firm specializing in customer satisfaction measurement, the service sector in the U.S. began rigorously measuring quality in the 1980s, and the U.S. transit industry began adopting these practices in the 1990s. In addition, the research behind the first two editions of the *Transit Capacity and Quality of Service Manual* (Transportation Research Board 1999) spent considerable effort on identifying and quantifying, in a consistent way, quality factors that are important to passengers. Unfortunately, these documents were not available in the Czech Republic at the time.

Until 1998, there were no verified methods created for measuring customer satisfaction, nor have there been any studies that have dealt with the status and nature of public transport and its customers. This was due primarily to the lack of attention to this issue on a theoretical level. Methods and procedures with which one could comprehensively characterize and assess quality from the passenger point of view have not yet been established.

For the reasons listed, a method for evaluating transportation quality and transportation alternatives from the viewpoint of the passenger was created for this study (Olivková 2009). The study also included a questionnaire for a poll survey of transportation passengers. Experimental verification of both the method and questionnaire was carried out by conducting a comprehensive quality assessment of transportation and transportation alternatives in the Ostrava mass transit system based on the creation of a transportation survey of a selected group of travellers (Olivková 2009). Supplementing the quality assessment method with a measurement of passenger satisfaction emerged from the necessity to be able to objectively describe, compare, and interpret facts collected in a transportation survey.

The model was applied in practice in an actual case study of the mass transit system in Ostrava; the findings are presented in this paper. The goal is the assessment of both the theoretical and practical experiences related to the measurement of passenger satisfaction and assessment of mass transit quality. The model described herein and its scientific verification are the original work of the author.
Description of the Model
To construct a model for measuring passenger satisfaction and assessing the quality of the mass transit system, the demands placed upon it must be defined:

- It must be a comprehensive model incorporating both a subjective component for measuring passenger satisfaction and an objective component for assessing the quality level of the mass transit system.
- It must include all relevant criteria (quantitative and qualitative) and must reflect the comprehensiveness of all aspects of the services.
- In addition to satisfaction, it must identify the importance of individual components of the services.
- It must guarantee expedient and financially feasible application, so that satisfaction assessment can be carried out regularly.

Taking into account all of the abovementioned demands, a model was devised and verified through implementation and is described in detail in the following sections.

Defining Mass Transit Quality Criteria
The criteria represent the views of the passengers on the services provided by mass transit. It is essential to pay close attention to the definitions of the mass transit quality criteria because this is an important step in the proposed methodology that can significantly influence the resulting overall assessment. The criteria set is designed to be exhaustive, i.e., it includes all of the significant mass transit quality components that are important to passengers. If this was not the case, it could lead to a skewing of the assessment results.

Six criteria were defined for the assessment of the quality assessment of the mass transit system, which fulfill and represent the concept of mass transit quality in the eyes of the passengers (Table 1). The criteria set contains two subsets: sub-criteria of the time and spatial offer of the mass transit systems, and vehicle comfort sub-criteria.
Table 1: Defining Mass Transit Quality Criteria

<table>
<thead>
<tr>
<th>No.</th>
<th>Criterion</th>
<th>Sub-Criterion No.</th>
<th>Sub-Criterion</th>
<th>Unit of Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transit time</td>
<td></td>
<td></td>
<td>time (min)</td>
</tr>
<tr>
<td>2</td>
<td>Punctuality</td>
<td></td>
<td></td>
<td>point scale</td>
</tr>
<tr>
<td>3</td>
<td>Time and spatial offer of mass transit system</td>
<td>3.1</td>
<td>Accessibility of stops</td>
<td>time (min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.2</td>
<td>Waiting for connection</td>
<td>time (min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.3</td>
<td>Transferability in mass transit network</td>
<td>time (min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.4</td>
<td>Arrangement of stops</td>
<td>point scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5</td>
<td>Operational information</td>
<td>point scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6</td>
<td>Arrangement of ticket presales</td>
<td>point scale</td>
</tr>
<tr>
<td>4</td>
<td>Comfort of vehicle</td>
<td>4.1</td>
<td>Vehicle occupancy</td>
<td>point scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2</td>
<td>Noise level and vibrations</td>
<td>point scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.3</td>
<td>Microclimate in vehicles</td>
<td>point scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.4</td>
<td>Driving style</td>
<td>point scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td>Layout of interior of vehicles</td>
<td>point scale</td>
</tr>
<tr>
<td>5</td>
<td>Transportation costs</td>
<td></td>
<td></td>
<td>point scale</td>
</tr>
<tr>
<td>6</td>
<td>Impact of mass transit system on city’s environment</td>
<td></td>
<td></td>
<td>point scale</td>
</tr>
</tbody>
</table>

All criteria listed in Table 1 have the same bearing from the passenger viewpoint. A lower nominal value of the given criteria is preferred (more useful) in the eyes of the passenger than a higher nominal value, and vice versa. The mass transit quality criteria can be divided into two groups according to manner of assessment (Carlsson and Fuller 1996):

a) Quantitative criteria – Nominal values were set objectively based on data on the individual components of transit time listed by passengers in the questionnaire.

b) Qualitative criteria – Nominal values were set subjectively by a passenger opinion survey on a five-point scale, where 1 is the best score (most desirable) and 5 is the worst score (least desirable).

Establishing Mass Transit Quality Criteria Weight

The assessment method must first establish the weight of the individual evaluation criteria that express the numeric meaning of the criteria (and/or the significance of the criteria from the evaluator’s standpoint) (Fotr and Píšek 1986).

The following relationship is applied for establishing the non-normalised weight (Fiala, Jablonský, and Maňas 1994):

\[ k_i = n + 1 - p_i \]

where,

- \( k_i \) = non-normalized weight of i-value criteria [-]
- \( n \) = quantity of criteria
- \( p_i \) = ranking of i-value criteria in its preferential order
Due to the requirements of the comparability of criteria weights established by various methods, it is necessary to normalize these weights (the sum of the normalized weights of the set is equal to 1). Criteria weight normalization is carried out according to the following relationship (Fiala, Jablonský, and Maňas 1994):

\[ v_i = \frac{k_i}{\sum_{i=1}^{n} k_i} \]  

(2)

where,

- \( v_i \) = normalized weight of i-value criteria [-]
- \( k_i \) = non-normalized weight of i-value criteria [-]
- \( n \) = quantity of criteria

For evaluating the quality level of the mass transit system, it was necessary to use an expanded set of criteria, which, for practical reasons, was divided into sub-groups according to the relationship of their substantive content (mass transit quality criteria, sub-criteria of the time and spatial offer of the mass transit systems, and sub-criteria of the comfort of the vehicle), and the following process of calculating criteria weight was applied:

- Respondents must prioritize the order of criteria based on their own subjective opinion. Based on this criteria ranking, the non-normalized weight of individual criteria is calculated and is then normalized so that the sum of the weights is equal to 1.

- The respondents then prioritize the order for each sub-criterion whose classification and significance create a subset of the specific criteria. Based on this sub-criteria ranking, the non-normalized weight of the individual sub-criteria is calculated; these are then also normalized.

- The resulting sub-criteria weights are always calculated by multiplying the sub-criteria weights by the weight of the criteria under which it is categorized.

Normalization of criteria weight as well as the weights of the individual sub-criteria then ensure that the resulting sub-criteria weights calculated by the abovementioned multiplication process are once again normalized, so that their sum across the entire criteria set equals 1.

The advantage of this process of establishing weights is based primarily in the fact that it decreases the demand on the user (passenger), who only needs to determine the preferential order of the criteria and immediately relevant sub-criteria. They are, therefore, not required to judge the significance (importance) of other, entirely substantively different criteria.

One final important aspect regarding establishing criteria weight is that the reliability of obtained results can be increased by utilizing a greater number of respondents (passengers) who determine criteria order individually and independently of one another.
**Mass Transit Criteria Assessment**

In the assessment of mass transit quality criteria, it may happen that a portion of the criteria is quantitative in nature (values are expressed on a metrical scale) and a portion is qualitative in nature (values are expressed on an ordinal scale). The means to achieve a statistical assessment typical for metrical scales while using ordinal rankings is through metrization, i.e., assigning point values on a point scale (Moreno, Fidélis, and Ramos 2014). For each position on the point scale, the level for each quality criteria is precisely defined using word descriptors. By assigning points from a point scale, the passenger determines to which degree the given criterion fulfills his/her expectations. Qualitative criteria nominal values are thus expressed subjectively based on the viewpoint of the passenger in scale values. Subjectively-expressed viewpoints can then be statistically objectivized.

Assessment of mass transit quality quantitative criteria (sub-criteria) is divided into the following steps:

1. **Construction of criteria sub-utility functions.**
   
   a) *Definition the domain of the sub-utility functions* – The domain of the criteria sub-utility function is the interval of nominal values $X_i = \langle x_{i\min}; x_{i\max} \rangle$.
   
   Nominal values are established objectively, based on quantitative data (on a metric scale) provided by passengers in the questionnaire. The endpoints of this interval can be labeled as $x_{i\min}$ and $x_{i\max}$, where $x_{i\min}$ is the lowest (minimum) value of $i$-value criteria and $x_{i\max}$ is the highest (maximum) value of $i$-value criteria.

   b) *Graphical representation of the investigation of the surveyed values using a dot chart* – Through the use of a five-point scale of quality criteria assessment, where 1 represents the best score and 5 the worst, passengers assign the specific criteria nominal value $x_i$ a utility value $u_i = 1, u_i = 0.75, u_i = 0.5, u_i = 0.25$ or $u_i = 0$. Ordered pairs $(x_i, u_i(x_i))$ create point coordinates that can be illustrated graphically using a dot chart in which criteria nominal values are plotted on the x-axis and the corresponding mean utility values are plotted on the y-axis.

   c) *Determination of the type of regression function (criteria sub-utility function) and establishing its parameters using the method of least squares* – The method of least squares can help identify the regression (approximation) function with the smallest sum of squared deviations of the observed (surveyed) values from the calculated (theoretical) $y_i$. The method of least squares consists of finding a regression (approximation) function for which the following relationship applies (Meloun and Militký 2002):

   $$\sum_{i=1}^{n} \left( y_i - \hat{y}_i \right)^2 = \min$$

   (3)
The procedure is as follows:

From the dot chart depicting values identified by the survey, it can be concluded that the dependence is quadratic. The function \( u_i(x) \) will be monotonically decreasing in its domain \( x_i = <x_{i\min}; x_{i\max}> \). Two types of \( u_i(x) \) functions can be expected, i.e., convex (Figure 1, type a) or concave utility functions (Figure 1, type c).

Surveyed values can, therefore, be approximated parabolically (quadratic function, second-order polynomial) with the equation \( y = f(x) = ax^2 + bx + c \). Estimations of their parameters can be obtained using the method of least squares, i.e., from conditions so that the sum of the squared deviations \( S \) were minimal (Anděl 2007):

\[
S(a,b,c) = \sum_{i=1}^{n} \left( y_i - ax_i^2 - bx_i - c \right)^2 \quad \text{min}
\]

The coefficient of determination indicates in what part the variability of the dependent value is explained by the chosen model (Meloun and Militký 2002):

\[
R^2 = \frac{\sum_{i=1}^{n} (y_i' - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}
\]

The coefficient of determination (labeled as \( R^2 \) in Microsoft Excel) takes on the values of the closed interval \( <0, 1> \).
2. Division of the domain of the criteria sub-utility functions into nominal value intervals and setting nominal value limits.

The domain function can be divided into five nominal value sub-intervals by transforming the quality criteria point value using the sub-utility function of \( u_i(x) \) criteria. Using the \( u_i(x) \) function, we can also get the limit of the nominal values \( x_i^1, x_i^{0.75}, x_i^{0.5}, x_i^{0.25}, x_i^0 \) for which \( u_i(x_i) \) takes on the values \( u_i(x_i^1) = 1, u_i(x_i^{0.75}) = 0.75, u_i(x_i^{0.5}) = 0.5, u_i(x_i^{0.25}) = 0.25 \) and \( u_i(x_i^0) = 0 \). Assessment of mass transit quality qualitative criteria (sub-criteria) is divided into the following steps:

a) Construction of criteria sub-utility functions.

i) Definition the domain of the sub-utility functions – The domain of the sub-utility function is the nominal value limits of criteria \( x_i = 1, x_i = 2, x_i = 3, x_i = 4, x_i = 5 \) that were established subjectively based on qualitative data, provided by passengers in the survey.

ii) Graphical representation of the surveyed values using a dot chart – Through the use of a five-point scale of quality criteria assessment, where 1 represents the best score and 5 the worst, passengers assign the nominal value limits \( x_i = 1, x_i = 2, x_i = 3, x_i = 4, x_i = 5 \), for which \( u_i(x_i) \) take on values \( u_i(1) = 1, u_i(2) = 0.75, u_i(3) = 0.5, u_i(4) = 0.25 \) and \( u_i(5) = 0 \). Ordered pairs \( (x_i, u_i(x_i)) \) create five point coordinates that can be graphically depicted using a dot chart with the x-axis plots the limits of the criteria nominal values, and the y-axis reflect the corresponding utility values.

iii) Determination of the type of regression function (criteria sub-utility function) and establishing its parameters using the method of least squares – From the dot chart depicting criteria values identified by the survey, it can be concluded that the dependence is linear. The function \( u_i(x_i) \) will be linearly monotonically decreasing in its domain \( x_i = <x_{\min}; x_{\max}> \) (Figure 1, type b). Values provided by the survey can, therefore, be approximated by a straight line (first-order polynomial) with the equation \( y = f(x) = ax + b \). Estimations of their parameters can be obtained using the method of least squares, i.e., from conditions so that the sum of the squared deviations \( S \) are the smallest possible (Anděl 2007):

\[
S(a,b) = \sum_{i=1}^{n} (y_i - ax_i - b)^2 = \text{min}
\]  

The appropriateness of the regression function can again be verified through the coefficient of determination \( S \).

b) Division of the domain of the criteria sub-utility function into nominal value intervals and setting nominal value limits – This step cannot be carried out for qualitative criteria because the sub-utility domain cannot be divided into nominal value intervals. The domain is created solely by nominal value limits.
Model Application Results

From 2011 to 2014, the model for measuring satisfaction and assessment of quality described above was implemented in Ostrava. A total of 2,120 respondents were surveyed, with 540 respondents being surveyed in 2011, 521 in 2012, 543 in 2013, and 516 in 2014.

The transportation survey focused on the residents of Ostrava and the surrounding area that utilize the mass transit system as a means of transportation on their way to work (or school). It did not include residents of other cities or users of the integrated transport system who use other systems of mass passenger transportation (bus and railway passenger transportation) and transfer to the urban mass transit system to travel from their place of residence to their place of work. One of the reasons was to focus the survey on passenger satisfaction assessment of the urban mass transit system. Another reason was the possibility of decreased objectivity in assessing the quality criteria of the urban mass transit system resulting from the use of a different transportation system during the course of travel. All types of mass transit system modes of transportation used by Ostrava Transport (buses, trams, trolley bus) or the combination thereof, in the case of transfers, are represented.

Taking into account similar surveys and personal experience from a study conducted in 2009 (Olivková 2009), the selection of surveyed individuals was carried out in the individual city districts of Ostrava based on a proportional representation according to the socio-demographic quota characteristics of the city. Interviewers were assigned a specific area in which they were to conduct their surveys as well as a quota according to sex, age, and level of completed education. Based on the results and measurements of already-completed studies in which quota sampling was used, the generally-recommended sample size was 500 or more statistical units (Nenadál et al. 2004).

The surveys were conducted in the form of face-to-face interviews. Respondents filled out a questionnaire in the presence of a trained individual (students of the Institute of Transportation, VŠB-Technical University of Ostrava) who oversaw the completion of the questionnaire. This also ensured that passengers could ask for clarification if they did not understand any of the presented questions.

Evaluation of Respondent Data

The following results apply to a defined base set—mass transit users over the age of 15 and who, in principle, can make their own decisions on the choice of mode of transportation. Evaluation of respondent data is depicted in Table 2, which presents both absolute and relative frequencies, expressed in percentages, for the individual years 2011–2014 and overall.
Evaluation of Criteria in Terms of Subjective Importance

The process described previously was used to calculate the weights of individual criteria (sub-criteria). From the collected data, average percentage representations of weight (level of relative importance) can be determined for:

- Mass transit quality criteria (Figure 2)
- Time and spatial offer of the mass transit systems sub-criteria (Figure 3)
- Vehicle comfort sub-criteria (Figure 4)
Figure 2 indicates the following weight ranking of mass transit quality criteria from the point of view of the passengers:

- Transit time (total travel time) – Passengers prefer that the time spent traveling to work be as short as possible.
- Punctuality, (adherence to prescribed timetable) – Passengers require the greatest accuracy possible in adherence to the mass transit system timetable.
- Transportation costs – Passengers expect low fare costs.
- Time and spatial offer of mass transit systems – Passengers require the greatest level of comfort possible outside of transportation vehicles. As is shown in Figure 3, this requirement applies primarily to short connection waiting times and accessibility of stops, which is related to the abovementioned requirement for short travel times.
- Comfort of the vehicle – Passengers expect acceptable levels of comfort inside the vehicle. Figure 4 indicates that this requirement applies primarily to low
occupancy (sufficient space for seated and standing passengers) and microclimate (sufficient ventilation, heating, and lighting, i.e., securing optimal temperature and lighting conditions).

- Impact of the mass transit system on the city’s environment – From the viewpoint of the passengers, mass transit pollutes the city’s environment with noise, vibrations, air pollution from emissions and exhaust, and fuel and oil leakage to a much lesser extent than private automobile transportation.

**Assessing Mass Transit Quality Criteria in Terms of Passenger Satisfaction**

The procedure for assessing quality criteria in terms of passenger satisfaction depends on the nature of the criteria. Assessment of quantitative criteria is governed by the procedures described previously and was determined by conducting an assessment of the transit time criteria.

Transit time is considered one of the most significant criteria that impacts a passenger’s decision to utilize mass transit transportation options. If a passenger has the opportunity to choose from a selection of several types of means of transportation (including automobiles) to reach a specific travel destination, the “door-to-door” transit time (total travel time) is essential. Transit time, therefore, is defined as (Surovec 1998):

\[
   t_p = t_1 + t_c + t_{dp} + t_{pf} + t_2
\]

where,

- \( t_p \) = transit time (min)
- \( t_1 \) = time spent walking to initial stop (min)
- \( t_c \) = connection wait time (min)
- \( t_{dp} \) = time spent traveling in the mass transit vehicle, transport time (min)
- \( t_{pf} \) = connection transfer time (including time spent waiting at a connecting stop) (min)
- \( t_2 \) = time spent walking from final stop to place of employment (min)

The criterion of transit time was assessed by passengers in terms of time spent traveling from their residence to their place of employment. Nominal values of transit time \( x_1 \) were calculated based on the data of the individual components of transit time (7) obtained from passengers in the survey.

On a scale from 1 to 5, passengers assigned the specific nominal value of \( x_1 \) a utility value \( u_1 = <1 ; 0> \). Ordered pairs \((x_1, u_1(x_1))\) create point coordinates that are illustrated graphically in Figure 5 (the x-axis plots the transit time nominal values, and the y-axis reflects the corresponding average utility values). Values collected by the survey can be best approximated by a parabola (quadratic function, second-order polynomial).
The sub-utility function \( u_1(x_1) \) has the form:

\[
u_1(x_1) = 6E-05 \cdot x_1^2 - 0.0188 \cdot x_1 + 1.3568 \quad (8)
\]

The coefficient of determination \( R^2 = 0.9756 \), which signifies good point spacing.

The function \( u_1(x_1) \) in its domain \( x_1 = <20; 115> \) is monotonically decreasing from the function value \( u_1(x_1^0) = 1 \) to the function value \( u_1(x_1^9) = 0 \); the behavior of the function is convex. Additions to the nominal values at the beginning of the domain represent a greater decrease in utility for passengers than additions of nominal values at the end of the domain.

The domain function was divided based on point scores assigned by passengers into five separate intervals (Table 3). Using the function \( u_1(x_1) \), one can also get limits of nominal values \( x_1^{0.75}, x_1^{0.5}, x_1^{0.25}, x_1^{0} \) for which \( u_1(x_1) \) takes on the value \( u_1(x_1^1) = 1, u_1(x_1^{0.75}) = 0.75, u_1(x_1^{0.5}) = 0.5, u_1(x_1^{0.25}) = 0.25, \) and \( u_1(x_1^{0}) = 0 \).

<table>
<thead>
<tr>
<th>Point Scores</th>
<th>Nominal Value Limits ( x_1^{(\min)} )</th>
<th>Nominal Value Limits ( x_1^{(\min)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Very satisfied</td>
<td>20–28</td>
<td>20</td>
</tr>
<tr>
<td>2 Satisfied</td>
<td>29–45</td>
<td>37</td>
</tr>
<tr>
<td>3 Neither satisfied nor dissatisfied</td>
<td>46–65</td>
<td>55</td>
</tr>
<tr>
<td>4 Dissatisfied</td>
<td>66–93</td>
<td>79</td>
</tr>
<tr>
<td>5 Very dissatisfied</td>
<td>94–115</td>
<td>115</td>
</tr>
</tbody>
</table>

The values listed in Table 3 indicate how passengers assess time spent in transit from their residence to their place of employment. Reaching the travel destination (place of employment) within 28 minutes brings the highest utility for passengers, although they indicated that they were "satisfied" with times of up to 45 minutes. Increasing time spent traveling to up to 65 minutes were labeled as neutral—"neither satisfied nor dissatisfied"; additional increases, however, were viewed by passengers as unacceptable.

The evaluation of qualitative criteria is governed by the procedures described in the previous section. Since the procedures for constructing sub-utility functions for the individual qualitative criteria is identical, it is described in general terms for all of these criteria.
Through the use of a five-point quality criteria assessment scale, where 1 represents the best score and 5 the worst, passengers assigned the nominal value limits $x_i = <1; 5>$ for which $u_i(x_i)$ takes on the values $u_i(1) = 1$, $u_i(2) = 0.75$, $u_i(3) = 0.5$, $u_i(4) = 0.25$ and $u_i(5) = 0$. Ordered pairs $(x_i, u_i(x_i))$ create five point coordinates that are plotted in Figure 6 (the x-axis plots the limits of the criteria nominal values, and the y-axis plots the corresponding average utility values). These points can be best represented by a linear regression curve. The sub-utility functions of qualitative criteria $u_i(x_i)$ have the form:

$$u_i(x_i) = -0.25x_i + 1.25 \quad (9)$$

The coefficient of determination $R^2 = 1$ which means that the curve passes through the specified points.

The sub-utility functions of qualitative criteria $u_i(x_i)$ in the domain $x_i = <1; 5>$ is monotonically deceasing from the function value $u_i(x_i^1) = 1$ to the function value $u_i(x_i^5) = 0$; the behavior of the function is linear. Qualitative criteria have a decreasing preference in which constant growth of the nominal value means a constant decrease in utility value for the respondents.

Table 4 lists the average values (utility) of individual criteria that were calculated overall for all passengers (respondents) who participated in the survey both for the individual years 2011–2014 and overall.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transit time</td>
<td>0.51 0.52 0.55 0.58 0.54</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Punctuality</td>
<td>0.67 0.76 0.73 0.77 0.73</td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Accessibility of stops</td>
<td>0.86 0.83 0.8 0.82 0.83</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>Waiting for connection</td>
<td>0.76 0.72 0.7 0.74 0.73</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Transferability in transit network</td>
<td>0.46 0.42 0.48 0.41 0.44</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>Arrangement of stops</td>
<td>0.60 0.58 0.66 0.68 0.63</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Operational information</td>
<td>0.63 0.64 0.67 0.68 0.66</td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>Arrangement of ticket presales</td>
<td>0.54 0.48 0.51 0.56 0.52</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Vehicle occupancy</td>
<td>0.41 0.48 0.49 0.45 0.46</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Noise level and vibrations</td>
<td>0.68 0.65 0.67 0.70 0.68</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Microclimate in vehicles</td>
<td>0.69 0.67 0.65 0.66 0.67</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Driving style</td>
<td>0.48 0.45 0.46 0.5 0.47</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Layout of interior of vehicles</td>
<td>0.74 0.78 0.76 0.79 0.77</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Transportation costs</td>
<td>0.52 0.46 0.48 0.42 0.47</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Impact of the city’s environment</td>
<td>0.49 0.44 0.47 0.46 0.47</td>
<td></td>
</tr>
</tbody>
</table>

It can be stated that eight criteria scored, on average, above 0.604 (the average level of satisfaction), i.e., passengers were satisfied with them. Seven criteria scored below this threshold, i.e., respondents were dissatisfied with them, which indicates a potential for improvement for the carrier. The following section discusses which quality criteria are in need of immediate improvement.

**Evaluating the Results of the Satisfaction Survey**

Evaluation of the results of the study was conducted using Strengths–Weaknesses–Opportunities–Threats (SWOT) analysis (Figure 7). It comprises a two-dimensional graph that graphically depicts the relationship of passenger satisfaction with the given criteria (vertical axis) and its true significance (horizontal axis). To interpret and evaluate the significance of individual criteria for further decision-making on the part of the carrier, each SWOT table was divided by a horizontal and vertical line into four quadrants. The horizontal dividing line creates the average level of satisfaction, and the vertical is the position level of the true significance of all criteria—the median of subjectively-perceived importance.
Overall, the services of the DP Ostrava transportation company earned a very high rating (Figure 7). This is evidenced by the position of the elements in the SWOT table in which, of the 15 evaluated quality elements, only 3 are listed under “Threats.” These criteria have a large impact on overall passenger satisfaction but have a negative rating. Therefore, they represent a significant threat to the company, and it is imminently necessary to implement corrective measures. Among these criteria is transit time, transferability in the mass transit network, and vehicle occupancy.

Special attention must be paid to the criterion of travel time. This quality component is significant for the overall assessment of mass transit services in Ostrava. Its average rating is unsatisfactory—passengers are not satisfied with the time it takes to travel from their point of departure to their destination. Put simply, passengers feel that the mass transit system is not fast enough. It is interesting that there are no significant differences of opinion in this area between the individual socio-demographic groups of transportation clients.

Since transfer time is also a critical component of mass transit quality in Ostrava with a significant impact on the satisfaction evaluation by passengers and is a significant part of travel time, it is important to take action in this particular area. Reducing the number of transfers, and thus decreasing transfer time, can significantly shorten the total travel time.
There are five criteria in the “Opportunities” section, which have a heavy impact on overall passenger satisfaction, and, additionally, have a positive rating. The carrier can be satisfied with its assessment. The important thing is to maintain a high level of quality in following years as well. These criteria include punctuality, accessibility of stops, connection wait times, noise level and vibrations, and microclimate in the vehicles.

There are three criteria in the “Strengths” section, which have a relatively small impact on overall passenger satisfaction, but have a positive rating. These criteria include the layout of the interior of the vehicles, operational information, and arrangement of the stops.

In the “Weaknesses” section are four criteria: arrangement of the ticket presales, transportation costs, driving style, and impact of mass transit on the city’s environment, which, although they have a below-average rating, are not as important to passengers. It is important to take note of the sub-criteria, driving style, which could be reclassified under the “Threats” label with even a slight increase in their weight value.

Conclusions

This paper studies the issues of measuring passenger satisfaction and assessing mass transit quality. It focuses specifically on a description of the model and the results of its experimental verification, carrying out a passenger satisfaction assessment and assessing the quality of the Ostrava mass transit system. The model was scientifically verified by conducting a transportation survey of passengers (Ostrava mass transit system users) that took place in 2011–2014. Quality criteria were rated by passengers in the questionnaire. Respondents were approached at their place of employment by a trained individual who supervised the proper completion of the questionnaire in its entirety.

The experimental verification indicated the following:

- The advantage of the model described in the paper lies in its theoretical reasoning.

- Since there is currently no existing established and commonly-used comprehensive method that includes both a passenger satisfaction assessment and a quality assessment of the mass transit system, the model described is an asset to the development of transportation science.

- Passenger satisfaction and mass transit quality can be comprehensively assessed by implementing the model, using mixed set criteria containing both qualitative and quantitative criteria, in which their informative value is not limited.

- Results indicating the model’s suitability for practical application in assessing the satisfaction with and quality of the mass transit system in the eyes of passengers are significant to evaluating the model itself, because they allow for:
  - identification of passenger expectations related to the level of quality of the mass transit system
  - identification of the existing level of quality
  - revealing the causes of passenger dissatisfaction
- revealing the strengths and weaknesses of the carrier
- providing information and data for quality improvement projects
- quantified results with the opportunity for trend assessment

The model’s primary advantages include the opportunity to present the basic results of the survey. By combining the values of satisfaction and importance for individual criteria or groups thereof can help formulate conclusions on the necessity of further action by the carrier.

A number of relevant methods of measuring the performance and satisfaction are described in the European Standard of Service (European Standard EN 13816 2002), and several examples of their utilization in public passenger transportation are listed. This norm is established as a source for defining service quality areas, both for objective measurement and also more recently for subjective CSS measurements (for example, Trompet et al. 2013). The method proposed by the standard for measuring customer satisfaction allows for more of a component (isolated) assessment of the individual quality criteria of urban mass transit travel; it does not address a comprehensive assessment of the quality of mass transit travel from the standpoint of all of the criteria. The standard allows for the use of alternative methods under the assumption that they will provide equivalent results. This is why using the model presented in this paper is recommended as an alternative to the methods suggested by the European Standard of Service.

References


**About the Author**

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New QR Survey Methodologies to Analyze User Perception of Service Quality in Public Transport: The Experience of Madrid

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Abstract

Customer Satisfaction Surveys (CSS) have become an important tool for public transport planners, as improvements in the perceived quality of service lead to greater use of public transport and lower traffic pollution. Until now, Intelligent Transportation System (ITS) enhancements in public transport have traditionally included fleet management systems based on Automatic Vehicle Location (AVL) technologies, which can be used to optimize routing and scheduling, and to feed real-time information into passenger information channels. However, surveys of public transport users could also benefit from the new information technologies. As most customers carry their smartphones when traveling, Quick Response (QR) codes open up the possibility of conducting these surveys at a lower cost.

This paper contributes to the limited existing literature by developing the analysis of QR codes applied to CSS in public transport and highlighting their importance in reducing the cost of data collection and processing. The added value of this research is that it provides the first assessment of a real case study in Madrid (Spain) using QR codes for...
this purpose. This pilot experience was part of a research project analyzing bus service quality in the same case study, so the QR code survey (155 valid questionnaires) was validated using a conventional face-to-face survey (520 valid questionnaires). The results show clearly that, after overcoming a few teething troubles, this QR code application will ultimately provide transport management with a useful tool to reduce survey costs.

**Keywords:** Public transport, Quality surveys, User perception, Information and Communication Technologies, ICTs, Quick Response codes, QR codes

**Customer Satisfaction Surveys in Public Transport**

The increase in Service Quality (SQ) in public transport has been shown to play a key role in attracting new passengers from private cars to the public transport system and in reducing traffic pollution as a result (Transportation Research Board 1999). The analysis of SQ perceived by passengers is of vital importance for both operators and public transport authorities. However, the concept of SQ is complex, fuzzy, and abstract, mainly because of the three aspects of service: intangibility, heterogeneity for each individual, and the inseparability of production and consumption (Parasuraman et al 1985). In addition to this complexity, a number of authors (Grönroos 1988) differentiate between consumer expectations and perception of service during the trip and maintain that the perception of SQ is the result of a comparison of consumer expectations with actual service performance. Other authors, such as Hu (2010), define service quality in terms of the difference between perceived quality and tolerable quality.

In any case, most research studies have analyzed only perceived service, and the only objective data for the operating companies is “quality of service provided,” normally established in the concession contracts. One of the most interesting and practically-minded SQ approaches comes from the European project QUATTRO (Quality Approach in Tendering Urban Public Transport), which presents a quality loop for the public transport system (European Union 1998), identifying four quality levels (see Figure 1), as follows:

- **Expected quality** – the level of quality desired by passengers and citizens in general.
- **Perceived quality** – the level of quality perceived—that is, observed more or less objectively—by passengers during their journeys.
- **Targeted quality** – the level of quality the company wishes to achieve. The targeted quality level is determined on the basis of expected quality, external and internal pressures, budgetary constraints, and competitors’ performance.
- **Delivered quality** – the level of quality obtained, on a daily basis, in real operating conditions.
The main tools used to analyze service quality in public transport are based on Customer Satisfaction Surveys (CSS), usually carried out by operating companies. CSS results can help managers choose from a long list of service attributes (e.g., cleanliness, on-time performance, availability, comfort, security) to more optimally focus their organization’s attention and resources. A considerable number of attributes are used to evaluate SQ, so they are normally grouped into a smaller number, called dimensions. Although there is no general agreement as to the nature or content of SQ dimensions, it is generally recognized that service quality is a multidimensional (Lehtinen and Lehtinen 1982), multilevel, or hierarchical (Brady and Cronin 2001) construct. Various papers (e.g., Eboli and Mazzulla 2007) have pointed to several categories of attributes that have a greater or lesser impact on SQ and satisfaction. In 2002, the European Committee for Standardization CEN (2003) established a quality standard—EN 13816, Service Quality Standard for Public Transport—in connection with QUATTRO research, and a final report. The EN 13186 standard classifies the characteristics of a service into basic, proportional, and attractive, depending on how compliance and non-compliance affects customer satisfaction. In the U.S., the Transit Capacity and Quality of Service Manual (TCQSM) (Transportation Research Board 2004) groups attributes into availability factors and comfort and convenience factors. The primary distinction made by the TCQSM is whether a transit service is offered; if it is, customers then consider both the type of availability (e.g., frequency or access) and comfort and convenience factors.

Once a group of attributes is selected for a specific survey, public transport operators and service industries need to know not only how the users rate the service on detailed service attributes (attribute–performance rating), but also the relative importance of these attributes to their customers (attribute–importance measures).

As indicated previously, CSS are widely used to analyze public transport quality, although the number of stated preference surveys has risen in recent years, mainly among academics. In conventional CSS, consideration of both of these factors (attribute–performance rating and attribute–importance measures) is crucial when the priority for the operator is to improve or sustain the current overall SQ. Normally, the rates are expressed on two scales: numeric or linguistic. Numeric scales are more widely used and have a wider range—3 to 11 points; linguistic scales are used less and have a narrower range—3 to 7 points (the 5-point Likert scales are the most widely adopted).
The design of the survey format depends strongly on the approach used to estimate the relative importance of the attributes to the customers.

According to Weinstein (2000), there are basically two main approaches: stated importance and derived importance. Stated importance is based on asking customers to rate each attribute on an importance scale; this is the more intuitive and direct of the two methods, but requires a significant increase in the length of the questionnaire (which can lower the overall response rate and the accuracy of the survey). It also can sometimes fail to differentiate sufficiently between mean importance ratings; if customers score nearly all the measures near the top of the scale, certain attributes may be rated as important even though they, in fact, have little influence on overall satisfaction. In contrast, the derived importance approach is less intuitive and is based on “deriving” a measure of attribute importance by statistically testing the strength of the relationship of individual attributes with overall satisfaction. Academics have focused on this last approach, and stated-importance methods practically have been abandoned (when other survey formats—for example, ranking attributes—could have been studied).

Recent literature is now set on seeking other alternatives (to the common methods used until now) for deriving importance, namely (a) bivariate Pearson correlations, (b) factor analysis, and (c) multiple regression analysis. These other alternatives include Structural Equations Models (SEM), based on a multivariate technique combining regression, factor analysis, and analysis of variance to estimate interrelated dependence relationships simultaneously. This approach allows a phenomenon to be modeled by considering both the unobserved “latent” constructs and the observed indicators that describe the phenomenon. SEM has also been adopted to describe customer satisfaction in several public transport services such as metropolitan public transport (Lai and Chen 2011). More recently, De Oña et al. (2012) used decision trees to derive attribute importance in public transport quality. Decision trees is a novel non-parametric data-mining technique that does not predefine underlying relationships between dependent and independent variables.

The authors of this paper were working on new stated-importance methods when Quick Response (QR) code research came up. The case study was the Madrid-Tres Cantos corridor (Spain) with four bus lines, in which a new type of survey questionnaire (to state importance) was being tested using a more sophisticated process of analytic hierarchy to reduce the length of the survey questionnaire (not all users were asked for the same attribute ranking). A conventional survey was required to validate this new stated importance method (designed to derive importance) and, as the whole campaign was based on face-to-face surveys, the survey campaign was starting to become very costly. In this context, the research group began to develop further research lines with new methods to reduce the campaign cost using the new Intelligent Transport System (ITS). The valuable database offered a sound scenario for testing a new ITS tool—QR codes—and, in view of the fact that most customers carry their smartphones when they travel, QR codes opened up the opportunity to conduct these surveys at a lower cost. Therefore, a third type of questionnaire was designed for the QR survey (also derived-importance) and uploaded to the operating company’s (ALSA) website. The QR code would be a simple way to provide users with a virtual link to the questionnaire.
This paper contributes to the limited existing literature by developing the analysis of QR codes applied to CSS surveys in public transport and highlighting their importance in reducing the cost of data collection and processing. The added value of this research lies in the first assessment of a real case study using QR codes. To describe the research as a whole, the paper is divided into the following parts: state of the art on SQ in the public transport sector and main objectives; description of the concept of QR codes and their current implementation in the public transport sector; case study description using a Spanish bus corridor located in Madrid (using a Spanish bus corridor located in Madrid) with a discussion of the results; validation of the QR survey using the conventional face-to-face CSS survey carried out in the same corridor; and presentation of the most important conclusions.

**Use of QR Codes in the Public Transport Sector**

Public transport can be made faster, more efficient, and more passenger-friendly by the use of ITS for traffic management and traveler support. Until now, ITS enhancements of public transport traditionally have included fleet management systems based on AVL technologies, which can be used to improve services, optimize routing and scheduling, and feed real-time information into various passenger information channels. However, surveys of public transport users, which are crucial for transport planners and operators (as discussed above), could also benefit from the new information technologies. In recent years and with increasing intensity, QR codes seemingly have invaded almost all the advertising spaces in our media.

A "QR code" is the trademark for a type of matrix barcode (or two-dimensional barcode) first designed for the automotive industry in Japan. QR codes were developed in 1994 by a Toyota subsidiary, Denso Wave, to help track automobile parts throughout production. This technology has been around for more than a decade and recently became popular as a medium for marketers to reach smartphone users. QR codes are have been used in marketing, inventory control, and manufacturing in Japan and Europe for the last 10 years (Sankara Narayanan 2012). A QR code consists of black modules (square dots) arranged in a square grid on a white background, which can be read by an imaging device (such as a camera) and processed using Reed–Solomon error correction until the image can be appropriately interpreted. The required data are then extracted from patterns present in both the horizontal and vertical components of the image. While designing a QR code may appear complex, creating ready-to-use QR codes is easy using free online QR code generators (Coleman 2011). Some of the advantages of QR codes for customers over traditional URLs are that they are potentially faster and easier to access the website, and they are not susceptible to typing errors.

As most customers carry their smartphones when they travel, QR codes open up the possibility of conducting customer satisfaction surveys at a lower cost, although this is not the primary application of this tool in the public transport sector. There are currently two main QR code implementations: e-ticketing (European Parliament 2014; Zhang et al. 2012; Finzgar and Trebar 2011) and real-time user information (Eken and Sayar 2014; Ganesan et al. 2012). Passenger transport companies all around the world use QR codes instead of paper tickets, almost all airlines offer boarding passes on mobile
phones, and long-distance and high-speed trains and some interurban bus companies use QR codes for ticketing.

Customer information is another application of QR codes in the transport sector. Many public transport companies already use GPS to track their vehicles, which enables location-based services through a web page connection. For example, QR codes can be printed at bus stop shelters, providing smartphone travelers with direct access to real-time bus departure information for the stop (Figure 2).

It should be noted that these two main QR code implementations in the public sector (e-ticketing and user information) require very different customer attitudes towards the new ITS device. When QR codes are used for e-ticketing, the company provides both the code and the scanner to read the code, and the customer attitude can be "passive." However, when QR codes are used for customer information and even surveys, the company provides the code but the customer must have a means of scanning the code and knowing how to use it. In the latter case, an "active" customer attitude is needed to achieve a successful result.

There are many case studies in the world in which QR codes have been applied to e-ticketing or user information in the public transport sector. However, to date, there has been little research exploring the use of QR codes as a procedure for collecting customer surveys. This approach is based on printed QR codes being provided to the users on board. Because QR codes can store addresses and Uniform Resource Locators (URLs), travelers with a camera phone equipped with the correct reader application can scan the QR code and open the operator's web page in the telephone's browser. The questionnaire can be located on the web page and the answers stored automatically. This could mean a significant reduction in the cost of the survey campaign and a faster information processing method.

The authors found very few similar experiences in the literature, although web-based surveys have been studied in depth in other sectors (Greenlaw and Brown-Welty 2009; Lin and Van Ryzin 2012), and there is interesting research in the U.S. on web-based transit surveys. For example, Cummins et al. (2013) compared responses to paper customer satisfaction surveys distributed on board and surveys e-mailed to a list of agency passengers. More recently, Agrawal et al. (2015) investigated the relative data quality of three different bus passenger survey methods distributed or administered on the transit vehicle: self-completed paper surveys, self-completed online surveys (with URLs or QR codes provided), and interviewer-assisted tablet-based surveys. Apart from
this U.S. experience, the European experience described in this paper helps to fill the gap in terms of QR codes, and the only way to validate our QR code survey was using the results of a conventional face-to-face CSS in the same bus corridor.

One of the main requirements for obtaining a representative sample in a survey using QR codes is that the users must be familiar with the technology and own a smartphone. The adoption of a new technology often is affected by its perceived utility and ease of use, both of which could vary due to cognitive differences according to age. Recent literature has analyzed age differences in the knowledge and usage of QR codes (Mendelson and Romano 2013). Overall, self-reported awareness, knowledge, and usage tend to be lower among older adults than younger and middle-age adults. Moreover, given that smartphones are necessary to use QR codes, the need to own one imposes a ceiling on the number of people who are able to use QR codes on a regular basis. The willingness to share personal data and the existence (and timing) of a reward for completing the survey, as with any type of survey (not only online ones) will be two key user factors for the success of the survey campaign. Much can be inferred from the influence of these two factors when using QR codes in loyalty campaigns (Okazaki et al. 2013). Recently, an increasing number of firms have shown interest in including QR codes in their promotional campaigns, and a quality survey of public transport users could learn from this approach. Our experience in Madrid confirms the Okazaki et al. (2013) findings on QR code promotion; we can expect a significant interaction effect between the existence and timing of rewards and the level of user involvement. As described in the next section, the offer of a reward was one of the tools used by the research group to obtain a representative sample in the case study.

**Case Study: Customer Satisfaction Survey in a Bus Corridor in Madrid**

The initiative to conduct a quality survey among urban bus users using QR codes is part of an ongoing research project led by the Universidad Politécnica de Madrid (UPM). The methodology included a conventional face-to-face survey campaign carried out in March 2013 in four peri-urban bus lines along the Madrid-Tres Cantos corridor and operated by the company ALSA. Figure 3 shows the location of the corridor. Bus lines 712, 713, and 716 connect the Madrid Public Transport Interchange Hub–Plaza de Castilla to the city of Tres Cantos along the M-607 corridor (a dual carriageway with two lanes in each direction). The last part of the route, already in Tres Cantos, separates into different routes inside the city. Line 714 is a special case, since it connects the interchange hub to the campus of Universidad Autónoma de Madrid (UAM), a few kilometres outside the city, which makes this bus service a specialized line for trips for the purpose of study.

To achieve the objectives of the research project, two previous groups of questionnaires were designed—one to determine the derived attribute importance (Group 1) and the other to find the stated importance (Group 2). Only Group 1 was used to validate the QR survey, as the format was comparable. Following some parameters of statistical significance and maximum error, 800 surveys were estimated, and 787 were conducted (520 from Group 1 and 276 from Group 2), from which 731 observations were drawn as valid. These results allowed the quality analysis to be completed with a sufficient sample.
size for the planned objectives. The pilot survey was carried out on February 20, 2013, and definitive surveys were made throughout the last week of March from 6:00–11:00 AM (18.3% of the sample), 11:01 AM–4:40 PM (64.8%), and 4:41–11:00 PM (16.9%), at both the main bus stops (Plaza de Castilla Interchange Hub, La Paz Hospital, Ramón y Cajal Hospital, Einstein-Rectorado UAM) and on board.

Table 1 shows the sample rate for each line for survey Group 1 (designated “conventional survey”). These sample rates present errors of around 5–7% for high confidence intervals. Line 714 has a distinct student dimension and, although the sample rate is low, the results are still considered sufficient for the analysis. All the bus lines have a similar age and gender distribution except for line 714—due to the fact that it is used mainly by students, it has a higher percentage of young users, and it also has more women than men. In the conventional survey, the number of valid questionnaires per user and trip profile (ticket type, gender, activity, frequency, age, and trip purpose) also are shown with their percentages in Table 1.
### TABLE 1.
Conventional Survey Collection per Bus Line – Sample Rates and Questionnaires Collected per User and Trip Profile

<table>
<thead>
<tr>
<th></th>
<th>Line 712</th>
<th>Line 713</th>
<th>Line 714</th>
<th>Line 716</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample Rate Estimation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working day demand (trips)</td>
<td>4,106</td>
<td>3,072</td>
<td>3,250</td>
<td>3,160</td>
<td>13,588</td>
</tr>
<tr>
<td>No. of surveys collected</td>
<td>207</td>
<td>116</td>
<td>91</td>
<td>106</td>
<td>520</td>
</tr>
<tr>
<td>Sample rate</td>
<td>5%</td>
<td>3.8%</td>
<td>2.8%</td>
<td>3.4%</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

#### Number of Valid Questionnaires per User and Trip Profile

<table>
<thead>
<tr>
<th>User Activity</th>
<th>Line 712</th>
<th>Line 713</th>
<th>Line 714</th>
<th>Line 716</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working</td>
<td>112 (54.1%)</td>
<td>68 (58.6%)</td>
<td>17 (18.7%)</td>
<td>62 (58.5%)</td>
<td>259 (49.8%)</td>
</tr>
<tr>
<td>Unemployed</td>
<td>11 (5.3%)</td>
<td>6 (5.2%)</td>
<td>1 (1.1%)</td>
<td>2 (1.9%)</td>
<td>20 (3.8%)</td>
</tr>
<tr>
<td>Retired</td>
<td>26 (12.6%)</td>
<td>9 (7.8%)</td>
<td>6 (6.6%)</td>
<td>6 (5.7%)</td>
<td>47 (9.0%)</td>
</tr>
<tr>
<td>Student</td>
<td>43 (20.8%)</td>
<td>26 (22.4%)</td>
<td>67 (73.6%)</td>
<td>29 (27.4%)</td>
<td>165 (31.7%)</td>
</tr>
<tr>
<td>Other</td>
<td>15 (7.3%)</td>
<td>7 (6.0%)</td>
<td>0 (0.0%)</td>
<td>7 (6.6%)</td>
<td>29 (5.6%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ticket</th>
<th>Line 712</th>
<th>Line 713</th>
<th>Line 714</th>
<th>Line 716</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>10 (4.8%)</td>
<td>6 (5.2%)</td>
<td>0 (0.0%)</td>
<td>7 (6.6%)</td>
<td>23 (4.4%)</td>
</tr>
<tr>
<td>10 trips</td>
<td>16 (7.7%)</td>
<td>10 (8.6%)</td>
<td>2 (2.2%)</td>
<td>5 (4.7%)</td>
<td>33 (6.3%)</td>
</tr>
<tr>
<td>Season ticket</td>
<td>176 (85.0%)</td>
<td>99 (85.3%)</td>
<td>89 (97.8%)</td>
<td>94 (88.7%)</td>
<td>458 (88.1%)</td>
</tr>
<tr>
<td>Other</td>
<td>5 (2.4%)</td>
<td>1 (0.9%)</td>
<td>0 (0.0%)</td>
<td>0 (0.0%)</td>
<td>6 (1.2%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency of trip</th>
<th>Line 712</th>
<th>Line 713</th>
<th>Line 714</th>
<th>Line 716</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥5 days</td>
<td>142 (68.6%)</td>
<td>84 (72.4%)</td>
<td>65 (71.4%)</td>
<td>73 (68.9%)</td>
<td>364 (70.0%)</td>
</tr>
<tr>
<td>3–4 days</td>
<td>22 (10.6%)</td>
<td>14 (12.1%)</td>
<td>13 (14.3%)</td>
<td>11 (10.4%)</td>
<td>60 (11.5%)</td>
</tr>
<tr>
<td>1–2 days</td>
<td>31 (15.0%)</td>
<td>9 (7.8%)</td>
<td>10 (11.0%)</td>
<td>13 (12.3%)</td>
<td>63 (12.1%)</td>
</tr>
<tr>
<td>Less than 1 day</td>
<td>12 (5.8%)</td>
<td>9 (7.8%)</td>
<td>3 (3.3%)</td>
<td>9 (8.5%)</td>
<td>33 (6.3%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trip purpose</th>
<th>Line 712</th>
<th>Line 713</th>
<th>Line 714</th>
<th>Line 716</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td>117 (56.5%)</td>
<td>65 (56.0%)</td>
<td>15 (16.5%)</td>
<td>63 (59.4%)</td>
<td>260 (50.0%)</td>
</tr>
<tr>
<td>Study</td>
<td>38 (18.4%)</td>
<td>23 (19.8%)</td>
<td>71 (78.0%)</td>
<td>25 (23.6%)</td>
<td>157 (30.2%)</td>
</tr>
<tr>
<td>Medical</td>
<td>11 (5.3%)</td>
<td>8 (6.9%)</td>
<td>0 (0.0%)</td>
<td>4 (3.8%)</td>
<td>23 (4.4%)</td>
</tr>
<tr>
<td>Leisure</td>
<td>10 (4.8%)</td>
<td>3 (2.6%)</td>
<td>0 (0.0%)</td>
<td>3 (2.8%)</td>
<td>16 (3.1%)</td>
</tr>
<tr>
<td>Other</td>
<td>31 (15.0%)</td>
<td>17 (14.7%)</td>
<td>5 (5.5%)</td>
<td>11 (10.4%)</td>
<td>64 (12.3%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age</th>
<th>Line 712</th>
<th>Line 713</th>
<th>Line 714</th>
<th>Line 716</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ to 23</td>
<td>48 (23.2%)</td>
<td>22 (19.0%)</td>
<td>60 (65.9%)</td>
<td>30 (28.3%)</td>
<td>160 (30.7%)</td>
</tr>
<tr>
<td>23–35</td>
<td>59 (28.5%)</td>
<td>33 (28.4%)</td>
<td>19 (20.9%)</td>
<td>24 (22.6%)</td>
<td>135 (25.9%)</td>
</tr>
<tr>
<td>36–50</td>
<td>38 (18.4%)</td>
<td>30 (25.9%)</td>
<td>7 (7.7%)</td>
<td>29 (27.4%)</td>
<td>104 (20.0%)</td>
</tr>
<tr>
<td>≥ 50</td>
<td>62 (30.0%)</td>
<td>31 (26.7%)</td>
<td>5 (5.5%)</td>
<td>23 (21.7%)</td>
<td>121 (23.2%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gender</th>
<th>Line 712</th>
<th>Line 713</th>
<th>Line 714</th>
<th>Line 716</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>66 (31.9%)</td>
<td>37 (31.9%)</td>
<td>33 (36.3%)</td>
<td>41 (38.7%)</td>
<td>177 (34.0%)</td>
</tr>
<tr>
<td>Female</td>
<td>141 (68.1%)</td>
<td>79 (68.1%)</td>
<td>58 (63.7%)</td>
<td>65 (61.3%)</td>
<td>343 (66.0%)</td>
</tr>
</tbody>
</table>

**TOTAL** | **207 (39.8%)** | **116 (22.3%)** | **91 (17.5%)** | **106 (20.4%)** | **520 (100%)**
In the conventional survey, in addition to the overall level of satisfaction with the service, the users were asked to rate the following attributes:

- Route (route of the line)
- Connections (connection with other lines and transport modes)
- Punctuality (on-time performance)
- Frequency (timetable and headway)
- Access (ease of access to the bus stop from origin –home, work, university, etc.)
- Information-incidents (delays, breakdowns, changes in the line, etc.)
- Cleanliness (cleanliness of the bus)
- Information-service (timetables, routes, etc.)
- Journey time (of the route)
- Comfort (air conditioning, seating, etc.)
- Information and Communication Technologies (ICTs) (Internet on board, mobile payment, real-time information screens both on-board and at stops)
- Shelters (along the route)

The statistical mode and median of the results of the analysis of the bus lines show that most of the variables had an average and median of "good"; only the variable “frequency” was deemed “not good” for the median, which indicates the importance of this variable and how it is valued by respondents. The statistical analysis by line does not reveal any substantial difference, except for the case of the valuation of ICTs by the users of line 714, who describe it as “very good.” This valuable database offered a sound scenario for testing a new ITS tool, and the research group assumed that in line 714, 60% of whose users are young students, the response rate using QR codes should be fairly acceptable. Nevertheless, the pilot survey of February 20 clearly showed that this first experience would run into quite a few difficulties. That same day, after posting the QR codes on the shelters of line 714 and designing a very simplified survey format (to make it short and schematic), only 10 surveys were registered on the bus operator website. The following reasons were found for this lack of success:

1. The use of QR codes requires not only the availability of a device with Internet access (phone, PC, tablet), but also a minimum knowledge of how to read a QR code (as discussed earlier). This means that people who have never used a QR code will not do so on the day of the survey if they are not sufficiently motivated and if they are not equipped with an application (app) for capturing and reading QR codes.

2. The saturation of QR codes for advertising purposes means that users have no particular interest in accessing a website with this kind of format. A reward could help achieve a higher level of user involvement in the survey (as demonstrated in QR loyalty campaigns for companies).
3. Posting the QR code on the bus shelters means that many users arriving just in time to board the bus fail to realize that they have the opportunity to fill in the questionnaire. and posting the QR code inside the bus may be insufficient to achieve a high response rate.

After this experience, it was decided to hand out the QR code printed on a piece of paper (a colorful book separator sheet provided by the operator, ALSA) at the access door of each bus that clearly explained how to read the QR code (see Figure 4). Following the experience of QR loyalty campaigns carried out by companies, participants also were eligible to win a tablet as a reward. Thus, in only one day, 155 valid surveys were registered on the operator’s website, and this sample was validated using the conventional survey results for line 714.

The survey format was simplified for two main reasons: the movement of the bus could prevent most users from reading a long and detailed survey on their smartphones (particularly standing passengers), and there was a space limitation due to the size of the smartphone screen. This made it necessary to select only a few SQ attributes (only the most relevant were chosen) and to reduce the length of the questions. The scale of response was also changed from five to three options (Good, Quite Good, and Not Good At All), and these were represented with emoticons (see Figure 4) to give the survey a more informal and user-friendly appearance.
Validation of QR Survey

The statistical tool used to compare the results of the two surveys was the Student’s t-test for independent samples, which guarantees that the perception of quality attributes (how users rate each SQ attribute) is the same regardless of the type of survey used. The Student’s t-test is any test in which the statistic has a Student’s t distribution if the null hypothesis is accepted. It is used when the population studied follows a normal distribution but the size of the sample is so small that the statistics on which the inference is based are not normally distributed. An estimate of the standard deviation is used rather than the real value.

The t-test for independent samples was used to compare means between two different samples. It could then be determined whether the attribute perception captured by the QR survey differs from the conventional survey. Assuming that the variances of the variables are different, this test analyzed whether the probability associated to t is higher than 0.05. This means that the null hypothesis is accepted—there is no difference in the measurement of each quality attribute with the QR and the conventional survey. SPSS software was used for the statistical analysis of this case study.

Once the statistical tool was defined, it was no easy task to validate the QR code survey. It should be noted for the comparative statistical analysis that the format of the perception survey was different, since to simplify the survey, the semantic (linguistic) scale of response was changed from five to three options, and respondents were asked to rate their perception of a smaller number of attributes. As an example, in the semantic (linguistic) scale used in the QR survey (Good, Quite good, Not Good At All), many intermediate levels of perception were overlooked. It was, therefore, necessary to reach a consensus on the design of the QR survey format to ensure that its simplicity allowed nuances to be captured. In any case, it was necessary to standardize the questions in the two surveys (see Table 2) before conducting the Student’s t-test for independent samples. In most cases, the need to reduce the length of a survey entails a real risk of losing part of the required information.

<table>
<thead>
<tr>
<th>TABLE 2. Comparative Analysis of Conventional and QR Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional Survey</strong></td>
</tr>
<tr>
<td>How do you rate the following features?</td>
</tr>
<tr>
<td>Bus schedule and frequency of buses</td>
</tr>
<tr>
<td>Bus punctuality</td>
</tr>
<tr>
<td>Comfort on board: seats, air conditioning etc.</td>
</tr>
<tr>
<td>User information (timetables, fares, etc.)</td>
</tr>
<tr>
<td>Duration of the bus route</td>
</tr>
<tr>
<td>Trip itinerary</td>
</tr>
</tbody>
</table>
The authors acknowledge that the simplification of the QR survey severely conditioned the validation and significance of the study results, and this fact should be corrected in further survey campaigns. Table 3 shows not only the comparative results of the statistical indexes (average, standard deviation and standard error) but also the results of the t-test for independent samples. The results seem to show that in spite of the different format and structure of both surveys, the measurement of the perception indicators—except for the attributes “seats” and “trip time”—does not appear to depend on the kind of survey. Indeed, as in Table 3, the wording of the questions for measuring both variables was not homogeneous, meaning that the users may have thought they were being asked about different attributes. The remaining attributes that were rated using similar wording were considered to have been validated, although there were some issues that require discussion. As noted by some leading experts in the field of transit passenger surveys (referring to this case study), from a strictly experimental viewpoint, comparative analysis is much better served when all key variables except for the item being tested (in this case, the survey method) are held constant. The fact that the satisfaction questions varied between the two survey methods raises some question about the results. The selection of a line with a ridership composed primarily of university students avoids the issue of how many riders have smartphones, and a QR-based survey would over-sample certain portions of current ridership and under-sample others. Validation is also threatened by different wording for terms such as “seats” and “trip time” and for other SQ attributes such as “frequency,” “route,” and “user information.” “User information” included specific examples of information in the paper survey but not in the online survey, and the difference in results was borderline significant. Indeed, “bus schedule” and “frequency” are not exactly the same concept, and the “route” questions appear to be worded differently.

**TABLE 3.** Results of Student’s t-Test for Independent Samples with Prior Comparison of Statistical Indexes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Type of Survey</th>
<th>N</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>t</th>
<th>Sig. (bilateral)</th>
<th>Average differences</th>
<th>Standard error differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Conventional</td>
<td>91</td>
<td>3.6044</td>
<td>0.84168</td>
<td>0.08823</td>
<td>-1.0</td>
<td>0.30</td>
<td>-0.14</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>QR</td>
<td>155</td>
<td>3.7484</td>
<td>1.29230</td>
<td>0.10380</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Punctuality</td>
<td>Conventional</td>
<td>91</td>
<td>4.0220</td>
<td>0.75980</td>
<td>0.07965</td>
<td>-0.2</td>
<td>0.85</td>
<td>-0.02</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>QR</td>
<td>155</td>
<td>4.0462</td>
<td>1.21325</td>
<td>0.09745</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seats</td>
<td>Conventional</td>
<td>91</td>
<td>3.9341</td>
<td>0.67991</td>
<td>0.07127</td>
<td>3.8</td>
<td>0.00</td>
<td>0.50</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>QR</td>
<td>155</td>
<td>3.4387</td>
<td>1.39146</td>
<td>0.11176</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Information</td>
<td>Conventional</td>
<td>91</td>
<td>4.0220</td>
<td>0.77428</td>
<td>0.08117</td>
<td>2.1</td>
<td>0.05</td>
<td>0.29</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>QR</td>
<td>155</td>
<td>3.7355</td>
<td>1.45975</td>
<td>0.11725</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trip time</td>
<td>Conventional</td>
<td>91</td>
<td>4.0989</td>
<td>0.63342</td>
<td>0.06640</td>
<td>-2.7</td>
<td>0.01</td>
<td>-0.27</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>QR</td>
<td>155</td>
<td>4.3677</td>
<td>0.98705</td>
<td>0.07928</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route</td>
<td>Conventional</td>
<td>91</td>
<td>4.1209</td>
<td>0.66391</td>
<td>0.06960</td>
<td>0.5</td>
<td>0.66</td>
<td>0.05</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>QR</td>
<td>155</td>
<td>4.0710</td>
<td>1.12302</td>
<td>0.09020</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Despite all these drawbacks, this pilot experience reveals most of the potential challenges facing transit agencies when deploying online surveys. Using QR surveys to measure quality of service is an acceptable practice as long as a representative sample is achieved, and every effort should be made to obtain a high level of respondent involvement. It should be noted that previous research works in the U.S. (Spitz et al. 2006) found a strong perception among U.S. transit agencies that respondents of online surveys (not specifically QR) were not representative of transit passengers generally. However, almost 10 years after the publication of these studies, smartphones and the cost of data plans are becoming cheaper (they probably are cheaper now in Europe than in the U.S.), making smartphones affordable to a larger number of people, which possibly would contribute to obtaining a high number of valid questionnaires.

One of the main targets of using this QR code application was ultimately to provide transport management with a useful tool for reducing transit agency survey costs. We estimated the cost reduction when using QR codes compared to conventional survey costs, considering the period of the survey campaign and the labor costs (per completed survey) in both experiences. Labor costs included survey development, deployment (survey campaign), and tabulation of the results. Our QR experience show reductions of more than 40% compared to conventional survey costs. This figure may be reduced in future experiences after correcting the problems detected in the pilot survey, and even in the definitive survey (which implies increased labor costs).

Finally, another important issue in this kind of campaign is the time period of the survey—namely, whether it should be conducted during the trip. From the authors' experience in the Madrid-Tres Cantos corridor, the website associated to the QR code was active the whole of the day of the survey until midnight. This implies that the survey could be filled in by non-passengers who had access to the QR code simply to obtain the reward, although from the similar performance of the samples (perception survey for line 714 and QR survey), this does not seem to be the case. However, this kind of risk could be partly avoided in future QR surveys by limiting the web access strictly to the period of the survey or, at most, to a few more hours. Other improvements could be implemented in the future to limit non-passenger access to the survey, including printing a single QR code per card to ensure that each code is used only once. This would require each card to have a different QR code associated to a unique numbered survey. After filling out the survey, each QR code would expire.

**Conclusions and Recommendations**

Traditional and recent literature on service quality provides policymakers with a large number of tools to obtain a global satisfaction index and quantify the importance of the attributes to passenger perceived quality. However, there has, so far, been little research exploring the best format and method of conducting the surveys to ensure a consistent database and reduce survey campaign costs. ITS enhancements to public transport traditionally have included fleet management systems based on AVL technologies, which can be used to improve services, optimize routing and scheduling, and feed real-time information into passenger information channels. Currently, there are two major QR code implementations in the public transport sector: e-ticketing and real-time user
information; however, surveys of public transport users, who are so crucial for transport planners and operators, have scarcely benefited from this new information technology.

The first experience using QR codes for a SQ survey in Spain was carried out in the Madrid-Tres Cantos corridor on one of the four bus lines operated by ALSA. The lessons learned from the failures of the pilot survey campaign were considerably more useful than those obtained through the validation process (using a Student t-test for independent samples). The QR survey was validated using a conventional face-to-face survey database, although the differences between the two questionnaire formats required a previous analysis of homogeneity and generated an important discussion on its significance. Differences in wording should be avoided in any repetition of these QR surveys to strengthen the validation process. The pilot survey confirmed some of the statements in the recent literature regarding the use of QR codes in loyalty campaigns—familiarity with QR codes and usage together with self-reported awareness is a key issue in this kind of survey. In this case study, despite the fact that the users of bus line 714 were university students traveling with a smartphone, many of them had never used a QR code before. The QR code also must be clearly visible, and simply posting the QR code on a bus shelter proved insufficient; one solution may be to hand out the printed QR code. Finally, as in the majority of surveys, respondent involvement may increase if some reward is clearly announced and delivered in the campaign.

After this experience, recommendations focus on the design of a prior pilot survey to quantify, in each case study, user smartphone availability and their QR knowledge and usage. Users smartphone availability is the only variable that can clearly condition the survey campaign, and any remaining problems detected during the pilot survey can be overcome, as shown in this research. This paper contributes to the limited existing literature by developing the analysis of QR codes applied to CSS surveys in public transport and highlighting their impact in reducing the cost of data collection and processing. The results clearly show most of the challenges facing transit agencies when deploying this type of online survey. If these challenges can be overcome, the application of QR codes will provide future transport policymakers with a useful tool for reducing survey costs.

**Acknowledgments**

The conclusions reached in this article are derived from an ongoing research work on service quality in public transport carried out by the authors of this paper as members of the Department of Transport at the Universidad Politécnica de Madrid (UPM) and the Consorcio Regional de Transportes de Madrid (CTRM). ALSA Group (the bus operator) made significant contributions to this research, particularly with regard to designing the customer satisfaction survey, authorizing on-board survey campaigns, and making bus staff available to the research team during the days of the study. The authors would like to thank the anonymous paper reviewers for their valuable comments and suggestions to improve the quality of the paper.
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New QR Survey Methodologies to Analyze User Perception of Service Quality in Public Transport: The Experience of Madrid

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Examining Accessibility and Reliability in the Evolution of Subway Systems

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Abstract

The subway system in the city of Seoul has dramatically evolved from a single subway line of less than 10 km in the early 1970s to one of the largest mass transit systems in the world, with more than 13 lines and 400 stations in 2014. This study aims to explore longitudinal changes in network accessibility and reliability in relation to the four evolutionary stages of the Seoul subway system (1979, 1985, 2001, and 2014). With rapid expansion of the network, accessibility and reliability have improved over time, but at a different pace and with different spatial patterns. The accessibility level has consistently increased, along with the core-to-periphery improvement spatial pattern, while reliability has been quickly enhanced as a result of the completion of a circular line in the second stage and stabilized early since the third stage. This study contributes to the field of transport network planning, in which well-balanced network functionality is a critical concern.

Introduction

The evolution of a public transportation system reflects the interplay of demography, economic development, and transportation needs over time, and mass transit systems are one of the most crucial elements in the evolution of cities and the dynamic processes that take place in them (Bettencourt et al. 2007; Niedzielski and Malecki 2012). Public transportation serves the development and growth of densely-populated metropolitan areas by facilitating labor movement from outside or within the metropolitan area with better accessibility (Lakshmanan et al. 2009). Better public transportation networks lower travel times and the travel costs of the individuals who use the networks, giving them more options for their trips and also enabling them to move further out of central areas in relation to housing or work options, which is directly related to land development in areas once considered unreachable (Lakshmanan and Anderson 2002, 2005; Lucas 2006). As such, improving accessibility...
Examining Accessibility and Reliability in the Evolution of Subway Systems

for all has been a focus of public transport planning. However, accessibility measures are concerned little with network reliability, which refers to how well the network is systematically organized to continue its operation at a desired level in the face of possible operational failures of nodes or links. Maintaining the system’s reliability at a desired level is as important as accessibility on the supply side because disruptions of mass transit systems can have severe adverse socio-economic impacts, along with degradation of network accessibility (D’Este and Taylor 2003). Furthermore, failure in a station can lead to cascading failures in the whole network system, raising issues about the resilience of the system (Nicholson and Dalziel 2003; Kim et al. 2015). The level of reliability is associated more with how many alternative routes are available than how efficiently flows are delivered at lower costs or shorter distance, which is the key factor determining the nodal accessibility (D’Este and Taylor 2003). Therefore, assessing existing network performance by considering both criteria is critical, as networks need to meet both demand and supply requirements.

Since it commenced operation in 1974, the Seoul subway system has expanded its size and the spatial extent of service by continually adding new stations and lines to accommodate the increasing public transportation demand and to support the activities in the expanded metropolitan area. The expansion of networks shows how spatially and temporally both accessibility and reliability of the system are improved to reflect economic development. For example, the southern area of Seoul, historically an underdeveloped area, experienced a considerable increase in the concentration of the population with the emergence of new Central Business Districts (CBDs) in Yeongdeungpo-Gu and Gangnam-Gu in the southern parts of Seoul as the first circular line, Line 2, was established in these areas in the late 1970s. The establishment of Line 2 involved constructing a handful of stations and resulted in considerable accessibility enhancement in the south of Seoul. On the other hand, the subway lines in Seoul occasionally have experienced unexpected delays or extreme congestion because of malfunctions resulting from natural disasters (e.g., flooding), train crashes, and transit strikes, as well as operational issues, including periodic maintenance (Zhu and Levinson 2012; Kim et al. 2015). Between 2008 and 2013, 11 critical accidents were reported on the Seoul subway system; these resulted in considerable socio-economic costs and recovery costs relating to the disruptions (ARAIB 2015). Such aspects can be assessed in terms of reliability.

This study aims to adopt a longitudinal point of view by exploring the changes in network accessibility and reliability following the evolution of the subway system in Seoul. Our empirical study involves three steps—1) defining both measures suitable for assessing a subway system; 2) examining changes in network characteristics at global and nodal levels; and 3) providing a set of results to highlight the characteristics of the evolution—followed, by way of conclusion, with a summary of the policy implications.

Evolution of the Subway System in Seoul

Seoul, the capital city of South Korea, is one of the largest and most densely-populated cities in the world, generating a large volume of trips and travel demand. This requires well-developed public transportation systems since private travel modes cannot
Examine Accessibility and Reliability in the Evolution of Subway Systems

accommodate the high demand effectively and can cause serious adverse effects such as congestion, pollution, and degraded public health within the area. Based upon the time trends in terms of number of passengers and addition of new lines, Song and Kim (2015) have divided the temporal expansion of the Seoul subway network into four stages: stage 1 (1974–1979), stage 2 (1979–1985), stage 3 (1985–2001), and stage 4 (2001–2014). Figure 1 shows the evolution of the subway network in relation to the location of CBDs. The old CBD area has functioned as the core of the capital city in terms of both economics and politics; the new CBD area began to be developed in the late 1970s; and the third CBD is the financial center (Song et al. 2012).

This division is supported by an early classification of the evolution of the Seoul subway system suggested by Lee and Lee (1998). In the first stage, the first subway line began to operate. Before that point, the public in Seoul had been very dependent upon the bus system to get around the city (Pucher et al. 2005). In the beginning, the Seoul subway had only one underground line, of less than 10 km, with a 6% modal share, and the bus was still the major mode chosen by the public. A noteworthy expansion occurred during stage 2, with a circular line (Line 2) being added to the existing linear form of the subway system, providing passengers with increased alternative routing.
choices and resulting in the subway becoming the most frequently-used travel mode in Seoul as a consequence (Lee and Lee 1998). As presented in Table 1, after 1996, more than 30% of modal share was achieved by the subway, absorbing the share of buses. This achievement was possible because the penetration of some new lines enabled the network to serve the dense peripheral residential areas through stage 3. By 2012, the subway system’s total network length had expanded to 327 km and was ranked fifth in the world (The Economist, 2013), and its modal share was more than 36% of all passenger journeys in 2010. Currently, there are 17 lines in operation in Seoul and its vicinity, and further expansion is expected.

<table>
<thead>
<tr>
<th>Year</th>
<th>Share by Mode</th>
<th>Private Car</th>
<th>Bus</th>
<th>Subway</th>
<th>Taxi</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Trips*</td>
<td>6,829</td>
<td>8,358</td>
<td>8,183</td>
<td>2,901</td>
<td>1,529</td>
<td>27,800</td>
</tr>
<tr>
<td></td>
<td>Share (%)</td>
<td>24.6</td>
<td>30.1</td>
<td>29.4</td>
<td>10.4</td>
<td>5.5</td>
<td>100</td>
</tr>
<tr>
<td>2002</td>
<td>Trips*</td>
<td>7,983</td>
<td>7,705</td>
<td>10,285</td>
<td>2,195</td>
<td>1,513</td>
<td>29,680</td>
</tr>
<tr>
<td></td>
<td>Share (%)</td>
<td>26.9</td>
<td>26.0</td>
<td>34.6</td>
<td>7.4</td>
<td>5.1</td>
<td>100</td>
</tr>
<tr>
<td>2006</td>
<td>Trips*</td>
<td>8,188</td>
<td>8,616</td>
<td>10,839</td>
<td>1,959</td>
<td>1,592</td>
<td>31,196</td>
</tr>
<tr>
<td></td>
<td>Share (%)</td>
<td>26.3</td>
<td>27.6</td>
<td>34.7</td>
<td>6.3</td>
<td>5.1</td>
<td>100</td>
</tr>
<tr>
<td>2010</td>
<td>Trips*</td>
<td>7,502</td>
<td>8,746</td>
<td>11,289</td>
<td>2,236</td>
<td>1,382</td>
<td>31,155</td>
</tr>
<tr>
<td></td>
<td>Share (%)</td>
<td>24.1</td>
<td>28.1</td>
<td>36.2</td>
<td>7.2</td>
<td>4.4</td>
<td>100</td>
</tr>
</tbody>
</table>

*Unit = thousands of trips per day.
Source: SMG 2014

The main purpose of network evolution is to maintain a good quality subway network and to provide an efficient and effective travel mode to the general public. As Lakshmanan et al. (2009) argued, based on their case study of New York City, economic and social activities in a densely-populated metropolis cannot be sustained without public transit systems. With the advent of rapid urban sprawl during the last few decades, a large proportion of the workforce now live far from their workplaces, and the majority rely on public transport for their work and business journeys. Kim and Zhang (2005) and Lee et al. (2010) also provided evidence from case studies on Seoul that show that accessibility is positively associated with commercial land rent and residential rent, such as housing value, in accordance with other international studies (Cervero and Duncan 2002; McMillen and McDonald 2004; Weinberger 2001). However, with increased dependency on mass transit systems, the system’s reliability becomes another critical factor that affects socio-economic activities because congestion, delays, and incidents resulting from operational failure and human errors affect the accessibility itself, as do travelers’ perceptions regarding the uncertainty of accessibility (Bell and Cassir 2000; Reggiani 2013; Kim et al. 2015).
Methodology

Accessibility Measurement

Although there is no consensus on the definition of accessibility, and numerous measures have been defined and used for specific research contexts (for an extensive review, refer to Reggiani 1998; Halden et al. 2005; Páez et al. 2012), generally, accessibility refers to the reachability of goods, services, activities, and destinations, which often is translated into a level of opportunities for potential interaction among demand (Hansen 1959; Harris 2001). The main idea is centered on the demand aspect, which represents people’s overall ability or opportunity to reach spatially-distributed services and activities, and measurement of the ease of their access (Harris 2001). Páez et al. (2012) suggested that many accessibility measures have two basic components: travel cost and quality or quantity of opportunities. This argument can be applied to those studies concerned with land use or regional planning. On the other hand, an approach that looks into the cost factors only, without taking account of the opportunities, is preferred when changes in network characteristics or the evolution of a network is the central subject to be investigated (Garrison 1960; Gould 1967; Tinkler 1972).

This study intends to measure the changes in subway accessibility at both stations and the entire system level over four stages and concentrates only on transport networks themselves. Unlike most recent accessibility studies—which tend to be overly complex and try to capture the impacts of other factors rather than the network itself—to characterize the change in a consistent manner, this study is concerned only about network accessibility based upon travel cost.

The accessibility of each station \(A_{i}^{node}\) is measured using the physical distances between station pairs, as shown in Equation 1, which enables us to focus on the network itself and thereby to facilitate the comparison with reliability measures.

\[
A_{i}^{node} = k \sum_{j \neq i}^{N} \frac{1}{d_{ij}}
\]

Where,

\(N = \) number of stations (\(N = 1 \) to \(n\))

\(k = \) scaling constant (=10^2)

\(d_{ij} = \) network-based physical distance between station \(i\) and \(j\)

\(k\) is a scaling constant, which is used to make the results more readable; \(10^2\) is used. Distances between origin and destination pairs were calibrated to obtain the shortest travel distances. An inverse distance sum was used in the calculation. The higher \(A_i\) indicates higher accessibility, i.e., shorter distance is covered to reach potential destinations from station \(i\).
Reliability Measurement

Reliability is widely used to assess a network’s robustness when either the empirical or hypothetical operational probability of a network component is known (Colbourn 1987; Kim et al. 2015), and this is commonly expressed as the operational probability of a network carrying out its stated mission satisfactorily for a certain period of time (Yoo and Deo 1988; Dhillon 2011; Kim et al. 2015). The potential degradation of the reliability of a network can be due to a variety of reasons, ranging from inconveniences such as scheduled maintenance to an excessive concentration of flows at nodes (stations or terminals) or links (subway lines or railways). It includes unexpected accidents such as natural disasters and intended attacks. The outcome includes delays in delivering flows in the network, shut-down of stations or subway lines and even intangible socio-economic costs. The concept of network reliability has been applied to examine the network resilience of transport networks or spatial economic infrastructure (e.g., Cox et al. 2011; Murray and Grubesic 2007; Matisziw et al. 2009; Murray et al. 2008; Nagurney and Qiang 2009; Reggiani 2013; Schintler et al. 2007). Less reliable areas and subway stations are more likely to discontinue their operation and incur potential disruptions (Allenby and Fink 2005). To identify the reliable or unreliable areas, first we need to measure a station’s reliability, named nodal reliability $R_{node}$. To do this, equation (2) is used to calculate route reliability from $i$ to $j$, followed by equation (3), which is used to compute $R_{node}$. Suppose that the operational probability (i.e., on-time performance or delay rate) of a link connecting two nodes $p(e)$ is known [i.e., $0 \leq p(e) \leq 1$]. Here, $p(e)$ is translated as the probability that any passenger flow from a station to the next station by the link can be delivered without there being any malfunction or delay. Let $r_{ij}$ be the route reliability for a pair of stations, $i$ and $j$, in subway system $G$, which is calculated using the sum of reliability for $k$ number of disjoint paths ($D_k$) between $i$ and $j$. A disjoint path $D_k$ is effectively enumerated based on the logic of the Boolean algebra method to the available paths $E_q$ for a pair of $i-j$. The path reliability $p(E_q)$ is calculated using $p(E_q) = \prod_{e \in E_q} p(e)$, where $Q$ is the set of links $e$, constituting the path $E_q$ (for these procedures in detail, see Yoo and Deo 1989).

$$r_{ij}(G, p) = \sum_{k=1}^{m} p(D_k) = \sum_{k=1}^{m} \left[ \prod_{q=1}^{r} p(\overline{E}_{q-1}) \cdot p(E_q) \right]$$

(2)

Where,

- $p(D_k)$ = the reliability for a disjoint path $D_k$ from the identified available paths $E_q$ for a pair of $i-j$, ($k=1$ to $m$)
- $p(E_q)$ = the reliability of an identified available path $E_q$ for a pair of $i-j$, $Q$ is the set of links $e$, constituting a path $E_q$
- $p(\overline{E}_q)$ = the complementary probability for $p(E_q)$
Then, using equation (3), $R_{i}^{\text{node}}$, the nodal reliability of station $i$, which is the average reliability in relation to all other stations $j$, is calculated.

$$R_{i}^{\text{node}}(G, p) = \frac{1}{N} \sum_{j=1}^{n} r_{ij}$$

Where $R_{i}(G, p)$ is the nodal reliability of station $i$, which defines the average reliability from station $i$ to other stations $j$, where reliability $p$ at link is known on network $G$.

This concept of $R_{i}^{\text{node}}$ has been employed in public transit or rail networks (Michael 2000; Vromans et al. 2006; Kim et al. 2015). Higher $R_{i}^{\text{node}}$ at station $i$ indicates that the station is highly reachable from other nodes without delay or failure most of the time. In general, the more paths that are available from other nodes $j$ to node $i$, the higher nodal reliability node $i$ has.

Basically, accessibility is represented as a form of index. This is useful for comparing the level of accessibility. However, the range of the index is dependent upon what measure is used. For example, the simplest form of accessibility measure is to use the number of direct and indirect paths at a station to other nodes based upon connectivity (i.e., connected or not connected). Alternatively, time distance or the opportunity costs between origin–destination pairs can be used for $d_{ij}$. However, for this case, the range of values cannot be well defined unless the calculation method is standardized. In contrast, reliability measures typically employ a probability, ranging from 0.0 to 1.0, to represent the operational success or failure among nodes. Thus, the reliability measure is easy to interpret and enables comparison among different networks.

**Data**

Given the four categories of evolutionary stages by Song and Kim (2015), we constructed the subway networks based on the subway network map at the end of each stage (i.e., 1979, 1985, 2001, and 2014). The station information is available at a public website, Korea Transport Database (www.ktdb.go.kr), in the form of point data. With the positional information provided by the public agency, the links were digitized to construct the network in a geographic information system (GIS) environment. Then, $A_{i}^{\text{node}}$ was measured based upon the shortest physical network-based distance among stations $i$ and $j$ from the network maps.

To compute $R_{i}^{\text{node}}$, two matrices—an incidence matrix and an on-time performance matrix—were used for each link between stations $i$ and $j$. Incidence matrix consists of $[0, 1]$, to represent the connectivity by links among nodes. For the on-time performance matrix, this study used hypothetical on-time performance data with $p(e)=0.9$ for all links in the reliability computation process because the empirical data of the Seoul subway system is not available for the stages. Note that this value is the commonly-accepted link on-time performance data in which empirical reliability data are not available for networks (Yoo and Deo 1988; Kim et al. 2015).
Analysis Results

Global Change of Accessibility and Reliability

Figure 2 presents three indices: the averages of nodal accessibility and reliability and the number of stations on the network at the end of each stage. For comparison, the values were standardized by reference to the year 1985 (1985=1.0). All three indices increase, but they do so at different rates at each stage, highlighting a different curve of maturity with network evolution. The number of subway stations increased nearly 10 times between 1979 ($n=28$) and 2014 ($n=271$). Along with a rapid expansion of the system, the averaged nodal accessibility increased by 5.6 times. However, network reliability was enhanced by only 1.6 times during the same period. In particular, the network experienced a significant improvement in reliability when it moved from stage 1 (0.661) to stage 2 (=1.0), but did not improve much when moving to stage 3 (=1.017) and even to the fourth stage (=1.11), indicating that the reliability of the Seoul subway system quickly matured when the evolution entered stage 2 but remained fairly stable through stages 3 and 4. In contrast, network accessibility significantly improved at both stages 3 and 4. During the same period, the annual ridership of the system increased rather consistently and rapidly—approximately 200 million in 1979, 500 million in 1985, 1 billion in 2000, and 1.8 billion in 2014.

![FIGURE 2. Change of network accessibility and reliability with evolution of Seoul subway system](image)

Note: Figures are relative to 1985 values.

To further investigate the association between two measures, the frequency distributions (unit: %) of nodal accessibility (3-a) and reliability (3-b) are presented in Figure 3. Notice that the overall distribution of both measures has moved towards the right-hand side, i.e., accessibility and reliability increased over time. However, accessibility improves with the steady progress of each stage, maintaining a bell-shaped distribution in relation to the stages (except the first stage, 1979). In contrast, nodal reliability quickly skewed right after stage 2, and this tendency is more distinguished in stage 4, suggesting that the critical transition had already been made between stages 1
and 2 and stabilized at a “high” network reliability status since then. The main reason for the considerable enhancement of the reliability at stage 2 was the completion of the “circular” line (Line 2), which enabled more alternative routes to be possible in the system. Figures 2 and 3 together imply that the evolution of the Seoul subway system has been asymmetrical as regards accessibility and reliability.

Changes in Nodal Accessibility and Reliability
Although accessibility and reliability are derived from the same root, which focuses on the performance of nodes based on network topology, and results in an increase of values overall with increased network complexity over time, this does not necessarily entail that the two measures are positively and strongly associated at the individual station level with network evolution. Table 2 clearly shows that the relationship between the two measures has not been strongly correlated. In the early stage (1979) of subway expansion, no significant correlations were observed, but both measures have positive correlations at the end of the second, third, and fourth stages. However, the strength is not improved consistently, as stage 4 has a diminished correlation, implying that some stations experience unbalanced improvements of accessibility and reliability while the structure of the network has been complicated with added stations and links. This fact raises the issue of how network evolution affects accessibility and reliability at node level from a geographic perspective.
The outlier stations observed at 95% confidence interval (CI) in the linear regression model between two measures were identified at the end of the subway networks and characterized as stations with either extremely low values of reliability or accessibility. However, their locations changed at each stage. For example, in stage 2, six outlier stations are located at the northern end of the newly established Line 3, while in stage 3 six outlier stations are identified at the eastern end and five other outlier stations are at the western end of Line 5. The stations at the end of subway lines or newly-added lines are more difficult to access than other existing stations, but their rankings in both measures changed quickly with the network’s evolution.

Table 3 and Figure 4 present the top-10 stations and their locations in terms of the accessibility and reliability rankings. Clearly, consistency in ranking within each measure across the stages is observed, but the rankings are not similar between measures, which strongly indicates that different geographical surfaces of accessibility and reliability are formed at each stage. Highly-accessible stations are found in the central area, and the rank did not change much over time. Considering stages 2, 3, and 4 in Table 3, nearly 90% of high-accessibility stations were transfer stations and only 50% of high-reliability stations were identified as transfer stations. Such findings support the fact that the spatial patterns and properties of the two measures do not necessarily correspond to each other, despite their positive correlation. Interestingly, all stations listed as top-10 stations in terms of accessibility are located in the northern part of Seoul, whereas 35% of the top-10 stations in terms of reliability are on the southern part of the Han River. Historically, the old CBD was located in the northern part of the city, from which the city has grown out in all directions. The southern part of the city has undergone faster development by adding lines at later stages (Song et al. 2012).

**TABLE 2.**

<table>
<thead>
<tr>
<th>Type of Correlation / Year</th>
<th>Stage 1 1979 (n=28)</th>
<th>Stage 2 1985 (n=117)</th>
<th>Stage 3 2001 (n=246)</th>
<th>Stage 4 2014 (n=271)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson’s r</td>
<td>-0.037</td>
<td>0.390*</td>
<td>0.501*</td>
<td>0.445*</td>
</tr>
</tbody>
</table>

*Note: p-value < 0.01.
TABLE 3. Stations with the Highest Accessibility and Reliability

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jongro-5ga</td>
<td>Uljiro-3ga</td>
<td>Uljiro-3ga</td>
<td>Uljiro-3ga</td>
<td>Seoul Station</td>
<td>Seoul Nat’l Univ of Edu</td>
<td>Nowon</td>
<td>Nowon</td>
</tr>
<tr>
<td>2</td>
<td>Dongdaemun</td>
<td>Chungmuro</td>
<td>Dongdaemun Park</td>
<td>Dongdaemun Park</td>
<td>Namyeong</td>
<td>Seocho</td>
<td>Chang-dong</td>
<td>Chang-dong</td>
</tr>
<tr>
<td>3</td>
<td>Jongro-3ga</td>
<td>Jongro-3ga</td>
<td>Sindang</td>
<td>Sindang</td>
<td>Yongsan</td>
<td>Sadang</td>
<td>Dobongsan</td>
<td>Suseo</td>
</tr>
<tr>
<td>4</td>
<td>Jonggak</td>
<td>Uljiro-4ga</td>
<td>Dongdaemun</td>
<td>Dongdaemun</td>
<td>Oryu-dong</td>
<td>Bangbæ</td>
<td>Banghak</td>
<td>Gunja</td>
</tr>
<tr>
<td>5</td>
<td>Hoegi</td>
<td>Dongdaemun</td>
<td>Cheonggu</td>
<td>Cheonggu</td>
<td>City Hall</td>
<td>Gangnam</td>
<td>Gunja</td>
<td>Banghak</td>
</tr>
<tr>
<td>6</td>
<td>Jeji-dong</td>
<td>Dongdaemun Park</td>
<td>Dongmyo</td>
<td>Dongmyo</td>
<td>Noryangjin</td>
<td>Yeoksam</td>
<td>Dobong</td>
<td>Dobongsan</td>
</tr>
<tr>
<td>7</td>
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<td>Chungmuro</td>
<td>Chungmuro</td>
<td>Gaebong</td>
<td>Konkuk Univ</td>
<td>Madeul</td>
<td>Daecheong</td>
</tr>
<tr>
<td>8</td>
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<td>Jongro-3ga</td>
<td>Jongro-3ga</td>
<td>Guro</td>
<td>Ichon</td>
<td>Junggye</td>
<td>Irwon</td>
</tr>
<tr>
<td>9</td>
<td>City Hall</td>
<td>Myeong-dong</td>
<td>Uljiro-4ga</td>
<td>Uljiro-4ga</td>
<td>Daebang</td>
<td>Seongsu</td>
<td>Taereung</td>
<td>Dobong</td>
</tr>
<tr>
<td>10</td>
<td>Hankuk Univ.</td>
<td>City Hall</td>
<td>Yaksu</td>
<td>Yaksu</td>
<td>Jonggak</td>
<td>Guui</td>
<td>Suraksan</td>
<td>Taereung</td>
</tr>
</tbody>
</table>

FIGURE 4. Top-10 stations in terms of accessibility and reliability
A comparison of Figures 5 and 6 highlights how the potential relationship between both measures have manifested geographically over time. To enable comparison between measures and times, the ranges of accessibility and reliability were standardized using z-scores, and the surface maps were generated using the Inverse Distance Weighted (IDW) function with higher polynomial functions to the standardized z-score.

**FIGURE 5.** Standardized accessibility with evolution of subway system
As illustrated in Figure 5, it is noticeable that the blue area, i.e., the high-accessibility area, has expanded as the network has evolved, which was highly predictable given the increasing accessibility average provided in Figure 3. Notice that the highly-accessible area identified in stage 1 was the so-called CBD and that the areas has grown, keeping the centralized form until stage 4, where the size of the blue area has increased significantly, covering half of Seoul city in the last stage. During this process, the peripheral areas were left with lower accessibility. This is due to the network expansion strategy, which focused on developing the public transit system from central Seoul toward peripheral areas but ignored connections to improve the accessibility of peripheral areas. As such, the spatio-temporal pattern of the change in accessibility in Seoul supports the argument of Roth et al. (2012) that “a core with branches radiating from it” (p. 2540) is a common feature of various large subway networks.
In contrast, the spatio-temporal change in reliability measures shown in Figure 5 is similar to the accessibility measurement results overall, but clear distinctions were found in the northern area, where the lines were least connected to the circular line compared to the southern areas, so that their reliability has not been positively enhanced over time. Compared to the accessibility patterns, the high-reliability area has not expanded with a core–periphery form; rather, it appears to have a directional pattern, forming corridors. In the first stage, an east–west contradiction was apparent. However, from stage 2 onwards, the spatial pattern of reliability radically changed: the south-eastern part of Seoul showed a high reliability level as a result of the circular line, then a wide southwest–northeast band appeared with strong reliability levels in stages 3 and 4 due to the added connections within the circular line. Since 2000, these areas have been characterized by an increased number of hub stations; as result, a number of alternative routes are enabled for passengers to travel to the southwest–northeast areas more easily, thereby enhancing nodal reliability for all of Seoul.

The perspectives of both concepts are different, as are their outcomes, although the methods on both sides focus on investigating network performance. Recent studies also imply that a station with high accessibility is not necessarily highly reliable, and vice versa (Li and Kim 2014; Kim et al. 2015). Accordingly, given these results, the evolution of a network could involve the development of different geographical areas in terms of reliability and accessibility, and the geographic representation of the surface indicates how well the public transit system has been developed in terms of balance between spatial opportunity in access and soundness in network operation.

Conclusions and Future Research
In this study, the spatio-temporal pattern of a subway network was investigated using two traditional network performance measures in relation to the case study of Seoul. The Seoul subway network has expanded quickly but steadily since its first operation, which has resulted in increasing patterns of accessibility and reliability. However, the spatial patterns and the level of maturation do not exactly correspond to each other. Accessibility has consistently improved from the core to peripheral areas, as suggested by other literature. As discussed in the early work by Lee and Lee (1998), highly-accessible stations were concentrated in the CBD area but spread from the CBD to local areas. On the other hand, reliability improved between stages 1 and 2, but, thereafter, the level of increase was not as impressive as the increase in accessibility as the system entered a mature period, with its improvement pattern being directional. In particular, this result highlights the critical role of the circular line in improving network reliability. Completion of the circular line at stage 2 was not critically important in terms of improving accessibility; however, it was a critical moment for the Seoul subway system in terms of providing high reliability for the whole area to maintain the desired level of reliability for the rest of the stages. As Li and Kim (2014) stated, the first way to improve network performance in a balanced manner is to increase hub stations to provide an increased routing choice of shorter paths and at the same time alternative routes for passengers (even though these may take longer than the single shortest route).
It should be noted that the results of this study are not universally applicable. Each transit system develops based upon the local context in which it is located. As such, the spatio-temporal patterns found in Seoul’s subway system may not be suitable to explain the evolution of different subway systems. However, it is clear that the evolution of the structure of networks involves both a change of network accessibility and network reliability from simple to complicated systems (Kim et al. 2015). In this context, this study contributes to the literature in various ways. First, accessibility and reliability are popularly-used measures in various subjects, but most studies focus only on one such issue at a time. We examined both accessibility and reliability in the case of the evolution of the Seoul subway system, one of the largest and most mature public transit systems in the world, in the context of the distinctive economic development of Seoul. Second, as an analytical framework, the spatio-temporal development pattern of Seoul’s subway network was tracked from the beginning to the present day using two different but consistent network measurement methodologies, which were standardized for longitudinal analysis and revealed the areas that benefited more and less in the context of public transport accessibility and reliability. Finally, using two measures at once allows transport policymakers, practitioners, and researchers to have a comprehensive view of the characteristics of the public transit networks in both supply and demand perspectives.

As a future extension of this research, the present analytical framework could be applied to other public transit systems across cities or metropolitan areas, from highly-developed networks such as New York and Beijing, through intermediate networks such as Washington DC and Berlin, to small but initial stage networks such as Glasgow and Algiers, for comparative analysis. Furthermore, as suggested by Reggiani (2013), an integrated measure should be developed for better network vulnerability analysis of various forms of rapid transit systems. There is great potential for the two measures used in this study—accessibility and reliability—to be developed into a universal standardized measure for the effective assessment of network resilience, as these measures have been used successfully in transit network system analysis.

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A Quick-Response Discrete Transit-Share Model for Transit-Oriented Developments

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Abstract

Various studies have highlighted an apparent lack of analyses associated with the modal choice characteristics of transit-oriented developments (TODs) and emphasized the need for quick response models for estimating transit share in TOD areas. In this paper, a methodology for developing transit-share model for TOD’s using travel activity data is presented. A transit-share model is formulated as an innovative combination of the direct generation, urban travel factor (UTF), and logit models. This model determines transit usage in TODs based on household auto ownership as the primary input and the transit system variables as secondary inputs. Validation of the model indicates a close agreement with observed data. Since the input requirements to the TOD transit-share model are minimal, this model structure is expected to be very useful for sketch analysis of many TOD project alternatives.

Keywords: Transit-oriented development, TOD, mode choice models, livability in transportation, smart growth.

Introduction

The concept of “smart growth” has been recognized as a robust urban planning alternative to the status quo of urban sprawl. Transit-oriented developments (TODs), as a form of land use, attempt to reduce auto trips by promoting the use of public transit and developing high-density mixed land uses (TCRP 2004; CTOD 2010). Thus, TODs are fundamental for a successful smart-growth policy.

The rapid pace in developing TODs and the relative neglect of this land-use phenomenon in the past has left policymakers and transportation planners in the United States with inadequate knowledge related to trip characteristics of TODs. The
travel demand parameters necessary to predict trip generation activity, develop trip
distribution models, identify mode choice characteristics, and determine assignment of
TOD-based trips are yet to be fully explored.

The state of the practice in transportation planning includes mode choice model
development and application at a resolution where traffic analysis zones (TAZs) are
aggregated to the district level (Milone 2013). Such aggregation to the district level loses
the fidelity associated with the unique nature of TODs. Despite significant influence
of TODs on mode choice, few studies have attempted to develop disaggregated mode
choice models to be used in conjunction with TAZs containing TODs. Cervero (2002)
ascertained that neither trip generation nor mode choice models included density
or any other land-use variables. Time constraints and data limitations precluded
the recalibration of models to directly account for built-environment influences.
Disaggregate models have potential for use in various sketch planning tools, which are
commonly employed during the preliminary planning stages of TODs.

Various studies have indicated an apparent lack of analyses associated with the modal
choice characteristics of TOD areas. There is limited data and analysis to ascertain
the net shift in travel modes of TOD residents before and after relocating to a TOD
environment (Hendricks et. al. 2005). The 2003 California TOD travel characteristics
study and the 2005 surveys of Portland-area TODs and transit-adjacent developments
for the TransNow Center attempted to determine the net mode shift in TOD residents
before and after relocating to a TOD environment. Results of these studies ranged
from 2–16% gain in transit mode share after relocation (TCRP 2007). The gain in transit
mode share included a significant change to the workplace by the TOD residents. The
correlation between transit mode share and the proximity of workplace to a transit
station is equally important to mode shift in a TOD environment than the place of
residence alone (Cervero 1993).

A number of studies have identified one-quarter mile radius (approximately 1,300 ft)
around a mass transit station as the ideal walking distance for a successful patronage
of transit among TODs (Ashalalfah and Shalaby 2007; Lund 2006; Lund et al. 2010).
O’Sullivan and Morall (1996) indicated that the average walking distance to suburban
stations in the city of Calgary was 649 meters (0.40 miles), with a 75th percentile of 840
meters (0.52 miles); however, the average and the 75th percentile walking distance at
CBD stations were 326 meters (0.20 miles) and 419 meters (0.26 miles), respectively
(O’Sullivan 1996). On the same note, Cervero (1993) determined that the number of
residents in the Bay Area who moved to 0.5-mile radius of a transit station and switched
their mode of travel from personal passenger car to transit exceeded 50%.

A few mode choice studies of TOD residents and office workers typically show that
transit travel times and their comparison to private car travel times is the strongest
predictor of transit ridership. In other words, travel time differentials are a critical factor,
and these differentials can vary greatly depending on local circumstances (Arrington
and Cervero 2006). In a study on transit usage by residents of TODs by various trip
purposes, Chatman (2006) randomly selected households and workers within 0.4-
mile radius of transit stations in San Diego and San Francisco, California, and collected
24-hour activity and trip diary via phone survey. The study concluded that people living or working near Metrorail stations have a higher non-auto share of commuting and non-work travel. The study further determined that the non-auto share dissipates as the proximity to transit stations increases.

TOD impacts are measured by studying mode choice variations before and after relocating to a TOD environment and also by comparing mode choice in TOD environments with non-TOD environments. Results of an analysis of data associated with the greater Washington DC area show that work, shop, and entertainment trips in TOD areas were performed mainly via transit (Faghri and Venigalla 2013; Faghri 2012). Messenger and Ewing (1996) observed that bus mode share by place of residence proved to be dependent primarily on automobile ownership and secondarily on jobs-housing balance and bus service frequency. Automobile ownership, in turn, proved to be dependent on household income, overall density, and transit access to downtown. Thus, three types of variables—socio-demographic, land use, and transit service—were found to affect bus use through a web of interrelationships.

Gebeyehu and Shin-ei (2007) found that bus fare, convenience, and frequency have a significant effect on user satisfaction with bus services. Using a binary logit model, Lin and Jen (2009) found that household income, household size, and floor space needs are negatively associated with TODs and the presence of children or older adult family members and preference for mixed land use are positively associated with TODs. The results of the study indicated that the household size has a negative impact on the decision to live in a TOD community. Furthermore, having children or older adult family members was positively associated with the preference to live in a TOD area.

Cervero (2002) argued for the explicit inclusion of land-use variables in the utility expressions of mode choice models in urbanized settings. Recalibrating mode choice models to incorporate characteristics of built environments is no easy task, in part because in many metropolitan areas variables related to land-use diversity and urban design are not readily available. Additionally, TODs are usually much smaller in size than the smallest geographic aggregation units, also known as traffic analysis zones or TAZs, in the traditional travel demand modeling methods such as the four-step planning process. For this reason, TOD data are aggregated to the level of its TAZ, thereby losing the fidelity of the TOD influence on trip-making and travel behavior. An alternative approach to incorporating land-use factors in the mode choice models is to treat certain TODs as separate TAZs and develop TOD specific disaggregate models for travel-demand forecasts.

This research seeks to address the gap in methodologies for developing and validating disaggregate transit choice model for work trips associated with TOD. The travel activity data from the 2007/2008 household travel survey within the Washington DC metro area are used for model development and validation. The logit model estimates TOD transit-share with household auto ownership as the primary predictor and transit variables as the secondary predictor. The attributes that represent the attractiveness (or the cost) associated with transit mode in the greater metro Washington DC area
include transit travel time (min), average wait time (min), transit fare cost (dollars), and average walk time to a transit station (min).

**Model Framework**

A common framework for the choice process is that an individual first determines the available alternatives, then evaluates the attributes of each alternative relevant to the choice under consideration, and finally uses a decision rule to select an alternative from among the available alternatives (Ben-Akiva and Lerman 1985). The attractiveness of an alternative is determined by the relative values of the utilities of all alternatives in the set (Lancaster 1971). Utility is an indicator of value to an individual. The utility maximization rule states that an individual will select the alternative from his/her set of available alternatives that maximizes his/her utility (Koppelman and Bhat 2006).

The utility $U$ of a mode $i$ (designated as $U_i$) is composed of a set of attributes (independent variables), which describes the attractiveness of a mode. A typical utility function frequently used in mode choice modeling assumes a linear form shown in Equation 1.

$$U_i = a_i + b_i \times TT_i + c_i \times WT_i + d_i \times COST_i + e_i \times WKT_i$$

(1)

Where,

$U_i =$ Utility of mode $i$

$TT_i =$ transit travel time for mode $i$

$WT_i =$ average wait time for mode $i$

$COST_i =$ cost of mode $i$

$WKT_i =$ average walk time for mode $i$

$a_i =$ model constant

$b_i, c_i, d_i, and e_i =$ coefficients for each attribute for mode $i$

Deterministic choice models are based on the utility maximization rule. Whereas the absolute values of utility of a mode are meaningless, the rule states that an individual chooses the alternative with the highest utility, implying no uncertainty in the individual’s decision process. The probabilistic choice models describe preferences and choice in terms of probabilities of choosing each mode among a competing set of travel modes (e.g., drive-alone, carpool, transit, walk, and bike) rather than predicting that an individual will choose a particular mode with certainty. Effectively, these probabilities reflect the population probabilities that people with the given set of characteristics and facing the same set of alternatives choose each of the alternatives (Koppelman and Bhat 2006). Probabilistic mode choice models often are formulated as logit models, mainly in the forms of multinomial logit (MNL) and nested logit (NL) (Chatterjee and Venigalla 2003). In the logit model framework, the relative difference in the utility value of competing modes manifests itself into the choice probabilities of the modes.
Formulating choice probabilities among competing alternatives (e.g., auto, carpool, transit) as logit models has been the traditional norm in mode choice modeling. Input data requirements for logit models can be extensive. A typical mode-share model requires as input transit travel time, average wait time, cost, and average walk time for each mode. Such extensive input requirements make the applicability of the mode choice models fairly restrictive to cases in which adequate input data are available.

On the other hand, sketch planning tools/models, which offer quick turnaround while requiring limited input data, are widely used in the evaluation of transportation projects, especially in the preliminary planning process. There is a dearth of sketch choice models for evaluating transit share in TOD areas. The potential of various other forms of transit mode-split models, such as the direct generation method and the urban travel factor (UTF) model for TOD transit-share estimation, are examined (Figure 1). In the direct generation methods, transit trips are generated directly either by estimating total person trips or by auto driver trips. In the UTF model, transit probabilities are formulated as a function of autos per household and/or population density (Garber and Hoel 2010). The advantage of the direct generation and UTF models is the model simplicity, especially in terms of input requirements.

An innovative transit-share model is formulated as a combination of the direct generation, UTF, and logit models. This transit share model is aimed at determining transit usage in TODs based on household auto ownership as the primary input and only the transit variables (travel time, average wait time, and average walk time) as secondary inputs. The transit-share probabilities for a given auto are obtained from the MNL formulation shown in Equation 2.
\[ P_{ti} = \frac{e^{U_i}}{\sum_{k=1}^{K} e^{U_k}} \]  

(2)

Where,

- \( P_{ti} \) = Probability of transit as the primary mode choice of work trips for auto ownership, \( i \) (\( i = 0, 1, 2, \text{and } 3 \))
- \( U_i \) = Transit utility value for auto ownership, \( i \)

The associated set of stochastic transit utility models \((U_i)\) for a given auto ownership \((i)\) are developed using multinomial logistic regression. The utility models represent utility of auto mode for a given set of transit variables. The independent transit variables associated with utility function \( U \) of the TOD transit-share model in the greater Washington DC area are assumed as transit travel time (min), average wait time (min), transit fare cost (dollars), and average walk time to a transit station (min).

**Case Study**

The data used for this research are from the 2007/2008 household travel survey obtained from the National Capital Region Transportation Planning Board (TPB) of the Metropolitan Washington Council of Governments (MWCOG). The activity-based survey data provide a wealth of transit-oriented corridors and diverse land uses. The use of these data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast. The data include a survey of 24-hour activity-based travel patterns for 11,000 households in the greater Washington DC area, which includes northern Virginia and parts of Maryland. The survey contains more than 25,000 person records, 16,000 vehicle records, and 130,000 trip records (MWCOG 2010). A disaggregate mode choice model is a suitable modeling selection for this study, due to disaggregate nature of the data.

**Data Preparation**

The data refinement process is a series of data manipulation and extraction via the use of MS Access and ArcGIS. The trip file from the MWCOG trip diary survey data is used to extract trips associated with the Rosslyn-Ballston corridor. The TAZs that were associated with the Rosslyn-Ballston corridor were identified and filtered through the trip file to obtain the number of trips inside the corridor. Home-based work trips that use transit as the primary mode of travel were extracted from the 24-hour activity-based data. The data were screened further to include only transit trips from the travel survey data that are within the 0.25-mile radius of all transit stations to include in the development of the TOD transit-share model. More details about data preparation are discussed in the dissertation work done by Faghri (2012).

The Rosslyn-Ballston corridor in Arlington, Virginia, which is arguably the showcase of a transit-oriented corridor in the nation, was selected as the TOD set for the case study (Figure 2). Each of the five TODs is represented by 0.25-mile radius around the Ballston, Virginia Square–GMU, Clarendon, Court House, and Rosslyn Metro stations. The reliable high-speed Metro transit service coupled with the interconnecting bus transit system provides a well-connected network of public transit for a variety of trip purposes in this corridor.
The TOD trips include trips within the TOD zone, as well as to and from non-TOD zones. Similarly, non-TOD trips include all trips within non-TOD areas as well as trips to and from TOD areas. The rate of use of transit within TOD zones is observed to be 12.5%, which far exceeds the 3% transit usage in non-TOD zones. Conversely, the rate of use of personal vehicles in non-TOD zones is higher than trips to, from, and between TOD zones.

As would be expected, the rate of use of transit within TOD zones far exceeds non-TOD zones (Figure 3). Similarly, the rate of use of personal vehicles in non-TOD zones is higher than trips to, from, and between TOD zones. However, a surprising element in the data is that when the rate of use of personal vehicles is compared inside vs. outside TOD zones, one can observe a higher rate for personal vehicle as opposed to transit usage.

Figure 4 illustrates primary travel mode of work trips within TOD and non-TOD zones. As the figure illustrates, the share of trips by transit, walk, and bike modes are much larger in the TOD zone. At the same time, the non-TOD zones show larger share of auto mode.
FIGURE 3.
Primary travel model of work trips: TOD vs. non-TOD

FIGURE 4.
Primary travel model of work trips: TOD vs. non-TOD

Metrorail Fare Model
The travel activity data lacked information on transit fare and average wait time. The survey data were augmented by generating required independent variables using the models developed or borrowed for estimating transit fare (Metrorail fare) and average wait times. The Metrorail fare data were obtained from the WMATA website, which contains extensive fare tables from every transit station to all other locations. A regression equation was developed to determine the regular Metrorail fare based on miles traveled and the travel time. A random set of 169 data points was selected; the data points pertain to traveling from a station to all other stations. The independent variables are travel time (min) and distance (miles) between the two stations. The regression model, thus, developed is shown in Equation 3:
\[ Y = 2.0196 + 0.00167 X_1 + 0.0210 X_2 \]  

(3)

Where:

- \( Y \) is the Metrorail fare in dollars ($)
- \( X_1 \) is miles travelling distance between the two stations, and
- \( X_2 \) is travel time in seconds

The regression coefficient (R^2) of the transit fare model is 0.88, the probability of Type I error of the model is nearly zero, and the standard error is 0.30. These regression parameters indicate that Equation 3 represent a robust transit fare model. The model was used as the basis to determine the Metrorail fare cost between the transit trip stations.

**Average Transit Wait Time**

For a long time, the average transit wait time is simply half the headway time between train arrivals. This model is based on random arrival of passengers and uniform arrival of trains, while passengers get on the first train that arrives (Holroyd and Scraggs 1966).

This model is widely accepted until the assumption of uniform and on-time arrival of trains is questioned. If train arrival is non-uniform, then the average waiting time for the passenger is expected to be longer. Osuna and Newell (1972) conducted research to overcome the shortcomings of the traditional model and developed a model for the expected waiting time \( W \), which is a function of the average headway \( \mu \) and variations in the headway \( s^2 \) (Equation 4):

\[ W = \mu \times (1 + \frac{s^2}{\mu^2})/2 \]  

(4)

Where:

- \( W \) = expected passenger waiting times,
- \( \mu \) = mean headways between buses,
- \( s^2 \) = variances of headways between buses

This equation was used to determine the expected wait times in the development of the transit utility model for this section. Transit fare and average transit wait times were then computed for each record in the travel survey data. Table 1 illustrates the input data set, which comprises data elements from the travel surveys as well as the transit attributes computed for inclusion in the transit share model.
A Quick-Response Discrete Transit-Share Model for Transit-Oriented Developments

Testing for Normality and Variable Transformations

According to the Central Limit Theorem, 1,660 data points comprise a sufficiently large set to ensure normality of mean for independent variables of the utility models. However, since some of the data pertaining to independent variables are generated using submodels (Metrofare model and wait-time model), a further look at the normality of independent variables was undertaken. The independent variables were subjected to various transformations to ensure normality. Figure 5 illustrates the transformation necessary for the independent variable travel time to maintain a normal distribution.
As the figure indicates, the natural logarithmic transformation of travel time ensures a normal distribution. In this particular case, normality of the predictor variables also was justified by the Kernel density estimate graphs. Variables wait time, cost, and walk time also were tested for normality with similar transformations (not shown in this paper). Table 2 shows the summary of data transformation that is necessary for the predictor variables to maintain normality.
A Quick-Response Discrete Transit-Share Model for Transit-Oriented Developments

For households in which transit is the primary mode for work trips, transit utility functions for different levels of household auto ownership were developed using the data analysis and statistical software Stata®. The following multinomial logistic regression (MLR) models (Equations 5–8) represent the said utility functions developed for the TOD transit-share model:

\[
U_0 = 1.16 - 0.667\ln(TT) + 0.559(W_T) + 14.523(Cost) - 0.0079(WK_T) \\
U_1 = 7.08 - 1.408\ln(TT) + 0.0923(W_T) + 4.20(Cost) - 0.401(WK_T) \\
U_2 = 4.681 - 0.7424\ln(TT) + 0.0645(W_T) + 0.799(Cost) - 0.1021(WK_T) \\
U_3 = 5.213 - 0.8478\ln(TT) + 0.0530(W_T) - 5.230(Cost) - 0.0354(WK_T)
\]

Where,

\( TT \) = Trip travel time (min)  \\
\( W_T \) = Wait time (min)  \\
\( Cost \) = Transit Fare Cost ($)  \\
\( WK_T \) = Walk time to transit station (min)

MLR models use the “maximum likelihood estimation,” which is an iterative process to reach minimum log likelihood. When the difference between two successive iterations is small, the model is converged, and no smaller value of log likelihood exists. Table 3 shows the results of above MLR models. The iteration log shows the list of log likelihood at five iterations until the model is converged.

TABLE 2. Mode Choice Model–Predictor Variable Transformation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time</td>
<td>Natural log (ln)</td>
</tr>
<tr>
<td>Wait time</td>
<td>Identity</td>
</tr>
<tr>
<td>Cost</td>
<td>Inverse</td>
</tr>
<tr>
<td>Walk time</td>
<td>Identity</td>
</tr>
</tbody>
</table>

Model Development

For households in which transit is the primary mode for work trips, transit utility functions for different levels of household auto ownership were developed using the data analysis and statistical software Stata®. The following multinomial logistic regression (MLR) models (Equations 5–8) represent the said utility functions developed for the TOD transit-share model:
### TABLE 3.
Transit Trips MLR Summary of Results

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Variable</th>
<th>Coef</th>
<th>P Value</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Travel time</td>
<td>-0.6674</td>
<td>0.526</td>
<td>-2.7323 - 1.3975</td>
</tr>
<tr>
<td></td>
<td>Wait time</td>
<td>0.0559</td>
<td>0.655</td>
<td>-0.1891 - 0.3010</td>
</tr>
<tr>
<td></td>
<td>Fare cost</td>
<td>14.5238</td>
<td>0.159</td>
<td>-5.6660 - 34.7138</td>
</tr>
<tr>
<td></td>
<td>Walk time</td>
<td>-0.0079</td>
<td>0.933</td>
<td>-0.1936 - 0.1777</td>
</tr>
<tr>
<td></td>
<td>Constant</td>
<td>1.1607</td>
<td>0.851</td>
<td>-10.9510 - 13.2726</td>
</tr>
<tr>
<td>1</td>
<td>Travel time</td>
<td>-1.4085</td>
<td>0.150</td>
<td>-3.3253 - 0.5082</td>
</tr>
<tr>
<td></td>
<td>Wait time</td>
<td>0.0923</td>
<td>0.427</td>
<td>-0.1356 - 0.3230</td>
</tr>
<tr>
<td></td>
<td>Fare cost</td>
<td>4.2002</td>
<td>0.661</td>
<td>-14.601 - 23.0014</td>
</tr>
<tr>
<td></td>
<td>Walk time</td>
<td>0.0401</td>
<td>0.649</td>
<td>-0.1328 - 0.2131</td>
</tr>
<tr>
<td></td>
<td>Constant</td>
<td>7.0832</td>
<td>0.217</td>
<td>-4.1595 - 18.3261</td>
</tr>
<tr>
<td>2</td>
<td>Travel time</td>
<td>-0.7424</td>
<td>0.427</td>
<td>-2.5759 - 1.0911</td>
</tr>
<tr>
<td></td>
<td>Wait time</td>
<td>0.0645</td>
<td>0.581</td>
<td>-0.1649 - 0.2941</td>
</tr>
<tr>
<td></td>
<td>Fare cost</td>
<td>0.7990</td>
<td>0.931</td>
<td>-17.3349 - 18.9331</td>
</tr>
<tr>
<td></td>
<td>Walk time</td>
<td>0.1021</td>
<td>0.250</td>
<td>-0.7192 - 0.2763</td>
</tr>
<tr>
<td></td>
<td>Constant</td>
<td>4.6814</td>
<td>0.394</td>
<td>-6.0940 - 15.4569</td>
</tr>
<tr>
<td>3</td>
<td>Travel time</td>
<td>-0.8478</td>
<td>0.456</td>
<td>-3.0757 - 1.3800</td>
</tr>
<tr>
<td></td>
<td>Wait time</td>
<td>0.0530</td>
<td>0.684</td>
<td>-0.2026 - 0.3086</td>
</tr>
<tr>
<td></td>
<td>Fare cost</td>
<td>5.2308</td>
<td>0.639</td>
<td>-27.0793 - 16.6176</td>
</tr>
<tr>
<td></td>
<td>Walk time</td>
<td>0.0354</td>
<td>0.720</td>
<td>-0.1585 - 0.2294</td>
</tr>
<tr>
<td></td>
<td>Constant</td>
<td>5.2128</td>
<td>0.435</td>
<td>-7.8616 - 18.2874</td>
</tr>
<tr>
<td>≥4</td>
<td>Base outcome</td>
<td>1,660</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Null hypotheses: regression coefficients across all models are equal to zero.
- When P-value is compared with a pre-set tolerance to accept a Type I error of \( \alpha = 0.05 \), the null hypothesis is rejected.
- The confidence intervals (CI) shown indicate that for a particular predictor we are 95% confident that the “true” coefficient lies between the lower and upper limit of the interval. If the CI includes zero, we would fail to reject the null hypothesis.

**Validation**

The model results were tested against the survey data to determine the validity. Using 40 data points, two sets of probability values were determined. The first set was what was obtained through the use of the logit model, and the second set was simply the probability of occurrence of the data points in the data set. This comparison in effect provided the probability of taking transit as the primary mode of travel in a transit-oriented environment given the users are classified as having 0, 1, 2, and 3 vehicles.
Figure 6 is an illustration of the results, which indicate that not only the use of transit decreases as the number of vehicles owned increases, it also validates models 13–16 and shows that the probability of using transit is similar between what is derived by the logit model and the observed values.

Conclusions and Discussion

A methodology for developing a disaggregate transit-share model for transit-oriented developments using the travel activity data is presented using Rosslyn-Ballston TOD corridor in the Washington Metro area as the case study. The model offers quick response method for estimating transit share of work trips in TODs. Consistent with intuition, the results indicate that the use of transit decreases as the number of vehicle ownership increase. Validation of the model indicated close agreement with observed data. Since the input requirements to the TOD transit-share model are minimal, this model is expected to be very useful for sketch analysis of many TOD project alternatives, especially in the Washington DC metro area and other comparable areas.

The model is useful as a sketch-planning tool in evaluating various policy alternatives for the existing or new TODs in the same or comparable urban areas. In the preliminary planning stages of a TOD project, by employing this model, planners can quickly estimate transit share of trips in the TOD area by controlling for policy variables such as household auto ownership, transit schedules and fare, walk access to transit stops, etc. Such quick-response modeling will lead to identification of a set of feasible alternatives that can be evaluated later during the detailed planning stage using more robust models.

The methodology presented in this paper is transferable to all TODs surrounding major transit stations and can be replicated in urban areas where location-specific travel activity data are available. Whenever travel survey data with adequate spatial resolution
are available, it is recommended that separate trip generation and mode choice models be developed for TODs.

Disaggregate trip generation and mode choice models are widely regarded as better models for travel demand modeling applications. However, due to a mismatch between TOD and TAZ in terms of special resolution, the applicability of disaggregate models developed for TODs in traditional travel demand modeling needs further exploration. Since most TODs are usually much smaller than TAZs, in the absence of a structured sensitivity analysis, it is not clear if differentiating trip generation models for TODs and other land uses will automatically lead to better results from the travel demand modeling process. A worthwhile extension of this study will be to treat TODs surrounding major transit stations as separate TAZs and examine the influence of the disaggregate models on overall travel demand model results.

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A Quick-Response Discrete Transit-Share Model for Transit-Oriented Developments


A Quick-Response Discrete Transit-Share Model for Transit-Oriented Developments


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Barriers for Parents with Disabilities Traveling with Children on ADA Complementary Paratransit

Jean Jacob, Ph.D., Megan Kirshbaum, Ph.D., and Paul Preston, Ph.D.

Through the Looking Glass

Abstract

Ninety-two transit agencies from across the United States completed a survey of their policies and procedures that impact parents with disabilities traveling with minor children. Results indicate that certain policies make it difficult for parents to use paratransit. These policies include limiting the number of children who can accompany a parent, lack of access to chain rides (i.e., no scheduled waits), lack of driver assistance with car seats, not providing car seats, not allowing storage of car seats on vehicles, and fares for adults and children that make regular use of paratransit cost prohibitive, particularly for parents on a fixed income. These policies have serious consequences for parents to obtain and maintain employment, meet their children’s educational, childcare, and medical needs, and, in some cases, even retain custody of their children. Contained in the article are recommendations to make paratransit systems more accessible to parents with disabilities.

Keywords: Parents with disabilities, Riding paratransit with children, Paratransit policies

Background

Under the Americans with Disabilities Act (ADA), transit agencies are required to provide ADA complementary paratransit services to individuals whose disability prevents them from using fixed-route bus or rail. These services must be provided for travel within ¼ mile of fixed-route systems and must be complementary to the fixed route in terms of hours and days of operation. Accessible transportation allows people with disabilities to access needed services, pursue employment, participate in their communities, engage with others socially, and lead active lives (American Association of People with Disabilities, n.d.).

One of the most important roles for many adults is being a parent. For parents, having access to transportation to meet their children’s needs is essential, whether that involves transportation to occasional doctor appointments, play dates, or daily trips to
daycare. Although individuals with disabilities increasingly are becoming parents, their prevalence has not yet been reflected in public policy or community resources such as transit systems (National Council on Disability 2012). The failure to recognize that an increasing number of people with disabilities are parents has resulted in paratransit policies that do not fully accommodate these parents’ unique needs.

From more than 30 years of providing services to parents with disabilities and their families, Through the Looking Glass (TLG) is familiar with the numerous barriers to parents’ use of paratransit services when traveling with young children and the resulting consequences for their families. For some parents with disabilities involved in custody cases, transportation challenges have made it difficult for them to attend visitations with their children (Kirshbaum et al. 2003). Missing visitations or court-ordered appointments clearly can have negative repercussions for parents involved in custody cases, including contributing to loss of custody of their children.

Accessing transportation can be challenging for people with disabilities. A national transportation availability and use survey found that 12% of people with disabilities reported difficulty in accessing transportation compared to 3% of those without disabilities (U.S. Department of Transportation 2002). The survey further found that more than half of paratransit riders (53%) reported difficulties with paratransit. Transportation barriers seem to be an even larger problem among parents with disabilities. A national study by Toms-Barker and Maralani (1997) conducted for TLG found that 79% of parents with disabilities reported that transportation problems limited or interfered with parent-child activities. Similarly, when TLG conducted the Parents with Disabilities and Deaf Parents Task Force with 55 San Francisco Bay Area representatives, transportation was identified as impacting parenting with a disability more than any other factor. Specific concerns were raised about Bay Area paratransit policies affecting parents’ ability to ride paratransit with their children. These concerns included whether children are allowed to travel with their parents, whether a personal assistant is allowed to ride with a parent in addition to a child, and whether paratransit can be used to transport a non-ADA eligible child to a childcare center or school (Preston 2006). The National Council on Disability found in its report regarding parents with disabilities that “many parents with disabilities face barriers to traveling with their families using paratransit services” (2012, 28).

Paratransit services may not be designed or implemented in a way to meet the needs of many eligible riders. Rosenbloom (2007) reported that most paratransit trips were taken by just a few riders, with many eligible riders—even those having been certified—never using paratransit. In one study of ridership in the JAUNT paratransit system in central Virginia, 47% of the trips were taken by just 7% of riders (Bearse et al. 2004).

There has been increasing recognition that some groups of potential paratransit riders have unique needs, and their ability to use paratransit may depend on making specific accommodations to services. Among these groups are older adults as baby boomers age (Marin County Civil Grand Jury 2013; Metaxatos 2012; Bailey 2004; Bailey et al. 2007), dialysis patients (Denson 2007), and adults with autism (Freeley 2010). Although there has been increasing awareness and research on these groups, there has been limited or
no research on parents with disabilities who travel on paratransit with young children. This is an important research need, as we know that in the United States 6% of parents of children under 18 have a disability (Kaye 2012).

Despite the lack of research, parents’ needs are starting to become apparent to at least a few transit agencies. Access Services in Los Angeles was awarded a federal New Freedom grant in 2010–2011 to provide premium paratransit services to parents with disabilities who travel with their children. Because parents are a growing segment of the disability community, transit agencies are highly encouraged to begin searching for ways to meet their unique needs to ensure that parents with disabilities are not being denied access to paratransit. To learn more about paratransit policies that impact parents’ ability to use paratransit with young children, TLG conducted a national survey of agencies providing ADA complementary services.

Methodology

Sample

Paratransit Managers or their designees from 117 public transportation agencies providing ADA complementary paratransit services were recruited to complete a questionnaire about their services and policies impacting parents traveling with minor children. Participating agencies were not randomly selected for participation in the study; rather, the sample was a convenience sample of agencies that the researchers were aware of that had received awards for best and innovative services, agencies that had completed prior surveys conducted by a consultant to the current study, and agencies located in states with high rates of disabilities among adults of childbearing ages. Specifically, the agencies included for recruitment were those identified by the Community Transportation Association of American (CTAA) for Best Practices, CTAA’s 2006 community-based transportation planning grantees, recipients of the 2010 CTAA awards, participants in CTAA 2010 professional workshop sessions, Easter Seals Project ACTION paratransit presenters, and advisory committee members or reviewers for the Federal Transit Administration’s (FTAs) Office of Civil Rights-funded ADA Transportation Topic Guides (Golden and Thatcher 2010). Additionally, transit agencies that had responded to past national surveys such as those included in the “2007 Public Transportation Programs for Seniors Final Report,” prepared by the Beverly Foundation in partnership with the American Public Transportation Association (APTA), and Nelson/Nygaard Consulting Associates’ (2008) “Status Report on the Use of Wheelchairs and Other Mobility Devices on Public and Private Transportation,” prepared for Easter Seals Project ACTION, were targeted for participation.

The decision to sample some of the most innovative systems stemmed from the recognition that parents with disabilities are a segment of the disability community whose needs are not frequently recognized, fully understood, or adequately addressed. By outreaching to systems using best practices, we hoped to include agencies that were taking steps to specifically meet parents’ needs. In our recruitment, efforts were undertaken to ensure that transit agencies in each of the 10 FTA regions were recruited to participate by selecting several agencies in each region and agencies serving rural, urban, and suburban areas as determined by the Rural Institute of Montana website.
data. Also targeted for recruitment were paratransit agencies in the 10 states identified as having the highest rates of disability for people ages 21–64 (i.e., Alabama, Alaska, Arkansas, Kentucky, Louisiana, Maine, Mississippi, Oklahoma, Tennessee, and West Virginia) in the “Disability Status Report” (2008), which analyzes data from the 2008 American Community Survey (ACS). Although we sought to obtain responses from paratransit agencies in every region, agencies in the 10 states with the highest rates of disability among childbearing age adults, and agencies serving rural, suburban, and urban areas, there was no plan to recruit additional agencies in the event that we were not successful in our recruitment.

**Materials**

A 29-item survey was developed for this research project. TLG’s experience in assisting parents with disabilities with their transportation needs through our National Center for Parents with Disabilities and Their Families informed question development, as did findings obtained from TLG’s past survey and task force reports: Toms-Barker and Maralani’s (1997) *National Survey of Parents with Disabilities* and Preston’s (2006) *Bay Area Parents with Disabilities and Deaf Parents Task Force Report*. Richard Weiner of Nygaard Consulting Associates; Annette Williams, Accessible Services Manager at San Francisco Municipal Transportation Agency; and Karen Hoesch, Executive Director of ACCESS Transportation Systems in Pittsburgh reviewed drafts of the questionnaire and provided suggestions for eliminating, adding, and revising questions. Parents with disabilities who had traveled on paratransit with a young child also provided feedback on survey questions. The survey covered general paratransit policies, practices, and procedures; issues around a parent scheduling a paratransit trip; use of car/booster seats in vehicles; and agency experience in transporting parents with disabilities traveling with minor children. Table 1 includes a list of survey questions.

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**TABLE 1.**

List of Survey Questions

<table>
<thead>
<tr>
<th></th>
<th>Question</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Please provide your paratransit agency’s name.</td>
</tr>
<tr>
<td>2</td>
<td>About how many trips were provided during your last fiscal year?</td>
</tr>
<tr>
<td>3</td>
<td>Where are ADA paratransit eligibility assessments conducted? (Transit office, Local social service agencies, Applicants’ homes, Other—please specify other sites, I don’t know)</td>
</tr>
<tr>
<td>4</td>
<td>If registrants indicated they need to travel with a personal care attendant during the eligibility assessment, may they ride without one? (Yes, No, I don’t know)</td>
</tr>
<tr>
<td>5</td>
<td>Does your agency require any type of professional verification of a registrant’s need for a personal care attendant? (Yes, No, I don’t know)</td>
</tr>
<tr>
<td>6</td>
<td>Do paratransit drivers offer assistance in carrying packages/items to these locations? (To the curb, To the door, Other—please specify other locations), No assistance is provided in carrying packages/items, I don’t know)</td>
</tr>
<tr>
<td>7</td>
<td>Do you provide SAME day trips on a space available basis? (Yes, No, I don’t know)</td>
</tr>
<tr>
<td>8</td>
<td>Some parents with disabilities are able to ride the fixed-route bus system when traveling alone. If they cannot safely navigate the same route when traveling with the minor children, would they be offered conditional eligibility? (Yes, No, I don’t know)</td>
</tr>
<tr>
<td>9</td>
<td>How do parents with disabilities learn about your policies regarding traveling with their minor children? (We discuss them during the eligibility assessment, We provide a rider’s guide and show parents the relevant policies, We provide a written copy of relevant policies, We inform them that the policies are on our website, Other—please specify other ways parents learn about these policies, I don’t know).</td>
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<tr>
<td>Table 1. List of Survey Questions (cont.)</td>
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<tr>
<td>----------------------------------------</td>
<td></td>
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<tr>
<td>10. To what extent do parents with disabilities use your services when traveling with their minor children? (Minimally—less than 1% of our annual ADA paratransit trips, Moderately—1–5% of our annual ADA paratransit trips, A lot—more than 5% of our annual ADA paratransit trips, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>11. At what age does a non-eligible child pay for a fare to travel with a parent?</td>
<td></td>
</tr>
<tr>
<td>12. Do the paratransit and fixed-route bus systems have the same policy regarding the required age at which minor children pay to travel (Yes, No—please describe how they differ, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>13. What is the maximum number of non-ADA paratransit eligible children who may accompany a parent with a disability on a trip? (One, Greater than one—print the number in the box, We have no limit, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>14. If a parent with a disability schedules a trip to travel with more than one non-ADA eligible child, can you guarantee space for all the children? (Yes, No—please describe how you guarantee space for all children who accompany a parent, No, I don’t know).</td>
<td></td>
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<tr>
<td>15. What do you think is the biggest challenge your agency faces in accommodating parents with disabilities when scheduling trips with more than one non-ADA eligible child?</td>
<td></td>
</tr>
<tr>
<td>16. Have staff reported concerns or worries when parents with disabilities travel with an ADA paratransit eligible child? (Yes—please describe the concerns or worries, No, I don’t know).</td>
<td></td>
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<tr>
<td>17. Can parents with disabilities get subscription service to transport their non-ADA eligible children to daycare or school? (Yes, No, I don’t know).</td>
<td></td>
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<tr>
<td>18. When parents with disabilities’ trips with their non-ADA eligible minor children involve two different destinations, must parents book two separate trips (for example, from home to the child's daycare and an additional ride from daycare to the parent’s workplace)? (Yes, No, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>19. Do drivers receive training on how to install car/booster seats? (Yes, No) Do you think your drivers might receive this training in the future (Yes, No, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>20. Do you provide car/booster seats for children traveling in your vehicles? (Yes, No, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>21. How has your agency obtained car/booster seats for your paratransit vehicles? (Purchased them, Developed other resources—for example, a &quot;Loaner Program&quot; with the County Health Department—please describe the resources you use and/or who provides car/booster seats for your vehicles, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>22. Can your agency guarantee that a vehicle with car/booster seats will be available at the time a parent with a disability requests a trip? (Yes, No, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>23. When parents with disabilities provide their own car/booster seats, do drivers assist with the following if parents are unable to so because of their disabilities? (Carry the car/booster seat to and from a location beyond the curbside, Load it on and off the vehicle, Install it in the vehicle, Place, secure, and remove the child, None of the above, I don’t know).</td>
<td></td>
</tr>
<tr>
<td>24. What do you think is the biggest challenge your agency faces in having drivers assist parents with disabilities who provide their own car/booster seats?</td>
<td></td>
</tr>
<tr>
<td>25a. Does your agency allow parents to stow their car/booster seats in a paratransit vehicle during appointments or while doing errands? (Yes, No, I don’t know).</td>
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</tr>
<tr>
<td>25b. What is the maximum number of car/booster seats that can be stowed?</td>
<td></td>
</tr>
<tr>
<td>25c. How do you ensure that the parents’ car/booster will be available on their return trips?</td>
<td></td>
</tr>
<tr>
<td>26. What do you think is the biggest challenge your agency faces in having parents stow their car/booster seats in a paratransit vehicle?</td>
<td></td>
</tr>
<tr>
<td>27. Has your agency experienced barriers/difficulties or challenges not covered in our questionnaire when providing services to parents with disabilities who travel with their minor children? (Yes—please list the barriers/difficulties or challenges, I am not aware of any but will check with other staff, and you may contact me at a later date, No).</td>
<td></td>
</tr>
<tr>
<td>28. Are you aware of any staff or Transit Board members’ suggestions for improving services to parents with disabilities who travel with their minor children? (Yes—please describe suggestions, I am not aware of any but will check with other staff, and you may contact me at a later date, None).</td>
<td></td>
</tr>
<tr>
<td>29. Are you aware of a paratransit agency that offers services beyond ADA minimum requirements to parents with disabilities when traveling with their minor children? (Yes—please provide the paratransit agency’s name and describe the service(s) being offered, No).</td>
<td></td>
</tr>
</tbody>
</table>
Additionally, an online rider’s guide for every paratransit agency that participated in the study was analyzed for policies affecting travel with a young child. Rider’s guides are documents produced by local paratransit agencies that provide detailed information about the agency’s policies and procedures (e.g., application procedures, eligibility requirements, hours of services, how to schedule rides, cost to travel, companion policy, riders’ rights and responsibilities, etc.).

**Procedure**
TLG research staff called paratransit agencies targeted for inclusion in the study to obtain the name, phone number, and mailing address of the Paratransit Manager or designee who typically would be responsible for completing questionnaires about the agency’s ADA complementary paratransit services. The identified individuals were sent a letter informing them about the research project and inviting them to participate. A research staff member then called potential participants to inquire about their willingness to complete the survey and answer any questions, and then sent a survey to those who agreed to participate. Throughout the data collection period, research staff repeatedly contacted Paratransit Managers who had not completed the survey by sending postcard and email reminders and making follow-up phone calls. Research staff tracked survey receipt and all outreach contact with participants on an Excel spreadsheet. Data collection took place from January 28, 2011, through April 29, 2011. Those who completed the survey were placed in a drawing to receive one of five $100 Visa gift cards. Survey responses were entered into SPSS version 19 for data cleaning and analysis.

Rider’s guides were analyzed to determine what type of information was available to parents about traveling with young children on paratransit. The guides were analyzed for stated policies on fares for children, requirements for car seats (age, height, weight), level of driver assistance with car seats (car seats provided, carried, installed, children secured in seats, car seat storage allowed, etc.), the number of children accompanying an eligible rider, etc. Information from the rider’s guides was coded and entered into a matrix in Excel to obtain frequencies for different policies.

**Results and Discussion and Observations**
A total of 93 (79%) of the 117 transit agencies contacted for participation completed the survey. One agency was excluded because it did not provide ADA complementary paratransit services. Responses were received from agencies in each of the 10 U.S. federal regions and 45 states. Surveys typically were completed by General Managers, Managers, Assistant Managers, and Operations Managers of the overall transit agency or the Paratransit division, Customer Service representatives, and Eligibility Specialists. The average number of self-reported rides provided by paratransit agencies during their last fiscal year was 524,341, with a range of 4,127 to 6,300,000.

**Eligibility**
Anyone wishing to use local paratransit services is assessed for eligibility by the transit agency to determine whether their disability prevents them from being able to use the fixed-route transit system. Agencies sometimes offer full eligibility (for all trips) or
conditional eligibility (for just some trips). Results from the survey show that agencies differ on whether they offer conditional eligibility for parents who are able to use the fixed-route system when traveling alone but are unable to use fixed-route transit when traveling with a young child. In total, 41% of agencies responded that the assessor would consider the impact of traveling with a child when determining eligibility for paratransit, 37% would not, and 22% did not know. One agency that would consider the impact of the child on the parent’s ability to use fixed-route transit explained that when determining eligibility, those who conducted the assessment considered whether the dyad, together as a team, were able to use the fixed-route system as opposed to assessing each individually. The participant explained, “Parents with small children are considered a ‘package’ during the eligibility process, whether it’s the parent that’s disabled or the child.” Other agencies, however, responded that only a rider’s functional abilities should be considered along with assistance provided by their personal care attendant (PCA), whose role is to assist a person with a disability with activities of daily living.

The fact that more than 1/3 of agencies do not offer conditional eligibility for parents who can use the fixed-route when traveling independently but cannot do so when traveling with a young child can result in denying a significant number of parents access to paratransit. Conditional eligibility traditionally has been used to consider how an individual’s functioning could be affected by weather conditions (e.g., ice, snow, temperatures), certain times of the day when traveling, specific destinations, or to accommodate episodic disabilities. However, there is some basis for considering how a parent and child’s functional abilities work together when determining eligibility. When assessing a child’s eligibility for paratransit services, FTA’s Office of Civil Rights-funded Topic Guide 3 on ADA Transportation noted that FTA has stated that the “eligibility process can consider the abilities of the ‘team’ (child and accompanying adult) when determining eligibility” (Golden and Thatcher 2010, 24).

This guidance of allowing for assessment of a parent and child as a “team” was provided in the context of how a parent may be able to assist a child with a disability so the child can ride the fixed-route system with the parent’s assistance and, therefore, not be eligible for paratransit services. The same guidance could be applied when assessing a parent with a disability who could not ride the fixed-route system when traveling with a child and, thus, could be determined to be eligible for paratransit services when traveling with the child.

Transit agencies should have a consistent policy for assessing eligibility for children and adults that considers the ability of parents and their children together.

Learning about Policies Regarding Traveling with Children

When asked about all the ways parents learn about policies regarding traveling with their minor child, the most frequently identified means by transit managers was rider’s guides, with 62% responding accordingly. As shown in Table 2, additional ways that agencies reported informing riders about these policies were discussing policies during assessment (44%), providing riders with a written copy of policies (40%), informing riders that policies are on the website (33%), and “other means” (23%). The primary “other” means identified was talking with someone in the Customer Service, Eligibility, or Reservations department.
TABLE 2. How Paratransit Riders Learn about Policies Regarding Traveling with their Minor Children

<table>
<thead>
<tr>
<th>Ways of Learning about Policies</th>
<th>Yes</th>
<th>No</th>
<th>Don't Know</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discussed during assessment</td>
<td>44%</td>
<td>54%</td>
<td>2%</td>
</tr>
<tr>
<td>Provided rider’s guide and shown policies</td>
<td>62%</td>
<td>37%</td>
<td>1%</td>
</tr>
<tr>
<td>Provided written copy of policies</td>
<td>40%</td>
<td>58%</td>
<td>2%</td>
</tr>
<tr>
<td>Informed polices are on website</td>
<td>33%</td>
<td>65%</td>
<td>2%</td>
</tr>
<tr>
<td>Other</td>
<td>23%</td>
<td>75%</td>
<td>2%</td>
</tr>
</tbody>
</table>

That 62% of agencies responded that parents learn about policies regarding children from the rider’s guide needs further exploration. Our analysis of participating agencies’ rider’s guides found that few agency guides explicitly discussed policies that are unique to parents. Typically, the guide contained more general information that did not mention parents traveling with their children. As a result, parents with disabilities are left trying to discern what the policy is when traveling with their children or whether the agency might have more flexibility in accommodating a family’s transportation needs. Specifically, our analysis found that only 41% of agency guides mentioned child car seats at all. More than 60% (63%) did not specify if car seats would be provided, 90% did not mention whether assistance would be provided in carrying car seats, and 88% did not mention if drivers would help install car seats. If rider’s guides are used as a primary source of information, they need to contain policies that apply to parents traveling with children, such as limits on the number of children, payment required for children, age and weight requirements for car seats, whether the agency provides car seats, specifically what assistance will be provided with carrying and installing car seats, and whether car seat storage is available. This information will help parents with trip-planning and provide them with enough information to determine whether paratransit is a realistic option.

Driver Assistance with Packages

As Table 3 shows, 21% of agencies responded that drivers provide no assistance with carrying packages, and just over half (55%) that drivers assist with carrying packages to the door.

<table>
<thead>
<tr>
<th>Type of Driver Assistance</th>
<th>Yes</th>
<th>No</th>
<th>Don’t Know</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carry packages to curb</td>
<td>76%</td>
<td>24%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Carry packages to door</td>
<td>55%</td>
<td>45%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Carry packages to other location</td>
<td>2%</td>
<td>98%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No assistance</td>
<td>21%</td>
<td>79%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Load car seat</td>
<td>51%</td>
<td>42%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>Carry car seat beyond curb</td>
<td>31%</td>
<td>63%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>Install car seat</td>
<td>35%</td>
<td>58%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>Place, secure, remove child</td>
<td>13%</td>
<td>81%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>None</td>
<td>28%</td>
<td>65%</td>
<td>5%</td>
<td>2%</td>
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</tbody>
</table>

Note: Due to rounding, all percentages may not equal 100%.
Agencies greatly differ in the number of packages that drivers will carry, with some limiting assistance to only one bag and others assisting with up to six. Parents traveling with a young child often need to travel with one or two bags filled with diapers, bottles, snacks, a change of clothes, and toys in addition to a car seat and often a stroller. Therefore, driver assistance with these types of packages can determine whether parents will be able to use paratransit for their transportation needs.

That just over half (55%) of agencies responded that drivers assisted riders by carrying packages to the door is unexpected, since ADA Topic Guide 5 instructs transit agencies to provide door-to-door service when needed by a rider. The guide states, “If a rider needs door-to-door service because of his or her disability and is carrying packages that would be allowable on the fixed route service, then the DOT Origin-to-Destination Guidance would require vehicle operators to carry a limited amount of groceries and other packages, if needed by the rider” (Golden and Thatcher 2010, 13). The DOT (2011) Final Rule on Transportation for Individuals with Disabilities reinforces this guidance by stating that the origin-to-destination guidance stands. The 2015 DOT Final Rule states that agencies will need to make reasonable modifications to policies, practices, and procedures to ensure non-discrimination against people with disabilities and explicitly states that agencies are required to provide origin-to-destination service, which would necessitate their providing door-to-door service if deemed necessary for a passenger to use paratransit. On the other hand, Appendix E of the Final Rule states that if the normal policy for an agency is that drivers are not required to assist with packages, they would not be required to do so if requested by a passenger, as this would modify the services provided by the driver. Nonetheless, if agencies have policies for drivers to assist a rider to the curb with packages, then drivers are required to assist to the door if necessary. Receiving assistance with packages such as diaper bags, strollers, etc. can be particularly important for parents traveling with young children who also have to ensure their child’s safety when disembarking from the vehicle to the home.

Driver Assistance with Car Seats and Car Seat Storage

Only 12% of agencies provide car/booster seats for their paratransit passengers, and an even lower percentage (7%) guarantee their availability for rides if requested. Moreover, as Table 3 shows, just over half (51%) of agencies assist with loading and unloading car/booster seats, only 35% assist with installation, and fewer than one third (31%) carry car seats from a location beyond the curb. Even fewer agencies (13%) place, secure, and remove children into and out of car/booster seats.

Also, only 3% of responding agencies allow riders to stow a car/booster seat on the vehicle once a passenger arrives at their destination. Reasons for not allowing car/booster seat storage on vehicles include ensuring safety for all passengers, providing flexibility for any vehicle to pick up any passenger for a return trip without needing to coordinate the transfer of a car seat, and guarding against liability issues for lost, stolen, or damaged items left in vehicles. These policies generally necessitate parents traveling with small children to bring their own car/booster seat, carry the seat from their homes to the vehicle while managing a small child, install the car/booster seat in the vehicle
while maintaining the safety of the child, and then bring the car/booster seat along with them once at their destination.

FTA has found that not providing assistance with car/booster seats violates the standard of “reasonable access.” A 2008 Transit Access Report contains a Letter of Finding (LOF) from FTA resulting from a complaint investigation against Maryland Transit Administration (MTA) for not loading a car seat on a paratransit vehicle and not securing a child in the car seat (Transit Access Report 2008). The LOF instructed MTA to accommodate a parent needing assistance with securing a car seat and transferring the child into and out of the seat. FTA interpreted MTA’s policy as counter to ADA regulations (Code of Federal Regulations, title 49, sec. 37.123 (f) (1) and (2)) that require companions to be provided with service. FTA reasoned that since state law requires children to be secured in a car seat, the agency would be responsible for taking steps needed to transport the companion legally. Additionally, FTA applied Department of Justice (DOJ) requirements regarding program accessibility and reasonable access that state that a public entity should alter its policies to make services accessible unless alterations would result in modifying the nature of the services (Code of Federal Regulations, title 28, sec. 35.130 (b) (7)). Reasonable modification has been explained by FTA Office of Civil Rights Officers Clark and Klein (2009) as modification that is “necessary for the rider to use the service, because of the rider’s disability,” is reasonable, and does not “constitute a fundamental alteration or direct threat” (p. 4). There was ambiguity as to whether paratransit agencies were subject to the reasonable modification provisions. Rulings by the Fifth Circuit (Melton v. Dallas Area Rapid Transit (DART) 2004), Ninth Circuit (Boose v. Tri-County Metropolitan Transportation District of Oregon 2009) and, most recently, the Second Circuit (Abrahams v. MTA Long Island Bus and Cruz v. Nassau County 2011) have interpreted the reasonable modification stipulation as not applying to transportation. However, as previously mentioned, the DOT Final Rule (2015) clearly states that transportation agencies are required to modify policies, practices, and procedures to ensure accessibility.

In our data, looking at agency responses about loading car/booster seats into and out of vehicles and carrying packages to the curb, an interesting distinction emerged. Although 76% of agencies answered that drivers would carry packages to the curb, just 51% answered that drivers would load car/booster seats onto and off the vehicle, essentially the same task. That a much smaller percentage of agencies would carry car/booster seats than an unspecified package shows an inconsistency. Agencies should have consistent policies for assistance with packages, regardless of the specific item to be carried, within the same weight limits.

Probably the best solution for agencies to address the challenge of young children needing to ride in a car/booster seat is to purchase vehicles with integrated car seats. As agencies purchase new vehicles to replace aging paratransit fleets, they can consider buying vehicles with integrated car seats that can be used by children that are over 20 pounds and at least 1 year old. Such seats will eliminate the need for drivers to load, install, and carry car seats and also help ensure the safety of children riding on paratransit vehicles by eliminating installation errors. Alternatively, transit agencies could explore the feasibility of providing car seats for rides taken in their vehicles, if
requested in advance. If neither of these solutions is workable, agencies could commit to providing driver assistance and find a way to store car seats on the vehicle during appointments, such as in rooftop storage containers or roof racks. Providing storage for car seats would most likely necessitate scheduling considerations so the same vehicle is used to drop off and pick up a passenger. Although scheduling could be a real challenge, agencies could work with riders to identify solutions so parents can travel with children who must ride in car seats.

**Limit on Companions**

As Table 4 shows, 18% of agencies responded that a maximum of one child could accompany an eligible rider, 19% responded that more than one child could accompany an eligible rider, 8% did not know, and 55% responded that there was no specific limit on the number of children who could accompany an eligible rider. However, when agencies that responded that they could accommodate more than one child or did not have limits on the number of children were asked if they could guarantee space for more than one child, 45% could not, 51% could, and 4% did not know.

<table>
<thead>
<tr>
<th>Maximum number of minor children who can accompany a parent?</th>
<th>18% (16)</th>
<th>19% (17)</th>
<th>55% (48)</th>
<th>8% (7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18% (16)</td>
<td>19% (17)</td>
<td>55% (48)</td>
<td>8% (7)</td>
</tr>
<tr>
<td>&gt;1</td>
<td>19% (17)</td>
<td>19% (17)</td>
<td>55% (48)</td>
<td>8% (7)</td>
</tr>
<tr>
<td>No limit</td>
<td>55% (48)</td>
<td>55% (48)</td>
<td>55% (48)</td>
<td>55% (48)</td>
</tr>
<tr>
<td>Don’t know</td>
<td>8% (7)</td>
<td>8% (7)</td>
<td>8% (7)</td>
<td>8% (7)</td>
</tr>
</tbody>
</table>

Guarantee space for more than one child?

<table>
<thead>
<tr>
<th>Yes</th>
<th>51% (35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>45% (31)</td>
</tr>
<tr>
<td>Don’t know</td>
<td>4% (3)</td>
</tr>
</tbody>
</table>

Space constraints were the most frequently listed challenge of accommodating multiple children. Other common challenges were issues with car seats, lack of supervision of children by parents, and children needing assistance from drivers. However, nearly 30% of agencies responded that they do not face any problems in accommodating multiple children accompanying an eligible parent.

Limiting the number of children who could accompany a parent or not guaranteeing space for more than one companion is a common practice that is a barrier to parents with more than one child. If a rider wants to travel with more than one companion, the individual typically is required to call the agency on the day of a trip to determine whether there is space. Needing to verify space availability for more than one companion on the same day as the ride can be particularly problematic for parents needing to transport children to appointments and can result in parents paying cancellation fees for missed appointments if space is not available. We recommend allowing riders to reserve space for all companions at the time a ride is scheduled. If this is not feasible for a system during peak hours when there is high demand by eligible riders, perhaps agencies could allow passengers to reserve space for all companions at the time of reservation for rides taken during non-peak times.
Subscription Service and Chain Trips

Subscription services are offered by many agencies to allow passengers to have a standing appointment for a ride regularly taken on the same day and time each week. Having subscription service prevents riders from needing to call and schedule appointments each week. A total of 69% of paratransit agencies reported that parents can get subscription service to transport children to day care or school. However, several agencies noted that this service depends on whether the agency is over capacity for its subscription services, as federal regulations stipulate that subscription service should not comprise more than half of the trips available at a given time (Code of Federal Regulations, title 49, sec. 37.133 (b)). Furthermore, a few agencies explained that even if parents had subscription service, the parent would need to disembark with the child at school and wait for another ride to continue on to work or return home. Just 5% of agencies are able to perform a 10-minute “scheduled wait.” Therefore, most agencies would require that the parent schedule another ride from the child’s daycare or school. One agency noted that the return ride would be at least 30 minutes later; another responded that it would be at least 90 minutes later.

That 69% of agencies responded that parents could get subscription service to transport their child to daycare or school is somewhat misleading, as 91% of agencies do not provide a “scheduled wait.” Although time constraints would definitely be a consideration for paratransit agencies in establishing the day’s manifest to ensure that all riders are picked up within the required pickup window, transit agencies could explore the feasibility of instituting scheduled waits. Those agencies wishing to institute scheduled waits could check with other agencies that do allow for chain trips about the economic impact and efficiency while also taking into consideration the unique constraints of their own system.

Age Children Pay to Ride

More than three quarters (78%) of paratransit agencies responded that the agency begins charging children at the same age as the fixed-route system, with 95% charging children age 7 and over; 20% of agencies charging children from birth, and nearly all charging children ages 7 years and older.

Because paratransit agencies are authorized to charge twice the fixed-route fare (Code of Federal Regulations, title 49, sec. 37.131(c)), costs for regularly riding paratransit can add up quickly, particularly for parents with multiple children. Cost can be a real barrier for parents with disabilities, as their median annual family income was found to be $35,000 compared to $65,000 for parents without disabilities in the 2008–2009 American Community Survey (Kaye 2012). Paratransit costs also can quickly escalate for riders who are unable to make chain trips such as for drop-offs, since each leg of a trip is charged separately. One gets a sense of how expensive paratransit is for a parent traveling with a child by estimating the daily cost of dropping of a child at child care and then continuing to the parent’s work. Using the fare of $2.09, which was the average fare in 2010 according to a U.S. Government Accountability Office (GAO) survey (2012), a parent would need to pay $12.54 per day to travel with his/her child to school, pay for a separate trip to work, and then reverse these legs of the trip at the end of day. Keep in
mind that this example trip involved only one child and did not include any additional stops such as stopping for groceries. Agencies could examine whether offering family rates would be possible or charge children only at the age that the fixed-route system charges them. Transit agencies have explored offering free fares to older adults in the Chicago metropolitan area (Metaxatos 2013) and eliminating fares for older adults in the state of Illinois (Metaxatos and Dirks 2012). Similar analyses could be undertaken to examine reduced fares for parents traveling with children, which would be a much smaller segment of the paratransit riding population than older adults and, therefore, not nearly as costly of a group to accommodate.

Same-Day Rides
The majority of paratransit agencies (58%) do not offer same-day rides. Many of the agencies that do noted that same-day rides often are based on availability and for emergency situations.

Same-day rides can be particularly important for parents who may need to get medical attention for their children, pick children up from school if children get sick, or meet some other unanticipated immediate need. Agencies that currently do not offer same-day rides could consider providing this service if space is available, for emergency- or health-related reasons. This would be helpful for all riders in communities that do not have accessible taxi service.

Parent Use of Service
Paratransit agencies perceive that parents with disabilities traveling with their minor children constitute a small percentage of riders. More than half of participating agencies (54%) responded that parents riding with their minor children used the service minimally (less than 1% of their ridership), 12% indicated that parents used the service moderately (1–5% of their ridership), just over 1% indicated that parents used the service a lot (more than 5% of their ridership), and 33% did not know how much parents used the service.

Paratransit providers perceive that parents with disabilities comprise a small percentage of their overall ridership, with more than half of agencies estimating that they comprise less than 1% of their ridership. Although outside the scope of the present study, determining if these numbers reflect the actual ridership of parents would be informative and, if so, also important would be determining how parents meet their family’s transportation needs, particularly those who do not have their own vehicles. Also noteworthy is the fact that more than 33% of agencies did not know what percent of the riders were parents, suggesting that many agencies do not ask or track such information.

Limitations of the Current Study
There are limitations of this study that must be considered when interpreting the findings. Paratransit agencies were not randomly selected for participation; the sample was a convenience sample of agencies having completed prior surveys and agencies recognized for engaging in innovative practices. Because agencies were not randomly
selected, findings may not be reflective of paratransit policies in other agencies not included for participation.

This research was focused exclusively on ADA complementary paratransit and, therefore, did not address the transportation challenges faced by parents with disabilities living in very rural areas that do not have this service. This is a significant limitation, since the Research and Training Center on Disability in Rural Communities notes that 21% of the population in the United States lives in rural areas and nearly 11 million have disabilities (Enders 2005). Clearly, people with disabilities who live in rural areas constitute a large proportion of the population, and because many very rural areas do not have regular fixed route transportation, these individuals face particularly difficult transportation challenges. Future research is needed that specifically addresses the transportation needs of parents with disabilities living in rural areas, as these parents may experience some of the most significant transportation barriers.

Finally, because paratransit managers completed the survey rather than drivers, responses may better reflect policy rather than actual practice. Future studies with drivers might provide a more accurate understanding of assistance actually provided to parents traveling with their children.

Nonetheless, findings from this study can be used by paratransit agencies to enhance services for parents with disabilities. Results suggest that for some policies, minor modifications could greatly facilitate the ability of parents to access paratransit services. Further, the data indicate that agencies are already informally accommodating some of these needs. In fact, some of the recommendations provided would simply involve agencies codifying steps they are already taking to best serve parents or making minor adjustments to current policies. Such adjustments include having drivers provide assistance with car seats and accommodating parents who travel with more than one child. Admittedly, some recommendations will result in transit agencies incurring additional expenses. Agencies can look to make changes incrementally, starting with those that do not entail additional expenses (such as obtaining information about parental status at intake and updating rider’s guides) while beginning to identify funding sources in the most recent federal transportation authorization, Moving Ahead for Progress in the 21st Century (MAP-21). For example, the Enhanced Mobility of Seniors and Individuals with Disabilities (5310) Program could help offset costs for implementing other changes beyond ADA requirements (such as providing scheduled waits, supplying car seats, or accommodating storage of car seats, allowing multiple children to ride with parents, or offering reduced rate family fares). Agencies can explore the use of volunteers to provide premium services beyond ADA requirements (same-day rides, outside-of-area rides, extended hours, etc.). Additionally, in some regions, agencies also could look to collaborate with other entities such as social service providers, employers, childcare programs, job training programs, and colleges and universities. Although such collaborations can be challenging, some research suggests these models can improve access for those most reliant on public transportation (Blumenberg 2002). Following are recommendations for agencies to consider implementing that may be particularly helpful to parents with young children.
Barriers for Parents with Disabilities Traveling with Children on ADA Complementary Paratransit

Recommendations
1. Identify paratransit riders who are parents with disabilities. Paratransit agencies should collect data on the parental status of their riders and inquire whether riders plan to use paratransit with their children, and if so, determine the children’s ages. These data should be collected at the time of initial application for services.

2. Consider the functional abilities of a parent and child together when assessing eligibility.

3. Provide all riders with detailed information about policies impacting riding paratransit with children.

4. Accommodate riders traveling with small children who are required to ride in car seats.

5. Revise policies to facilitate use of paratransit by parents with disabilities such as:
   - Providing riders with door-to-door service when necessary.
   - Establishing “family-friendly” companion policies that allow family units to book rides to travel together as families can on fixed-route transit systems.
   - Providing discounts for young children traveling with their parents—start charging children only at the age the fixed-route system does and establish reduced family rates.
   - Offering chain-trips so riders can use paratransit for serial rides such as for transporting children to daycare and then continuing on to work.
   - Offering same-day rides for emergency situations and urgent medical appointments.

6. Think creatively about ways to improve services to parents. Traveling with small children can be challenging. Innovative paratransit systems have successfully found ways to make the process easier for parents and other riders. Strategies include improving scheduling to reduce travel times and limit the number of stops on rides, charging premium fares to offer services beyond ADA requirements (same-day rides, out-of-area rides, after-hour rides, etc.), and developing volunteer programs and collaborating with other entities to fill in gaps between ADA requirements and riders’ needs.

As people with disabilities are increasingly becoming parents, transit systems should establish policies to address their needs and ensure their ability to freely access transportation services.
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