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Integrating Livability Principles into Transit Planning: Screening Chicago Bus Rapid Transit Opportunities

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Abstract

Pilot Chicago Bus Rapid Transit (BRT) routes proposed in 2008 were impractical to build, did not meet Institute for Transportation and Development Policy defined “gold standard” BRT, and were selected without considering the Livability Principles guiding investment by the U.S. government. Streets incompatible with BRT and not meeting basic constructability standards were eliminated. The remaining contiguous street sections were scored on the weighted performance of 14 quantitative proxies for the Livability Principles. Transit connectivity considerations further refined the pool to produce potential BRT routes. For discussion purposes, these routes were organized into a hypothetical BRT network to complement the existing rapid transit system; potential 2010 travel demand impacts were modeled. This study identified 10 potential BRT routes for further consideration. The integration of the Livability Principles into the study was promising but had limited impact because of the greater than anticipated influence of right-of-way width requirements.

Introduction

In 2008, the U.S. Department of Transportation (USDOT) chose four proposals submitted by the Chicago Transit Authority (CTA) as potential locations for a demonstration bus rapid transit (BRT) project (Chicago Transit Authority 2008). The four proposals had enhancements with elements similar to BRT, but were not “gold standard” BRT (i.e., dedicated bus lanes, at-grade boarding, pay-before-you-board stations, and signal-prioritized intersections) as defined by the Institute for Transportation and Development Policy (ITDP) prior to their establishment of the point-based “BRT Standard” in January 2012 (Weinstock et al. 2011; Institute for Transportation & Development Policy 2013). The 2008 CTA proposal ultimately failed.

In 2009, the U.S. Environmental Protection Agency (USEPA), U.S. Department of Housing and Urban Development (USHUD), and USDOT formed an interagency collaboration, Partnership for Sustainable Communities, to better coordinate community investment. The Partnership was guided by six strategies—“Livability Principles”—that sought to bet-
ter integrate the housing, transportation, environmental, and equity goals of the three agencies (U.S. Environmental Protection Agency 2009).

Following renewed interest in a BRT system in Chicago in 2011, this study was undertaken to assist decision makers in identifying BRT opportunities in Chicago and demonstrate that the Livability Principles could be quantitatively integrated into the transportation planning process. This was a screening study intended to produce, as Kittelson & Associates (2003b, 2-2) noted, “alternatives for further refinement and/or analysis.”

This study adhered to ITDP’s characterization of the “gold standard” BRT as best practice; however, it is not the sole commentary on BRT (Weinstock et al. 2011). The variability of operational BRT systems is well-documented by the work of Levinson et al. (2003a), Wright and Hook (2007), Deng and Nelson (2011), and Weinstock et al. (2011)—some “gold standard” and some not. As of 2012, federal funding of 20 BRT systems in the United States had not been predicated on adherence to the gold standard (Government Accountability Office 2012). Subsequent to this study, the “BRT Standard” had both guided Chicago Department of Transportation’s (CDOT) design efforts and provided funding opportunities for upcoming Chicago BRT routes (ITDP 2013; City of Chicago 2013). Moving Ahead for Progress in the 21st Century (MAP-21) revisions to 49 U.S.C. §5309 divided BRT projects into fixed guideway (New Starts) and corridor-based (Small Starts)—definitions generally differentiated by the presence and absence, respectively, of “gold standard” required dedicated right-of-way (ROW).

At the time of this study, there was no explicit consideration of the Livability Principles in a transportation study; however, 49 U.S.C. §5309(d)—under the Safe, Affordable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) and, to a greater extent, MAP-21 had land use and economic development project justifications complementary to the spirit of the Livability Principles. The requirements of 49 U.S.C. §5309(d) (2008) had been reflected in the BRT transportation planning guidance provided by Kittelson & Associates (2007). Some project sponsors of existing BRT systems in the United States had at least hoped for ancillary benefits beyond mobility improvements (Government Accountability Office 2012).

From 2009–2012, the Partnership for Sustainable Communities cited various examples of projects that aligned with the Livability Principles (Partnership for Sustainable Communities 2012). The Partnership also jointly reviewed the Federal Transit Administration (FTA) Alternative Analysis Planning Grant (49 U.S.C. §5339 (2008)) under guidance of the Livability Principles. The alternative analysis, being a subsequent step to screening, was part of the impetus for this study; however, the program was repealed under MAP-21.

The literature lacked BRT screening studies, with the notable exceptions of research by McNamara et al. (2006) and the Center for Urban Transportation Research (2004) (the latter discussed later). McNamara et al. (2006) used a phased approach to select BRT routes from the existing Metropolitan Transportation Authority bus network. This study replicated that approach using four phases but differed in the metrics used to evaluate bus routes:
• **Phase I—Preliminary Route Screening** eliminated routes not relevant to the study and consolidated routes with service overlap.

• **Phase II—Segment Analysis** was divided into two parts that established potential routes for BRT. First, the existing street network was evaluated to determine if the ROW was sufficient for BRT. Next, streets were evaluated on 14 criteria that attempted to broadly assess existing transit demand and complementary land uses in the surrounding areas. This section is congruent with, albeit prematurely in a screening study, Kittelson & Associates' (2007) recommendation for consideration of ridership, travel times, constructability, and land development for a BRT alternatives analysis. In their statistical analysis of 46 BRT systems, Hensher and Li (2012) found transit connectivity to be “crucial” to BRT ridership. Mobility improvements were also requirements of 49 U.S.C. §5309 under SAFETEA-LU and MAP-21.

• **Phase III—Route Analysis** evaluated the integration of each route with the existing rail network and reintroduced or modified potential to improve transit connectivity.

• **Phase IV—Travel Demand Analysis** applied a travel demand model to the routes that passed Phase III to illustrate the impacts of a hypothetical BRT system.

This study was not a comment on the efficacy of BRT in the Chicago area over other forms of transit. Recommendations are based on existing conditions rather than potential benefits from a BRT route or system. The final grouping of recommended routes will require additional analysis, which is beyond the scope of this study.

**Methodology**

*Phase I: Preliminary Screening*

All CTA bus routes in service in October 2009 (155 routes) were examined using a two-part analysis consisting of consolidation and elimination. The system (see Figure 1) was chosen because it has a demonstrated demand for public transit.

First, two or more routes with only small deviations in alignment were consolidated into a single route. Next, three types of routes were eliminated from further analysis—Lake Shore Drive segments of some routes, downtown circulators, and special routes (seasonal, temporary, or short-run feeder routes).

This study did not deny the potential for enhanced transit along Lake Shore Drive; however, its purpose was to identify a small number of arterial routes that could provide maximum community benefits rather than identifying the robust system of supporting routes that Lake Shore Drive would require.

*Phase II: Segment Analysis*

The purpose of the segment analysis was to establish routes based on ROW constructability (Part 1) and access, transit performance, transit equity, and infill development potential (Part 2) scaled at a street-segment level. The extents of a street segment are defined by intersections with other streets as shown in Figure 2.
Part 1: Right-of-Way Constructability Analysis
The purpose of the ROW Constructability Analysis was to determine if sufficient public ROW width was available for a bi-directional BRT system along the street segments that passed Phase I.

- **Step 1: Establish absolute minimum ROW width.** Used for this study were minimum ROW widths recommended by the Institute of Transportation Engineers (2010) and Levinson et al. (2003b) for frontage zones; pedestrian travel ways; edge and furnishing strips; through, parking, bike, and BRT lanes; medians; and BRT stations. Based on those recommended minimum dimensions, two BRT standard minimum dimension scenarios were selected—a street segment with a BRT station (97 feet, 29.2 m) and a street segment without a BRT station (86 feet, 26.2 m).

- **Step 2: Assign ROW width to each street segment.** Each street segment provided by CDOT came coded with ROW width information. Street segments outside the city, provided by the Illinois Department of Transportation (IDOT), did not have ROW width information; therefore, those street segments were coded by measuring the distance between parallel property lines using GIS.
• **Step 3: Designate street segments to be removed.** Street segments not meeting the 86-foot (26.2 m) minimum ROW width were identified but not immediately removed. In some instances, a street segment represented a short narrowing of street ROW width, such as occurs at a railroad viaduct. These segments were not deleted if preceded and followed by at least 0.25 miles (0.4 km) of suitable ROW. Based on recommended station distributions from 0.25 miles (0.4 km) to 2 miles (3.2 km) apart (Levinson et al. 2003b), at least 0.25 miles (0.4 km) of suitable ROW flanking a narrow street segment indicated the potential for a station and warranted the inclusion of a narrow street segment.

• **Step 4: Establish minimum route length.** A BRT route requires a series of street segments wide and long enough for operations. Although information was available on establishing maximum BRT route lengths, the literature did not contain sufficient rationale to establish a minimum route length. Instead, the average length (3-miles, 4.8 km) of the four proposals submitted to USDOT in 2008 by CTA was used as an absolute minimum route length. Detailed modeling in future phases of subsequent studies would eliminate any impractical routes.

• **Step 5: Remove Unsuitable Segments.** Street segments less than 3 miles (4.8 km) in length were removed from the analysis. The remaining series of street segments required an adequate distribution of 97-foot (29.6 m) ROW widths to accommodate stations. A 0.5-mile station frequency distribution was selected based on recommendations for arterials by Kittelson & Associates (2007). Any series of street segments that did not have a distribution of 97-foot (29.6 m) ROW widths at least 0.5 miles (0.8 km) apart were removed from the analysis. If a terminating series of street segments did not have at least one segment of 97-foot (29.6 m) ROW at its terminating end (allowing for a station), the entire terminus was removed. If the removal of any street segments caused a series of street segments to be less than 3 miles (4.8 km) in length, the entire series was removed from the analysis. The remaining street segments were advanced to the Livability Analysis.

**Part 2: Livability Analysis**

The purpose of the Livability Analysis was to provide a holistic approach to the transit screening process. Using 14 criteria—proxies for the Livability Principles (see Table 1)—this analysis created a score for every street segment in the study area, which allowed a segment-by-segment analysis.

The method was similar to research by the Center for Urban Transportation Research (2004), which used four main criteria to quantify the propensity for successful BRT implementation in Miami-Dade based on existing conditions: 1) total average weekday existing bus ridership normalized by route length; 2) population and employment within 0.5 miles (0.8 km) of each route normalized by mile; 3) households with zero automobile ownership; and 4) households below $15,000 in annual income.
### TABLE 1.
Livability Analysis Criteria

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Study Measure</th>
<th>Rationale for Selection</th>
<th>Corresponding Livability Principles</th>
</tr>
</thead>
</table>
| Connectivity to Community Services | Number of community destinations within 0.5 miles (0.8 km) of street segments | People need transit access to vital community services such as day care, vocational rehabilitation centers, and services for older adults. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Connectivity to Educational Institutions | Number of high schools, post-secondary educational institutions, and libraries within 0.5 miles (0.8 km) of street segments. | People of all ages need transit access to educational opportunities such as high schools, community colleges, and libraries. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Connectivity to Entertainment Venues | Number of cinemas, convention centers, landmarks, museums, performing arts centers, stadiums, and zoos (within 0.5 miles (0.8 km) of street segments. | Transit access to cultural, entertainment, and social destinations, (e.g., movie theaters and museums) is a major quality-of-life benefit for many people. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Connectivity to Food Stores      | Total annual sales of food stores within 0.5 miles (0.8 km) of street segments. | People need transit access to fresh food at grocery stores, produce markets, and other types of food stores. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Connectivity to Major Medical Care | Number of hospitals within 0.5 miles (0.8 km) of street segments. | Patients and visitors need transit access to critical medical care at major hospitals. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Connectivity to Major Open Space | Number of community level parks—defined by the Chicago Metropolitan Agency for Planning (2008) as being over 25 acres (10.1 hectares)—and forest preserves within 0.5 miles (0.8 km) of street segments. | Transit access to recreational destinations can improve usage rates and health. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Connectivity to Retail           | Total annual retail sales at pedestrian-oriented businesses within 0.5 miles (0.8 km) of street segments. Automobile-related businesses such as gas stations and auto dealerships were omitted. | People require transit access to retail opportunities to meet their shopping and socialization needs. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Employment/Job Access            | Total employment at all businesses within 0.5 miles (0.8 km) of street segments. | Employees working in close proximity to BRT lines are a major group of potential riders, and BRT would increase their ability to live and work near transit. | • Provide more transportation choices.  
• Enhance economic competitiveness.  
• Support existing communities.  
• Value communities and neighborhoods. |
| Existing Transit Ridership       | Average passenger flow by street segment (controlling for direction) during the AM peak period. | Bus ridership demonstrates existing demand for transit along the study routes. | • Provide more transportation choices. |
| Existing Transit Travel Time     | Average passenger speed by street segment (controlling for direction) during the AM peak period. | Travel time reduction for passengers is a main function of BRT. It is important to identify routes where this benefit will be maximized. | • Provide more transportation choices. |
Each street segment for each criterion in the Livability Analysis was scored (to allow for comparable values) using the following percent-rank equation:

\[
\text{Percent Rank} = \frac{(\text{Absolute Rank of a Street Segment} - 1)}{(\text{Number of Street Segments} - 1)}
\]

**Individual Scoring:** For each criterion, a 0.5-mile (0.8 km)—considered a reasonable walking distance by Nabors et al. (2008)—area around each street segment was spatially joined to each respective study measure. This was expressed as a point or polygon GIS shapefile. The Existing Transit Ridership and Existing Transit Travel Time criteria used a 0.25-mile (0.4 km) buffer and a 0.125-mile (0.2 km) buffer, respectively, to control for more localized impacts. For each street segment, criteria were quantified by summing or averaging each study measure, as specified in Table 1. The percent rank function was used to score each street segment based on the summation or average of each metric relative to all other street segments.

**Overall Scoring:** The overall score, expressed as a percentage, was a composite of the weighted individual scores of each criterion. Weighting assigned importance to a criterion relative to all other criteria. The drawback of subjective weighting was considered to be offset by the benefit of expressing qualitative public policy goals and initiatives.

Each criterion was classified into four general scoring groups: 1) access to important trip generators, 2) transit performance, 3) transit equity, and 4) infill development potential. Criteria were weighted equally within each scoring group.
The “access to important trip generators” scoring group included Employment/Job Access, Population, and all the “connectivity” criteria. This group echoed the FTA’s recommendation to plan a BRT network that “connects disparate major generators of travel” (Panero et al. 2012, 14). Project sponsors of some existing BRT systems in the United States felt that BRT “provided new or improved connections between regional employment and activity centers,” a rationale for focusing BRT development in areas of high activity (Government Accountability Office 2012, 38).

The Existing Transit Ridership and Existing Transit Travel Time criteria represented the “transit performance” group. Given the relative importance of existing transit service to a BRT system, it was considered reasonable to give the Existing Transit Ridership and Existing Transit Travel Time criteria among the highest weightings. In evaluating project justification for major capital investment grants (49 U.S.C. §5309(d)(3)(H) (2008)) and New Fixed Guideway Grants (49 U.S.C. §5309(d)(2)(B)(ii) (2012)), USDOT was required to evaluate current transit ridership in the transportation corridor.

“Transit equity” comprised the Population 0.5 Miles or More from Rail and Transportation Costs criteria. The Population not Served by Rail and Transportation Costs criteria shared the highest scoring with the transit performance measures to emphasize equity in transit distribution. This group also conformed to grant requirements under 49 U.S.C. §5309(d)(2)(A)(iv) (2012) requirement that projects are “supported by policies and land use patterns that promote public transportation....” (similar SAFETEA-LU language under 49 U.S.C. §5309(d)(2)(B) (2008)).

Deng and Nelson (2011) and the Government Accountability Office (2012) suggested growing evidence for a positive BRT impact on land value. “Infill development potential” at 3 percent of the overall score of each street segment was represented only by its namesake criterion because it could not be reasonably categorized elsewhere.

The remaining 97 percent of the overall score of each street segment was divided between the three remaining scoring groups (i.e., each group received 32.33% of the score).

After calculating the overall score of each street segment, the street segments were divided into “weak scoring” and “strong scoring” categories. The division between the categories was the median value of the overall score.

All street segments in the weak scoring category were removed from the analysis unless those street segments were flanked by an equal length of strong scoring segments (for the purpose of including isolated weak sections). The remaining routes were passed into Phase III.

**Phase III: Route Analysis**

The Route Analysis removed routes that did not have the potential to make connections to existing fixed guideway transit and reintroduced corridors that improved transit connectivity.

To be considered connected with existing transit, the BRT routes had to be located within 330 feet (100.6 m) of a Metra or CTA rail station. The 330-foot (100.6 m) buffer was con-
sidered a reasonable, uncontrolled transfer distance between two fixed guideway transit lines.

The reintroduction or modification of routes was a qualitative approach driven by the desire to increase transit connectivity between existing transit and the BRT routes. Specific rationale behind the inclusion or exclusion of specific routes is described in the Results section.

Phase IV: Travel Demand Analysis
The purpose of this phase was to examine the potential transportation impact of a hypothetical BRT system based on the routes passing Phase III. Resource constraints did not allow modeling of individual routes or projections of future conditions; however, TCRP recommends that "BRT lines should be planned as an interconnected system" (Kittelson & Associates 2007, S-2).

Potential BRT routes were modeled using the Chicago Metropolitan Agency for Planning (CMAP) "trip-based" travel demand model (stored and manipulated using INRO's Emme 3). The assumptions used in the model, but not the methodology behind the model (i.e., CMAP's manipulation of input data provided by the authors of this study), is discussed in this section.

CMAP provided modeling outputs for three scenarios: No Build, BRT with a 50 percent reduction in local bus service, and BRT with no local bus service. For both the BRT scenarios, two lanes (one in each direction) of existing travel lanes were removed for use as BRT-only lanes.

Assumptions on the average speed and headway of the BRT system were derived from research by Levinson et al. (2003b) and Kittelson & Associates (2007). Average speed was assumed to be a conservative 15 mph (24.2 km/h), accounting for a 30-second dwell time at each stop. The headway was set at five minutes based on a preference for high peak period performance.

The BRT stopping pattern was based on spacing recommendations from Levinson et al. (2003b) and Kittelson & Associates (2007). Stops were established approximately every 0.5 mile (0.8 km), generally stopping at the major arterials in Chicago. Stops also were established at every Metra or CTA rail station regardless of whether this created a stopping frequency of less than 0.5 mile (0.8 km). Connections to the local bus network only occurred where BRT stations and the local bus system overlapped.

Automobile non-work trips were modeled during the midday period. Automobile work trips, transit work trips, and transit non-work trips were modeled during the morning peak period.
Results

Phase I: Preliminary Route Screening

A total of 10 circulators and 22 special routes were eliminated, and 2 pairs of routes were consolidated. There were 121 routes that passed Phase I.

Phase II: Segment Analysis Results

The routes passing Phase I were converted into 11,891 street segments and then used in the Segment Analysis. There were 2,084 street segments and 23 series of street segments that collectively satisfied the 86-foot (26.2 m) minimum, 3-mile (4.8 km) length minimum, and 97-foot (29.6 m) station requirements. These street segments were used in the Livability Analysis. The results of the overall score of the Livability Analysis for each criterion are shown in Figure 3.

Phase III: Route Analysis Results

Two potential routes, North Avenue and Peterson Avenue, were removed because they did not connect to existing transit. Seven routes were reintroduced or altered from their previous alignments. These routes and a rationale for their reintroduction or alteration are included in Table 2. These routes were joined by Western, Irving Park, and Pulaski/Crawford, which did not require revision. The alignments of routes passing Phase III are shown in Figure 4.
TABLE 2.
Rationale for Reintroduction of Routes in Phase III

<table>
<thead>
<tr>
<th>Route</th>
<th>Action Taken</th>
<th>Rationale for Reintroduction/Alteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fullerton/Grand</td>
<td>Extended north to North 75th Court, Elmwood Park, IL</td>
<td>• Connectivity to the Elmwood Park Metra Station</td>
</tr>
<tr>
<td>Garfield</td>
<td>Reintroduced</td>
<td>• Connectivity to the Garfield station of the CTA Red and Green “L” lines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Access to Washington Park and University of Chicago (university and major medical facility)</td>
</tr>
<tr>
<td>95th</td>
<td>Reintroduced and extended north to South Cicero Avenue, Oak Lawn, IL</td>
<td>• Connection of 6 potential BRT routes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Connectivity of 4 transit lines (Metra Rock Island Branch, Metra Rock Island Main, Metra Electric, and the CTA “L” Red Line)</td>
</tr>
<tr>
<td>Cicero</td>
<td>Reintroduced, extended north to West 21st Place and south to West 95th Street</td>
<td>• Connectivity between Midway Airport and the western most termini of the CTA Pink and Orange “L” lines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Connectivity to the potential 95th BRT route</td>
</tr>
<tr>
<td>Ashland</td>
<td>Extended south to West 95th Street</td>
<td>• Connectivity to the potential 95th BRT route</td>
</tr>
<tr>
<td>Halsted</td>
<td>Extended north to South Vincennes</td>
<td>• Connectivity to the Metra Gresham Station</td>
</tr>
<tr>
<td>King/ Stony Island</td>
<td>Reconfigured (see Figure 4)</td>
<td>• Access to McCormick Place Convention Center, Washington Park, and University of Chicago</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Connectivity to the CTA Red and Green “L” lines and the Metra electric line in 2 locations</td>
</tr>
</tbody>
</table>

FIGURE 4.
Map of routes passing Phase III
Phase IV: Travel Demand Analysis Results
CMAP staff produced modeling results for all three scenarios. The results of the two BRT scenarios were almost identical given the demand model constraints; therefore, the results of the BRT/Reduced scenario will not be discussed.

Person Trips
There were approximately 2,423,000 daily person trips (transit and automobile) beginning and ending within the BRT Corridor (defined by traffic analysis zones adjacent to the 10 BRT routes) modeled in the No Build scenario. The BRT scenario had higher results within the BRT Corridor at 2,457,000 person trips, a 33,000 person trip (1.4%) increase over the No Build scenario.

Transit Trips
There were 40,000 (13.8%) more transit trips beginning and ending within the BRT Corridor than in the No Build scenario. The total number of transit trips originating in the BRT Corridor increased by 51,000 trips (6.8%). The total number of transit trips ending in the BRT Corridor increased by 47,000 trips (10.6%).

Transit Mode Share
Transit mode share increased from 12.0 to 13.5 percent for trips beginning and ending within the BRT Corridor. Transit mode share increased from 14.7 to 15.8 percent for trips that either began or ended within the BRT Corridor.

Vehicle Impacts
Vehicles miles traveled (VMT) within the BRT Corridor decreased by 468 miles (753.1 km), a 2 percent decrease. Congested VMT increased by 953 miles (1,533.7 km), a 16 percent increase. Vehicle hours traveled within the BRT Corridor also increased by 62 hours, a 4 percent increase. Average vehicle speed within the BRT Corridor decreased by 1 mph (1.6 km/h), to 16 mph (25.7 km/h).

Discussion and Recommendations
The 10 routes emerging from Phase III were selected based on whether they 1) were practical, 2) best complemented existing livability conditions, and 3) would improve current transit connectivity.

The Right-of-Way Constructability Analysis in Phase II identified where a BRT route potentially could be constructed given the selected ROW constraints. Streets removed in this part of the analysis possibly could accommodate BRT if other street components (i.e., bike lanes, parkways, etc.) were removed or reduced in width; however, Complete Streets ideology necessitated the inclusion of sufficient ROW not only for the BRT system but also for other users of the public space. Exceptions to ROW requirements were made for the Cicero and King/Stony BRT routes for network integration purposes. In these instances, the benefit of better transit connections was considered to outweigh the loss of other ROW uses.

The importance of the Right-of-Way Constructability Analysis does not wholly undermine the intent of this paper to integrate the Livability Principles. The purpose of the
study was to include the Livability Principles in selecting the final routes, not to use the Livability Principles as the only consideration. It is hoped that further research will replicate and refine the Livability Analysis method.

Although the modeling results of the 10 potential BRT routes may appear to be relatively insignificant, three key considerations should be given to the results. First, CMAP’s demand model was not designed for the purpose of assessing a BRT system. Although the model had been modified, it was still limited. Second, the BRT model results reflected ridership as it would be in 2010. It did not consider the possibility of ridership increases over time. The model results did not describe ridership on the BRT routes themselves, but rather overall ridership within the BRT corridor. Further modifications to the network may be needed.

Conclusion

The study was innovative in that it went beyond traditional transportation metrics to attempt to screen the existing CTA bus network for the best first implementation of BRT routes in the Northeastern Illinois Region. In April 2013, CTA announced its plan to construct “gold-standard” BRT on Ashland Avenue (the same route recommended in this study) following a FTA-funded Livability Alternatives Analysis (Chicago Transit Authority 2012; Chicago Transit Authority 2013).

Application of the study methodology or variations thereof to other geographies and modes with less stringent physical constraints would provide beneficial insight into the validity of incorporating livability measures into transportation planning. The Chicago Metropolitan Agency for Planning (2012), for example, used a modified application of the Livability Analysis metrics—drawn explicitly from this study—for promoting extension of the CTA “L” Red Line. Additional changes to the Livability Analysis to conform to 49 U.S.C §5309 (2012) instead of the Livability Principles directly may be beneficial.

Acknowledgments

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Integrating Livability Principles into Transit Planning: Screening Chicago Bus Rapid Transit Opportunities

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Josh Ellis (jellis@metroplanning.org) is a Program Director at the MPC. His focus is on advancing the MPC’s environmental and economic goals through policy research, advocacy, and community engagement. He also manages the MPC’s geospatial analysis of emerging environmental, economic, and demographic trends. He directs MPC’s water resources programs and provides technical assistance through several regional partnerships, including the Northwest Water Planning Alliance. He co-authored Before the Wells Run Dry and now works with state, regional, and local leaders on strategies to sustainably manage Illinois’ finite water resources.
The Effect of Density and Trip-Chaining on the Interaction between Urban Form and Transit Demand

Sisinnio Concas and Joseph S. DeSalvo
University of South Florida

Abstract

It is unclear whether policies designed to reduce auto and increase transit usage achieve their objective. Evidence is mixed because most empirical research on these policies use ad hoc specifications, whereas our models are drawn from economic theory. Three models of increasing generality show how endogenizing relevant variables changes results obtained by others. The theoretical hypotheses are empirically tested using a dataset that integrates travel and land use. Our main findings are (1) population density has a small impact on transit demand, which decreases when residential location is endogenous; (2) households living farther from work use less transit, a result of trip-chaining; and (3) reducing the spatial allocation of non-work activities, improving transit accessibility at and around subcenters, and increasing the presence of retail locations in proximity to transit-oriented households would increase transit demand.

Introduction

Recently, urban policies have sought to reduce presumed inefficiencies associated with urban sprawl. Since it is assumed the auto is the main cause of urban sprawl (Glaeser and Khan 2004), the policies are intended to produce a more compact urban area, which, presumably, would reduce auto usage and increase transit usage. Evidence favorable to such policies is mixed.

The difficulty of generalizing findings is highlighted by the growing literature reviews and meta-analyses. In their most recent effort, Ewing and Cervero (2010) report that there are more than 200 studies in this topic, with two dozen surveys of the literature and two reviews of the many reviews. Most of this research involves regression of various measures of travel behavior on residential and employment density while controlling for traveler demographic characteristics. These studies have led to the conclusion that policy interventions to increase density are capable of reducing automobile use (Burchell et al. 1998; Cao et al. 2006; Ewing 1997). Nevertheless, criticism has centered on ad hoc specifications and omitted-variable bias. The former is due to lack of a theoretical foundation for the
empirical work, and the latter is due to likely simultaneity and endogeneity in the relationship between urban form and travel (Badoe and Miller 2000).

The influence of urban form on travel behavior is complicated by the evolution of the built environment, which might lead to residential self-sorting. "Self-sorting" refers to factors that induce households to choose a residential location, in part, due to idiosyncratic preferences for travel and location. If residential self-sorting is not accounted for, empirical findings overstate the efficacy of policies to affect travel behavior by changing the built environment. Mokhtarian and Cao (2008) provide a comprehensive review of empirical work on residential self-sorting. Although researchers recognize that idiosyncratic preferences for travel and location affect residential location, there is disagreement on how best to handle such preferences, which, if ignored, result in omitted-variable bias. The empirical treatment of omitted-variable bias in this context ranges from nested logit models (Cervero 2007) to sophisticated error-correlation models (Bowes and Ihlanfeldt 2001; Pinjari et al. 2007) and two-part models (Vance and Hedel 2007). Findings suggest that, after accounting for self-sorting, the built environment affects commute mode-choice behavior.

In addition, empirical work is lacking on the relationship between urban form and travel behavior that accounts for trip-chaining. A trip chain is defined as a sequence of trips linked together between two anchor destinations, such as home and work. The dearth of research on the effects of trip-chaining on the built environment is recognized by Ewing and Cervero (2009), who are unable to report land-use elasticity estimates in response to changes in multipurpose trip-chaining behavior.

To our knowledge, there is no empirical work accounting for the joint determination of residential location, trip-chaining, the area of non-work activities, and socio-demographic differences among individuals, with a theoretical foundation based on the tradeoff between commuting and non-work travel.

This paper attempts to fill this gap in the literature. We formulate three models of increasing generality. The purpose is to show how endogenizing relevant variables changes the results obtained by others. The theoretical hypotheses are empirically tested using a dataset that integrates travel and land-use.

Theory

Introduction

Economic analysis of the interaction between residential and work locations began with Alonso (1964), with important subsequent contributions by Mills (1972) and Muth (1969). In a budget-constrained, utility-maximization framework, the theory determines residential location as the result of a tradeoff between housing and transportation expenditures, given tastes, income, housing price, and transportation costs, in which all transportation for work and non-work activities is to the central business district (CBD) of the urban area. Individuals locate at a distance at which the marginal cost of transportation equals the marginal housing cost savings obtained by a move farther from the CBD. We retain this tradeoff but assume it occurs in a polycentric urban area, rather than a monocentric one. In this, we follow Anas and Kim (1996) and Anas and Xu (1999).
Trip-chaining describes how travelers link trips between locations within an activity space. A trip from home to work with an intermediate stop to drop children off at daycare is an example of a trip chain. Trip-chaining occurring on the home-job commute pair saves time. This time-saving, in turn, can be allocated either to additional non-work travel, thus increasing the overall demand for travel, or to a longer commute. The positive relationship between more complex trip chains and the home-work commute is confirmed by empirical work (Bhat 1997; Bhat 2001; Davidson 1991; Kondo and Kitamura 1987; McGuckin and Murakami 1999; Strathman 1995).

Both residential location and trip-chaining take place within a geographical area called the activity space. Drawing on Anas (2007), we assume that the activity space results from utility-maximizing behavior determining non-work travel. Individuals prefer to visit different locations, a behavior that positively affects the size of the activity space. The activity space, therefore, accounts for the effect of the built environment on the spatial dispersion of out-of-home activities. The activity space follows from the time geographic concept of the space-time prisms first introduced by Hägerstrand (1970) and subsequently used to simulate travel behavior responses to space-time constraints (Timmermans et al. 2002).

These variables all relate to travel demand, which we define as the number of work and non-work transit trips made by all members of a household. Finally, land use (which we proxy with population density) directly affects the spatial allocation of activities.

The General Model

These variables are brought together in the following general model (theoretically endogenous variables are in upper-case letters, while exogenous variables are in lower case).

\[ TC = TC(AS, RL, walk\_dist, veh, act\_tt, act\_dur, sch, subc\_dist) \]  
\[ AS = AS(TC, D, act\_dur, inc, r\_est) \]  
\[ TD = TD(TC, AS, RL, walk\_dist, t\_work, prk\_ride, ts\_tod, veh) \]  
\[ RL = RL(TC, TD, h\_price, h\_age, rooms, div, pov, own) \]  
\[ D = D(RL, AS, subc\_dist, c\_bd\_dist) \]

Equation (1) describes trip-chaining behavior occurring on the commute trip. Trip chaining, jointly determined with the activity space (AS) and residential location (RL), is affected by transit station proximity (walk_dist), vehicle availability (veh), travel behavior (act_tt and act_dur), number of school-age children (sch), and the distance between home and the nearest subcenter (subc_dist).

Equation (2) describes how the spatial extent of non-work activities (AS) responds to changes in urban form, being jointly determined with trip-chaining (TC) and urban form.
The activity space responds to the duration of non-work activities ($act\_dur$), household income ($inc$), and retail establishment concentrations ($r\_est$).

Equation (3) describes the demand for transit trips ($TD$), due to non-work travel, which is jointly determined with trip-chaining ($TC$), the activity space ($AS$), and residential location ($RL$). Transit-station proximity ($walk\_dist$) and the presence of a nearby transit stop ($tswork$) and of a park-and-ride facility ($prkride$) at the workplace also determine transit demand. To test the efficacy of transit-oriented-development policies in affecting ridership, we include the presence of a transit-oriented development near the residential unit ($ts\_tod$). Finally, the number of autos at the disposal of the household ($veh$) also determines transit demand.

Equation (4) describes residential location ($RL$), jointly determined with trip-chaining ($TC$) and transit demand ($TD$). We consider housing characteristics—pricing ($hprice$), age ($hage$), size ($rooms$), and tenure choice ($own$)—as factors affecting residential location, in addition to neighborhood characteristics, diversity ($div$) and poverty ($pov$).

Equation (5) describes population density ($D$), as jointly determined with residential location ($RL$) and the activity space ($AS$). In addition, the equation introduces variables serving as proxies for centrality dependence ($cbd\_dist$) and for polycentricity ($subc\_dist$).

Discussion of Our Choice of Variables

Residential Location ($RL$)

We define residential location as the job-residence pair ($RL$), measured as the distance in miles between home and work. This definition of residential location differs from that used in the current literature. Some researchers have considered residential location as a choice to reside within a geographical unit, such as a traffic assignment zone (Bhat and Guo 2004; Pinjari et al. 2007). Others have used transit proximity as a proxy for residential location (Cervero 2007). Although these usages are dictated by the need to distinguish the influence of the built environment from that of self-sorting, they are not based on a formal theory of residential location.

For the variables affecting $RL$, we use household income ($inc$), median house price ($hprice$), and, as proxies for transportation cost, distance between home and the CBD ($cbd\_dist$) and distance between home and the nearest subcenter ($subc\_dist$). The use of distance measures as controls in multivariate analysis of transit travel behavior is a common practice (Cervero and Wu 1998; Kuby et al. 2004; Pushkarev and Zupan, 1977; Pushkarev and Zupan, 1982; Zupan and Cervero, 1996).

We assume the location decision is based in part on idiosyncratic preferences for location and travel, which relaxes the assumption of common tastes in earlier models. To capture idiosyncratic preferences, we use house age ($hage$), number of rooms ($rooms$), and tenure choice, that is, whether the household is a renter or an owner ($own$). These variables control for housing preferences not directly affecting travel behavior but directly affecting the residential choice decision. To control for neighborhood characteristics, we include the percentage of households living below the poverty line ($pov$) and a diversity index ($div$). The former serves as a proxy for crime, while the latter is an index of ethnic heterogeneity that varies from 0 (only one race in the neighborhood) to 1 (no race is prevalent).
similar to Shannon’s diversity index. The Shannon Index compares diversity between habitat samples in terms of the proportion of individuals of a given species in the set (see Begon, Harper, and Townsend [1996] for a review).

Of these variables, house age has been used before as an instrumental variable in multivariate regression studies that considered travel behavior as endogenous to urban form (Boarnet and Crane 2001; Boarnet and Sarmiento 1998; Crane 2000; Crane and Crepeau 1998a; Crane and Crepeau 1998b), while the remaining ones are unique to this study although controls for neighborhood characteristics have been used elsewhere. For example, the proportion of block-group or census-tract population that is Black and the proportion Hispanic have been used as instruments by Boarnet and Sarmiento (1998) and the percent of foreigners by Vance and Hedel (2007).

**Trip Chaining (TC)**
In addition to determining residential location in a polycentric urban area, Anas’ theory (2007) also determines the sequence of non-work trip chains. To capture non-work trip chains, we use variables to control for factors affecting both the spatial extent of non-work activities and the ensuing travel behavior, specifically, travel time (act_tt) and the duration of non-work activity (act_dur). To capture variables affecting trip-chaining, we use the number of school-age children (sch), the number of vehicles owned by the household (veh), and the number of retail establishments (r_est) in the activity space. These variables are commonly used in the activity-based literature in modeling activity duration and scheduling (Bhat 1997; Bhat 1999; Bhat 2001; Bhat and Guo 2004) and activity travel patterns (Kuppam and Pendyala 2001).

**Activity Space (AS)**
There are several ways to measure the activity space. The simplest measure is represented by the standard distance deviation (SDD), calculated as a standardized distance of out-of-home activities from a mean geographic center. The mean activity center is analogous to the sample mean of a dataset, and it represents the sample mean of the x and y coordinates of non-work activities contained in each household activity set. Interpretation is relatively straightforward: a larger SDD indicates greater spatial dispersion of activity locations. Ebdon (1977) notes, however, that this measure is adversely affected by the presence of outliers. As a result of the squaring all the distances from the mean center, the extreme points have a disproportionate influence on the value of the standard distance. To attenuate this problem, we have chosen the standard distance ellipse (SDE), using the formula described in Levine (2005). These measures are illustrated in Figure 1.
The literature provides additional activity-space measures. For example, while Buliung and Kanaroglou (2006) use SDE, they also introduce the household activity space (HAS). HAS is an area-based geometry that defines a minimum convex polygon containing activity locations visited by a household during a reference period (i.e., the travel-survey period). The advantage of HAS is that it weights the activity space by the relevance of activities, such as their type (recreational, maintenance, etc.) and their relative frequencies. Although HAS reports an accurate geographical measurement of the activity space, Buliung and Remmel (2008) show that the use of the minimum convex polygon algorithm provides similar results to SDE in terms of behavioral interpretation. Other research shows that the choice of an appropriate shape representing an individual’s activity space is highly dependent on the spatial distributions and frequencies of the locations visited by the person in the given time period (Rai et al. 2007).

We hypothesize that densely-populated urban areas exhibit clustered activity locations, thus shrinking the size of the activity space, while the opposite is the case for less densely-populated areas. This affects the spatial allocation of activities, which affects the demand for travel. Recent research finds that households residing in decentralized, lower-density urban areas have a more dispersed travel pattern than their counterparts residing in centralized, high-density urban areas (Buliung and Kanaroglou 2006; Maoh and Kanaroglou 2007).

**Travel Demand (TD)**

We define travel demand (TD) as the number of work and non-work transit trips at the household level, a usage that departs from that of other researchers. For example, Boarnet and Crane (2001) assume that trip demand is either directly affected by land use or indirectly by influencing the cost of travel. In our models, land use (which we proxy with population density, D) directly affects the spatial allocation of activities.

Our measure of transit-station proximity (walk_dist) differs from that used elsewhere. Proximity is usually measured as the radius of a circular buffer around a station. Cervero
(2007), for example, used a half-mile radius. This measure of transit proximity fails to account for barriers that prevent access to a station located within the radius, which is why we use walking distance from the residence to the nearest transit station. Empirical studies on the relevance of transit station proximity to transit patronage show a strong relationship between transit use and station proximity (Cervero 2007; Cervero and Wu 1998). We also include the following measures of transit supply to account for the presence of a transit stop near the workplace (tswork), the supply of park-and-ride facilities near a transit stop (prkride), and the presence of a transit-oriented development (ts_tod) near the residential unit.

**Population Density** \((D)\)

In the long run, the simultaneous choice of location and travel decisions is assumed to affect density levels across a given urban area. Population density is treated as endogenous to the process and is affected by household travel decisions and location behavior. Aspects of this relationship and its influences on transit patronage have been previously considered in the literature. For example, while modeling long-run transit demand responses to fare changes, Voith (1997) treats density as endogenous and being affected directly by transit patronage levels. In the long run, these levels are affected by supply-side changes. Voith (1997) assumes that as transit services improve, more people tend to live in proximity to transit stations, thus increasing the demand for transit services. Empirically, we measure density, \(D\), as gross population density of the Census block group in which the household residential unit is located. The Census block-group area is measured in square miles.

**Data**

We use travel-diary data from the 2000 Bay Area Travel Survey (BATS2000). BATS2000 is a large-scale regional household travel survey conducted in the nine-county San Francisco Bay Area of California by the Metropolitan Transportation Commission (2008). Completed in the spring of 2001, BATS2000 provides consistent and rich information on travel behavior of 15,064 households with 2,504 households that make regular use of transit.

Household activity locations are those visited by surveyed household members during a specified period—in this case, two representative weekdays. BATS2000 reports the longitude and latitude of each activity. Using geographic information systems (GIS), we geocoded to the street address or street intersection 99.9 percent of home addresses and 80 percent of out-of-home activities, giving us precise locations of non-work activities, jobs, and residences.

Using GIS spatial matching procedures, we combined BATS2000 travel data with geographical data from the U.S. Census Bureau Summary File 3 and U.S. Census Bureau County Business Patterns (CBP), which gave us detailed social, economic, and housing characteristics at the block group level and variables related to non-residential land use, such as commercial densities. Table 1 contains the variable names, brief descriptions, and descriptive statistics.

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2 In MTC usage, a transit household has one or more members using transit at least once during the two-day surveying period.
TABLE 1. Variables and Descriptive Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Mean</th>
<th>S.D.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>inc</td>
<td>Household Income (1 if &lt; $10k to 15 if &gt; $150k)</td>
<td>10.34</td>
<td>3.45</td>
<td>1.00</td>
<td>15.00</td>
</tr>
<tr>
<td>sch</td>
<td>Number of children pre-k to middle school</td>
<td>0.65</td>
<td>0.98</td>
<td>0.00</td>
<td>7.00</td>
</tr>
<tr>
<td>veh</td>
<td>Household vehicles, number</td>
<td>1.85</td>
<td>0.95</td>
<td>0.00</td>
<td>9.00</td>
</tr>
<tr>
<td>own</td>
<td>Housing tenure (1=own, 0=renter)</td>
<td>0.69</td>
<td>0.46</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>walk_dist</td>
<td>Walking distance to nearest transit station, miles</td>
<td>0.31</td>
<td>0.37</td>
<td>0.00</td>
<td>3.00</td>
</tr>
<tr>
<td>tsw</td>
<td>Transit stop near work (1 within 0.5 mile, 0 otherwise)</td>
<td>0.25</td>
<td>0.43</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>prkride</td>
<td>Park &amp; ride lot near work (1 within 0.5 mi., 0 otherwise)</td>
<td>0.07</td>
<td>0.25</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>ts_tod</td>
<td>TOD stop near residence (1 within 0.5 mi., 0 otherwise)</td>
<td>0.01</td>
<td>0.12</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>cbd_dist</td>
<td>Residential unit distance to CBD, miles</td>
<td>44.70</td>
<td>25.20</td>
<td>0.17</td>
<td>137.12</td>
</tr>
<tr>
<td>subc_dist</td>
<td>Residential unit distance to nearest subcenter, miles</td>
<td>2.89</td>
<td>2.36</td>
<td>0.01</td>
<td>38.39</td>
</tr>
<tr>
<td>r_est</td>
<td>Retail establishment density (number/mile); ZIP code level</td>
<td>22.51</td>
<td>55.91</td>
<td>0.00</td>
<td>1,281.74</td>
</tr>
<tr>
<td>hprice</td>
<td>Median housing price, $; block group level</td>
<td>399,591</td>
<td>204,767</td>
<td>0</td>
<td>1,000,001</td>
</tr>
<tr>
<td>hage</td>
<td>Median housing age, year; block group level</td>
<td>35.49</td>
<td>14.86</td>
<td>1.00</td>
<td>61.00</td>
</tr>
<tr>
<td>rooms</td>
<td>Median number of rooms; block group level</td>
<td>5.92</td>
<td>1.04</td>
<td>0.00</td>
<td>9.10</td>
</tr>
<tr>
<td>pov</td>
<td>Proportion of households living below poverty level; block group level</td>
<td>0.06</td>
<td>0.06</td>
<td>0.00</td>
<td>0.79</td>
</tr>
<tr>
<td>div</td>
<td>Diversity index, 0=homogenous, 1=heterogeneous; block group level</td>
<td>0.58</td>
<td>0.19</td>
<td>0.00</td>
<td>0.99</td>
</tr>
<tr>
<td>act_dur</td>
<td>Non-work activity duration, minutes</td>
<td>131.05</td>
<td>89.86</td>
<td>2.00</td>
<td>1,440</td>
</tr>
<tr>
<td>act_tt</td>
<td>Travel time to non-work activity, minutes</td>
<td>81.16</td>
<td>98.23</td>
<td>0.00</td>
<td>2,897</td>
</tr>
<tr>
<td>TC</td>
<td>Stops on home-work route, number</td>
<td>1.17</td>
<td>1.33</td>
<td>0.00</td>
<td>8.00</td>
</tr>
<tr>
<td>TD</td>
<td>Household linked transit trips, number</td>
<td>0.39</td>
<td>0.99</td>
<td>0.00</td>
<td>9.00</td>
</tr>
<tr>
<td>AS</td>
<td>Household activity space, size of SDE; miles</td>
<td>16.83</td>
<td>32.61</td>
<td>0.75</td>
<td>437.23</td>
</tr>
<tr>
<td>RL</td>
<td>Distance home-work, miles</td>
<td>10.52</td>
<td>9.81</td>
<td>0.00</td>
<td>79.38</td>
</tr>
<tr>
<td>D</td>
<td>Gross population density, persons/mile; block group level</td>
<td>9,144</td>
<td>11,065</td>
<td>0.00</td>
<td>172,400</td>
</tr>
</tbody>
</table>

Note: Means represent proportions for 0/1 variables.

Estimation

Versions of the Model for Estimation

Equations (1)–(3) of the general model constitute Model I, which treats residential location and density as exogenous. Given these variables, the model jointly defines the activity space and the trip chain, which, in turn, determine travel demand, given consumption and location decisions. This may be interpreted as a short-run model in that residential location and density are predetermined.

Model II comprises Equations (1)–(4). In this extension, we relax the assumption of exogenous residential location. Treated as a choice variable, residential location is the outcome of a tradeoff between transportation and housing costs. Accounting for idiosyncratic
preferences for transportation and location, households choose an optimal home-work commute, while optimizing non-work trip chaining and the activity space, which, in turn, determine transit demand. This may be interpreted as an intermediate-run model in that residential location is endogenous while density is exogenous.

Model III is composed of Equations (1)–(5). In Equation (5) population density is endogenous. Explanatory variables serve as proxies for centrality dependence (cbd_dist) and for polycentricity (subc_dist). This may be interpreted as a long-run model in that it treats density (urban form) as endogenous.

In the structural equations of the models, endogenous variables appear on the right-hand side. Consequently, estimation requires structural equation modeling (SEM), also called simultaneous equation modeling. SEM is used to capture the causal influences of the exogenous variables on the endogenous variables and the causal influences of the endogenous variables on one another. In the transportation literature there exist several applications of SEM using cross-sectional data, for example, Pendyala (1998), Fuji and Kitamura (2000), and Golob (2000). Additional examples are discussed by Golob (2003). There are also studies of the causal relationships among travel behavior and urban form that are effectively represented in a structural equation framework (Cao et al. 2007; Guevara and Moshe 2006; Mokhtarian and Cao 2008; Peng et al. 1997).

**Model I: Endogenous Trip-Chaining, Activity Space, and Transit Demand**

In this specification, residential location (RL) and density (D) are exogenous. Given these variables, the model jointly determines the trip chain (TC), the activity space (AS), and transit demand (TD).

\[
TC = \alpha_0 + \alpha_1 \log(AS) + \alpha_2 \log(RL) + \alpha_3 \log(WD) + \alpha_4 \text{veh} + \alpha_5 \text{act}_{t_{\text{dur}}} + \\
\alpha_6 \text{act}_{t_{\text{sch}}} + \alpha_7 \text{sch} + \alpha_8 \text{subc dist} + \varepsilon_1
\]

\[
AS = \beta_0 + \beta_1 TC + \beta_2 D + \beta_3 \text{act}_{t_{\text{dur}}} + \beta_4 \text{inc} + \beta_5 r_{\text{estd}} + \varepsilon_2
\]

\[
TD = \gamma_0 + \gamma_1 TC + \gamma_2 AS + \gamma_3 WD + \gamma_4 RL + \gamma_5 \text{tswork} + \gamma_6 \text{prkride} + \\
\gamma_7 \text{ts tod} + \gamma_8 \text{veh} + \varepsilon_3
\]

The equations of Model I are estimated by three-stage least squares (3SLS). All three equations pass the rank condition for identification. The first equation is overidentified, and the other two are just identified. The results are given in Table 2. To ensure normality assumptions are met, some of the variables are entered in logs, namely, AS, D, and walk_dist.

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3 Endogeneity tests led to cbd_dist, subc_dist, and r_est being treated as endogenous in Model III.

4 Details are in an unpublished appendix available on request.
The joint determination of trip chaining and the spatial extent of non-work activities relate to transit patronage as hypothesized earlier. The presence of a transit stop at the workplace (tswork) positively affects transit demand, as does the presence of a TOD transit stop in proximity to the residence (ts_tod). The size of the activity space reduces as density increases, which, in turn, positively affects the demand for transit. At locations where non-work activities are more clustered, the need to engage in journeys requiring modes other than transit decreases, resulting in increased transit usage. This finding suggests that policies affecting the clustering of non-work activities, such as mixed land-use policies, are likely to significantly affect transit ridership levels. The relevance of this relationship is better appreciated, however, when residential location is endogenous.

### Table 2

Regression Results for Model I

<table>
<thead>
<tr>
<th>Equation</th>
<th>Coefficient</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Trip chaining, TC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS</td>
<td>0.0648</td>
<td>0.6960</td>
</tr>
<tr>
<td>RL</td>
<td>0.0096</td>
<td>0.0160</td>
</tr>
<tr>
<td>walk_dist</td>
<td>–0.0570</td>
<td>0.0000</td>
</tr>
<tr>
<td>veh</td>
<td>–0.0793</td>
<td>0.0100</td>
</tr>
<tr>
<td>act_tt</td>
<td>0.0014</td>
<td>0.0010</td>
</tr>
<tr>
<td>act_dur</td>
<td>–0.0022</td>
<td>0.0000</td>
</tr>
<tr>
<td>subc_dist</td>
<td>0.0439</td>
<td>0.0000</td>
</tr>
<tr>
<td>sch</td>
<td>0.0778</td>
<td>0.0000</td>
</tr>
<tr>
<td>constant</td>
<td>1.2771</td>
<td>0.0000</td>
</tr>
<tr>
<td>(2) Activity space, AS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>0.5863</td>
<td>0.0000</td>
</tr>
<tr>
<td>D</td>
<td>–0.0974</td>
<td>0.0000</td>
</tr>
<tr>
<td>act_dur</td>
<td>0.0001</td>
<td>0.6880</td>
</tr>
<tr>
<td>inc</td>
<td>0.0299</td>
<td>0.0000</td>
</tr>
<tr>
<td>r_est</td>
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</tr>
<tr>
<td>constant</td>
<td>1.7226</td>
<td>0.0000</td>
</tr>
<tr>
<td>(3) Transit demand, TD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>–0.6548</td>
<td>0.0000</td>
</tr>
<tr>
<td>AS</td>
<td>–0.3002</td>
<td>0.0010</td>
</tr>
<tr>
<td>RL</td>
<td>–0.0057</td>
<td>0.0070</td>
</tr>
<tr>
<td>walk_dist</td>
<td>–0.0800</td>
<td>0.0000</td>
</tr>
<tr>
<td>tswork</td>
<td>0.3848</td>
<td>0.0000</td>
</tr>
<tr>
<td>prkride</td>
<td>–0.0737</td>
<td>0.1510</td>
</tr>
<tr>
<td>ts_tod</td>
<td>0.2063</td>
<td>0.0600</td>
</tr>
<tr>
<td>veh</td>
<td>–0.0456</td>
<td>0.0390</td>
</tr>
<tr>
<td>constant</td>
<td>–0.1256</td>
<td>0.2150</td>
</tr>
</tbody>
</table>

N= 8,229; $\chi^2_{TC} = 589.8; \chi^2_{AS} = 514.4; \chi^2_{TD} = 1,697.5$
To appreciate the magnitude of the estimated effects, Table 3 reports point elasticities of transit demand with respect to selected explanatory variables. Elasticities are evaluated at data means and, because the models involve at least three simultaneous equations, are complicated to calculate.\footnote{Two unpublished appendices are available at request that detail the comparative static analyses and the elasticity calculations.}

Table 3 shows that a 20-percent increase in gross population density (D), equal to about 1,830 persons per square mile, produces a 1.8-percent increase in transit demand (TD). A doubling of the average walking distance (walk\textunderscore dist) to the nearest transit station, an increase from 0.3 miles to 0.6 miles, decreases transit demand by 7.9 percent; at about 1 mile, transit demand declines by 18.5 percent. The presence of a transit station within a half-mile of the workplace (tswork) increases transit demand by 38.5 percent. Living in proximity to a TOD transit station (ts\textunderscore tod) increases transit demand by about 20.6 percent. There is a ridership bonus for proximity to a station with accessibility features to promote transit use. We find a negative elasticity between residential location (RL) and transit use. This is consistent with the hypothesis that households with longer commutes engage in more complex trip chains, which positively affect the spatial extent of non-work activities. With exogenously fixed transit supply, as the activity space expands, transit demand declines.

The results also show that transit demand is sensitive to the presence of nearby subcenters (subc\textunderscore dist) or, in general, to decentralization. The farther a household lives from a subcenter, the less it uses transit. A 50 percent increase in distance to a subcenter, from 2.9 to 4.3 miles, decreases transit demand by about 14.1 percent. This happens because households rely more on other modes to carry out complex trip chains, a finding confirmed by the elasticity of trip-chaining with respect to distance to the nearest subcenter. This result is consistent with the current literature on transit competitiveness and polycentric metropolitan regions. For example, Casello (2007) finds that transit improvements between and within subcenters are necessary to realize the greatest improvements in transit performance.

**Table 3.** Selected Elasticities for Model I

<table>
<thead>
<tr>
<th>Elasticity</th>
<th>RL</th>
<th>D</th>
<th>walk_dist</th>
<th>subc_dist</th>
<th>r_est</th>
<th>tswork*</th>
<th>ts_tod*</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC</td>
<td>0.090</td>
<td>-0.006</td>
<td>-0.051</td>
<td>0.113</td>
<td>-0.047</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AS</td>
<td>0.062</td>
<td>-0.101</td>
<td>-0.035</td>
<td>0.077</td>
<td>-0.051</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TD</td>
<td>-0.097</td>
<td>0.089</td>
<td>-0.079</td>
<td>-0.282</td>
<td>0.045</td>
<td>0.385</td>
<td>0.206</td>
</tr>
</tbody>
</table>

*Indicates a proportional change.

**Model II: Endogenous Trip-Chaining, Activity Space, Transit Demand, and Residential Location**

In this extension, we relax the assumption of exogenous residential location. Given density, the model jointly determines the trip chain, the activity space, transit demand, and residential location. The equations of Model II are estimated by three-stage least squares (3SLS). All four equations pass the rank condition for identification.
The first equation is overidentified, and the other three of just identified. The results are given in Table 4.

\[ TC = \alpha_0 + \alpha_1 AS + \alpha_2 RL + \alpha_3 WD + \alpha_4 veh + \alpha_5 act_{tt} + \alpha_6 act_{dur} + \alpha_7 sch + \alpha_8 subc_dist + \epsilon_1 \]

\[ AS = \beta_0 + \beta_1 TC + \beta_2 D + \beta_3 act_{dur} + \beta_4 inc + \beta_5 r_{estd} + \epsilon_2 \]

\[ TD = \gamma_0 + \gamma_1 TC + \gamma_2 AS + \gamma_3 WD + \gamma_4 RL + \gamma_5 tswork + \gamma_6 prkride + \gamma_7 ts_{tod} + \gamma_8 veh + \epsilon_3 \]

\[ RL = \delta_0 + \delta_1 TC + \delta_2 TD + \delta_3 hprice + \delta_4 hage + \delta_5 rooms + \delta_6 div + \delta_7 pov + \delta_8 own + \epsilon_4 \]

The first equation is overidentified, and the other three of just identified. The results are given in Table 4.
### Table 4. Regression Results for Model II

<table>
<thead>
<tr>
<th>Equation</th>
<th>Coefficient</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(1) Trip chaining, TC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS</td>
<td>0.0725</td>
<td>0.7140</td>
</tr>
<tr>
<td>RL</td>
<td>0.0096</td>
<td>0.4130</td>
</tr>
<tr>
<td>walk_dist</td>
<td>–0.0573</td>
<td>0.0000</td>
</tr>
<tr>
<td>veh</td>
<td>–0.0786</td>
<td>0.0130</td>
</tr>
<tr>
<td>act_tt</td>
<td>0.0014</td>
<td>0.0020</td>
</tr>
<tr>
<td>act_dur</td>
<td>–0.0022</td>
<td>0.0000</td>
</tr>
<tr>
<td>subc_dist</td>
<td>0.0435</td>
<td>0.0000</td>
</tr>
<tr>
<td>sch</td>
<td>0.0778</td>
<td>0.0000</td>
</tr>
<tr>
<td>constant</td>
<td>1.2604</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>(2) Activity space, AS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>0.2357</td>
<td>0.0000</td>
</tr>
<tr>
<td>D</td>
<td>–0.0858</td>
<td>0.0000</td>
</tr>
<tr>
<td>act_dur</td>
<td>–0.0007</td>
<td>0.0000</td>
</tr>
<tr>
<td>hhinc</td>
<td>0.0412</td>
<td>0.0000</td>
</tr>
<tr>
<td>r_est</td>
<td>–0.0014</td>
<td>0.0000</td>
</tr>
<tr>
<td>constant</td>
<td>2.0943</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>(3) Transit demand, TD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>–0.6964</td>
<td>0.0000</td>
</tr>
<tr>
<td>AS</td>
<td>–0.2598</td>
<td>0.0250</td>
</tr>
<tr>
<td>RL</td>
<td>–0.0090</td>
<td>0.3110</td>
</tr>
<tr>
<td>walk_dist</td>
<td>–0.0669</td>
<td>0.0000</td>
</tr>
<tr>
<td>tswork</td>
<td>0.3716</td>
<td>0.0000</td>
</tr>
<tr>
<td>prkride</td>
<td>–0.0669</td>
<td>0.2020</td>
</tr>
<tr>
<td>ts_tod</td>
<td>0.1304</td>
<td>0.2560</td>
</tr>
<tr>
<td>veh</td>
<td>–0.0365</td>
<td>0.0990</td>
</tr>
<tr>
<td>constant</td>
<td>–0.1119</td>
<td>0.2720</td>
</tr>
<tr>
<td><strong>(4) Residential location, RL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>3.7324</td>
<td>0.0000</td>
</tr>
<tr>
<td>TD</td>
<td>–1.2408</td>
<td>0.0080</td>
</tr>
<tr>
<td>hprice</td>
<td>–2.8117</td>
<td>0.0000</td>
</tr>
<tr>
<td>hage</td>
<td>–0.0849</td>
<td>0.0000</td>
</tr>
<tr>
<td>rooms</td>
<td>1.1279</td>
<td>0.0000</td>
</tr>
<tr>
<td>div</td>
<td>–2.6312</td>
<td>0.0000</td>
</tr>
<tr>
<td>pov</td>
<td>–5.9629</td>
<td>0.0130</td>
</tr>
<tr>
<td>own</td>
<td>0.4966</td>
<td>0.0620</td>
</tr>
<tr>
<td>constant</td>
<td>39.1808</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

N = 8,212; \( \chi^2 \) _{TC} = 341.5; \( \chi^2 \) _{AS} = 419.9; \( \chi^2 \) _{TD} = 1845.0; \( \chi^2 \) _{RL} = 444.8
The Effect of Density and Trip-Chaining on the Interaction between Urban Form and Transit Demand

Table 5 reports selected point elasticities for statistically significant estimates. Compared to Model I, endogenous residential location reduces the magnitude of the elasticity of travel demand with respect to density by 19 percent. When households can locate anywhere in an urban area and when they adjust trip chaining and commuting costs, an exogenous 20-percent increase in density produces a 1.4-percent increase in the demand for transit.

<table>
<thead>
<tr>
<th>Elasticity</th>
<th>D</th>
<th>walk_dist</th>
<th>subc_dist</th>
<th>r_est</th>
<th>tswork*</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC</td>
<td>-0.006</td>
<td>-0.052</td>
<td>0.115</td>
<td>-0.002</td>
<td>-</td>
</tr>
<tr>
<td>AS</td>
<td>-0.087</td>
<td>-0.014</td>
<td>0.032</td>
<td>-0.033</td>
<td>-</td>
</tr>
<tr>
<td>TD</td>
<td>0.072</td>
<td>-0.051</td>
<td>-0.277</td>
<td>0.028</td>
<td>0.372</td>
</tr>
<tr>
<td>RL</td>
<td>-0.006</td>
<td>-0.002</td>
<td>0.060</td>
<td>-0.002</td>
<td>-</td>
</tr>
</tbody>
</table>

*Indicates a proportional change.

Accounting for self-sorting, through choice of residential location, reduces the relevance of transit-station proximity to the residence, indicated by a 35-percent decrease in magnitude in the point elasticity estimate with respect to Model I. An increase from 0.3 to 0.6 miles to the nearest transit station reduces transit demand by only 5.1 percent, as opposed to the 7.9-percent reduction of Model I. This result shows that self-sorting is less relevant than Cervero (2007) noted. He found that self-sorting accounts for about 40 percent of transit ridership for individuals residing near a transit station.

The specification of Model II helps us understand the reasons for the changes from Model I. In Model II, households optimally choose residential location and non-work activities, choices that optimally define the spatial extent of non-work activities. Households locate their residences farther from their job locations, trading lower housing costs for increased commute distance. Trip chaining optimization is part of this tradeoff, which leads to an expansion of the activity space. This, in turn, reduces opportunities to use transit for non-work travel. This behavior is empirically validated by the statistical significance of all housing and neighborhood controls in the residential location equation.

Model III: Endogenous Trip-Chaining, Activity Space, Transit Demand, Residential Location, and Density

In this extension, we relax the assumption of exogenous density at the residential unit location. The model jointly determines the trip chain, the activity space, transit demand, residential location, and density.
The Effect of Density and Trip-Chaining on the Interaction between Urban Form and Transit Demand

\[ TC = \alpha_0 + \alpha_1 AS + \alpha_2 RL + \alpha_3 WD + \alpha_4 veh + \alpha_5 act_{tt} + \alpha_6 act_{dur} + \alpha_7 sch + \alpha_8 subc\_dist + \varepsilon_1 \]

\[ AS = \beta_0 + \beta_1 TC + \beta_2 D + \beta_3 act\_dur + \beta_4 inc + \beta_5 r\_estd + \varepsilon_2 \]

\[ TD = \gamma_0 + \gamma_1 TC + \gamma_2 AS + \gamma_3 WD + \gamma_4 RL + \gamma_5 tswork + \gamma_6 prkride + \gamma_7 ts\_tod + \gamma_8 veh + \varepsilon_3 \]

\[ RL = \delta_0 + \delta_1 TC + \delta_2 TD + \delta_3 hprice + \delta_4 hage + \delta_5 rooms + \delta_6 div + \delta_7 pov + \delta_8 own + \varepsilon_4 \]

\[ D = \vartheta_0 + \vartheta_1 RL + \vartheta_2 AS + \vartheta_3 subc\_dist + \vartheta_4 cbd\_dist + \varepsilon_5 \]

All five equations pass the rank condition for identification. The first equation is overidentified, and the other equations are just identified. The equations of Model III are estimated by three-stage least squares (3SLS). The results are given in Table 6.

In the long run, the simultaneous choice of location and travel affects urban density. Aspects of this relationship have been considered in the literature. For example, while modeling long-run transit demand responses to fare changes, Voith (1997) treats density as endogenous and as being affected directly by transit patronage levels. In the long run, these levels are affected by supply-side changes. Voith (1997) assumes that as transit services improve, more people live in proximity to transit stations, thus increasing the demand for transit services. Our estimation shows that both CBD and subcenter distance from the residence are statistically significant in determining density. The signs of \textit{cbd\_dist} and \textit{subc\_dist} are negative, as expected.
<table>
<thead>
<tr>
<th>Equation</th>
<th>Coefficient</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Trip chaining, TC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS</td>
<td>1.00867</td>
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</tr>
<tr>
<td>RL</td>
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</tr>
<tr>
<td>walk_dist</td>
<td>−0.66261</td>
<td>0.0000</td>
</tr>
<tr>
<td>veh</td>
<td>−0.02917</td>
<td>0.3570</td>
</tr>
<tr>
<td>act_tt</td>
<td>−0.00093</td>
<td>0.0560</td>
</tr>
<tr>
<td>act_dur</td>
<td>−0.00036</td>
<td>0.2650</td>
</tr>
<tr>
<td>subc_dist</td>
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</tr>
<tr>
<td>sch</td>
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<td>0.0000</td>
</tr>
<tr>
<td>constant</td>
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<td>0.0000</td>
</tr>
<tr>
<td>(2) Activity space, AS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>0.53891</td>
<td>0.0000</td>
</tr>
<tr>
<td>D</td>
<td>−0.28170</td>
<td>0.0000</td>
</tr>
<tr>
<td>act_dur</td>
<td>−0.00004</td>
<td>0.8390</td>
</tr>
<tr>
<td>hhinc</td>
<td>0.01819</td>
<td>0.0000</td>
</tr>
<tr>
<td>r_est</td>
<td>−0.00177</td>
<td>0.0790</td>
</tr>
<tr>
<td>constant</td>
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<td>0.0000</td>
</tr>
<tr>
<td>(3) Transit demand, TD</td>
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<td></td>
</tr>
<tr>
<td>TC</td>
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<td>0.0030</td>
</tr>
<tr>
<td>AS</td>
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<td>0.0540</td>
</tr>
<tr>
<td>RL</td>
<td>0.01619</td>
<td>0.0700</td>
</tr>
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<td>walk_dist</td>
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</tr>
<tr>
<td>tswork</td>
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<td>0.0000</td>
</tr>
<tr>
<td>prkride</td>
<td>−0.07878</td>
<td>0.0840</td>
</tr>
<tr>
<td>ts_tod</td>
<td>0.12797</td>
<td>0.1980</td>
</tr>
<tr>
<td>veh</td>
<td>−0.06411</td>
<td>0.0020</td>
</tr>
<tr>
<td>constant</td>
<td>−1.31138</td>
<td>0.0000</td>
</tr>
<tr>
<td>(4) Residential location, RL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>2.46949</td>
<td>0.0000</td>
</tr>
<tr>
<td>TD</td>
<td>−1.16775</td>
<td>0.0130</td>
</tr>
<tr>
<td>hprice</td>
<td>−2.79304</td>
<td>0.0000</td>
</tr>
<tr>
<td>hage</td>
<td>−0.09605</td>
<td>0.0000</td>
</tr>
<tr>
<td>rooms</td>
<td>1.34316</td>
<td>0.0000</td>
</tr>
<tr>
<td>div</td>
<td>−6.19042</td>
<td>0.0000</td>
</tr>
<tr>
<td>pov</td>
<td>−4.50750</td>
<td>0.0060</td>
</tr>
<tr>
<td>own</td>
<td>1.37799</td>
<td>0.0000</td>
</tr>
<tr>
<td>constant</td>
<td>40.31047</td>
<td>0.0000</td>
</tr>
<tr>
<td>(5) Density, D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RL</td>
<td>−0.00907</td>
<td>0.4000</td>
</tr>
<tr>
<td>AS</td>
<td>−0.53331</td>
<td>0.0000</td>
</tr>
<tr>
<td>cbd_dist</td>
<td>−0.04010</td>
<td>0.0000</td>
</tr>
<tr>
<td>subc_dist</td>
<td>−0.07071</td>
<td>0.0190</td>
</tr>
<tr>
<td>constant</td>
<td>11.76875</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

N= 8,212; $\chi^2_{TC} = 2,512.8$; $\chi^2_{AS} = 611.2$; $\chi^2_{TD} = 1,712.7$; $\chi^2_{RL} = 646.3$; $\chi^2_{D} = 1,448.6$
Findings
Table 7 compares the point elasticities of Model III with preceding estimates and summarizes our main findings. We find that exogenous density change does not have a large effect on transit demand, and the magnitude of the effect decreases when residential location becomes endogenous. A 20-percent increase in gross population density (1,830 persons per square mile) increases transit demand from a minimum of 1.4 percent to a maximum of 1.8 percent.

Treating density endogenously results in a more elastic travel demand with respect to distance to the nearest transit center. The elasticity of transit demand with respect to distance to the CBD (–0.09) is substantially less in absolute value than the elasticity with respect to distance to the nearest subcenter (–0.45).

### TABLE 7.
Selected Transit-Demand Elasticities

<table>
<thead>
<tr>
<th>Elasticity</th>
<th>Model I&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Model II&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Model III&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.089</td>
<td>0.072</td>
<td>na</td>
</tr>
<tr>
<td>Walking distance</td>
<td>–0.079</td>
<td>–0.051</td>
<td>–0.769</td>
</tr>
<tr>
<td>Transit station at workplace*</td>
<td>0.385</td>
<td>0.372</td>
<td>0.446</td>
</tr>
<tr>
<td>TOD station*</td>
<td>0.206</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Distance to CBD</td>
<td>na</td>
<td>na</td>
<td>–0.087</td>
</tr>
<tr>
<td>Distance to nearest subcenter</td>
<td>–0.282</td>
<td>–0.277</td>
<td>–0.385</td>
</tr>
<tr>
<td>Retail establishments density</td>
<td>0.045</td>
<td>0.028</td>
<td>0.077</td>
</tr>
<tr>
<td>Residential location</td>
<td>–0.097</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

<sup>a</sup>Residential location and density exogenous.
<sup>b</sup>Density exogenous.
<sup>c</sup>All endogenous.
<sup>na</sup> = not available.
*Indicates a proportional change.

Subcenters play a more important role, and our findings support a policy of providing transit services in decentralized employment and residential areas to increase ridership. In other words, transit patronage is more responsive to a residential location near a subcenter than near the CBD. This result is consistent with recent findings of increased transit use in better served decentralized urban areas (Brown and Thompson 2008; Thompson and Brown 2006) and findings showing that transit ridership is not affected by the CBD (Brown and Nego 2007).

The importance of station proximity to transit demand decreases after accounting for idiosyncratic preferences for location. In Model II, the elasticity of transit demand with respect to walking distance is about one-third smaller than in Model I, in which residential location and density are exogenous. This decline in magnitude results from allowing households to choose their residential location and by accounting for omitted-variable

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<sup>4</sup>The variables cb_dist, subc_dist, and r_est appear as explanatory variables but are treated as endogenous in Model III. An initial specification treated these three variables as exogenous, but overidentification tests show that this treatment led to weak instruments, a problem leading to inconsistent estimates. McMillen (2001) finds that subcenters are endogenous to density.
bias. On the other hand, the endogenous treatment of density and station proximity results in a much higher elasticity (−0.77).

Transit station proximity to a workplace also has a significant positive impact on ridership, as indicated by the magnitude of the proportional changes across all three models. Likewise, in Model I transit-oriented development near transit stations has a positive impact on transit use; a TOD stop increases transit demand by about 21 percent. A transit station near a workplace exerts a positive impact on ridership, as indicated by the magnitude of the proportional changes across all three models.

The importance of mixed-use development to increase transit patronage is highlighted by the elasticity of travel demand with respect to retail establishment density. Model II shows that a 20-percent increase in retail establishment density (or about 28 establishments per square mile) increases transit demand by 1.5 percent.

Households living farther from work use less transit, which is due to trip-chaining behavior. Such households engage in complex trip chains and have, on average, a more dispersed activity space, which requires reliance on more flexible modes of transportation. The results support policies that would reduce the spatial allocation of activities and improve transit accessibility at and around subcenters. Similar results can be obtained by policies that increase the presence of retail locations in proximity to transit-oriented households.

Conclusions
The debate on the relationship between urban form and transit travel has shifted from the need to determine minimum density thresholds that support transit to the need to provide reliable information to guide decision makers about what mix of land-use policies would better promote transit use. The models developed in this paper move towards this direction by studying the relationship between transit travel and the built environment in an increasingly suburban environment and decentralized employment. By explicitly acknowledging the complexity of travel arrangements (i.e., trip-chaining), we show that land-use policies can be successful in increasing transit patronage. The results of our work indicate that while population density is a factor in determining demand, targeting land-use policies affecting residential location decisions and development in suburban areas can be more effective.

The models of this study require a substantial amount of information, not only in terms of travel behavior data from travel diaries, but also on the spatial location of residences, work, and non-work activities. The increased sophistication of communication systems that can easily track individuals’ travel patterns in space and time is making the data-collection effort less daunting, allowing increased use of sophisticated models, such as the ones developed in this paper.

Notwithstanding the validity of the post-estimation tests, there still exists the possibility of endogeneity of some of the exogenous variables. This endogeneity, although confuted by statistical tests, is not ruled out by theoretical assumptions. For example,
while this study treats vehicle ownership as exogenous and not directly influenced by the location decision, the literature contains studies that consider vehicle ownership as a discrete-choice variable endogenous to the residential location process and to density levels (Spissu et al. 2009). As discussed in this paper, the implications of treating a variable as exogenous, while being endogenous to the process, are not trivial.

Finally, the behavioral models we presented rely on the assumption that households can save time by engaging in trip chaining. Time savings are then reallocated to either more non-work travel or to an extended commute. The model does not explicitly explain what happens to leisure time. The inclusion of total time constraints that include all relevant time uses (in-home and out-of-home) could provide additional insight on time use and its effect on trip chaining.

References


About the Authors

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Improving Fuel Efficiency and Reducing Carbon Emissions from Buses in India

Sudhir Gota
Parthaa Bosu and Sameera Kumar Anthapur, Clean Air Asia

Abstract

There is a growing public transport crisis in India, with a tremendous increase in the number of private vehicles. Many public bus corporations are operating with net financial losses and rely on government subsidies to keep operations going; therefore, investment in new buses and technology upgrades is rare. Of the various expenditures that bus corporations incur, fuel costs account for 30 percent. There is a strong need to improve fuel efficiency of buses to not only improve the financial viability of the bus companies but also to reduce their environmental and related health impacts. This study analyzes data on more than 500 buses from 3 leading bus corporations in India and identifies measures that can be implemented to improve fuel efficiency and reduce emissions.

Introduction: Status of Bus Transport in India

In Asia, growing income and increasing investments in the transport sector, especially in infrastructure, are translating into exploding growth in both urban and intercity transport activities, with rapid increases in motorization levels. In India, vehicle registrations increased from 1.8 million in the early 1970s to more than 100 million in 2008 (Ministry of Road Transport and Highways 2008). Two-wheelers and cars constitute more than 85 percent of registered vehicles. In 2008, buses represented only 1.3 percent of registered vehicles, a substantial drop from 11 percent in 1960s (Ministry of Urban Development 2008). The Ministry of Urban Development (MOUD) report (2008) compared the public transport trips for six different city types based on population and found a decrease in all of them, ranging from 20–72 percent.

The majority of the Indian bus fleet is held by private bus operators, who are not formally organized. The organized sector of the bus industry—the State Road Transport Undertakings (SRTUs)—is supported by the government under the Road Transport Corporation (RTC) Act of 1950 and accounts for only 8 percent of the national bus fleet based on vehicle registrations. Data for bus transport exist only for this 8 percent of the bus fleet. In 2010, the SRTUs carried 70 million passengers per day, generating about 501 billion passenger kilometers (pkm) annually, and approximately 95 percent of these passenger kilometers represent intercity travel. (Report of the Sub Group on State Road Transport Undertakings).
In 2006, the Indian Government formulated the National Urban Transport Policy (NUTP) with a view to provide better transport facilities. The policy was supported by the launch of Jawaharlal Nehru National Urban Renewal Mission (JNNURM), which facilitated the funding for urban services, including transport. Recognizing that organized bus transport services were available in only 24 Indian cities in 2007 (Singh 2010), increasing the number and quality of buses was taken up as a priority. To further this objective, as part of a stimulus package in 2009, the Government of India provided financial incentives for bus purchases by municipal governments that implemented a set of prescribed reforms. The target was the procurement at least 15,000 new buses nationwide. According to the financing mechanism, cities with populations over 4 million (per Census 2001) were eligible for Central Government assistance equivalent to 35 percent of the total project costs. For cities with populations between 1 and 4 million, assistance was available for 50 percent, and for cities with less than 1 million, the share was 80 percent. This stimulus scheme resulted in visible increases in bus numbers in many cities between 2009 and 2011, but most of the public transport agencies are still in financial loss. In 2009–2010, only five state transport corporations had net annual profits, and the total combined losses of the 34 reporting SRTUs were more than 50.8 billion INR (Indian Rupee) or US $1.01 billion (CIRT 2010). This issue is discussed in subsequent sections.

**Bus Carbon Emissions and Fuel Costs**

It is estimated that 20 percent of India’s CO\textsubscript{2} emissions from the transportation sector are from buses (Clean Air Asia 2012). Further, it has been estimated that if the current trip mode share of public transport is retained, CO\textsubscript{2} emissions will increase two- or three-fold between 2008 and 2025 due to a rapid growth in urban population and an increase in the number of trips (Fabian and Gota 2009).

Buses accounted for 12 percent of the total diesel consumption in India in 2008–2009 (Government of India 2010) and were a significant contributor to urban air pollution (Clean Air Asia 2012, CPCB 2011, Fabian and Gota 2009). Fuel cost is about 30 percent of the total expenses for Indian bus companies (ownership, management, maintenance, employees, etc). Over the past decade, the fuel cost per kilometer of bus travel has increased from INR 3.64 in 2000 to INR 7.24 in 2009 (CIRT 2010, 7) in spite of slight improvements in fuel efficiency of the buses (CIRT 2010). With the partial deregulation of diesel prices in 2013, the expenditure on fuel and, therefore, per-kilometer cost will tend to increase further, assuming the fuel efficiency remains the same or continues to reduce. Improvements in fuel efficiency can improve a bus company’s financial viability and reduce environmental and related health impacts associated with bus transport.

**Objective**

The objective of this research was to investigate the potential for improving fuel efficiency and reducing CO\textsubscript{2} emissions of Indian bus fleets.

**Methodology**

The focus of this research was an understanding of bus operation and management practices by collecting and analyzing operational data to determine improvement measures.
The bus corporations chosen were of both intercity and urban operations and consisted of different types of buses in emission standards, manufacturer types, models, etc. All three bus corporations—Bangalore Metropolitan Transport Corporation (BMTC), Karnataka State Road Transport Corporation (KSRTC), and State Express Transport Corporation (SETC)—are recognized as top performers in the country in the areas of finance, application of best practices, adoption of new technology, high efficiency, and patronage. Therefore, insights from these organizations should ideally set a benchmark for the rest of the industry. A questionnaire based on the 2011 Energy Sector Management Assistance Program (ESMAP) study was developed to capture management insights and was incorporated into the toolkit as an intervention measure. The responses were captured in one-on-one meetings with top management. A multi-stakeholder approach was then adopted for consultations with key bus industry, public transport agencies, government officials, research institutions, and non-government organizations to discuss the data and develop the recommendations.

**Insights from Data Analysis**

Detailed operational and maintenance data from more than 500 buses was collected. Data from a period of one year was collected for each of the buses. The analysis was conducted by grouping bus data by depot, as each depot had the same bus manufacturer, and then grouping data by the emission standards the buses were designed to meet.

<table>
<thead>
<tr>
<th>TABLE 1.</th>
<th>Data Collected from Bus Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bus registration number</td>
</tr>
<tr>
<td>2</td>
<td>Year of manufacture</td>
</tr>
<tr>
<td>3</td>
<td>Fuel type</td>
</tr>
<tr>
<td>4</td>
<td>Manufacturer (company)</td>
</tr>
<tr>
<td>5</td>
<td>Bus type (low floor, standard)</td>
</tr>
<tr>
<td>6</td>
<td>AC or non-AC</td>
</tr>
<tr>
<td>7</td>
<td>Operation (city, intercity)</td>
</tr>
<tr>
<td>8</td>
<td>Total carrying capacity</td>
</tr>
<tr>
<td>9</td>
<td>Fuel consumed per year (kilo liters)</td>
</tr>
<tr>
<td>10</td>
<td>Effective km per year</td>
</tr>
<tr>
<td>11</td>
<td>Dead km per year</td>
</tr>
<tr>
<td>12</td>
<td>Days used per year</td>
</tr>
<tr>
<td>13</td>
<td>Average speed, peak hour (kmph)</td>
</tr>
<tr>
<td>14</td>
<td>Average speed, non-peak hour (kmph)</td>
</tr>
<tr>
<td>15</td>
<td>Average occupancy, peak hour</td>
</tr>
<tr>
<td>16</td>
<td>Average occupancy, non-peak hour</td>
</tr>
<tr>
<td>17</td>
<td>Total ridership per year</td>
</tr>
<tr>
<td>18</td>
<td>Total idling time per day (min)</td>
</tr>
<tr>
<td>19</td>
<td>Number of trips per day</td>
</tr>
<tr>
<td>20</td>
<td>Average trip length (km)</td>
</tr>
</tbody>
</table>
Improving Fuel Efficiency and Reducing Carbon Emissions from Buses in India

From the data collected under the parameters in Table 1, the summary of the indicators developed is shown in Table 2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BMTC</th>
<th>KSRTC</th>
<th>SETC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of buses</td>
<td>185</td>
<td>312</td>
<td>52</td>
</tr>
<tr>
<td>Average fuel efficiency (kmpl)</td>
<td>3.77</td>
<td>4.28</td>
<td>5.04</td>
</tr>
<tr>
<td>Number of days used per year</td>
<td>312</td>
<td>334</td>
<td>260</td>
</tr>
<tr>
<td>Bus utilization per day (km)</td>
<td>225</td>
<td>432</td>
<td>692</td>
</tr>
<tr>
<td>Average passengers per bus on road per day</td>
<td>504</td>
<td>281</td>
<td>85</td>
</tr>
<tr>
<td>Passenger load factor (%)</td>
<td>104</td>
<td>70</td>
<td>76</td>
</tr>
<tr>
<td>Total passenger-kilometers (M)</td>
<td>747</td>
<td>1475</td>
<td>288</td>
</tr>
<tr>
<td>Average passenger lead (avg. distance traveled by passenger, km)</td>
<td>25.85</td>
<td>313</td>
<td>294</td>
</tr>
<tr>
<td>Dead kilometers (00,000)</td>
<td>1.07</td>
<td>8.38</td>
<td>1.01</td>
</tr>
<tr>
<td>Gross bus utilization/year (00,000)</td>
<td>0.7</td>
<td>1.41</td>
<td>1.81</td>
</tr>
<tr>
<td>Average speed (kmph)</td>
<td>40</td>
<td>48</td>
<td>67</td>
</tr>
<tr>
<td>Average effective km (%)</td>
<td>99.1</td>
<td>98</td>
<td>98.9</td>
</tr>
<tr>
<td>Average dead km (%)</td>
<td>0.86</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>Average age of bus (yr)</td>
<td>6.26</td>
<td>3.29</td>
<td>4.02</td>
</tr>
<tr>
<td>Scrapping limit (yr)</td>
<td>10</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Number of over-age buses</td>
<td>15</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Average idling time (min)</td>
<td>34</td>
<td>45</td>
<td>43</td>
</tr>
</tbody>
</table>

BMTC = Bangalore Metropolitan Transport Corporation  
KSRTC = Karnataka State Road Transport Corporation  
SETC = State Express Transport Corporation

There is a perception among industry experts and fleet managers that introducing new buses with improved emission standards causes a substantial decrease in the fuel efficiency of buses, thus lowering the fleet fuel efficiency. However, as shown in Table 3 and based on our analysis, it was found that old buses with lower emissions standards are experiencing lower fuel efficiency when compared with newer buses. Data from all the three agencies substantiate this argument, except in the case of Euro I of BMTC. The deterioration of buses due to extensive use over the years dominates the impact of fuel efficiency reductions due to emissions standard improvement. So, as a new bus replaces an older bus, it would be incorrect to assume that the fuel efficiency of buses would be reduced.
Improving Fuel Efficiency and Reducing Carbon Emissions from Buses in India

### TABLE 3.
Kilometers Traveled and Fuel Consumed Based on Emissions Standards

<table>
<thead>
<tr>
<th>Agency</th>
<th>Bus Type</th>
<th>Year of Manufacture</th>
<th>Fuel Consumed (kilo liters)</th>
<th>Vehicle km Traveled (km)</th>
<th>Fuel Efficiency (kmpl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMTC</td>
<td>Euro IV</td>
<td>&gt;2010</td>
<td>117</td>
<td>517,940</td>
<td>4.43</td>
</tr>
<tr>
<td></td>
<td>Euro III</td>
<td>2006–2010</td>
<td>2,022</td>
<td>6,886,458</td>
<td>3.41</td>
</tr>
<tr>
<td></td>
<td>Euro I</td>
<td>2000–2001</td>
<td>355</td>
<td>1,629,026</td>
<td>4.59</td>
</tr>
<tr>
<td>KSRTC</td>
<td>Euro III</td>
<td>2006–2010</td>
<td>5,402</td>
<td>23,396,049</td>
<td>4.33</td>
</tr>
<tr>
<td></td>
<td>Euro II</td>
<td>2002–2005</td>
<td>4,773</td>
<td>20,193,029</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>Euro I</td>
<td>2000–2001</td>
<td>135</td>
<td>497,667</td>
<td>3.68</td>
</tr>
<tr>
<td>SETC</td>
<td>Euro III</td>
<td>2006–2010</td>
<td>149</td>
<td>832,369</td>
<td>5.60</td>
</tr>
<tr>
<td></td>
<td>Euro II</td>
<td>2002–2005</td>
<td>1,722</td>
<td>8,554,555</td>
<td>4.97</td>
</tr>
</tbody>
</table>

BMTC = Bangalore Metropolitan Transport Corporation  
KSRTC = Karnataka State Road Transport Corporation  
SETC = State Express Transport Corporation

### TABLE 4.
Variation of Fuel Efficiencies among Fleets

<table>
<thead>
<tr>
<th>Agency/Type</th>
<th>Highest (kmpl)</th>
<th>Lowest (kmpl)</th>
<th>Average (kmpl)</th>
<th># Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMTC Non-AC</td>
<td>5.33</td>
<td>3.88</td>
<td>4.38</td>
<td>160</td>
</tr>
<tr>
<td>BMTC AC</td>
<td>1.99</td>
<td>1.56</td>
<td>1.70</td>
<td>160</td>
</tr>
<tr>
<td>KSRTC Non-AC</td>
<td>5.68</td>
<td>4.38</td>
<td>5.23</td>
<td>159</td>
</tr>
<tr>
<td>KSRTC AC</td>
<td>4.84</td>
<td>3.22</td>
<td>3.73</td>
<td>153</td>
</tr>
<tr>
<td>SETC Non-AC</td>
<td>5.82</td>
<td>5.1</td>
<td>5.31</td>
<td>42</td>
</tr>
<tr>
<td>SETC AC</td>
<td>3.94</td>
<td>3.59</td>
<td>3.85</td>
<td>10</td>
</tr>
</tbody>
</table>

BMTC = Bangalore Metropolitan Transport Corporation  
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There exists a substantial difference in fuel efficiency of the buses among different depots within a single agency in a city. Traffic characteristics do not vary significantly among depots within a city and, thus, this points towards establishing a need for having a standardized maintenance code and practices and rewarding depots that achieve higher fleet fuel efficiency values.

**FIGURE 1.**  
Comparison of fuel efficiency of buses at different depots in BMTC
A questionnaire was designed to evaluate the commitment of the agencies in improving fuel efficiency of the buses and maintenance practices. A set of 19 questions was discussed with top management of the agencies, and the results are summarized in Table 5.

<table>
<thead>
<tr>
<th>TABLE 5.</th>
<th>Questionnaire for Management on Fuel Efficiency Initiatives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I. Management commitment and ownership</strong></td>
<td>1. Is there a senior executive in charge of fleet fuel economy, and is some part of his/her bonus tied to meeting fuel economy goals?</td>
</tr>
<tr>
<td></td>
<td>2. Do you benchmark and set appropriate fuel economy goals by bus type for each year?</td>
</tr>
<tr>
<td></td>
<td>3. Do you communicate the fuel economy results achieved each year to both employees and the public to create an environment-friendly brand?</td>
</tr>
<tr>
<td></td>
<td>4. Is a strategy to replace old buses actively pursued?</td>
</tr>
<tr>
<td></td>
<td>5. Is a policy to improve the speed of the buses actively pursued?</td>
</tr>
<tr>
<td></td>
<td>6. Is a strategy to reduce idling and emissions actively pursued?</td>
</tr>
</tbody>
</table>

| **II. Data collection and analysis** | 7. Is the data collection process automated to the extent feasible, and do you use analysis software to support maintenance? | No | No | No |
|  | 8. Have you set up data quality assurance procedures? | No | No | No |
|  | 9. Do you analyze the data for separating the effects of driver, route and bus-related effects on fuel economy? | Yes | Yes | Yes |
|  | 10. Do you use a GPS or a black box to collect data on driver behavior and infrastructure routing? | No | No | No |
|  | 10a. Do you use data to refine periodic maintenance? | Yes | Yes | Yes |

| **III. Maintenance** | 11a. Do you select at least 10% of the fleet showing the lowest fuel economy and conduct simple checks at depots? | Yes | Yes | Yes |
|  | 11b. Do you conduct detailed checks at the central facility if the bus passes step 11a to determine the issues? | Yes | Yes | Yes |
|  | 11c. Do you compare pre- and post-repair fuel economy data on these buses to estimate program benefits? | Yes | Yes | Yes |
|  | 12. Do you check repair quality on a random and periodic basis? | Yes | Yes | Yes |
|  | 13. Do you obtain mechanic sign-off on repairs for traceability? | Yes | Yes | Yes |
|  | 14. Do you conduct an independent team audit of repairs across depots? | No | No | No |
|  | 15. Do you retrain mechanics and update repair procedures periodically? | Yes | Yes | Yes |

| **IV. Training of low-performing drivers** | 16. Do you train drivers on fuel-efficient driving techniques and periodically retrain them? | Yes | Yes | Yes |
|  | 17. Do you select at least 10 percent of drivers with the lowest fuel efficiency and conduct special additional training? | Yes | Yes | Yes |

| **V. Employee communications and rewards** | 18. Do you publicly display the fuel economy performance by driver and bus depot to employees? | No | No | No |
|  | 19. Do you reward mechanics at the depot level and drivers individually for exceeding targets? | No | Yes | Yes |

*BMTC = Bangalore Metropolitan Transport Corporation*
*KSRTC = Karnataka State Road Transport Corporation*
*SETC = State Express Transport Corporation*
It was found that agencies do not prioritize the automated data collection process (question 7) to understand driver behavior and use the data to train drivers, although analysis of the data is conducted to study the impact on driver, route, and bus. Some of the other learnings that emerged in this process are the following:

- Top management is not directly held responsible for ensuring improvement in fuel efficiency.
- There is no strategy to reduce emissions.
- Maintenance works are recorded and documented.
- Driver and mechanic training is given emphasis to get the best out of them.
- Fuel economy targets and achievements are not well-publicized internally and externally.

It was observed that due to factors such as congestion and route, the variation in annual distance traveled by different buses was very high, with a range of 10,000–230,000 km/year. Due to operational issues, such as lack of adequate buses, many fuel “guzzlers” were used for greater distances when compared to more efficient buses. Ideally, low fuel-efficient buses should not be used to travel longer distances per day, while buses with higher fuel efficiencies should be used to travel more kilometers per day to optimize the fuel efficiency of the fleet.

FIGURE 2.
Fuel efficiency target of 5.50 kmpl displayed prominently at a depot.
BMTC, the over-utilized buses did an average of 287 km per day while the under-utilized buses did 233km per day (Table 6). This is a significant observation, as traffic characteristics do not radically alter within a depot influence area.

**TABLE 6.**

<table>
<thead>
<tr>
<th>Bus Utilization vs. Fuel Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMTC</td>
</tr>
<tr>
<td>For 20 over-utilized and under-utilized buses data</td>
</tr>
<tr>
<td>Over-utilized</td>
</tr>
<tr>
<td>Average fuel efficiency (km/liter)</td>
</tr>
<tr>
<td>Total km/bus/day</td>
</tr>
<tr>
<td>Fleet avg. km/bus/day</td>
</tr>
</tbody>
</table>

An hour of idling for a bus consumes almost two liters of fuel (Clean Air Asia 2012). Based on the data analyzed, it was observed that, on an average, idling resulted in consumption of more than 1.2 liters of fuel per day per bus (Table 7). This was very high, as very few buses were air-conditioned, thus indicating poor driving practices. The main reason suggested by drivers was lack of confidence in restarting the buses on the congested roads and junctions or, in the case of intercity air-conditioned buses, the buses had to be kept on to keep the air-conditioner working.

**TABLE 7.**

<table>
<thead>
<tr>
<th>Average Idling Time and its Impact on Fuel Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMTC</td>
</tr>
<tr>
<td>Avg. idling time (min)</td>
</tr>
<tr>
<td>Fuel impact per bus per day (ltr)</td>
</tr>
</tbody>
</table>

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There is a non-linear relationship between speed and fuel consumed. The ideal speed or speed at which maximum fuel efficiency is obtained depends on each vehicle class; for buses, it is approximately in the range of 55–60 kmph (Asian Development Bank and Ministry of Transport 2009). Beyond that speed, aerodynamic resistance is very high, thereby reducing fuel efficiency. However, emphasis on the speed impact on fuel efficiency is not given much importance. If the average speed of buses can be increased through interventions such as bus rapid transit (BRT), transit signal priority (TSP), exclusive bus lanes, high-occupancy vehicle lanes, etc., significant fuel savings can be achieved. It has been estimated that if the bus speed can be increased from 15kmph, which is the average bus speed in city conditions in India (Bangalore Traffic Improvement Project B-TRAC 2010), to 20kmph, a nearly 25 percent improvement in fuel efficiency could be observed, resulting in a saving of 4,000 liters of fuel per year per bus (Asian Development Bank and Ministry of Transport 2009).

By replacing some of the older buses, which have high emissions and are beyond productive life, with new buses, fleet emissions can be reduced. The average age of the fleets was around five years, and nearly seven percent of the buses were found to have exceeded the scrapping limit set by the respective agencies (as seen in Table 2) but still were being
used due to lack of resources to purchase new buses and high public transport demand. With the introduction of newer buses that meet BS IV standards (equivalent to Euro IV), emissions are greatly reduced, since newer buses adhere to stricter emission norms. For example, by scrapping 15 ordinary buses that are 11–15 years old and by introducing 15 new buses, Particulate Matter (PM) savings of 2.19 tons per year and NOx savings of 27.54 tons per year can be achieved. Along with reduced emissions, one can also ensure greater productivity (more than 2,000km/year) due to fewer repairs, breakdowns, and maintenance issues from new buses.

**Recommendations**

Based on the analysis of the sample data and the literature survey, it was observed that a 10 percent increase in fuel efficiency can be easily targeted by initiating several measures.

- **Fuel Economy Targets** – Bus operators need to be engaged in setting fuel efficiency targets for their fleets and monitoring the impact. For example, national level targets or key performance indicators (KPI) for buses/fleets on road should be designed for different types of buses and buses operating in different regions. A branding scheme such as a star rating system could be established. Buses/fleets satisfying the standards could be branded and incentives could be packaged. This kind of initiative can be undertaken only with regulatory, legal, and institutional support. A good example of this is China’s proposed Green Freight Initiative scheme for awarding truck operators or its Green and Yellow label for vehicles based on emissions standards (Ministry of Environmental Protection, China 2009). It was found that by mandating fuel efficiency targets, making top management responsible for achieving the targets, collecting scientific data, and conducting training, 3–5 percent fuel efficiency improvements can be achieved (ESMAP 2011).

- **Branding** – Buses need to go beyond a brand “logo.” The Ministry of Road Transport and Highways, which is the national ministry responsible for transport in India, needs to take an active lead in designing and implementing a communication strategy on Clean Buses. The vision of such a strategy should be that the public image of bus transforms from “dirty buses” to “clean/green buses.” One of the strongest reasons branding exercises need to be done is to bring bus transport to people’s attention and project it as a friendly, safe, and reliable mode. One example of bus communication and branding is “Bus Day” organized by BMTC on the 4th of every month.

- **Capacity Building** – National training should be conducted for drivers, mechanics, and operators to improve bus repair, bus maintenance, and driver behavior. Universities and research institutions need to take a lead in developing and providing a national mid-level management training program on optimizing, routing, scheduling, and synchronizing of bus movements. Bus manufacturers can play an important role in training mechanics and drivers. Current training methods adopted are not scientific and are carried out on old buses with different technologies.

- **Data** – Currently, the Central Institute of Road Transport in India collates and publishes the performance data on State Transport Undertakings (STUs). There is need to include bigger private bus companies in such annual reviews so that
adequate comparison can be made and insights drawn. The annual reporting needs to be compulsory, and guidelines for data collection need to be developed. The data collection process for distance, fuel consumption, and driving behavior needs to be updated and automated as much as possible. Annual monitoring of fuel efficiency values should be linked with incentives for good performers (awards or subsidy).

- **Finance** – An appropriate microfinance/revolving fund/subsidy scheme should be designed to target gross polluters using strategies such as technology retrofit, repair-maintenance, repower, and replace.

- **Urban Participation** – Fuel efficiency measures are directly linked with land-use, ridership improvement, speed improvement, and accessibility improvement measures. Bus agencies, unfortunately, do not have direct control on many of such variables and, thus, improving fuel economy measures needs to go beyond buses. Bus operators need to play an active role as important stakeholders in urban transport issues and ensure that the city transport system supports the buses as much as the buses support the city transport system.

- **Technology** – Smart technologies such as signal prioritization can be a solution to reduce junction idling. By installing wider doors, faster ingress and egress can be achieved, resulting in reduced idling at bus stops. By constructing exclusive lanes, idling related to congestion and traffic jams can be reduced.

**References**


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Critical Appraisal of Web-Based Passenger Information Systems

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Abstract
Passenger information is vital for developing a user-friendly public transportation system. Websites are rapidly gaining popularity for public transport information dissemination, particularly due to their anytime-anywhere availability and their suitability for the multimodal applications and multilingual interface. Internet-based Passenger Information Systems (PIS), therefore, have become common in developed countries. The development of PIS for urban transport in India however, is at an experimental stage with very few operational deployments. This paper attempts to examine the current state-of-the-art features in Web-based passenger information systems in India and abroad, while critically evaluating the existing sources of public transport information in Ahmedabad as a case study. Ahmedabad, like several other Indian cities, has fixed-route regular bus services in conjunction with a recently-introduced bus rapid transit (BRT) system. The study compares the information content in printed transit timetables, Google Transit, and websites of the transit agencies, with the spatial dataset of public transport network prepared by integrating information from several sources. The results highlight the issues pertaining to accuracy, coverage, and timeliness of information contents available in developing countries, requiring innovative technological interventions to meet the growing information needs of commuters.

Introduction
Public transport information systems form an integral part of any modern public transport deployment. Relevant information is vital for developing a user-friendly public transportation system (O’Flaherty 1997), and its availability may profoundly influence the use of public transport (Iles 2005). An effective public transport information system may enable potential users to plan multimodal journeys, minimize wait times at stations, and increase overall satisfaction with the service.
The information regarding the schedules and routes of public transport services is mostly fragmented and scattered across various sources (Zografos et al. 2009), which not only inconveniences the transit users but also discourages modal shift from private to public transport modes. Printed transit timetables, occasionally with network maps, are published by public transport operators and are the most commonly-available form of information at the disposal of transit users. However, difficulty in understanding such timetables, due to very large information content, limited circulation, and slow process of updates, have become a barrier in the use of such information (Bae 1995). Cain (2007) investigated the extent to which the lack of ability to use printed transit information materials correctly for trip planning may be a hindrance to transit use. The study concluded that only 52.5 percent of transit users were able to plan their journeys correctly using printed information. The problem is further compounded when multimodal trips are to be planned (Caulfield 2007; Tam and Lam 2005).

Telematics-based public transport information systems, therefore, may complement the conventional media, such as timetables and network maps, by providing reliable and near real-time data. Websites are rapidly gaining popularity among passengers, particularly due to their anytime-anywhere availability and their suitability for multimodal applications and multilingual interface. Web-based Passenger Information Systems (PIS) are user-friendly, easily accessible, and timely and have proved to be advantageous in both pre-trip and en-route information (Infopolis Consortium Inc. 1998; TRB 2003b).

India's National Urban Transport Policy (Ministry of Urban Development 2006) contemplates the establishment of a multimodal public transport system providing seamless travel across different modes in Indian cities. To combat the conventional “service for the poor” image, the policy has placed significant emphasis on modernization of urban transport infrastructure, improved passenger information systems, and use of intelligent transport systems for monitoring and control, apart from several other recommendations. The last decade alone witnessed introduction of bus rapid transit (BRT) systems, complementing the existing regular bus services in several Indian cities. A PIS has been identified as an important component of a range of Intelligent Transport Systems (ITS) contemplated as part of BRT projects, and thereby in-terminal and on-board PIS have been deployed. However, given the increasing requirement for multimodal travel, Web-based PIS also have become essential.

This paper attempts to review the current state-of-the-art features in Web-based PIS in India and abroad, while critically evaluating existing sources of public transport information in Ahmedabad city of Gujarat as a case study. The second section reviews studies on design and development of Web-based PIS, mostly in developed countries, along with the studies intended for evaluating such PIS implementations. The third section elaborates on experimental as well as operational PIS in India, and the fourth section identifies and critically examines various sources of public transport information in Ahmedabad. The final section presents conclusions and identifies issues to be addressed in Indian cities for an effective Web-based PIS.
Web-Based PIS: Global Scenario

Casey et al. (2000) identified three categories of transit information, each with a unique set of information and different preferred modes of information dissemination: (1) pre-trip information, (2) in-terminal or way-side information, and (3) on-board information. Pre-trip information, which includes general service information, itinerary planning, real-time information, and multimodal traveler information, is required prior to commencement of the journey. Caulfield (2007) concludes that websites are found to be particularly useful for meeting information requirements at the pre-trip planning stage.

The integration of transit information with spatial information has benefited immensely from the developments in Internet Geographical Information Systems (GIS). Peng and Huang (2000) discussed the taxonomy of Web-based transit information systems and observed that most transit websites provided Web-browsing and text-search capabilities with static graphic links to transit networks but lacked Internet GIS capabilities. They proposed a three-tier architecture comprising a Web browser, a Web server, and an application server composed of a map server, a network analysis server, and a database server. The proposed transit information system based on Internet-GIS with an interactive map interface provided information on transit routes, schedules, and trip itinerary planning. Cherry et al. (2006) emphasized the need for map-based input of trip origin and destination in transit trip planners apart from manually entering the text and selecting a landmark from a drop-down box. They developed a prototype of an itinerary planner using an ArcIMS for the Sun Tran bus network in Tucson, Arizona, with an interactive map to point and click on a location for the origin and destination. Gou (2011) confirmed that a schematic transit map indeed affects the path choices of transit users in London Underground subway.

Web-based PIS have been found advantageous in situations where multiple modes and multiple agencies are involved. Zografos and Androutsopoulos (2008) proposed a multimodal PIS called ENOSIS for urban and interurban trips, particularly to provide information on intermediate transfers between systems with different modes and geographic coverage. It provided an interface to external information systems for receiving real-time alerts from transit service providers, which are communicated to users by the Travel Life Cycle Manager (TLCM) that tracks a trip during its life cycle for a given trip itinerary. The primary issue involving multimodal transport information is the involvement of multiple agencies. Jung et al. (2001) proposed architecture for an Intelligent Transport Support System (ITSS) for acquisition, integration, and dissemination of information over the Internet from multiple information sources. Wang and Kampke (2006) emphasized the need for a decentralized traveler information system ensuring privacy and control on the data held by multiple transit service providers. Peng and Kim (2008) addressed the problems encountered by commuters when the journey involves more than one transit agency, which causes problems involving interoperability and data exchange across transit agencies. They proposed XML-based Advanced Traveler Information System (ATIS) standards for data exchange across multiple agencies. The system, however, requires commitment of transit service providers in implementing such standards while designing PIS.

Transit information can be of a static nature, such as route maps, schedules, and fares, which are updated only once in a while, or it may be dynamic, such as route delays and
real-time arrival estimates that are continuously updated (Casey et al. 2000). In recent years, the incorporation of Automatic Vehicle Location (AVL) technologies in public transport systems has resulted in an increase in real-time passenger information systems. The Transportation Research Board (2003a) notes that 88 transit agencies in the United States had operational AVL systems, and 142 were planning such systems by the end of year 2000. GPS has emerged as a common positioning technology owing to low infrastructure cost, easy deployment, and reasonably high level of accuracy. Although real-time passenger information is largely offered at wayside or in-terminal stages, transit websites are increasingly being used for the purpose. Peng and Huang (2000) conceptualized an interface for displaying bus locations using AVL data. Hiinnikainen et al. (2001) proposed architecture for a PIS for public transport services, which, in addition to other features, also incorporated real-time information dissemination to the personal mobile terminals using the telecommunication network. TRB (2003a) provided an exhaustive review of various aspects of real-time bus arrival information systems, including case studies of Regional Transportation District, Denver; King County Metro, Seattle; Tri-County Metropolitan Transportation District of Oregon, Portland; San Luis Obispo Transit; Acadia National Park—Island Explorer Bus System; and London Bus Services Limited. Websites are also useful in providing additional information necessary for making the trip, fulfilling the very purpose for which the trips are made. Watkins et al. (2010) developed a search tool for local restaurants, shopping, parks and other amenities based on transit availability from the user’s origin. Farag and Lyons (2012) agree that public transport information should be marketed simultaneously with public transport use.

The proliferation of Web-based PIS in several cities across the globe has enthused researchers in evaluating the performance of such deployments. Quantification of the benefits of Web-based PIS, such as an increase in transit ridership and improvement in user ability to use transit systems, is difficult, and often subjective. Eriksson et al. (2007) developed an evaluation tool based on an E-S-QUAL scale to assess the quality of public transport information on the Internet. The study analysed 58 responses to a questionnaire to quantify the quality of websites. Grotenhuis et al. (2007) studied the quality of integrated multimodal travel information in public transport and its role in time and effort savings of the customers. Politis et al. (2010) evaluated real-time bus passenger information system from the user point of view in Thessaloniki, Greece. Cheng (2011) investigated passenger perceptions of electronic service quality (e-SQ) delivery through the Taiwan High Speed Rail’s (THSR) website to examine the quality of transportation information as well as website services.

Websites have become a common medium of information dissemination for transit agencies in developed countries, resulting in a large number of operational Web-based transit information systems. The Infopolis-2 (1998) project prepared an inventory of more than 300 websites of public transit service providers in Europe, covering different modes such as rail, bus, metro, tram, ferry, and coach, and with varying functionalities. It further adds that out of 27 websites that responded to their survey, nine supported more than three transit modes. Casey (1999) identified that 163 transit agencies in the U.S. that already had or planned to implement an automated traveler information system. Radin et al. (2002) investigated transit trip planners provided by 30 public transport service providers
in the U.S., detailing the inputs, outputs, and advanced features such as multimodal and multilingual support, offered by these agencies.

Transport Direct, a multimodal journey planner for Britain (England, Wales, and Scotland), which became operational in December 2004, offers national journey planning across all modes (Maher 2008). The journey plans returned by Transport Direct are actually composite plans formed via queries to several different regional journey planners, some of which are created and maintained by third-party organizations. Journey plan responses are received in form of JourneyWeb XML standard, an XML protocol allowing the exchange of journey planning queries and answers (DfT 2013). Traveline Travel Services (2010) in the UK, BayernInfo (2013) in Germany, Kings Metro Transit Service (King County 2013) in Seattle, Bay Area Rapid Transit (San Francisco Bay Area Rapid Transit District 2013), and 511 (Metropolitan Transportation Commission 2013) in the San Francisco Bay Area are few other successful deployments of Web-based PIS. In recent years, Google Transit (Google Maps–Transit 2013), supported by its very-high-resolution satellite imagery and cartographic-quality maps (Google Maps 2013), has become the de facto choice in providing transit information. As of December 2012, more than 500 cities all over the world have adopted Google Transit (Google Maps–Transit 2013).

Web-based PIS have evolved over the past decade with the integration of Internet GIS (Peng and Huang, 2000; Cherry et al. 2006) to multimodal (Zografos and Androutsopoulos 2008) and multiagency systems (Wang and Kampke 2006, Peng and Kim 2008). The information content also has advanced from simple static information to real-time information (Peng and Huang 2000, Hiinnikainen et al 2001) and further integration with information regarding the purpose of trip (Watkins et al. 2010). MacDonald et al. (2006) claim that despite tremendous growth in traffic and traveler information services in the past decade, issues pertaining to information accuracy and reliability, multimodal support, timeliness of information, delivery of information, and service continuity across national borders present opportunities for future research in Europe. Similar concerns were raised by the Transportation Research Board (TRB 2003b) for transit information systems in the U.S. The quality of data used by traveler information systems needs to be improved with respect to level of detail, coverage, accuracy, and maintenance. Traveler information from multiple sources, including information on traffic and travel time, needs to be integrated, with the aim of providing more customer-focused and personalized information along with the real-time information.

**PIS in India**

The development of PIS for urban transport in India is at an experimental stage with very few operational deployments, as discussed herein.

**Experimental Systems**

Reddy (2002) developed an intelligent transport system in a GIS environment and proposed an ATIS for Hyderabad. The system was developed on ESRI’s ArcView software and provided detailed transport- and tourist-related information. Ballaji et al. (2003) proposed a public transport information system for Chennai city using ESRI’s ArcView software. Yoganand (2004) proposed a multimodal ATIS for Delhi Metro using ESRI’s MapControl.
in Visual Basic. The application provided information about transport facilities in Delhi in addition to enabling the shortest path computation between given locations based on road length. A Web-based system was also developed using HTML and JavaScript with basic features such as pan, zoom, identify, and attribute search. Singh (2007) proposed a three-tier client-server architecture for an ATIS for developing countries for pre-trip information dissemination and also proposed design guidelines pertaining to organization and management of data used for information dissemination. Kasturia and Verma (2010) developed a multi-objective transit PIS for the regular bus service in Thane city using TransCAD.

**Operational Systems**

PIS has been planned as a part of BRT projects in several cities in India. Delhi deployed a Web-based PIS, developed by Delhi Integrated Multi Modal Transit System Ltd. (DIMTS 2010), which enabled passengers to track buses (both AC and non-AC) on BRT routes in Delhi. It provided route-wise expected arrival time of buses while displaying the location of buses on Google Maps. In Bangalore, the private firm MapUnity (2013) developed a traffic information system in collaboration with Bangalore Traffic Police and a private mobile service provider. It has also developed Urban Transport Information Systems for a number of other Indian cities, such as Bangalore, Chennai, Hyderabad, and Delhi. This system uses several types of input, such as teledensity data from a mobile telecom tower network, video images from police cameras, and location-tracking of buses and taxis, to create real-time knowledge of traffic conditions in the cities. These are made available through the mobile telecom network to city residents and are also accessible online. The website also offers determination of route between user-specified origin and destination stations for regular bus services.

Google Transit (2013) has identified nine Indian cities—Delhi, Bangalore, Hyderabad, Mumbai, Chennai, Ahmedabad, Pune, Kolkata, and Thane—to publish transit information online providing transit routes between an origin-destination pair. In a similar initiative, the Indian Bus Route Mapping Project (2013) has developed a transit trip planner for Chennai city using map data from OpenStreetMaps and a collaborative effort in mapping public transport network of the city. The efforts in development of Web-based PIS have gained momentum in Indian cities in recent years. The information content in such websites, however, presents challenges pertaining to reliability and completeness, which needs to be reviewed to improve customer acceptance.

**Public Transport Information in Ahmedabad**

To assess the quality of passenger information available in Indian cities, Ahmedabad has been selected as a case study for detailed analysis. The city is the fifth largest city in India, as per Census of India 2011, and operates regular fixed-route bus service in conjunction with BRT service, thereby representing the public transportation systems of most of the metropolitan cities in India. The BRT service in Ahmedabad has been widely acclaimed in India and abroad (AMC 2013) and is being considered as a model for other Indian cities as well. Furthermore, as the city is also covered by Google Transit, Ahmedabad offers the most appropriate case study for analyzing the quality of passenger information in Indian cities.
Ahmedabad is the largest city of the state of Gujarat, located in the western part of India. The population of Ahmedabad Municipal Corporation, which was 3,520,085 in 2001, has already surpassed the 50 million mark, per provisional estimates released by Census of India 2011. The city is an established manufacturing hub and a center of trade and commerce. The public transport demand of the city is serviced by regular fixed-route bus services operated by Ahmedabad Municipal Transport Service (AMTS) and BRT service operated by Ahmedabad Janmarg Ltd. (AJL). AMTS operates more than 150 routes in Ahmedabad, covering nearly 500 km road length. BRT, which was introduced in the city in December 2009, is currently operational on 10 lines, with more than 100 BRT stops.

The public transit information in Ahmedabad is fragmented and scattered, which inconveniences transit users in planning multimodal journeys. The information regarding AMTS can be obtained from printed transit timetables and Google Transit. The printed transit timetables published by AMTS provide general service information, including a list of routes and major stops and a schedule of departure from origin stop. An updated list of routes and a text-based transit trip planner have also been provided on the website (AMTS 2013). Transit timetables are published in the native language, Gujarati. Google Transit, on the other hand, provides a map-based itinerary planner for AMTS-operated bus service. The information source for BRT is primarily its website (AMC 2013) and the in-terminal passenger information system. The website provides general service information, including routes, timetables, and stops, and the terminals provide transit network maps and real-time information on bus arrivals.

The quality of information with respect to level of detail, coverage, accuracy, and maintenance has been recognized as an important aspect for the success of Web-based PIS (TRB 2003b). To assess the quality of spatial and non-spatial contents of existing sources of information, a reference set of data was first prepared. The road network of Ahmedabad was mapped at 1:10,000 scale using Indian remote sensing data acquired by a Cartosat-1 PAN sensor fused with IRS P6 LISS-IV multispectral data. The spatial data of the bus stops of AMTS were created by integrating information from multiple sources such as printed timetables, Google Maps, published city atlases and guide-maps, and GPS. The bus routes were mapped based on the sequence of stops listed in the printed timetable of AMTS, and BRT stop locations were obtained from the website of Ahmedabad BRT and handheld GPS. Thus, a reference transport network dataset of the study area comprising all roads as links and the end-points of such links as nodes, including the stops of AMTS and BRT, was prepared for the assessment of quality of passenger transport information in Ahmedabad.

**AMTS Printed Transit Timetables**

The printed transit timetables published by AMTS include 1,025 bus stops out of the 1,533 bus stops identified and mapped on the reference transport network of the study area. The stops were compared with the actual number of bus stops marked on the reference transport network. It was observed that only 40 percent of the bus stops were listed in any given route, thereby providing incomplete transit information to the users, as shown in Figure 1. It is evident that as many as 50 percent of the bus routes have more than 50 bus stops. Incorporation of all bus stops in printed timetables along with their
corresponding schedules will result in large booklets, which will not be handy for customers. Moreover, the production costs of such large timetables will rise, thereby making them unviable for distribution at the nominal fees being charged at present.

The inclusion of only selected bus stops may prove to be hindrance to trip planning if commuters are not aware of the bus route number beforehand. The difference in the number of routes passing through a given bus stop according to the information content of AMTS timetable and that of the reference database is shown in Figure 2. According to the AMTS timetable, only 9 bus stops are connected by more than 50 routes, while the database identifies 35 such stops. Similar observations can be made for bus stops connected by 5–10 routes, 11–20 routes, 21–30 routes, and 31–50 routes.

The inclusion of only selected bus stops may prove to be hindrance to trip planning if commuters are not aware of the bus route number beforehand. The difference in the number of routes passing through a given bus stop according to the information content of AMTS timetable and that of the reference database is shown in Figure 2. According to the AMTS timetable, only 9 bus stops are connected by more than 50 routes, while the database identifies 35 such stops. Similar observations can be made for bus stops connected by 5–10 routes, 11–20 routes, 21–30 routes, and 31–50 routes.
To understand the update frequency of the route structure in the transit timetables, routes listed in the 2010 ATMS timetable were compared with the undated AMTS bus route status from the ATMS website. The total number of routes listed in the AMTS timetable was 189 (including shuttle routes); the number of routes in March 2012 (from the ATMS website) was 171. This does not necessarily indicate the restructuring of AMTS routes, but rather hints at changes in information content over the period, as the ATMS timetable does not list shuttle routes. It was further observed that 26 routes had undergone changes in terms of route origin or destination, 16 routes from the AMTS timetables were not included in the 2012 route information, and 35 new routes were found in the AMTS route information.

**AMTS Information on the Internet**

Google Transit offers a transit trip planner for AMTS-operated regular bus service in Ahmedabad. The trip planner allows users to minimize either the journey time, the walk distance, or the transfers. The origin and destination points of the itinerary can either be located on a map or can be searched from the place-tags marked by Google Map users. The path returned is displayed graphically as a line diagram and is also plotted on the map. The path information comprises the name and location of the nearest boarding and alighting bus stops, the bus route(s) name and geometry as plotted on the map, and walk connections from trip origin and destination points to the respective nearest bus stops.

The quality of information content of Google Transit’s trip planner depends primarily on its database of bus stops, bus routes, and timetable. To evaluate the bus stop information in Google Transit, 10 percent of bus stops (156) were randomly selected from the reference transport network of Ahmedabad, ensuring unbiased geographical coverage. These bus stops were searched in Google Transit, first using a map-based search and then a text-based search.

The map-based search using Google Transit was able to locate 98 bus stops out of the 156 initially sampled. An additional 58 stops were selected near the locations where Google Transit stops could not be identified, thereby increasing the sample size to 156 stops on Google Transit and a total of 214 stops in the reference database. The sample of bus stops thus selected included 165 stops identified in AMTS timetable, 25 stops obtained from Google Transit, and 27 stops from published city atlases. It was observed that the names of only 22 percent of the total stops in the sample perfectly matched the names in Google Transit, including 36 stops from the AMTS timetable and 11 stops from Google Transit. The difference in the number of stops mapped using Google Transit (25) and the number of stops with matching names (11) is due to corrections made to names incorporated based upon knowledge of local language and ancillary data at the time of database creation.

The dissimilarity in the names of bus stops from multiple sources was quantified using Jaro-Winkler distance and Levenshtein distance. The Jaro-Winkler distance metric is used to measure string similarity and is particularly advantageous for detecting typographical errors in short strings such as names. Levenshtein's distance, on the other hand, measures the difference in the sequence and determines the number of single-character edits required to change one word into another. The lower the value of these metrics, the lower is the similarity between strings being compared. The results of string similarity, as shown
in Figure 3, indicates that nearly 48 percent of stop names have a similarity score greater than 95 percent on Jaro-Winkler similarity, and 33 percent have a Levenshtein distance above 95 percent, which implies that not only conventional key-word based searches are liable to fail but also that significant effort will be necessary to rectify the errors in the database. The dissimilarities in names are due to not only typographical errors but, in several instances, semantic issues arising on account of language; for example, in Table 1, the term “temple” may be written as “mandir” in Hindi and Gujarati, giving rise to two different names, “ISKCON Temple” and “ISKCON Mandir,” both referring to the same place.

The text-based search was evaluated on the basis of the sample of 214 bus stops selected from reference transport network. The name of every bus stop mentioned in the reference transport database and its name in Google Transit obtained in a map-based search was entered as the origin in Google Transit’s trip planner, and Lal Darwaja Bus Terminus, which is the largest bus terminal of Ahmedabad with the highest accessibility, was marked as the destination. The directions between the pair of origin and destination locations using public transport modes was computed to minimize the walking distance, which ensured that the nearest stop to the selected place-tag was located. The best path minimizing walk distance returned for each bus stop was tabulated according to the format shown in Table 1. The Node-ID (column 1) and Reference Node Name (column 2) were obtained from the reference database, the Google Transit Name (column 3) was obtained from the map-based search, and the remaining information in columns 4–9 was retrieved through the text-based search. In the example shown in the table, Node IDs 836, 2621, and 3454 indicate the correct identification of stops in both the map-based and the text-based searches, but route 44/3 for node 2621 does not exist. Nodes 278, 6148, and 6412 were identified only in the map-based searches but could not be located in the text-based searches. Node 6928 was located in the text-based search but returned a different stop than the desired stop. Nodes 6538 and 7425 could not be detected in either the text-based search or the map-based search. Node 7425 is connected by an out-city route, which appears to be outside the coverage area of Google Transit.
### Table 1.
Evaluation Format for Keyword-based Search using Google Transit

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Reference Node Name</th>
<th>Google Transit Name</th>
<th>No. of Tags</th>
<th>Closest Place- Tag Name</th>
<th>Bus Stop Nearest to Tag</th>
<th>Distance from Tag to Stop (m)</th>
<th>Route # to Lal Darwaja</th>
<th>Travel Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>836</td>
<td>Iskcon Temple</td>
<td>ISKCON Mandir</td>
<td>1</td>
<td>ISKCON Temple, Satellite, Ahmedabad, Gujarat 380059</td>
<td>ISKCON Mandir</td>
<td>200</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>278</td>
<td>Purushottam Nagar</td>
<td>Purushottam Nagar</td>
<td>4</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2621</td>
<td>Law College</td>
<td>Law College</td>
<td>1</td>
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It was observed that the text-based search was able to locate only 50 percent of bus stop names searched in the sample dataset. The average distance of these place-tags from their respective nearest bus stop in Google Transit was observed to be 294.96 m, with only 25 percent of stops being located within 100.0 meters of the place-tag. Moreover, only 27 percent of the place-tags were actually able to locate the desired bus stop. It was further observed that in nearly 82 percent of the searches, more than one place-tag was located, and most often these tags referred to locations in different localities than desired.

The route information retrieved from Google Transit for each pair of origin-destination stops in the sample was compared with the routes listed in AMTS timetable. As discussed above, of the 214 bus stops searched in Google Transit, only 107 could be located by a text-based search, and route from these stops to the Lal Darwaja Bus Terminus were determined by Google Transit’s trip planner, which resulted in 54 distinct routes. In comparison with the AMTS route timetable, it was observed that only three routes had errors, and one route had temporarily been closed. It was further noticed that of the three routes, one route corresponded to the old timetable, which raises concerns about the maintenance of AMTS information on Google Transit. It is, therefore, desirable that transit websites provide information on the date of last updates.

In addition to Google Transit’s trip planner, the ATMS website also provides useful information on public transport services, including a PDF file in the native language (Gujarati) containing the information on bus routes operated by AMTS. It also provides a text-based trip planner to search the route connecting a pair of origin and destination stops. The ATMS trip planner is far less effective as compared to Google Transit. The bus routes originating at the bus stops in the sample selected from the reference transport network and ending at the Lal Darwaja Bus Terminus were searched using the ATMS trip planner.
It was observed that only 68 bus stops (32%) could be located by name, and routes to the Lal Darwaja Bus Terminus for only 25 stops (12%) could be retrieved in the sample of 214 bus stops. The information content of the AMTS website is, therefore, not adequate for pre-trip information.

**BRTS Information on the Internet**

Web-based PIS has been contemplated as a part of BRT system specifications. BRT, which was introduced in Ahmedabad in 2009, is being implemented in a phased manner. The system is, therefore, undergoing continuous changes that the website, maintained by AJL has to follow. As BRT currently operates on 10 routes with only 110 stops, the system is considerably smaller and, hence, less complex as compared to the AMTS route network.

The Ahmedabad BRT website provides information on stops, routes, fares, and schedules. BRT stops may be selected from a drop-down list, and bus lines passing through that stop are listed along with estimated arrival times of buses. While a map-based search is currently not available, the website provides Open Street Maps (OSM), which shows the location of BRT stops. Similarly, a bus line may be selected from the drop-down list and its corresponding timetable may be retrieved. Bus lines also can be plotted on OSM data. A fare calculator is available to compute fares between origin and destination stops. The website is still in the development stage, and much work needs to be done to make it more user-friendly and informative.

**Opportunities for PIS development in India**

With the introduction of BRT and the efforts towards overhauling public transport in several Indian cities gaining momentum in the past decade and with government programs such as the Jawaharlal Nehru National Urban Renewal Mission, etc., requirements for multimodal information have become a necessity for the public transport users. Websites have been recognized as a preferred medium for the dissemination of such information, as global experience reflects. The responsibility for public transport in Indian cities lies with the local government, although they are more often than not dependent upon central and state governments for funding and technical support. The multi-agency involvement in public transport calls for efforts to streamline data exchange and interoperability to fulfil the requirements of multimodal information systems.

The quality of data with regard to accuracy and updating is paramount to the success of any information system. The problems regarding data quality are further compounded by the multi-lingual population in India. Ahmedabad, for example, has Gujarati as its official State language and Hindi as its official National language, but English is the common language on the Internet. It was observed that several of the errors in the names of bus stops were due to the semantics of names. As government websites are not updated frequently, the problem is further aggravated. Transit agencies, which are already constrained by both financial and human resources, require cost-effective solutions with the lowest level of skill to ensure high-quality information content delivered over the Web.
Conclusion

To combat the conventional “service for the poor” image, the National Urban Transport Policy (2006) emphasizes modernization of urban transport infrastructure, improved passenger information systems, and the use of intelligent transport systems for monitoring and control, apart from several other path-breaking recommendations. In the last decade, the introduction of BRT in several Indian cities has significantly altered the information needs of commuters, particularly for multimodal travel, as BRT in most Indian cities is operating in conjunction with regular bus services. In-terminal and on-board PIS have been deployed as part of BRT implementation, but Web-based multimodal information systems are yet to materialize. This paper reviewed the current state-of-the-practice in Web-based PIS in India and abroad and critically evaluated the existing sources of public transport information in Ahmedabad as a case study.

The printed transit timetables published by the public transport operators are not user-friendly, and their information content is incomplete. It was observed that only 40 percent of bus stops on a given route are listed in the transit timetables. Google Transit’s trip planner is superior in terms of user-friendliness and information content when compared with the websites of public transport agencies and their printed transit timetables. The study, however, indicated that a map-based search of bus stops using Google Transit was able to locate only 62.8 percent of bus stops in a sample of 156 bus stops selected randomly from the reference public transport database of Ahmedabad. Moreover, a text-based search was able to identify only 50 percent of the stops. The study further observed that only 48 percent of the stop names have a similarity score greater than 95 percent on Jaro-Winkler similarity, and 33 percent have a Levenshtein distance above 95 percent, which implies that not only are conventional key-word based searches liable to fail, but also that significant effort will be necessary to rectify errors in the database.

Private sector initiatives such as Google Transit are continuously improving the quality of the user experience while setting high standards for service delivery. The issues pertaining to accuracy, coverage, and timeliness of the information in Google Transit highlights the necessity for proactive and continuous involvement of transit agencies in the development of Web-based PIS. Transit agencies in India need to adopt standards such as Google Transit Feed Specifications (GTFS) for transit data exchange across various stakeholders. The successful deployment of Transport Direct in the United Kingdom, which enables nationwide public transport information flows with the adoption of standards such as JourneyWeb, TransXChange, NaPTAN, and National Public Transport Gazetteer (DfT 2013), is an apt example for developing countries such as India to follow. While these standards have addressed the issues of syntactic heterogeneity, ontologies are increasingly being considered for attaining the semantic heterogeneity in information exchange (Billen et al. 2011). Service providers and technology providers will need to work in tandem to ensure the availability of high-quality data for dependable PIS for users of public transport in developing countries.
Acknowledgments

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References


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Analysis of Visitor Satisfaction with Public Transport in Munich

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Abstract

This study investigates the use of public transport by visitors in the city of Munich, Germany. It seeks to understand how visitors perceive public transport services and which factors influence their level of satisfaction. Data were collected from a survey in April and May 2012 with a random sample at selected tourist sites in Munich. Factor analysis resulted in four different service dimensions—traveling comfort, service quality, accessibility and additional features. Visitors were found to be generally satisfied with public transport services in Munich, and their perceptions are independent from most factors.

Introduction

Among various modes of land transport (Duval 2007; Page 2011), the use of public transport (or mass transit, public transit, public transportation) has multiple environmental, social, and economical benefits (Litman 2011; Gwilliam 2008; Litman 2007). However, most research on public transport focuses on local users rather than the public transport needs of visitors. Yet, given the significance of the visitor economy for many urban areas, including resort areas, understanding and facilitating tourist use of public transport is becoming of increased importance. Although car use is the most popular visitor transport mode (Regnerus, Beunen, and Jaarsma 2007; Guiver et al. 2007), congestion, pollution, traffic problems, and demands for sustainable transport practices have led to a renewed focus on the importance of public transportation in urban tourism development. However, encouraging a modal shift is not an easy task (Redman et al. 2013; Dickinson, Robbins, and Fletcher 2009; Lumsdon, Downward, and Rhoden 2006). To promote public transport use, whether to visitors or to local users, it is critical to have an effective and efficient system. Specifically, transport services should be demand-oriented, and a
good knowledge of customer behavior is thus of great importance (Gronau and Kagermeier 2007).

This paper examines the use of public transport by visitors in the city of Munich, Germany. Public transport mentioned in this study refers primarily to rail (train, tram, subway) and buses. It explains how visitors evaluate public transport services and what factors influence their perception. The most important service aspects determining overall satisfaction are also discussed. In addition, recommendations for public transport management and operator are offered.

**Customer Satisfaction with Public Transport**

Measuring customer satisfaction with public transport services is an important topic in transportation research and practice. To improve services and increase the number of customers, providers need to understand how much customer expectations have actually been fulfilled. Customer surveys are critical, as they provide transport operators with valuable information such as what aspects are important for customers and what they are particular happy or unhappy about.

Felleson and Friman (2008) reported on an annual transnational public transport customer satisfaction study in eight European cities (Stockholm, Barcelona, Copenhagen, Geneva, Helsinki, Vienna, Berlin, Manchester, and Oslo). Four satisfaction dimensions were delineated from a factor analysis of 17 attribute-related statements: system, comfort, staff, and safety. However, the results were not consistent in all cities, meaning that public transport services were perceived differently. Several factors contribute to the variation of customer perceptions, including those related to management (how the services were provided) and personal group (culture and tradition).

In her study of customer satisfaction with public transport in Indonesia, Budiono (2009) identified two groups of service attribute. The “soft quality” factor includes security issues and comfort, and the “functionality quality” consists of frequency, travel time, punctuality, and time, with the latter being the more influential on levels of the customer satisfaction. In contrast, Tyriopoulos and Antoniou (2008) emphasized the differences of customer perception between different transit operators due to their specific characteristics and service conditions. In general, the most important satisfaction attributes across transit operators are service frequency, vehicle cleanliness, waiting conditions, transfer distance, and network coverage. However, the results are varied among transit systems. For instance, vehicle cleanliness, staff behavior, and ticketing systems are the most important attributes for metro (subway) operators. In the case of bus operators, customers stressed service frequency, vehicle cleanliness, and network coverage. A well-coordinated and reliable transportation environment is strongly preferred by all users. In their study of Swedish residents in Göteborg, Friman, Edvardsson, and Gärling (2001), and Friman and Gärling (2001) indicated a relationship between frequency of negative critical incidents and satisfaction with public transport (low frequency led to increased satisfaction). Moreover, the authors believed staff behavior was of significant importance in customer perception, along with service reliability, simplicity of information and design. In contrast, Lai and Chen (2011) suggested that service quality and perceived value should
receive greatest attention in improving customer satisfaction, whereas Eboli and Mazzula (2007) stressed the role of service planning and reliability.

Diana (2012) examined the degree of satisfaction of multimodal travelers with public transport services in Italy. Nine service aspects were measured. The author found that satisfaction and frequency of use of urban transit are not correlated. Public transport received greatest use in city centers, followed by towns of above 50,000 inhabitants. However, satisfaction levels tended to be highest in smaller towns and lowest in metropolitan areas.

A study of travel mode switching in Switzerland indicated that satisfaction and attitudes were related to behavior and habits (Abou-Zeid et al. 2012). Those who switched to public transport tended to be more satisfied than those who did not. Furthermore, as is often found in customer satisfaction studies (Song et al. 2012; Tribe and Snaith 1998), expectation is also a factor influencing satisfaction with public transportation experience. Additionally, public transport satisfaction is affected by travel time: longer travel times result in lower levels of satisfaction (Gorter, Nijkamp, and Vork 2000). Similarly, crowded or unreliable services and long wait times often make customers less satisfied (Cantwell, Caulfield, and O’Mahony 2009).

These studies have provided significant insights into how passengers evaluate public transport performance. However, they targeted local residents rather than visitor users of public transport. Nevertheless, tourists may make up a substantial proportion of public transport use at urban destinations, and their behavior, expectations, and perceptions of public transport performance potentially are considerably different from those of local users and worthy of separate investigation. The following sections describe the use of public transport by tourists at the destinations.

**Tourist Use of Public Transport**

Tourists exhibit diverse perceptions and attitudes towards transport (Dallen 2007). Their satisfaction with transport is influenced by several factors. It was found that visitors differ significantly from local users in terms of their needs and use of public transport (Kinsella and Caulfield 2011). Newcomers to the city of Dublin were more concerned with the provision of information and reliability of service and placed less emphasis on traditional aspects of public transport such as service quality and safety. By contrast, Dubliners considered punctuality, frequency, and waiting times as most important. In addition, tourists are also different from local users in their information search behavior: they require more information and use different sources (Thompson 2004). Specifically, information centers, word-of-mouth, attraction leaflets, the Internet, and hotel reception are common information sources for tourists.

Stradling et al. (2007) argued that age and frequency of use are the most influential on tourist satisfaction with transport, whereas factors such as household income, car availability, and gender are less significant. A study in Turkey and Mallorca, however, identified cultural background as an important dimension (Kozak 2001). For example, British tourists are generally more satisfied with local transport services during their summer
holidays than German tourists. Other influences on satisfaction include word-of-mouth communication, purchase intention, and complaining behavior (Kim and Lee 2011).

In the UK, public transport (mainly buses) in rural areas generally received relatively high satisfaction levels in service dimensions such as comfort, cleanliness, information, and driver helpfulness. On the other hand, there were also complaints about poor service delivery, unreliability, poor information, bad driving or inferior vehicles, and, above all, frequency of services (Guiver et al. 2007).

Public transport is considered an additional tourism product, which adds to the total tourist experience (Duval 2007). Thompson and Schofield (2007) examined the relationship between public transport performance and destination satisfaction. Their study of tourists in Greater Manchester showed that how tourists evaluate public transport performance could slightly influence their satisfaction with the destination. The authors emphasized the importance of public transport’s ease-of-use, as it has great impact on satisfaction than efficiency and safety. However, the study is limited to public transport at one place (Greater Manchester) and only to overseas visitors. Furthermore, the paper has a focus on the public transport and destination satisfaction relationship, whereas other influences were, unfortunately, neglected. There is, therefore, a need to understand tourist perceptions of public transport in another context and with extended dimensions. It is important to explore not only customer satisfaction but also influencing factors and their impacts on customer perception. A study on tourist use of public transport in Munich is of significance to this area.

Public Transport in Munich

Munich is the capital of the state of Bavaria and the third largest city in Germany. A commercial, industrial, and cultural center, Munich is the second most visited city in Germany (after Berlin), with 5.2 million foreign visitors in 2010 (German National Tourist Board 2011). Along with its long history and rich culture, the city also boasts several remarkable arts museums, historical sites, and festivals that attract millions of tourist arrivals every year, especially during Oktoberfest. As a growing city with increasing numbers of tourists, having a well-developed public transport system is part of the City’s forward-looking transport policy, which emphasized an efficient transport system as pivotal for the proper functioning of a large modern city (City of Munich 2005a, 2005b).

Munich has a well-developed and extensive traffic and public transport network. The public transport systems in Munich include 275 miles of S-Bahn (suburban trains), 59 miles of U-Bahn (underground trains), 49 miles of tram, and 282 miles of local bus route. The systems are operated by different organizations under the supervision of the Munich Transport and Tariff Association (MVV—Münchner Verkehrs und Tarifverbund). In 2011, public transport systems in Munich transport 522 million passengers. Sixty-six per cent of the residents of Munich use the underground, bus, and tram several times per week, and 35 percent of them are daily user of the systems (Münchner Verkehrsgesellschaft 2010).

A city of 1.3 million inhabitants, of which more than 300,000 commute each day, and with about 5 million visitors every year, Munich is facing increasing problems in traffic management (Thierstein and Reiss-Schmidt 2008). This is especially so when among the 300,000
work commuters, only about 48 percent are public transport users. In addition, more than 500,000 cars cross the city boundaries daily, and this number is expected to have increased a further 30 percent by 2015. Consequently, without appropriate integrated policy intervention, increasing congestion, noise, and air pollution will be inevitable in Munich.

Since the early 20th century, the city of Munich has placed importance in urban planning and transport management. Several transport projects and development plans have been undertaken in Munich, including Perspective Munich, which was initiated in 1998 aiming at better urban expansion management (City of Munich 2005a, 2005b). With the motto “Compact, Urban, Green,” Perspective Munich is a flexible guide founded on two principles: sustainability and urbanism. The city invested one million euros per year to implement the mobility management concept “München–Gsheid mobil,” targeting increased (sustainable) mobility for four groups: new citizens, children and young people, companies, and other important target groups including older adults (Schreiner 2007). Several efforts have been made to build up a sustainable mobility in the metropolitan region of Munich; however, the tourist user group so far has been neglected.

While the majority of users of public transport are local residents, tourists also benefit from the system. Munich has tremendous appeal to tourists, and the provision of excellent public transport services is necessary to support the growing number of tourists while simultaneously contributing to environmental goals (Münchner Verkehrsgesellschaft 2010). An important component of this is a greater understanding of tourist demands, expectations, and satisfaction with public transport in Munich.

Methodology
To examine tourist use and satisfaction with public transport in Munich, data were collected from a visitor survey. Questionnaire-based surveys are a standard method to research customer behavior (see, for example, Bansal and Eiselt 2004, Fellesson and Frieman 2008) and are also adopted in this study. Due to time and labor constraints, self-administered surveys were used.

Questionnaire Design
Respondents were filtered by the question “Have you used public transport in Munich during this visit?” Users of public transport were then asked to indicate their level of satisfaction with 16 service aspects of public transport in Munich. This list of attributes was developed with reference to the literature review above. A five-point Likert scale was used (1 = very dissatisfied to 5 = very satisfied). This question was preceded by the question, “In general, how satisfied are you with public transport in Munich?” to examine whether tourist satisfaction with particular service dimensions is correlated with their satisfaction with the total service as a whole.

Data Collection
To generate the largest number possible of respondents, the survey was carried out at the most popular tourist sites in Munich. The top 10 attractions in Munich (according to tourist information websites) were all considered as survey sites. Site examination and pre-tests resulted in three main study sites: the English Garden, the Residenz, and the
Pinakothek Museums. These are sites that are both popular with tourists and convenient for approaching them. The survey assistants (three in total) divided their time among these sites.

Respondents were recruited using a random intercept approach. The survey assistant approached the tourists near the entrance of the attraction, introducing herself, briefly outlining the research project, and inviting the tourists to participate in the survey. Questionnaires were handed out to those who had agreed to participate.

Following pilot testing, the survey was conducted in April and May 2012. Overall, 2,481 people were approached and about 500 questionnaires were distributed. Of the 483 questionnaires collected, 466 were usable and 17 were rejected because the questionnaire was not properly completed, most of the important questions were skipped, or the respondents were not considered as tourists.

Data Analysis

Data were analyzed in three steps. First, tourists’ levels of satisfaction with each service aspect were compared by means, median, and mode. Second, principle component analysis with the Varimax orthogonal rotation method was adopted to delineate the underlying dimensions that were associated with the satisfaction with public transport in Munich. Factors were extracted using the following criteria: an eigenvalue greater than 1 and factor loadings greater than 0.5. A reliability analysis (Cronbach’s alpha) was used to assess the correlation between variables of each identified factor. All factors with an α reliability above 0.50 were accepted for the purpose of this study. Third, Discriminant Function Analysis (stepwise method) was run to identify the most important factors influencing the tourists’ satisfaction with public transport in Munich. This step has been proven as effective in identifying predictors of customer satisfaction in previous studies (Kim and Lee 2011; Fellesson and Friman 2008).

Findings

Respondents’ Profile

The survey sample includes 466 respondents, of which 82 percent (380 visitors) have used public transport in Munich during their visit. As shown in Table 1, around half of the respondents were female, and the majority (40%) were ages 18–29. Most public transport users are well-educated (48% university/college graduates and 14% post-graduates). Germans were the largest group of visitors (21%), and all other European visitors represent 51 percent. A majority of users (87%) indicated no health restrictions. Almost half of the sample (48%) had previously been to Munich. A stay of 2–3 days is most common (41%), followed by 4–6 days (32%). Most visitors traveled with their friends (31%), partner (23%), and family or relatives (22%). The majority of them visited Munich on holiday (54%) or for VFR purposes (22%). About 39 percent of the visitors stated rare or non-use of public transport, whereas 36 percent used public transport almost every day at their home residences. Most of the respondents possessed a valid driver license (93%), and 77 percent indicated ownership of a car.
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<td>Hearing</td>
<td>7</td>
<td>1.8</td>
<td>Driver license ownership</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No restriction</td>
<td>332</td>
<td>87.4</td>
<td>Yes</td>
<td>352</td>
<td>92.5</td>
</tr>
<tr>
<td>More than one restriction</td>
<td>7</td>
<td>1.8</td>
<td>No</td>
<td>28</td>
<td>7.5</td>
</tr>
<tr>
<td>Car ownership</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>293</td>
<td>77.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>87</td>
<td>22.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tourist Use of Public Transport in Munich
As expected, public transport was mainly used for tourism-related purposes such as to get to attractions (77% of total respondents) or to travel around Munich for an overview of the city (54%). Tourists also used public transport for shopping (47%), visiting friends and relatives (21%), and business-related purposes (13%). The majority of the sample (51%) tended to use public transport for all their trips made in the city, compared to 11 percent who had used public transport in Munich only once. The U-Bahn (underground train) appeared to be the most popular public transport mode (used by 88% of respondents), followed by S-Bahn (suburban train) (67%). Other types (tram and bus) are relatively less common (43% and 39%, respectively).

The most popular tickets used by tourists are the partner-day ticket (29%), followed by three-day ticket (27%), single-day ticket (20%), and single-trip ticket (18%). Other types of tickets, such as a weekly ticket, a monthly ticket, and a Bavaria ticket (allows a single person or a group of up to five to use unlimited regional public transport in Bavaria for one day), were only used by fewer than 10 percent of the respondents. Interestingly, the CityTourCard, a combination ticket that includes travel by public transport and discounts for several tourist attractions, was only used by around 5 percent of the respondents.

Visitor’s Satisfaction with Public Transport in Munich
Respondents were asked to indicate how satisfied they were with public transport with regard to 16 service dimensions. Table 2 illustrates a comparison of the service items by means, median and mode (in descending order by means). Visitors tended to be satisfied with most service aspects of public transport in Munich, as indicated by the fact that almost all items (except ticket price) have a score above 3.0 (neither dissatisfied nor satisfied). Characteristics of public transport in Munich that were highly appreciated (M>=4.00, somewhat satisfied) include punctuality, reliability, network connection, and service frequency. Items received lowest scores are staff service, comfort while waiting at bus stops or train stations, and ticket price. These items were also most mentioned in visitors’ comments and suggestions for service improvement.
In addition to detailed assessment of satisfaction with specific aspects of the public transport services, respondents were asked to rank their overall satisfaction. Findings indicated a high level of satisfaction with public transport in Munich, with a mean score of 4.08 and mode of 4.0.

The 16 service dimensions were subjected to factor analysis using SPSS 16.0, which resulted in four factors, explaining 66.4 percent of the total variance (Table 3). Each factor was labeled according to the appropriateness of individual items it included.
TABLE 3.
Factor Analysis of Public Transport Service Dimensions

<table>
<thead>
<tr>
<th>Service Aspect</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traveling comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space on vehicle</td>
<td>0.835</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleanliness of the vehicle</td>
<td>0.788</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seat availability</td>
<td>0.776</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comfort while waiting at bus stops or train stations</td>
<td>0.736</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety on board</td>
<td>0.701</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service quality</td>
<td></td>
<td>0.803</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Punctuality</td>
<td></td>
<td>0.799</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td>0.698</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service frequency</td>
<td></td>
<td></td>
<td>0.619</td>
<td></td>
</tr>
<tr>
<td>Convenience of time schedule</td>
<td></td>
<td></td>
<td>0.598</td>
<td></td>
</tr>
<tr>
<td>Network connection</td>
<td></td>
<td></td>
<td></td>
<td>0.598</td>
</tr>
<tr>
<td>Accessibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility of train stations and bus stops</td>
<td></td>
<td></td>
<td>0.820</td>
<td></td>
</tr>
<tr>
<td>Accessibility of vehicles</td>
<td></td>
<td></td>
<td>0.676</td>
<td></td>
</tr>
<tr>
<td>Additional features</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ticket price</td>
<td></td>
<td></td>
<td></td>
<td>0.712</td>
</tr>
<tr>
<td>Ease of use</td>
<td></td>
<td></td>
<td></td>
<td>0.656</td>
</tr>
<tr>
<td>Staff service</td>
<td></td>
<td></td>
<td></td>
<td>0.636</td>
</tr>
<tr>
<td>Information</td>
<td></td>
<td></td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>3.48</td>
<td>3.02</td>
<td>2.10</td>
<td>2.02</td>
</tr>
<tr>
<td>Variance (%)</td>
<td>21.77</td>
<td>18.85</td>
<td>13.07</td>
<td>12.62</td>
</tr>
<tr>
<td>Cumulative variance (%)</td>
<td>21.77</td>
<td>40.62</td>
<td>53.67</td>
<td>66.31</td>
</tr>
<tr>
<td>Reliability coefficient</td>
<td>0.87</td>
<td>0.86</td>
<td>0.82</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Factor 1, Traveling Comfort ($\alpha=0.87$), explains 21.8 percent of the variance. It includes five variables (space on vehicle, cleanliness of the vehicle, seat availability, comfort while waiting at bus stops or train stations, and safety on board) and reflects the importance of the conditions and facilities of the vehicles and stations. As expected, visitors demonstrated a strong preference for traveling comfortably. The second factor ($\alpha=0.86$) includes five items (punctuality, reliability, service frequency, convenience of the time schedule, and network connection). It describes different service aspects of the public transport system and therefore was labeled Service Quality. It explains 18.9 percent of the total variance. The third factor ($\alpha=0.82$) includes two aspects indicating the accessibility of the train stations, bus stops, and vehicles. The factor explains 13.1 percent the total variance. The fourth factor ($\alpha=0.67$) includes ticket price, ease-of-use, staff service, and information and explains 12.6 percent of the total variance. These four aspects first appeared to be quite different from each other. On the other hand, they are also very distinctive from the other three factors. It can be seen that all these aspects describe additional features/benefits of the public transport system, which are highly valued by visitors and, hence, was labeled Additional Features.
Factors Influencing Visitor Satisfaction with Public Transport

Satisfaction with Public Transport: Comparisons between Different Groups

The relationship between satisfaction with public transport and other variables was investigated using the Spearman Test. The results show that satisfaction with public transport was independent from most variables (demographic and trip-related characteristics) except for country of residence. There is a slight connection between tourists’ country of residence and their satisfaction with public transport ($r = 0.128$). Asians and visitors from the U.S. and Canada tended to be more satisfied; German and other European visitors were more critical in comparison.

Predictor of Satisfaction

Public transport performance was evaluated in multiple aspects. However, the influences of these aspects to the overall satisfaction differ from each other. Identifying the most influential service aspects is important for service improvement. To determine which individual service aspect has the strongest influence on tourists’ overall satisfaction, a Discriminant Function Analysis was performed (with “overall satisfaction with public transport” as the grouping variable and the independent variables are 16 specific service dimension evaluation). Six items were revealed as being most important to visitor satisfaction with public transport: information, ticket price, service frequency, space on the vehicle, cleanliness of the vehicle, and ease of use (Table 4).

**TABLE 4.**

Results of Discriminant Function Analysis $^{a,b,c,d}$

<table>
<thead>
<tr>
<th>Step</th>
<th>Entered</th>
<th>Wilks’ Lambda</th>
<th>Exact F</th>
<th>Approximate F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>$df_1$</td>
<td>$df_2$</td>
<td>$df_3$</td>
</tr>
<tr>
<td>1</td>
<td>Information</td>
<td>0.724</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Cleanliness of vehicle</td>
<td>0.601</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Service frequency</td>
<td>0.540</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Ease of use</td>
<td>0.510</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Space on vehicle</td>
<td>0.492</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Ticket price</td>
<td>0.475</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

At each step, variable that minimizes overall Wilks’ Lambda is entered.

$^a$ Maximum number of steps is 32.

$^b$ Maximum significance of F to enter is 0.05.

$^c$ Minimum significance of F to remove is 0.10.

$^d$ F level, tolerance, or VIN insufficient for further computation.
Discussion and Conclusions

Improving Public Transport Services

Public Transport Service Dimensions
As discussed earlier several dimensions of public transport service have been identified in the literature. In this study, four service dimensions were found: traveling comfort, service quality, accessibility, and additional features. Each of these dimensions comprises at least two individual interrelated service aspects. Collectively, the four dimensions explain 66.4 percent of the total variance. A comparison of the present findings with those of previous studies shows some similarities as well as differences (Table 5).

Table 5. Public Transport Service Dimensions Identified

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Service Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budiono (2009)</td>
<td>Soft quality, functionality quality</td>
</tr>
<tr>
<td>Fellesson and Friman (2008)</td>
<td>Systems, comfort, staff, safety</td>
</tr>
<tr>
<td>Thompson and Schofield (2007)</td>
<td>Ease-of-use, efficiency and safety, good parking</td>
</tr>
<tr>
<td>Tyrinopoulos and Antoniou (2008)</td>
<td>Quality of service, transfer quality, service production, information/ courtesy</td>
</tr>
<tr>
<td>This Study</td>
<td>Traveling comfort, service quality, accessibility, additional features</td>
</tr>
</tbody>
</table>

As with Fellesson and Friman (2008), this study identified traveling comfort as an important service dimension. This factor describes features needed for a comfortable trip. It covers the requirements for vehicles (space, cleanliness, seat availability, and safety) as well as stations.

Service quality is another significant dimension of public transport performance, which was also explored in earlier studies (Budiono 2009; Tyrinopoulos and Antoniou 2008). Visitors appreciate an effective and efficient system with high punctuality and reliability, frequent services, convenient schedule, and good network connection.


Accessibility is the new dimension found in this study, which was not examined in previous research. Accessibility is an important criterion for high-quality, sustainable public transport systems (Soltani et al. 2012; Gutiérrez 2009). Accessible stations and transport vehicles are necessary for the improvement of customer penetration.

Most Important Service Aspects Influencing Overall Satisfaction
In conclusion, visitors in Munich were relatively satisfied with the public transport services. However, there is still room for service enhancement. The six most important attributes were identified, which include both new aspects and those previously found in studies of local users. Improvement of public transport system in Munich should focus on these six key aspects, as discussed below.
1. **Information** is recognized as very important for visitors when using public transport (Friman, Edvardsson, and Gärling 2001; Friman and Gärling 2001). According to Thompson (2004), tourists require more information than residents. One reason could be much transport information is linked to local knowledge (e.g., train station location, departure and arrival points), whereas tourists are unfamiliar with the place and the systems. Second, there are differences in terms of information sources referred. Real-time information was considered most important by local public transport users (Molin and Timmermans 2006). Conversely, tourists tend to rely on traditional information sources such as a tourist information center, word-of-mouth, attraction leaflets, the Internet, and hotel reception (Thompson 2004). In this study, train stations and bus stops, the Internet, local people, accommodation receptions, and tourist information centers were found to be the most common sources. Language is also another problem indicated in the survey. Many non-German-speaking tourists suggested that English information was either unavailable or insufficient. Public transport providers should cooperate with tourist centers, tourist attractions, and hotels to give tourists accurate and updated information. More information in English should be offered.

2. **Ticket price** has a major influence on the attractiveness of public transport (Redman et al. 2013; Budiono 2009). Fare promotion and special ticket schemes have proven positive in the case of encouraging local residents to use public transport. The same method could be applied to tourists. A considerable number of negative comments from respondents were related to ticket prices. Compared to other European cities, ticket prices for public transport in Munich are relatively high. The ticketing system was also perceived as complicated and difficult to use. Therefore, it is essential that the types of tickets and ticket zones be presented in a clear and simple way. Electronic smart ticketing systems should also be a topic for future planning.

3. **Service frequency** is a major factor to customer satisfaction with public transport, and this aspect consistently appeared in studies on public transport service assessment (Budiono 2009; Del Castillo and Benitez 2012; Tyrinopoulos and Antoniou 2008; Redman et al. 2013). While Munich has an extensive transport network, public transport does not run very frequently, especially during off-peak hours. (The U-Bahn runs every 10 minutes and and the S-Bahn runs every 20 minutes.) Increasing service frequency is believed to stimulate ridership (Wall and McDonald 2007). However, the decision of increasing services might be affected by several factors, including finance and budget. On the other hand, providing more services in major tourist routes could be one possible solution.

4. **Ease of use** of a public transportation system is essential for passengers (Dziekan 2003; Redman et al. 2013; Thompson and Schofield 2007). Thompson and Schofield (2008) suggested ease of use is more important for visitors than efficiency and safety. In this study, respondents were relatively satisfied with the public transport ease of use (mean=3.87 and mode=4). Spearman correlation tests show that visitors’ perception of ease of use is independent from most descriptive variables (demographic and trip-related variables) and is slightly related to the following variables:
• First time visitor to Munich ($r_s=0.156$): As expected, returning visitors found public transport easier to use compared to first-time visitors. Similarly, the number of previous trips also has a positive effect on visitors’ perception ($r_s=0.153$).

• Frequency of public transport use in Munich ($r_s=0.129$): The more often respondents used public transport during their visit, the easier they thought it was to use the system.

• Valid driver license ownership ($r_s=-0.131$): Respondents who owned a driver license tended to find public transport easier to use compared to those who did not.

• Recommend to use ($r_s=-0.106$): Visitors tended to recommend others to use public transport if public transport was perceived as “easy.” However, it is noted that the number of respondents who did not recommend others to use public transport was small (9 respondents).

• Improving ease of use is also related to information and ticketing system improvement. As discussed, more information in English and clear ticketing systems are essential to make public transport in Munich easier for visitors to use.

5/6. Comfort attributes are revealed as important for visitors traveling by public transport, in line with findings from Redman et al. (2013). In particular, areas should also receive more attention are the vehicle’s cleanliness and space. Clean and more spacious (i.e., less crowded) buses and trains are desirable. Upgrading of the waiting area at train stations and bus stops should also be noted. Providing more seats for passengers while waiting for their trains or buses is recommended.

Implications for Future Research

Transport is an essential element in tourism systems, and public transport plays a vital role in sustainable tourism development. However, there is little information on tourist use of public transport at destinations. This paper contributes to the understanding of tourist satisfaction with public transport and the factors that influence their perception. Four service dimensions were identified: traveling comfort, service quality, accessibility, and additional features. In line with findings from Thompson and Schofield (2007), dimensions of public transport services identified in this study suggest considerable resemblance to research on local users.

Public transport services in Munich were positively evaluated by tourists, and their perceptions are independent from most factors. Visitors were most satisfied with system punctuality, reliability, network connection, and service frequency. On the other hand, ticket price received the lowest rating and were perceived as “expensive” and “complicated.” Improvement of waiting facilities at bus stops and train stations is essential. Other areas that need further attention include staff service, seat availability, space, and cleanliness of the vehicle.

Though carefully planned and conducted, this study is not without limitations. First, most study sites are centrally located and relatively easy to access by public transport. More respondents in remote tourist attractions would have provided a better picture of tourist satisfaction with public transport.
perception. Second, as with all self-completed surveys, some respondents might not have answered the questionnaire carefully or understood the questions correctly. In addition, more open-ended questions would have provided useful further information in tourist behavior.

Despite these limitations, the paper has shed light on the use of public transport by tourists. Improving customer satisfaction is vital to the future development of public transport. Further studies are necessary to better understand tourist behavior and improve their experience with public transport, especially as such research may not only bring economic returns to a destination but also contribute to sustainable transport goals.

References


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Evaluating the Effectiveness of Onboard Video Feedback Systems on Reducing Transit Collisions and Injuries

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Mineta Transportation Institute, San Jose State University

Abstract

In the mid-2000s, public transit agencies began testing onboard video feedback systems on buses, which capture short video clips when triggered by an unusual event such as hard braking, a sharp turn, or impact with an object. The objective of this study was to determine whether the systems have enhanced passenger safety by reducing the frequency and severity of collisions and injuries and to identify lessons learned from the implementation of such systems. The study concludes that the systems appear to have a positive impact on transit safety achieved through a reduction in collisions and injuries and the risky driving behaviors that contribute to them. The systems provide transit managers with a wealth of information about their employees’ driving habits that was not previously available. Transit agencies should consider investing in such systems as one component of an overall safety and training program.

Introduction

In the mid-2000s, a handful of public transit agencies in the United States began installing video feedback systems in buses specifically intended to improve transit operator safety and adherence to safety regulations. Although this technology has been used on commercial fleet vehicles for a number of years, its application in the public transit industry is still relatively recent. Proponents of the systems argue that they provide feedback that helps identify potentially dangerous driving behavior before it leads to a collision or injury. Such feedback also serves to deter operators from violating transit-specific safety regulations such as bans on use of personal electronic devices. Manufacturers of the video systems claim they can lead to significant reductions in the frequency and severity of crashes, as well as the number of worker compensation and personal injury claims (DriveCam 2011).

However, the video feedback systems also have prompted objections from union officials, and transit operators themselves, who believe they constitute an invasion of privacy and are not a cost-effective solution to improve transit safety. Such feedback has been shown to lead to significant reductions in safety-relevant events in young drivers and commercial
Evaluating the Effectiveness of Onboard Video Feedback Systems on Reducing Transit Collisions and Injuries

over-the-road truckers (Carney et al. 2010; McGehee et al. 2007; Hanowski et al. 2010). To date, there have been no formal studies examining the effectiveness of these types of systems on improving safety in the transit industry through a reduction of safety-related events and the frequency and severity of crashes and injuries.

There are currently two primary companies that manufacture video-based driver feedback systems used by transit operators: DriveCam, Inc. (now Lytx, Inc.) and SmartDrive Systems, Inc., both based in San Diego, California. This research project evaluates the effectiveness of the DriveCam system used by six public transit operators and three private contractors and develops lessons learned in implementing the system. The Los Angeles County Metropolitan Transportation Authority’s (Metro) experience with the SmartDrive system also is discussed. In addition, after the research period was complete, Veolia switched its video system provider from DriveCam to SmartDrive. DriveCam and SmartDrive both are used by trucking firms, private motorcoaches, taxi cabs, and a wide variety of other fleet vehicles; however, this study focuses specifically on use of the systems in transit buses. Similar systems also are in limited use on transit buses in Europe and South Africa, although their effectiveness has yet to be examined in published research.

Although several past research studies have explored the impact of using behavior-based techniques, including video recording devices, to improve safety in the trucking and motorcoach industries, there have been no published reports regarding the use of such technology in the U.S. public transit industry. This study examines whether the systems have been successful in enhancing safety in the transit industry by reducing the frequency and severity of collisions and injuries.

Background and Literature Review

The video-based driver feedback systems currently used by transit industry clients use a small, palm-sized dual-lens video camera that is mounted on the vehicle windshield, usually behind the interior rear-view mirror of the bus. A wide-angle camera captures the view out the front windshield of the bus; an interior view, including a clear view of the operator; and, typically, the farebox and at least a portion of the passenger seating area. The cameras also include a microphone to capture audio inside and outside the vehicle.

Although the cameras are always on during operation, the system is set to save short (12–15 second) video clips only when triggered by gravitational forces (g-forces) that approximate about 0.5 g, such as sudden braking or acceleration, swerving, sharp turns, or the impact of a collision. The camera systems automatically save video footage from before and after a triggered event. Transit clients using the DriveCam system receive video clips of 8 seconds before and 4 seconds after each triggered event. If the driver operates the vehicle in a safe manner, the system never records an event. The transit operator also can press a button to manually trigger a clip to be saved if there is a particular event he or she wants recorded.

Role of Video Feedback in Behavior-Based Safety

A 2003 Transportation Research Board (TRB) report discusses the recommended use of behavior-based safety techniques to improve safety in the trucking and private motorcoach industry, including on-board video systems (Knipling et al. 2003). The report
defines behavior-based safety as “a set of methods to improve safety performance by teaching workers to identify critical safety behaviors, perform observations to gather data, provide feedback to each other to encourage improvement, and use gathered data to target system factors for positive change” (Knipling et al. 2003, 27). It found that behavior-based safety has been used successfully for decades in industrial settings to reduce risky behaviors, encourage safe behaviors, and prevent occupational injuries and compensation claims (Knipling et al. 2003). Studies also show safety benefits when behavior-based safety techniques are used in the trucking and motorcoach industries, where it is much more difficult to conduct direct behavioral observation and feedback (Hanowski and Hickman 2010).

Truck drivers, motorcoach drivers, and transit operators generally operate their vehicles independently. It is difficult and cost-prohibitive for managers to provide direct, real-time supervision of all drivers in the field, unlike in the manufacturing industry, in which many workers are based in the same location and their activities can be viewed by management. As a result, transit operators resemble “street-level bureaucrats,” which have frequent, direct interaction with the public, but enjoy a relatively high degree of independence in their work due to the difficulty of providing direct supervision (Lipsky 1980).

The TRB report also discusses the use of electronic feedback systems as a safety tool in the trucking and motorcoach industries. Video feedback provides critical context and goes far beyond the ubiquitous “How’s my driving?” placard. It is not reliant on the potentially-biased testimony of other drivers, and this can help exonerate drivers who have done nothing wrong. On-board video systems also eliminate the subjectivity of relying on other drivers or, in the case of the transit industry, passengers to report unsafe driving behavior. Penn + Schoen Associates (1995) found that commercial drivers were skeptical of new technology that could be perceived as an invasion of privacy or as diminishing the role of driver judgment. Their study also showed that on-board monitoring was the least-accepted technology by the drivers, even though they generally acknowledged its potential safety benefits. However, the study looked at continuous monitoring, which is more invasive than the video-based driver feedback systems that are the subject of this paper, and there has been a cultural shift in perceptions of privacy since 1995, particularly with the advent of social media. Hickman and Geller (2002) found that instructing short-haul truck drivers to use self-management strategies to monitor their driving behavior resulted in significant decreases in at-risk driving behaviors such as hard braking and speeding.

The authors of the TRB study conclude that “[On-Board Safety Monitoring] technology and behavioral applications are underused in truck and bus transport in relation to their safety potential,” and that the technology should be used in safety training programs to demonstrate that unwanted driving behaviors that are likely to increase the likelihood of a crash (Knipling et al. 2003, 45).

**Effectiveness of Video-Based Driver Feedback Systems**

Although there have been no formal studies to date examining the effectiveness of video-based driver feedback systems on improving safety in the transit industry, at least one formal study has examined the technology’s impact on safety in the trucking industry. In April 2010, the Federal Motor Carrier Safety Administration (FMCSA) funded a study that
conducted an independent evaluation of the DriveCam system at two private trucking firms (Hanowski and Hickman 2010).

The study found that participating drivers at the two firms reduced the mean frequency of recorded safety-related events per 10,000 vehicle miles traveled by 37 percent and 52.2 percent, respectively, during a 13-week “intervention” after implementation of DriveCam, compared to a four-week “baseline” phase before the system was in place. Although installation of the DriveCam system alone provided safety benefits, the recommended coaching program improved the results even further. “The coaching sessions where drivers reviewed a video of a safety-related event resulted in significant safety benefits, whereas the feedback light alone and/or coaching sessions without videos were less robust” (Hanowski and Hickman 2010, 34). The authors of the study concluded that, “Safety benefits on the scale found in this study highlight the potential for [video-based driver feedback systems] to have a robust impact in reducing truck crashes on our nation’s highways” (Hanowski and Hickman 2010, 34).

In 2009, Loomis Armored conducted a six-month pilot study of the SmartDrive system involving more than 2,800 drivers and more than 1,000 vehicles. Loomis experienced a 53 percent reduction in collision frequency during the pilot program and reported “significant per-driver improvements across four important metrics that are leading factors in collisions” (Trucks at Work 2009, 1). Distracted driving dropped 54 percent, fatigue behind the wheel dropped 56 percent, non-use of seatbelts dropped 68 percent, and speeding dropped 53 percent (Trucks at Work 2009).

Finally, 2007 and 2010 studies by the University of Iowa examined the impact of installing the DriveCam system in the cars of newly-licensed drivers. The DriveCam equipment used in the studies was similar, but not identical, to that used in transit buses. The studies found a significant reduction in the number of safety-relevant events, with drivers reducing their rate of safety-related events from an average of 8.6 events per 1,000 miles during the baseline phase to 3.6 events per 1,000 miles, or approximately 58 percent during the intervention phase. The group further reduced its rate of safety-related events to 2.1 per 1,000 miles in the following nine weeks (weeks 10–18), achieving a 76 percent reduction from the baseline. Among the riskiest drivers, safety-relevant events were reduced by 88 percent. The studies’ authors concluded that an event-triggered video system, paired with feedback in the form of a weekly graphical report card and video review, can result in a significant decrease in unsafe driving behaviors (McGehee et al. 2007; Carney et al 2010.).

Overall, the published research to date indicates that video-based driver feedback systems generally have proven effective at reducing risky driving behaviors where they have been implemented—risky driver behaviors that often can lead to collisions. However, these studies have included only a few hundred drivers, so measuring crash and injury reduction is difficult to do with such small N studies. Safety-relevant events provide the best estimates to evaluate such technologies. Driving in over-the-road trucking and passenger vehicles is different when compared to transit buses, in which bus drivers make frequent stops and also must interact with passengers.
Methodology
This study synthesizes data from the U.S. transit agencies currently using video-based driver feedback systems to determine if there is a pattern that indicates that the cameras are an effective tool to enhance safety by preventing risky driving behaviors and, in turn, reducing the frequency and severity of collisions and injuries. The two primary data sources used to evaluate effectiveness are National Transit Database (NTD) crash and injury statistics and qualitative results reported directly by transit operators in interviews.

NTD crash and injury statistics were examined for each of the six public transit operators using the DriveCam system through calendar year 2012 to look for any trends in the safety performance of directly-operated bus services that could be correlated with adoption of video-based driver feedback systems. Due to the complexity of tracking which of the firms’ transit clients were using DriveCam and on which portion of the fleet during a particular time period, however, NTD data were not analyzed for the three contracted operators using DriveCam—First Transit, MV Transportation, and Veolia Transportation. This information is summarized in Tables 1 and 2.

<table>
<thead>
<tr>
<th>Transit Agency</th>
<th>Average Change in Frequency of Collisions, Passenger Injuries After Implementation Compared to Four Years Before Implementation per NTD Data</th>
<th>Results Reported by Transit Agency Managers Interviewed</th>
<th>Implementation Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Metro</td>
<td>Yes/no; 15% reduction in passenger injuries in 5 years after implementation of DriveCam in 2007; number of collisions increased by 4%</td>
<td>Noticeable reduction in frequency of scored events, number of rule violations, and severity of collisions, but no clear reduction in collision frequency.</td>
<td>Use DriveCam to incentivize &quot;event-free&quot; driving; provide continuing education on how to improve driving.</td>
</tr>
<tr>
<td>LA Metro</td>
<td>Yes; 19% reduction in collisions, 36% reduction in injuries in 3 years since SmartDrive installed in 2009.</td>
<td>30% reduction in &quot;events with safety concern&quot; in 1st year of program.</td>
<td>Ensure bus operators understand that intent of system is training, not discipline.</td>
</tr>
<tr>
<td>New Jersey Transit</td>
<td>Yes; 68.5% reduction in collisions and 57% reduction in injuries over 5 years since DriveCam installed in 2007.</td>
<td>&quot;Significant&quot; decrease in scored events; noticeable reduction in &quot;egregious&quot; safety violations.</td>
<td>Program not as effective if 100% of fleet not equipped with DriveCam.</td>
</tr>
<tr>
<td>Pace Bus</td>
<td>Yes/no; 20 reduction in collisions, 23% increase in passenger injuries in 2 years since implementation in 2010.</td>
<td>&quot;Dramatic decrease&quot; in number and frequency of risky driving behaviors; useful in combating fraudulent claims.</td>
<td>Use incentives to recognize safe, defensive driving coupled with timely coaching.</td>
</tr>
<tr>
<td>SFMTA</td>
<td>Yes; 28% reduction in collisions and 44% decrease in injuries over 3 years since DriveCam installed in 2009.</td>
<td>33% reduction in scored events and 35% decrease in severity of incidents after 10 months.</td>
<td>Using DriveCam in coordination with progressive discipline policy is key to seeing fewer incidents .</td>
</tr>
<tr>
<td>WMATA</td>
<td>No. 19% increase in collisions and 21% increase in passenger injuries in 2 years since DriveCam installed in 2010.</td>
<td>23% reduction in frequency and 25% reduction in severity of scored events after 6 months.</td>
<td>Timely training/coaching key to seeing results; should combine progressive discipline with recognition of good driving.</td>
</tr>
</tbody>
</table>
TABLE 2.
Contracted Operators without Safety Data Available for Analysis

<table>
<thead>
<tr>
<th>Transit Agency</th>
<th>Average Change in Frequency of Collisions, Passenger Injuries After Implementation Compared to Four Years Before Implementation per NTD Data</th>
<th>Results Reported by Transit Agency Managers Interviewed</th>
<th>Implementation Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Transit</td>
<td>N/A; NTD data not analyzed due to multiple transit clients.</td>
<td>50% reduction in scored events; reduction in collision frequency from 10 per million vehicle revenue miles to 6. Began using DriveCam in 2006.</td>
<td>Ensure management team prepared to monitor wealth of information DriveCam provides and take appropriate action.</td>
</tr>
<tr>
<td>MV Transportation</td>
<td>N/A; NTD data not analyzed due to multiple transit clients.</td>
<td>30–40% reduction in collisions. Began using DriveCam in 2004.</td>
<td>Managers should use DriveCam to observe and correct risky driving behaviors before they lead to a crash.</td>
</tr>
<tr>
<td>Veolia</td>
<td>N/A; NTD data not analyzed due to multiple transit clients.</td>
<td>“Clear decrease” in crash frequency and severity.” Began using DriveCam in 2004, switched to SmartDrive in 2011.</td>
<td>Need to tie motivational program for good driving with disciplinary component for risky driving.</td>
</tr>
</tbody>
</table>

NTD safety data for each transit client are segregated into two groups: Directly-Operated and Purchased transportation. Because some transit agencies use multiple contract operators to provide service under the Purchased transportation category, NTD data could not be used to track the effectiveness of the systems being used on contracted services. Finally, data tracking the number of monthly scored events and collisions per event recorder were obtained from DriveCam, Inc., for its transit-industry clients to analyze safety trends following the launch of the DriveCam system.

Supplemental information was gathered through phone interviews with managers at each transit agency. Some agencies provided specific metrics on results experienced since implementation of the camera systems, while others provided more anecdotal information. The interviews also explored what policies and procedures each transit agency put in place when implementing the new video systems to determine whether and how implementation procedures may have had an impact on safety statistics.

**Safety Impacts of Driver Feedback Systems**

Based on the feedback provided by transit agencies that have installed the systems, as well as the data obtained from NTD reports and DriveCam records, video-based driver feedback systems appear to have enhanced transit safety through a reduction in risky driving behaviors and the frequency of collisions and injuries that ultimately result from those risky behaviors at the agencies examined. In some cases, crash rates appear to actually increase slightly immediately after the systems are installed; however, this may be due to the fact that minor crashes that previously went unreported are now being captured and logged at several transit agencies. Such minor collisions result can result in significant property damage—damage that is sometimes difficult to assign to particular drivers.
A reduction in the number of collisions per million miles traveled of up to 50 percent occurred following implementation of DriveCam at agencies that have had DriveCam in place for at least two years (see Tables 1 and 2). Not all transit agencies profiled experienced clear declines in the number of collisions and passenger injuries following implementation of the systems. However, interviews with officials at each transit agency revealed that all agencies believed the frequency and severity of “scored events” captured by the systems had declined, indicating that transit operators were adapting their driving habits to avoid risky behaviors, even if the agencies had not yet seen quantifiable reductions in crashes and injuries.

These findings are appropriately evaluated in the context of trends in the total number of collisions and injuries on U.S. transit buses reported through the NTD safety and security database. The average number of collisions per million vehicle revenue miles on transit buses nationwide was 4.12 in 2002–2007 before dropping to 1.61 in 2008, then trending slightly upward to 1.73 by 2012. The sudden drop in collisions apparently is due to a change in NTD reporting requirements between 2007–2008 that adjusted the thresholds required for collisions to be reported. The number of passenger injuries nationwide decreased slightly, from 4.86 per million passenger miles in 2002–2007, to 3.64 in 2008, before trending slightly up to 4.19 in 2012. Of the six transit agencies examined in this study, four implemented video feedback systems after 2008 and would not be impacted by the change in reporting requirements. New Jersey Transit and Pace both implemented the systems in 2007 but continued to see a downward trend in the number of collisions between 2008–2012.

Information provided during in-person meetings with DriveCam, but not included as an exhibit in this study, supports that conclusion, as it shows that the number of monthly “scored events” per event recorder at five transit agency clients declined at a relatively steady pace since the implementation of DriveCam. This indicates that transit operators are changing their behavior because of the DriveCam system and learning to avoid the risky driving behaviors that cause an event to be captured and scored. Other data provided by DriveCam tracks the number of scored events and collisions per active event recorder among DriveCam’s transit industry clients from 2009–2011. The number of scored events captured over time declined consistently, with a slightly less consistent downward trend in number of collisions. A reduction in scored events ultimately should lead to an improvement in overall safety, as these risky behaviors are the precursors to more serious crashes and injuries.

The nine transit agencies and contractors using these systems each stated that adoption of the system must include a comprehensive training and coaching component. Most agencies cite the ability to use video footage as a training tool—on both an individual and a group basis—as one of its main benefits. The majority of the transit agencies profiled in this study downplayed the use of DriveCam for disciplinary purposes. However, it appears that agencies experience the best results when they use DriveCam not only to recognize and reward desirable driving behavior, but also to impose discipline to discourage undesirable or risky behavior.
Based on prior published research as well as interviews conducted with the transit agencies cited earlier, video-based driver feedback systems can be effective at encouraging safer driving in a number of ways:

1. As a group training tool showing peers engaging in risky driving behaviors and for demonstrating good defensive-driving techniques.
2. As an incentive to drive safer due to the awareness that any risky behaviors will be captured on video.
3. As an individual training tool to help transit managers identify and correct chronic risky driving behaviors that eventually will lead to crashes and injuries.
4. As a means to observe clear traffic code or transit policy violations committed by operators, such as running a red light, not wearing a seatbelt, or using a personal electronic device, leading to disciplinary measures.
5. By providing the indisputable context of an event—difficult to argue against because the cause is clear.

Although there is an upfront capital cost and ongoing operation and maintenance costs associated with implementing video-based driver feedback systems such as DriveCam and SmartDrive, the nine transit agency officials interviewed in this study were nearly unanimous in their view that, over time, the systems would more than pay for themselves through reduced costs and claims associated with crashes and injuries. However, none of the agencies could provide a specific calculation of return on investment.

**Addressing Privacy Concerns**

One challenge to implementing video-based driver feedback systems is the perception, particularly by transit operators and the unions that represent them, that installing such systems is an invasion of privacy. However, the fact that these systems are event-triggered and not continuous recordings actually makes them much less intrusive than any system that records continuously. While there are many other types of video surveillance systems found in banks, hotels, department stores, and countless other public places, including security cameras on transit buses, they are designed to record all activities. Because DriveCam and SmartDrive are event-triggered, video cannot be viewed real-time by transit managers and cannot be randomly inspected; it must be triggered by a potentially risky event or manually by the transit operator. This arguably offers transit operators a greater degree of privacy than video surveillance systems used in most other settings.

In the transit industry, managers cannot constantly monitor each bus operator in the field. Before implementing video-based driver feedback systems, transit agencies used ride-alongs by administrative staff or “mystery rider” programs to observe transit operators. However, at most transit agencies, the number of staff assigned to observe transit operators is dwarfed by the number of transit operators. This is also very expensive for operators. As a result, ride-alongs typically occur only with transit operators who already have been singled out by passenger complaints for risky behaviors, and there is very little random monitoring for potentially risky behaviors. Transit operators already work in a very public setting, so it is difficult to understand the argument that these systems
“violate” a transit operator’s right to privacy. Any perceived privacy concerns may be outweighed by the public safety benefits of video-based driver feedback systems.

**Impacts on Risk Management**

One of the benefits of video-based driver feedback systems frequently touted by manufacturers is their ability to reduce claim costs by exonerating operators in the case of a collision or other incident that results in a driver or passenger injury. The previously-cited TRB report observes that, “In situations of litigation, the data could be used to exonerate or lessen the liability of drivers. Unfortunately, event-data recorders could also be a liability threat to commercial drivers and their companies in at-fault crash situations, and this perceived vulnerability has limited the use of event-data recorders by commercial fleets” (Knipling et al. 2003, 29).

Transit officials currently using video-based driver feedback systems stated that the systems have been very useful in combating fraudulent claims and exonerating transit operators after collisions. There was general consensus among those interviewed that, at least thus far, footage from the systems has helped dismiss claims, fight traffic tickets, and reduce liability more often than it has posed a liability to transit agencies. Several officials noted that even if the video footage showed the transit agency was at fault, they would rather have all the facts up front and settle at-fault situations quickly rather than pay crash reconstruction and legal fees to fight it out in court, which sometimes can drag on for years and cost millions of dollars.

**Conclusions**

Based on interviews with six public transit agencies and three private transit contractors and review of the quantitative data currently available, it appears that video-based driver feedback systems are a promising addition to the transit industry’s arsenal of potential safety measures. Further quantitative analysis still is necessary to determine the long-term impact of these systems on collisions and passenger injuries in transit buses. However, the transit agencies that have implemented them have shown that onboard video feedback systems can serve as valuable training tools that provide real-world examples of both desirable and risky driving behaviors, and prior research has shown the systems to be highly effective in other domains such as young drivers and commercial fleet drivers (McGehee et al. 2007, Carney et al. 2010, Simons-Morton et al. 2013, Hanowski et al. 2010). The systems seem particularly effective at reducing the risky driving behaviors that act as precursors to an incident. Based on academic research regarding the use of on-board video systems in behavior-based safety programs in the trucking and motorcoach industries, as well as the experiences of public transit agencies that have implemented the systems, a number of best practices have emerged:

1. Simply installing cameras is not enough. On-board camera systems are most effective when tied to a comprehensive coaching and training program that recognizes safe driving habits and provides timely coaching to prevent repetition of risky behaviors. This kind of coaching service is part of both DriveCam and SmartDrive subscriptions and thus does not add much cost to an operation.
2. Transit agencies should ensure there is clear management and union buy-in about how the video systems will be used and who will have access to the footage (chain of custody) and ensure that drivers and union officials understand the primary intent of the system is as a training tool.

3. Transit agencies should carefully weigh the potential liabilities and benefits of implementing video-based driver feedback systems from a risk management perspective, although there appears to be general consensus based on the interviews conducted that cameras generally have reduced transit agency liability where they have been implemented, rather than increased it.

Public transit agencies should consider investing in video-based driver feedback systems as one component of an overall safety and training program. However, additional research needs to be conducted to better quantify the long-term impact on crash and injury rates, as well as the return on investment transit agencies have seen due to reductions in claims and insurance premiums.

References


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HOT for Transit?  
Transit’s Experience of High-Occupancy Toll Lanes  

Gregory L. Newmark  
Center for Neighborhood Technology  

Abstract  
As more and more regions seek to implement high-occupancy toll or HOT lanes, more and more transit agencies seek knowledge to take advantage of this new infrastructure opportunity. Unfortunately, as is often the case with the rapid diffusion of a new technology, little information is available to guide policy. This research addresses the need for knowledge on the integration of transit with HOT lanes. It first identifies the salient elements of HOT lanes for transit agencies and then systematically compares these features across all 12 HOT lane facilities operating in the United States at the start of 2012. This paper combines a review of the limited literature on HOT lane/transit integration with detailed data collection from functioning projects. The text aims at a general comparison; however, the tables offer an additional degree of detail to facilitate further exploration.

Introduction  
Cities in the United States have begun to vary roadway tolls to manage traffic congestion, particularly via the politically-acceptable high-occupancy toll or HOT lane (Fielding and Klein 1993). HOT lanes allow motorists who do not want to face possible freeway congestion to purchase access to a parallel and uncongested tollway. Vehicles that meet an occupancy threshold may access HOT lanes at no cost. By 2012, 12 such facilities were in operation.

While HOT lanes are promoted as a new option for drivers, they also represent a new option for transit (Fielding 1995). As more and more regions seek to implement HOT lanes, more and more transit agencies seek knowledge to take advantage of this burgeoning infrastructure. Unfortunately, as is often the case with the rapid diffusion of a new technology, there is little information available. The most extensive treatment considers

1 Orange County’s SR-91 is the sole exception to this rule. That HOT lane charges eastbound high-occupancy vehicles half tolls during the afternoon peak. It should be noted that most HOT lanes also allow free access to select sets of vehicle types, such as motorcycles and certain alternatively-fueled vehicles.
only a quarter of current facilities (Turnbull 2008). Given concerns that transit agencies are not optimizing the opportunity afforded by such congestion pricing (Hardy 2009), there is a need to comprehensively examine and assess the integration of transit with HOT lanes in the United States. This research is a response to that need.

This work identifies the salient elements of HOT lanes for transit and then systematically compares these across all 12 facilities operating at the start of 2012. This research combines a review of the limited literature with detailed data collection from each HOT lane. The text aims at a general comparison; however, the tables offer an additional degree of specificity to facilitate further exploration.

This article contains three sections. The first focuses on the HOT lane itself and how facility origin and configuration can affect transit. The second section describes current transit integration with HOT lanes to provide a cross-sectional look at bus service levels, park-and-ride provision, and transit ridership. The third section explores HOT lane revenue generation and the use of those revenues to fund bus service.

HOT Lanes in the United States

Figure 1 shows the locations of the 12 HOT lanes in the United States, all of which, with the sole exception of the 2 facilities in Minneapolis, are in the faster-growing South and West. These lanes serve major roadways experiencing sufficient congestion to warrant an express service. Nine are on Interstate highways, two are on state highways, and one is on a U.S. highway.

![HOT lanes in the United States (January 2012)](image)

**Origin**

Table 1 orders these lanes by their opening dates to show that all HOT lanes have been built since 1995 and two-thirds since 2005.
TABLE 1.
HOT Lanes in the United States (January 2012)

<table>
<thead>
<tr>
<th>Region</th>
<th>Name</th>
<th>Corridor</th>
<th>Opened*</th>
<th>Origin</th>
<th>Miles</th>
<th>Lanes</th>
<th>Reversible</th>
<th>Separation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange County</td>
<td>91 Express Lanes</td>
<td>SR-91</td>
<td>Dec 1995</td>
<td>New construction</td>
<td>10</td>
<td>4</td>
<td>No</td>
<td>Plastic posts</td>
</tr>
<tr>
<td>San Diego</td>
<td>I-15 Express Lanes</td>
<td>I-15</td>
<td>Dec 1996</td>
<td>Conversion/new construction</td>
<td>20</td>
<td>4</td>
<td>Partial</td>
<td>Concrete wall</td>
</tr>
<tr>
<td>Houston</td>
<td>Katy Freeway Managed Lanes</td>
<td>I-10</td>
<td>Jan 1998</td>
<td>Conversion/new construction</td>
<td>12</td>
<td>4</td>
<td>No</td>
<td>Plastic posts</td>
</tr>
<tr>
<td>Houston</td>
<td>Northwest Highway QuickRide</td>
<td>US-290</td>
<td>Dec 2000</td>
<td>Conversion</td>
<td>15</td>
<td>1</td>
<td>Yes</td>
<td>Concrete wall</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-394 MnPASS Express Lanes b</td>
<td>I-394</td>
<td>May 2005</td>
<td>Conversion</td>
<td>8</td>
<td>2</td>
<td>Partial</td>
<td>Painted lines/concrete wall</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>I-15 Express Lanes</td>
<td>I-15</td>
<td>Sept 2006</td>
<td>Conversion</td>
<td>40</td>
<td>2</td>
<td>No</td>
<td>Painted lines</td>
</tr>
<tr>
<td>Denver</td>
<td>I-25 Express Lanes</td>
<td>I-25</td>
<td>June 2006</td>
<td>Conversion</td>
<td>7</td>
<td>2</td>
<td>Yes</td>
<td>Concrete wall</td>
</tr>
<tr>
<td>Seattle</td>
<td>SR-167 HOT Lanes c</td>
<td>SR-167</td>
<td>May 2008</td>
<td>Conversion</td>
<td>12</td>
<td>2</td>
<td>No</td>
<td>Painted lines</td>
</tr>
<tr>
<td>Miami</td>
<td>95 Express</td>
<td>I-95</td>
<td>Dec 2008</td>
<td>Conversion/new construction</td>
<td>7</td>
<td>4</td>
<td>No</td>
<td>Plastic posts</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-35W MnPASS Express Lanes c</td>
<td>I-35W</td>
<td>Sept 2009</td>
<td>Conversion/new construction</td>
<td>16</td>
<td>2</td>
<td>No</td>
<td>Painted lines</td>
</tr>
<tr>
<td>Bay Area</td>
<td>I-680 Sunol Express Lanes d</td>
<td>I-680</td>
<td>Sept 2010</td>
<td>Conversion</td>
<td>14</td>
<td>1</td>
<td>No</td>
<td>Painted lines</td>
</tr>
<tr>
<td>Atlanta</td>
<td>I-85 Express Lanes</td>
<td>I-85</td>
<td>Sept 2011</td>
<td>Conversion</td>
<td>16</td>
<td>2</td>
<td>No</td>
<td>Painted lines</td>
</tr>
</tbody>
</table>

* This date refers to the first opening of the HOT lane while the remaining columns refer to current conditions. In some cases, particularly San Diego (I-15) and Houston (I-10), the facilities have been expanded so that current conditions do not reflect those when the lane opened.

b Minneapolis (I-394) is composed of two segments. The western segment from I-494 to SH-100 consists of a single dedicated lane in each direction painted line separated from the general purpose lanes. The eastern segment from SH-100 to I-94 consists of two reversible lanes concrete barrier separated from the general purpose lanes.

c HOT lane is longer in the northbound direction than the southbound direction. The longer length is presented here and used for subsequent calculations.

d This lane currently operates only in the southbound direction. Subsequent calculations, such as bus ridership, consider flows only in one direction.

HOT lane origin affects transit. HOT lanes may be newly-constructed, converted from an existing high-occupancy vehicle (HOV) lane, or a combination of both. New construction adds managed road capacity, whereas conversion adds managed road access for low-occupancy vehicles willing to pay the toll.

Capacity expansion (building new HOT lanes) is thought to generally benefit transit as the new and managed infrastructure speeds transit travel and improves reliability. For example, Miami’s I-95 project, which combined new construction with conversion, reduced bus travel times along the corridor by 68 percent (Pessaro and Van Nostrand 2011). These benefits are thought to grow if the new lanes link previously-unconnected portions of a regional HOV network (Poole and Orski 2003; Barker and Polzin 2004; Buxbaum et al. 2010), as is the vision in the San Francisco Bay Area (Metropolitan Transportation Commission 2007). In a worst case scenario, new HOT lane capacity is unlikely to degrade existing conditions for transit.
By contrast, access expansion (opening HOV lanes to paying motorists) without capacity expansion raises the specter of new low-occupancy vehicles worsening the traffic conditions for buses in the managed lane (Turnbull 2008; Perez, Giordano, and Stamm 2011). This outcome is seen as particularly inequitable for existing transit users (Lari and Buckeye 1999; Weinstein and Sciara 2006) and appears to be happening along Salt Lake City’s I-15, where lane underpricing (due to legal restraints on toll levels) and poor lane enforcement have resulted in new peak-period congestion in the converted HOT lane.

To ward off such negative possibilities, HOT lanes can prioritize their operations to place transit at the top of a hierarchy of users (Swisher et al. 2003). For example, an agreement between Denver’s I-25 HOT lane and the local transit agency specifies that any degradation in bus travel times triggers a policy review and may lead to consideration of a toll increase (State of Colorado and Regional Transportation District 2011). Consequently, monthly progress reports list the number of buses that exceed the allotted lane travel time (HPTE 2010). This process has produced positive results. For example, Turnbull (2008) reports that Denver’s HOT lane management acted quickly when it discovered that the additional vehicles on the newly-converted HOT lane were overwhelming the clearing capacity of a pre-existing traffic signal at the lane’s exit ramp and causing some upstream delay. The agency had the signal timing adjusted to account for the now higher vehicle flows debouching from the HOT lane. Legislating such monitoring programs to avoid service degradation is seen as critical for ensuring public confidence with HOV to HOT conversions (Perez, Giordano, and Stamm 2011; Parsons Brinckerhoff 2011). Besides Salt Lake City, such monitoring programs seem to be working. A federal review found that “generally, HOT lane conversions have achieved their goals of gaining better use of underutilized HOV lanes and maintaining congestion-free travel for toll paying users without subjecting HOV and transit users to lower service levels” (K.T. Analytics and Cambridge Systematics 2008). In fact, many argue that converting HOV lanes to HOT lanes and raising occupancy thresholds is the only way to maintain levels-of-service into the future as the number of qualifying carpools grow (Poole and Orski 1999; Metropolitan Transportation Commission 2007; Swisher et al. 2003; Meyer et al. 2006).

**Configuration**

Table 1 also describes the configuration of the HOT lanes. Currently, the typical HOT lane has a median length of 13 miles, serves a downtown area, and sees strong inbound flows in the morning and outbound flows in the afternoon. Salt Lake City’s I-15 is an outlier at 40 miles in length (and under expansion to 60). This lane connects the many communities of the Wasatch Front and reports less-pronounced directional flows. The HOT lanes in Seattle, the Bay Area, and Orange County also vary slightly, as they serve commuting flows to secondary centers, not their respective region’s primary downtown.

HOT lane facilities range between one and four lanes. Two facilities currently consist of only a single lane—Houston’s US-290 is a reversible lane, and the Bay Area’s I-680 runs only southbound—but both are slated for expansion. Six facilities consist of two lanes. These are typically a single lane in each direction; however, Denver’s I-25 and the eastern portion of Minneapolis’s I-394 are reversible double lanes, which switch direction to accommodate peak traffic flow. The remaining four facilities consist of two lanes in each
direction. San Diego’s I-15 has a movable barrier between those lanes to toggle between a 2/2 and a 3/1 lane configuration. Single and fully-reversible lanes can present a problem for transit service, as reverse-commute and deadheading buses cannot follow the same return path. The need to operate an alternative route may be a source of confusion for passengers, and the potential to face additional traffic may both slow cycle times (thus requiring more buses to provide the same capacity) and reduce the agency’s ability to serve growing reverse-commute markets. There appears to be a trend to replace fully-reversible facilities with lanes operating continuously in both directions based on recent and planned projects in Houston and San Diego.

HOT lanes are separated from the adjacent unmanaged general-purpose lanes and have limited access points. Separation treatments range in cost, permanence, and permeability from a simple painted line to concrete walls (Jersey barriers). A middle ground that has been favored in several implementations is a barrier made of breakaway plastic posts (candlestick pylons), which deter illegal entry into the lanes but still allow for access in emergency situations (for more discussion on barriers see Hlavacek, Vitek, and Machemehl 2007, or Davis 2011).

Transit operators report improved travel conditions once inside converted HOT lanes, as the limited access increases the predictability of traffic and prevents the random and disruptive merging endemic to open-access HOV lanes (Munnich and Buckeye 2007). At the same time, transit operators report increased difficulty in specific locations of entering the converted HOT lanes now that access is limited. For example, many bus drivers along Seattle’s SR-167 forgo using the HOT lane, as quickly crossing from the right-side highway entrance ramp to the left-side HOT lane entry is a difficult maneuver. Similarly, bus drivers along Minneapolis’s I-394 found entry difficult at one particular access point and complained that motorists, who were now enjoying the smoother flows of the limited-entry HOT lane, were less likely to yield to buses at the access points (Cambridge Systematics 2006). Transit agencies need to be involved in HOT lane planning to avoid conflicts with bus routes (Loudon, Synn, and Miller 2010). One configuration solution to access problems, implemented in Houston and San Diego, is to construct direct-access ramps to the HOT lanes. Another solution is to expand the access areas. Minneapolis’s I-35W, for example, is designed to be largely open access and systems elsewhere are considering such policies.

Transit Integration with HOT Lanes

**Bus Service Provision**

Table 2 shows that every HOT lane has bus service, which suggests that transit is not only compatible, but also complementary. Transit is seen as central to achieving the person-throughput objectives of HOT lanes as demand grows over time. Consequently, the development of a HOT lane often provides a unique opportunity to increase transit supply in a corridor. Miami, which had repeatedly failed to gain voter approval for increasing local transit funding, was able to use federal monies for the HOT lane project to purchase buses to operate three new express routes (Florida Department of Transportation 2012). Federal funding was similarly leveraged in Minneapolis (Buckeye 2011) and Atlanta (Vu 2011). In San Diego, the HOT lane project was designed, in part, to fund new express bus service along the corridor (Supernak 2005).
TABLE 2.
Bus Service on HOT Lanes

<table>
<thead>
<tr>
<th>Region</th>
<th>Corridor</th>
<th>Operators</th>
<th>Weekday Bus Routes</th>
<th>Fares</th>
<th>Bus Route Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Routes</td>
<td>Trips</td>
<td>Trips / Routes</td>
</tr>
<tr>
<td>Orange Co.</td>
<td>SR-91</td>
<td>2</td>
<td>2</td>
<td>39</td>
<td>20</td>
</tr>
<tr>
<td>San Diego</td>
<td>I-15</td>
<td>1</td>
<td>6</td>
<td>141</td>
<td>24</td>
</tr>
<tr>
<td>Houston</td>
<td>I-10</td>
<td>1</td>
<td>6</td>
<td>391</td>
<td>65</td>
</tr>
<tr>
<td>Houston</td>
<td>US-290</td>
<td>1</td>
<td>4</td>
<td>236</td>
<td>59</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>I-15</td>
<td>1</td>
<td>12</td>
<td>76</td>
<td>6</td>
</tr>
<tr>
<td>Denver</td>
<td>I-25</td>
<td>1</td>
<td>12</td>
<td>434</td>
<td>36</td>
</tr>
<tr>
<td>Seattle</td>
<td>SR-167</td>
<td>2</td>
<td>2</td>
<td>88</td>
<td>44</td>
</tr>
<tr>
<td>Miami</td>
<td>I-95</td>
<td>2</td>
<td>4</td>
<td>259</td>
<td>65</td>
</tr>
<tr>
<td>Bay Area</td>
<td>I-680</td>
<td>1</td>
<td>1</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Atlanta</td>
<td>I-85</td>
<td>2</td>
<td>8</td>
<td>133</td>
<td>17</td>
</tr>
</tbody>
</table>

Note: Information current for January 2012. In the Bus Route Number column, **bolded** routes charge the lower fares, **underlined** routes have weekend service, and *italicized* routes charge local fares. Houston has multiple fare levels which are noted in (parentheses) for routes that do not charge the highest or lowest fare.

HOT lanes generally offer express, weekday bus services often only in the peak-flow direction. This express orientation is not surprising since longer bus routes without intermediate stops benefit the most from the reliable travel times offered by HOT lanes. Furthermore, HOT lanes typically funnel traffic to dense employment centers, which favors express, weekday operations. Table 2 shows that of the 121 bus routes identified that use HOT lanes, only 4 charge local fares and only 6 run on weekends.

The longer-distance nature of HOT lane bus service increases the likelihood of routes crossing jurisdictional boundaries and, consequently, of multiple transit operators using the same HOT lane. Multiple operators serve HOT lanes in 4 of the 10 regions studied, typically when a bus route starts in a different county from the HOT lane, such as a Riverside County bus using Orange County’s SR-91. This situation increases the challenge of coordinating information for users. Miami’s I-95 website, for example, very elegantly presents unified information on all bus routes using the facility even though two transit agencies provide those services. This presentation is exceptional. No other HOT lane website includes a map of transit service available on the facility. Among transit agencies, only Minneapolis’s MetroTransit provides unified information on routes from different operators using the HOT lanes.
The express nature of HOT lane bus service commands high and variable fares. Nine HOT lanes serve bus routes that charge between $4 and $5 per trip, much higher than standard fares. Furthermore, HOT lane bus service typically has two pricing tiers, which reflect distinctions in the distance traveled (Atlanta has two distance rates), the quality of service (San Diego offers “express” and “premium express” service with more comfortable buses and fewer stops), or the operating agency (Riverside Transit Agency and the Orange County Transportation Authority charge different express rates along the same corridor). Houston’s HOT lane bus service has even more fare variation, with three distance-based express-bus pricing tiers as well as one local rate. Table 2 shows that the vast majority of routes charge the higher fare.

Transit agencies have adopted two general strategies to bus provision on HOT lanes. The first and more popular approach provides lower-coverage, higher-frequency line-haul service and typically collects passengers already assembled at park-and-ride lots and transit centers. The second approach provides higher-coverage, lower-frequency feeder plus line-haul service and collects passengers from neighborhoods as well. Figure 2 presents the number of bus routes on each HOT lane and the ratio of daily trips per route. Houston, Miami, and Seattle exemplify the first strategy, with few routes but many trips per route. Minneapolis and Salt Lake City exemplify the second strategy, with many routes but fewer trips per route. Denver presents a third option, with a high number of routes and high frequencies per route.

![Figure 2. Transit service on HOT lanes](image-url)
**Park-and-Ride Provision**

Bus provision on all HOT lanes is supported by park-and-ride lots either upstream or along the managed lanes themselves. While general park-and-ride design principles, such as maximizing upstream flows and managing bus headways (Neudorff et al. 2011), continue to hold, HOT lanes offer some unique possibilities.

First, the development of a HOT lane often provides substantial funding to increase park-and-ride provision. For example, Atlanta’s I-85 HOT lane conversion was part of a $182 million regional congestion reduction project that allocated $80 million for park-and-ride capacity expansion at 11 sites around the region (roughly twice the $42 million spent on new over-the-road coaches). Two new park-and-ride lots were built and one park-and-ride lot was expanded to serve the HOT lane specifically (Georgia State Road and Tollway Authority 2010). These three sites combined added roughly 2,200 new parking spots (Vu 2011).

Second, because HOT lanes have limited entry points, the physical connection between these lanes and the park-and-ride lot takes on added importance. Many lots are sited well upstream of the HOT lane entrance and need no special accommodations. For example, the HOT lane expansion on Houston’s I-10 included the construction of the new 2,377 spot Kingsland Park-and-Ride lot eight miles upstream from the HOT lane’s entrance. Buses leaving the Kingsland lot enter the HOT lane downstream like any other vehicle. However, lots located along the lane may require difficult movements for buses to enter the highway and then cross all the general-purpose lanes to enter the HOT lane. The Houston I-10 expansion also included the construction of the new 2,428 spot Addicks Park-and-Ride lot just downstream from the lane’s entrance. Buses leaving this lot use a special bridge to pass over the general-purpose lanes and have a direct-access ramp down to the HOT lane. Such direct-access ramps, as noted earlier, minimize traffic conflicts and maximize the speed at which an express bus can pass between the HOT lane and an off-line park-and-ride lot.

Just as not all park-and-ride lots serving a HOT lane are located along that lane, not all park-and-ride lots located along a HOT lane serve bus routes traveling on that lane. Many lots are designed exclusively for carpooling and vanpooling or serve a perpendicular transit line that does not use the HOT lane. Table 3 presents comparative statistics for all the park-and-ride lots that are both located within one mile of a HOT lane and have bus service that actually uses those HOT lanes. By this definition, three quarters of HOT lanes have at least one park-and-ride lot along their corridor. Of these facilities, the median number of lots is five, with an average spacing of one lot every three miles. The median number of parking spaces in these lots is 1,845, with a median ratio of 513 spaces per lot or 160 spaces per mile of HOT lane.
TABLE 3.
Park and Ride Lots within a One-Mile Buffer of HOT Lanes

<table>
<thead>
<tr>
<th>Region</th>
<th>Corridor</th>
<th>Lots</th>
<th>Spaces</th>
<th>Lot Names and Number of Parking Spaces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>Per</td>
<td>(organized from furthest out to downtown, where applicable)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mile</td>
<td>Lot</td>
<td></td>
</tr>
<tr>
<td>Orange Co.</td>
<td>SR-91</td>
<td>0</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>San Diego</td>
<td>I-15</td>
<td>12</td>
<td>0.600</td>
<td>1,845 154 92</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Escondido Transit Center (580); Felicita Ave (30); Del Lago Transit Station (160); Rancho Bernardo Rd (15); Rancho Bernardo Transit Station (190); Rancho Carmel Dr (125); SR56 (70); Sabre Springs / Peñasquitos Transit Station (250); Stoney Creek Rd (132); Paseo Cardiel (88); Freeport Rd (102); Poway Rd (103);</td>
</tr>
<tr>
<td>Houston</td>
<td>I-10</td>
<td>2</td>
<td>0.167</td>
<td>2,623 1,312 219</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Addicks P&amp;R (2,428); Northwest Transit Center (195)</td>
</tr>
<tr>
<td>Houston</td>
<td>US-290</td>
<td>4</td>
<td>0.800</td>
<td>4,596 1,493 360</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Northwest Station (2,361); W. Little York (1,102); Pinemont (938); Northwest Transit Center (195)</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-394</td>
<td>5</td>
<td>0.625</td>
<td>1,351 270 169</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Plymouth Road Transit Center (111); CR 73 (732); General Mills Boulevard (123); Louisiana Ave Transit Center (330); Park Place (55)</td>
</tr>
<tr>
<td>Salt Lake</td>
<td>I-15</td>
<td>5</td>
<td>0.125</td>
<td>1,459 292 37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>160N 600W, Kaysville (231); Layton Hills Mall (379); Thanksgiving Point Station (422); 100 E. Main St, American Fork (227) American Fork Station (200)</td>
</tr>
<tr>
<td>Denver</td>
<td>I-25</td>
<td>0</td>
<td>0.000</td>
<td>0 0 0 --</td>
</tr>
<tr>
<td>Seattle</td>
<td>SR-167</td>
<td>5</td>
<td>0.417</td>
<td>1,985 662 165</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Auburn Station (631); Auburn P&amp;R (358); Kent Station (996);</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-95</td>
<td>0</td>
<td>0.000</td>
<td>0 0 0 --</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-35W</td>
<td>5</td>
<td>0.313</td>
<td>2,566 513 160</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heart of the City (370); Burnsville Transit Station (1,370); St. Luke’s (100); South Bloomington Transit Center (195); Knox Ave (525)</td>
</tr>
<tr>
<td>Bay Area</td>
<td>I-680</td>
<td>1</td>
<td>0.071</td>
<td>127 127 9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mission Boulevard (127)</td>
</tr>
<tr>
<td>Atlanta</td>
<td>I-85</td>
<td>2</td>
<td>0.125</td>
<td>1,060 530 66</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Discover Mills (554); Indian Trail (506)</td>
</tr>
</tbody>
</table>

Note: Only those lots that are served by bus routes that use the HOT lanes are considered here. Bolded lots have direct access ramps to the HOT lanes.

Transit Ridership

The purpose of bus and park-and-ride provision is to encourage transit ridership. The most recent comparative information on weekday ridership, shown in Table 4, demonstrates that transit can attract riders in HOT lane corridors. On a typical weekday, the 12 HOT lanes in the U.S. carry more than 67,000 bus passengers. The median weekday transit ridership per HOT lane is 3,882 riders; however, the 3 most transit-productive facilities, those in Denver and Minneapolis, each carry more than 11,000 bus passengers per weekday. The only HOT lanes that carry fewer than 2,000 bus passengers per weekday are those in Orange County and the Bay Area, where the HOT lane serves secondary centers with dispersed employment locations.
TABLE 4.
Weekday Bus Trips and Ridership on HOT Lanes

<table>
<thead>
<tr>
<th>Region</th>
<th>Corridor</th>
<th>Weekday Bus Trips</th>
<th>Riders</th>
<th>Rider Count Period(s)</th>
<th>Riders/Trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange Co.</td>
<td>SR-91</td>
<td>39</td>
<td>450</td>
<td>March 2010; Oct 2011</td>
<td>12</td>
</tr>
<tr>
<td>San Diego</td>
<td>I-15</td>
<td>141</td>
<td>2,158</td>
<td>Spring 2011; Nov 2011</td>
<td>15</td>
</tr>
<tr>
<td>Houston</td>
<td>I-10</td>
<td>391</td>
<td>8,027</td>
<td>Fiscal Year 2011</td>
<td>21</td>
</tr>
<tr>
<td>Houston</td>
<td>US-290</td>
<td>236</td>
<td>4,526</td>
<td>Fiscal Year 2011</td>
<td>19</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-394</td>
<td>548</td>
<td>12,141</td>
<td>Calendar Year 2011</td>
<td>22</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>I-15</td>
<td>76</td>
<td>3,477</td>
<td>Calendar Year 2011</td>
<td>46</td>
</tr>
<tr>
<td>Denver b</td>
<td>I-25</td>
<td>434</td>
<td>14,840</td>
<td>Aug – Dec 2011</td>
<td>34</td>
</tr>
<tr>
<td>Seattle</td>
<td>SR-167</td>
<td>88</td>
<td>2,334</td>
<td>Oct-Dec 2011; Dec 2011</td>
<td>27</td>
</tr>
<tr>
<td>Miami</td>
<td>I-95</td>
<td>259</td>
<td>4,286</td>
<td>June 2011</td>
<td>17</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-35W</td>
<td>495</td>
<td>11,647</td>
<td>Calendar Year 2011</td>
<td>24</td>
</tr>
<tr>
<td>Bay Area c</td>
<td>I-680</td>
<td>30</td>
<td>307</td>
<td>Calendar Year 2011</td>
<td>10</td>
</tr>
<tr>
<td>Atlanta</td>
<td>I-85</td>
<td>133</td>
<td>3,179</td>
<td>Sept 12 – Oct 7, 2011</td>
<td>24</td>
</tr>
</tbody>
</table>

* Trips based on January 2012 schedules.
* The B, L, and 120X routes also operate some service in the reverse commute direction. This service does not use the HOT lanes, but the data on those trips and ridership are included in these totals.
* Since the Bay Area (I-680) HOT Lane is southbound only, only buses running in that direction and their ridership are counted.

The bus service on HOT lanes is relatively efficient with an average load factor of 23 passengers per bus trip. Salt Lake City’s I-15 reports a particularly high load factor of double the national average due to the combination of strong demand for the limited peak-period service and the large seating capacity of the over-the-road coaches. The unfavorable land use conditions for transit along the HOT lanes in Orange County and the Bay Area result in the lowest load factors of 12 and 10, respectively.

A common concern of HOT lane development, particularly for HOV to HOT conversions, is that people who formerly rode transit to enjoy the managed-lane benefit will make a socially-undesirable mode shift to driving alone once they can purchase access to the same managed-lane benefit. Some HOT lane policies are expressly designed to limit this possibility. For example, the peak-period tolls on Denver’s I-25 are legally bound to be at or above the express bus fare along the corridor (State of Colorado and Regional Transportation District 2011) so that driving never has an out-of-pocket cost advantage.

It is difficult to address this concern knowledgeably, as there has been limited research into such behavioral changes. An April 1998 examination of paying users of Houston’s I-10 HOT lane, during a period when two-occupant vehicles could purchase peak-direction access otherwise restricted to three-occupant vehicles, found that 10.6 percent of the morning users and 5.3 percent of the afternoon users had previously taken the bus (Burris and Stockton 2004). A stated preference study of bus passengers on Houston’s HOT lanes was conducted in 2003 to predict the modal impacts of allowing single-occupant vehicles to purchase access to the lanes. That study predicted that even with extended HOT lane hours and the maximum time savings at the lowest toll tested, fewer than 6.1 percent of current bus riders would shift to driving alone (Chum and Burris 2008). Evaluations of Orange County’s SR-91 found that transit passengers did not shift to driving with the addition of the HOT lane (Sullivan 2002, 2000). These three studies hint at only small shifts from transit to driving.
but do not provide particularly conclusive evidence. The first study was of a very small sample of early adopters to a very limited service, the second study was based on beliefs about future actions, and the third study considered the only HOT lane that had not been an HOV facility (and, therefore, did not previously afford transit any advantage).

Since a small amount of former transit users switching to driving with the introduction of a HOT lane may be compensated for by new riders, it is important to consider the net ridership impacts along the corridor. Here, the trends are not clear-cut, and a recent federal review could only characterize the effect as “mixed” (GAO 2012). Available studies report neutral impacts along Orange County’s SR-91 (Sullivan 2002, 2000) and Denver’s I-25 (Chum and Burris 2008) and positive impacts along Minneapolis’s I-394 (13% increase) (Chum and Burris 2008), Minneapolis’s I-35W (18% increase) (Buckeye 2011), Seattle’s SR-167 (8% increase) (Parsons Brinckerhoff 2011), and Miami’s I-95 (57% increase) (Pessaro and Van Nostrand 2011). No study reports negative impacts. These findings suggest that while the introduction of a HOT lane is unlikely to reduce ridership, it does not guarantee its growth. Unfortunately, many of these studies only look at growth on the bus lines on the HOT lane itself without necessarily considering the losses from parallel transit services.

The source of the “new” transit riders is critical. Ideally, these riders would be former drivers and thus represent a shift towards greater sustainability. In practice, many new riders of buses on HOT lanes come from other transit modes and, therefore, do not represent growth in system ridership. For example, a survey of the new riders on Miami’s 95 Express Bus service found that 45 percent came from transit and a third of those from commuter rail (Pessaro and Van Nostrand 2011). This latter example demonstrates that the combination of bus and HOT lane may serve as a reasonable commuter rail alternative. Former rail patrons in Miami can leave from the same park-and-ride lot, but they arrive at their destination by a well-appointed, over-the-road bus without needing to transfer. However, this example also demonstrates the danger of counting only passengers along the HOT lane itself rather than considering competing transit routes. Since the ability to choose between long-haul transit modes is relatively common (e.g., bus routes on HOT lanes in Orange County, Seattle, Salt Lake City, and the Bay Area also have collocated stations along parallel commuter rail lines), reporting needs to be careful to net out losses on competing transit services when measuring bus gains on HOT lanes.

Finally, the development of HOT lanes presents a very important opportunity to market existing or new transit services to the general public. Because HOT lanes do represent a novelty, they are often featured on news stories. The annual report of Miami’s I-95 HOT lanes counts the number of media mentions as “helping in providing the public valuable information on 95 Express goals and operations” (Florida Department of Transportation 2012). Publicity is seen as contributing to the success of the project, as 53 percent of new riders said the opening of the new HOT lanes influenced their decision to use transit. Similarly, public pressure has caused HOT lane marketing campaigns to promote transit in Denver (Ungemah, Swisher, and Tighe 2005) and Minneapolis (Munnich and Buckeye 2007).

**HOT Lane Revenues and Transit Subsidies**

An appealing feature of HOT lanes is that they earn revenues, which, in theory, could be used to subsidize transit. This section explores whether supportive legal structures are
in place, whether toll revenues are available, and whether available revenues are actually transferred to subsidize transit.

**Legal Structures for Revenue Transfer**

Table 5 shows that most HOT lanes can legally transfer toll revenues to support transit along the corridor. Typically, the transferable funds are described as “excess” or “net” revenues and refer to monies earned after expenses. This approach raises the question of what constitutes an expense. Most systems only include operating expenses; however, some, such as Minneapolis’s I-394, also include capital expenses. Including more expenses reduces the availability of excess revenues for transit. An alternate approach, taken by Miami’s I-95, is to define HOT lane expenses to include the transit subsidy. There, express bus service is seen as essential to the operation of the HOT lane and the two bus providers are guaranteed subsidy payments regardless of net revenues.

**TABLE 5.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Corridor</th>
<th>Operator</th>
<th>Legislated Revenue Transfer to Transit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange Co.</td>
<td>SR-91</td>
<td>Transit Agency</td>
<td>[No transfer despite transit agency owning facility]</td>
</tr>
<tr>
<td>San Diego</td>
<td>I-15</td>
<td>MPO</td>
<td>“All remaining revenue shall be used in the I-15 corridor exclusively for (A) the improvement of transit service, including, but not limited to, support for transit operations, and (B) high-occupancy vehicle facilities and shall not be used for any other purpose.”</td>
</tr>
<tr>
<td>Houston</td>
<td>I-10</td>
<td>Toll Authority</td>
<td>[No transfer]</td>
</tr>
<tr>
<td>Houston</td>
<td>US-290</td>
<td>Transit Agency</td>
<td>[Excess revenues goes into transit general fund as transit agency owns the facility]</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-394</td>
<td>State DOT</td>
<td>“The commissioner shall spend remaining money in the account as follows: … one-half must be transferred to the Metropolitan Council for expansion and improvement of bus transit services within the corridor beyond the level of service provided on the date of implementation.”</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>I-15</td>
<td>State DOT</td>
<td>[No transfer]</td>
</tr>
<tr>
<td>Denver</td>
<td>I-25</td>
<td>State DOT</td>
<td>“Excess revenues may then be used for transit purposes in the corridor. … The parties wish to clarify their intent that (1) the corridors to be benefitted by the Facility and (2) the corridors where excess revenue may be expended include US 36 and North I-25 and may extend beyond the boundaries [of] the Facility.”</td>
</tr>
<tr>
<td>Seattle</td>
<td>SR-167</td>
<td>State DOT</td>
<td>[No transfer]</td>
</tr>
<tr>
<td>Miami</td>
<td>I-95</td>
<td>State DOT</td>
<td>“All tolls so collected shall first be used to pay the annual cost of the operation [which includes peak-period express bus service], maintenance, and improvement of the high-occupancy toll lanes or express lanes project or associated transportation system. Any remaining toll revenue from the high-occupancy toll lanes or express lanes shall be used by the department for the construction, maintenance, or improvement of any road on the State Highway System within the county or counties in which the toll revenues were collected or to support express bus service on the facility where the toll revenues were collected.”</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>I-35W</td>
<td>State DOT</td>
<td>“The commissioner shall … allocate any remaining amount as follows: … 75 percent to the Metropolitan Council for improvement of bus transit services within the corridor including transit capital expenses.”</td>
</tr>
<tr>
<td>Bay Area</td>
<td>I-680</td>
<td>CCMA</td>
<td>“All net revenue generate by the program … shall be allocated pursuant to an expenditure plan adopted biennially by the administering agency for transportation purposes within the program area. The expenditure plan may include funding for the following: … (B) Transit capital and operations that directly serve the authorized corridors.”</td>
</tr>
<tr>
<td>Atlanta</td>
<td>I-85</td>
<td>Toll Authority</td>
<td>[No transfer]</td>
</tr>
</tbody>
</table>
The legal structures also distinguish between allowing revenue transfers and requiring them. Denver’s I-25, Miami’s I-95, and the Bay Area’s I-680 all allow transfers of excess revenues for transit purposes but, to date, have chosen not to expend them on transit. (Excess revenues in Denver are being held in escrow to eventually help fund a tributary HOT lane and BRT service, and Miami is already subsidizing transit as part of its expense structure.) San Diego’s I-15 and the two Minneapolis HOT lanes are required to transfer specified portions of their net revenues. San Diego must transfer its entire surplus to support transit, while Minneapolis must transfer three-quarters of net revenues along I-35W and half of net revenues along I-394.

There is some variety in the transit services that can be subsidized. Most systems require the subsidized transit be geographically located within the tolled corridor. Denver has amended its agreement to clarify that the monies from I-25 can be used on a tributary corridor beyond the tolled facility (Colorado Department of Transportation and Regional Transportation District 2011). Several regions specify that subsidies must support transit improvements and expansions. Minneapolis’s I-394 agreement is explicit that this refers to “bus transit services within the corridor beyond the level of service provided on the date of implementation” (State of Minnesota 2012). Other HOT lane agreements, such as those in Denver and the Bay Area, suggest that toll revenues can be used to subsidize existing services. No HOT lane limits transit subsidies to either operating or capital expenses; however, two facilities felt the need to make this explicit. Orange County’s SR-91 legislation calls out operational expenses as acceptable while Minneapolis’s I-394 legislation does the same for capital expenses.

A final case is when the transit agency operates the HOT lane. A logical assumption is that excess revenues would come back to the agency’s general fund, which is the case with Houston’s US-290; however, this arrangement is not consistent. Orange County’s SR-91, which is also operated by a transit agency, is not allowed to divert any excess revenues from corridor highway improvements and the agency is, therefore, looking to double the length of the HOT lanes.

**HOT Lane Revenues and Expenses**

A supportive legal framework is only useful if there are toll revenues available for transferring. Loudon et al. (2010) delicately note that “the expectations for revenue generation by decision makers and the public are often inflated.” Table 6 presents the reported revenues for fiscal year 2011, which vary widely from $25,467 on Houston’s I-290, which tolls for only an hour and a quarter in one direction on weekday mornings, to $41,245,590 on Orange County’s SR-91, which tolls all day in both directions every day of the week. The latter HOT lane had such a profit potential that it was initially built and owned by a private company. The median HOT lane revenue in fiscal year 2011 was a modest $2.6 million.
Table 6. Revenues and Transit Subsidies of HOT Lanes (Fiscal Year 2011)

<table>
<thead>
<tr>
<th>Region</th>
<th>Corridor</th>
<th>Operating</th>
<th>Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Income</td>
<td>Expenses</td>
</tr>
<tr>
<td>Orange County</td>
<td>SR-91</td>
<td>$41,245,590</td>
<td>$22,381,682</td>
</tr>
<tr>
<td>San Diego</td>
<td>I-15</td>
<td>$4,015,371</td>
<td>$2,456,865</td>
</tr>
<tr>
<td>Houston</td>
<td>I-10</td>
<td>$6,715,041</td>
<td>$2,873,430</td>
</tr>
<tr>
<td>Houston</td>
<td>US-290</td>
<td>$25,467</td>
<td>$30,000</td>
</tr>
<tr>
<td>Minneapolis’</td>
<td>I-394</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>I-15</td>
<td>$439,474</td>
<td>$711,896</td>
</tr>
<tr>
<td>Denver</td>
<td>I-25</td>
<td>$2,553,591</td>
<td>$2,003,131</td>
</tr>
<tr>
<td>Seattle</td>
<td>SR-167</td>
<td>$750,446</td>
<td>$1,092,346</td>
</tr>
<tr>
<td>Miami</td>
<td>I-95</td>
<td>$15,085,957</td>
<td>$7,560,000</td>
</tr>
<tr>
<td>Minneapolis’</td>
<td>I-35W</td>
<td>$2,640,684</td>
<td>$2,509,593</td>
</tr>
<tr>
<td>Bay Area’</td>
<td>I-680</td>
<td>$628,961</td>
<td>$670,449</td>
</tr>
</tbody>
</table>

* The income and expenses in Minneapolis are calculated jointly; however, subsidies are currently generated and allocated only along the I-35W corridor where the capital costs were fully paid for. This accounting arrangement results in a transit subsidy that appears to exceed the net revenues. It is expected that in 2014 the capital costs of I-394 will be paid off and I-394 will generate net revenues similar to those currently generated on I-35W to be used as subsidies.

* Estimated by HOT lane operator.

* The Bay Area’s I-680 HOT lanes opened in September 2010 and had just over nine months of operation in FY 2011. Atlanta’s I-85 HOT lanes were not open during FY 2011 and are excluded from this table.

Table 6 also compares revenues to expenses to show that only six HOT lanes reported a surplus in 2011. The four facilities where capacity has been added through new construction are doing particularly well, with a median profit margin of 48 percent and a combined net revenue of $32 million. Several of the currently unprofitable lanes are projected to generate a surplus in the near future. For example, Seattle’s SR-167 reported revenues exceeding expenses in the last quarter of FY 2011 (Washington State Department of Transportation 2011) and Houston’s US-290, which renegotiated its maintenance contract, showed a 31 percent profit margin for the 2012 fiscal year.

**Transit Subsidies**

The availability of excess toll revenues does not guarantee that they will be used to subsidize transit. Of the six HOT lanes reporting excess revenues, only three transferred portions of these monies to support bus service on the corridor. Miami spent $2.6 million and San Diego spent $1.0 million to fully subsidize express bus service along their respective HOT lanes. Minneapolis’s I-35W spent $179,000 to support transit. These transfers are perhaps less than the windfall that policy makers may imagine when instituting the policies; however, as King (2009) notes, these subsidies can be quite significant for funding service in the HOT lane corridor itself.

HOT lanes also may indirectly increase transit funding by assuming costs for HOV maintenance formerly borne by transit agencies. For example, Denver’s I-25 and Houston’s I-10 HOT lanes had previously been transit agency-operated HOV lanes. When these HOV lanes were converted to HOT lanes, toll authorities took over responsibility for operation and maintenance. These assumed costs can be substantial. For example, in FY 2011, Denver’s I-25 spent $305,459 for daily operation of the HOT lane, which includes reversing...
its direction and maintaining the gates, as well as an additional $381,648 for contracted maintenance, which includes routine tasks such as sweeping, crack sealing, guard rail repair, etc., and seasonal responsibilities such as snow and ice removal. These savings can occur only if the transit agency can shed all the associated costs of operating the lane. In Houston, the transit agency redistributed the labor force previously working on the I-10 lane to provide support elsewhere in their HOV network and, therefore, did not realize savings from off-loading that HOV maintenance responsibility to the HOT lane operator.

Conclusions
HOT lanes represent a new opportunity for transit agencies with many potential benefits, including increased funding, faster travel speeds, more riders, and greater community visibility. However, these benefits do not emerge automatically. Transit agencies need to work closely with HOT lane developers to realize these positive externalities and avoid negative ones, such as access conflicts, increased traffic congestion, and ridership losses. This paper uses the experience at existing facilities to explain how HOT lanes impact transit. The purpose of this research is to establish the stakes involved with HOT lane development and to help transit agencies to take advantage of this new opportunity.

Acknowledgment
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Intelligent Taxi Dispatch System for Advance Reservations

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Ruey Long Cheu, The University of Texas at El Paso
Der-Horng Lee, The National University of Singapore

Abstract

This research proposes and tests a new taxi dispatch policy to improve the existing systems used by taxi companies in Singapore. The proposed method chains trips made by reservations at least 30 minutes before the customer pick-up times. In this paper, the taxi dispatching system, Singapore Taxi Advance Reservation (STAR), is defined. A novel trip-chaining strategy based on a customized algorithm of Pickup and Delivery Problem with Time Window (PDPTW) is proposed. The idea is to chain several taxi trips with demand time points that are spread out within a reasonable period of time and with each pick-up point in close proximity to the previous drop-off location. The strategy proposed has the potential to lower the taxi reservation fee in Singapore to encourage advance reservations that facilitate trip chaining, which translates to lower taxi fares for customers, higher revenue for taxi drivers, and lower fleet ownership cost for taxi companies.

Introduction

Taxis are a popular transportation mode in the compact city state of Singapore. With the high cost of private vehicle ownership, taxis play an important role in offering an alternative transportation service. Fast and efficient fleet dispatching is essential to the provision of quality customer service in a competitive taxi industry. Satellite-based taxi dispatching systems, which track taxis using Global Positioning System (GPS) technology, are currently deployed by taxi companies in Singapore. Taxis on the road network are tracked, located, and dispatched to customers in real-time.

Table 1 shows the related data of major taxi companies in Singapore. Based on the reservation fees (known locally as “booking surcharges”), there are generally two categories of taxi reservations in Singapore: current and advance. Current reservations are those in which customers request vacant taxis (i.e., taxis without passengers) to reach them in less than 30 minutes. Advance reservations (known locally as “advance bookings”) are requests made at least 30 minutes in advance. The focus of this paper is on advance reservations.
TABLE 1.
Major Taxi Companies in Singapore and Their Fare Structures

<table>
<thead>
<tr>
<th>Taxi Company</th>
<th>Fleet Size (veh)</th>
<th>Current Reservation Fee</th>
<th>Advance Reservation Fee</th>
<th>Fare for 1st km</th>
<th>Meter Fare by Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prime Taxis</td>
<td>731</td>
<td>SGD $3.50</td>
<td>SGD $5.00</td>
<td>SGD $3.00</td>
<td>SGD $0.20/385m between 1 km and 10 km; SGD $0.20/330m after 10 km</td>
</tr>
<tr>
<td>Premier Taxis</td>
<td>2,436</td>
<td>SGD $3.50</td>
<td>SGD $8.00</td>
<td>SGD $3.00</td>
<td>SGD $0.22/400m between 1 km and 10 km; SGD $0.22/350m after 10 km</td>
</tr>
<tr>
<td>Yellow-Top</td>
<td>1,090</td>
<td>SGD $3.50</td>
<td>SGD $8.00</td>
<td>SGD $3.00</td>
<td></td>
</tr>
<tr>
<td>CityCab</td>
<td>2,441</td>
<td>SGD $5.00</td>
<td>SGD $10.00</td>
<td>SGD $3.00</td>
<td></td>
</tr>
<tr>
<td>Smart Taxis</td>
<td>15,200</td>
<td>SGD $3.50</td>
<td>SGD $8.00</td>
<td>SGD $3.00</td>
<td></td>
</tr>
<tr>
<td>Comfort Taxis</td>
<td>4,230</td>
<td>SGD $3.30</td>
<td>SGD $6.50</td>
<td>SGD $3.00</td>
<td></td>
</tr>
<tr>
<td>SMRT Taxis</td>
<td>3,150</td>
<td>SGD $3.30</td>
<td>SGD $8.00</td>
<td>SGD $3.00</td>
<td></td>
</tr>
</tbody>
</table>

Note: SGD $1.00 = US$0.81 in May 2013; other fees such as peak hour surcharge, midnight surcharge, and airport surcharge, etc., are not included in this table.

The paper is organized as follows. Following this introduction, a description of the existing taxi dispatch systems in Singapore and their deficiencies are presented. The proposed taxi dispatch system to handle advance reservations is presented in the next section. This is followed by several sections that illustrate the computational methodologies of the new system, which includes the paired Pickup and Delivery problem with Time Window (PDPTW) models; a review of closely-related literature; the Singapore Taxi Advance Reservation (STAR) system with its special requirements; a customized two-phase trip-chaining solution algorithm; and the study network and Application Program Interface (API) programming for traffic simulations. The results of simulation experiments are subsequently presented, followed by a discussion on the performance of the proposed system. Finally, the benefits of the proposed system for customers, drivers, and taxi companies are highlighted in the conclusion.

Existing Taxi Dispatch System and Its Deficiencies

In Singapore’s taxi industry, taxi companies own the vehicles. Drivers rent taxis from companies by paying fixed daily fees. All the taxis subscribe to, and are part of, the company’s dispatch system. When a customer requests a taxi in advance, either by phone or by Internet, the company’s dispatch center broadcasts the trip information immediately to all taxis (with and without passengers) in its fleet. Since advance reservation is a service that should be fulfilled at least 30 minutes later, it is up to the taxi drivers to decide if they want to bid to serve this customer. Drivers do not have to pay for the bid; the dispatch system assigns the job to the first driver who bids for it.

Under this dispatch policy, trip demands and taxi assignments are distributed without any consideration of fleet or revenue optimization. For instance, up to 100 different taxis might be assigned to fulfill an equal number of reservations. Hence, the taxi supply may not be significantly used.

A commitment to a reserved trip usually affects a taxi’s street pick-up service. Taxi drivers often face a dilemma when the time is approaching for a customer who has made an
Intelligent Taxi Dispatch System for Advance Reservations

advance reservation to be picked up. If a driver picks up a roadside passenger, he/she may not be able to subsequently pick up the customer who has made an advance reservation. Conversely, if the driver gives up the street pick-up business, this becomes opportunity cost for him/her to serve the customer with an advance reservation. This situation has been used by taxi companies in Singapore to justify why the advance reservation fee is more than two times than that of current reservations, in all except one company (see Table 1).

Taxi customers in Singapore have to bear an unreasonable price structure when making reservations. To some extent, customers are encouraged to shop for taxi services at the last minute, either through street hailing or through current reservations, to avoid paying higher fees. This cost-saving behavior causes the customer to take the risk of not being able to find a vacant taxi.

These problems are essentially due to the inability of the existing taxi dispatch systems to make full use of customer advance reservation information. Hence, a new and more intelligent taxi dispatch system that encourages advance reservations and makes better use of this information for fleet optimization is an urgent priority.

Concept of Trip Chaining

To take full advantage of advance reservation information, several trips may be chained to form a “route” and offered to a taxi driver as a package. This means that several reserved trips with spatial and temporal distributions of customer requests may be linked, provided that (1) each pick-up point is within close proximity to the previous drop-off location and (2) the pick-up time for the next customer must be later than the estimated drop-off time of the previous customer, but not too late. This will help the driver to minimize his/her vacant time (cruising around in search of roadside customers), as most of his/her time will be spent carrying passengers on board and generating revenue.

Computation Methodologies

In this research, the heuristics for the PDPTW were adapted to chain taxi trips in the proposed taxi dispatch system.

Paired PDPTW Models

Paired PDPTW models the situation in which a fleet of vehicles must serve a collection of transportation requests. Each request specifies a pair of pick-up and delivery locations. Vehicles must be routed to serve all the requests, satisfying time windows and vehicle capacity constraints while optimizing a certain objective, such as minimizing the total number of vehicles used or the total distance traveled. PDPTW is a generalization of the well-known Vehicle Routing Problem with Time Window (VRPTW). Therefore, PDPTW is also an NP-hard problem, since VRPTW is a well-known NP-hard problem (Savelsbergh 1995).

Related Works in Literature

PDPTW can be used to model and solve many problems in the field of logistics and public transit. As a special case of pick-up and delivery, dial-a-ride emphasizes human convenience (Cordeau and Laporte 2002)—for example, door-to-door transportation
services for older adults, or people who are sick or have disabilities (Borndorfer et al. 1997; Madsen et al. 1995; Toth and Vigo 1997) and shuttle bus services connecting airports and customer homes. Parragh et al. (2008a, 2008b) conducted a comprehensive survey on the topic of pick-up and delivery. In practice, transportation requests using dial-a-ride are usually booked at least one day in advance. Therefore, much research focuses on the static and deterministic version of this problem.

William and Barnes (2000) proposed a reactive Tabu search approach to minimize travel cost by using a penalty objective function in terms of travel time, a penalty for violation of overload, and time window constraints. The approach was tested on instances with 25, 50, and 100 customers. These test cases were constructed from Solomon’s C1 VRPTW benchmark instances (Solomon 1987), which were solved optimally.

Researchers such as Lau and Liang (2002) and Li and Lim (2001) generated many test cases for PDPTW from Solomon’s benchmark instances that were initially designed for VRPTW and proposed different versions of Tabu search embedded meta-heuristics to solve PDPTW.

Recently, Parragh et al. (2009) used a variable neighborhood search heuristics coupled with path relinking to jointly minimize transportation cost and average ride time for a dial-a-ride system with multiple service criteria. In addition, many authors, such as Beaudry et al. (2010) and Jorgensen et al. (2007), incorporated quality-of-service considerations into the solution of the dial-a-ride problem. However, few papers modeled after real-world applications with large-scale sample size have been found in published literature.

The STAR Problem and its Special Requirements

This section analyzes the problem as defined by the authors as the STAR problem. Based on the characteristics of the taxi dispatch service for advance reservations, the differences between STAR and the normal PDPTW are as follows:

1. Multiple vehicles are available throughout the street network instead of starting from a central depot.

2. Pick-up and delivery jobs are paired and directly connected without any interruption from other pick-up or delivery jobs.

3. There is a hard time window—customers will complain if the taxi is late by more than three minutes. Therefore, the pick-up time window becomes \([-\infty, \text{pick-up time as specified by the customer}]\).

4. Vehicle capacity constraints are automatically respected by customers—in real life, customers will consider this constraint when specifying the number of taxis to be booked.

5. There is a short confirmation response time—after submitting an advance reservation request, customers usually expect to receive a confirmation (by phone call, text message, or email) with a taxi’s license plate number, pick-up time, and location in less than five minutes; therefore, “real-time” route planning is highly desirable.
During route planning (chaining of trips), the following information is available:

1. Requests for taxi service are identified in advance at each planning horizon.
2. For each customer, pick-up location (origin), delivery location (destination), and desired pick-up time are known.
3. Driving distances between these locations are well understood, and driving time between each origin-destination (O-D) pair is known.
4. Average service time, i.e., time consumed after customers get on board, pays, and alights from the vehicle, is based on historical statistics.

There is a wide variety of objective functions for PDPTW. In the STAR problem, the following objectives are considered:

1. Minimizing the number of vehicles, the highest cost component for a taxi company.
2. Minimizing the travel time or distance, which usually translates into minimizing fuel consumption, the highest component of operating cost for drivers.

To model these objectives, the following function has been considered:

Minimize \[ C \times m + f(R) \]  

where, \( m \) is the total number of taxis used, \( R \) is a pick-up and delivery route plan, \( f(R) \) is the total travel cost (converted from driving time or distance), and \( C \) is a coefficient set to penalize the high cost of vehicle. The first term in the above objective function may be considered as the fixed cost and the second term the variable cost.

**The Two-Phase Solution Heuristics for the STAR Problem**

It has been shown that a successful approach for solving PDPTW is to construct an initial set of feasible routes that serve all the customers (known as the construction phase) and subsequently improve the existing solution (known as the improvement phase) (Gendreau et al. 1994; Glover and Laguna 1997). However, the characteristics and requirements of the STAR problem preclude straightforward implementation of most algorithms that have been developed for the normal VRPTW or PDPTW. In this section, a two-phase approach for solving the STAR problem is proposed.

**Construction Phase**

The nearest-neighbor heuristic adds on the closest customer for extending a route. A new vehicle is introduced when no more customers can be accommodated by the current vehicle in use (Toth and Vigo 2000).

1. Let all the vehicles have empty routes (with no customer assignment).
2. Let \( L \) be the list of unassigned requests.
3. Take a trip \( v \) from \( L \) in which the requested pick-up location is the nearest from the previous drop-off location of a route.
4. Insert \( v \) to extend the abovementioned route (if \( v \) satisfies all the constraints).
5. Remove $v$ from $L$.

6. If $L$ is not empty, go to step 3; otherwise stop.

The earliest time insert heuristic always inserts the trip with the earliest pick-up time instead of the nearest pickup location.

The sweep heuristic builds routes by using a sweep technique around a certain location. The sweep heuristic for VRP is shown below:

1. Let $O$ be a site (usually the depot) which serves as a central point, and let $A$ be another location, which serves as a reference.

2. Sort the jobs by increasing angle $\angle AOJ$, where $J$ is the pickup location. Place the result in a list $L$.

3. The jobs in $L$ will be allocated to taxis in the above order as long as constraints are respected.

The initial feasible solution is then improved in the improvement phase.

**Improvement Phase**

In the improvement phase, two types of move operations—exchange and relocate—are combined with Tabu search to improve the solution. A move in this approach corresponds to one of the traditional vehicle-routing move operations. In this study, the steepest descent search was applied.

An exchange operation swaps trips in two different existing routes, whereas in a relocation operation, a customer is removed from an original route, inserted into another route, or reinserted into the same route but at a different position. A move is considered feasible if the corresponding operation does not violate any requirement (for instance, time constraints). Hence, the neighborhood of the current solution is defined as all the feasible moves. In each iteration of the steepest decent approach, the feasible move that gives the best improvement (or least deterioration) of the cost is selected.

To avoid the search from revisiting the same solution in the near future, the Tabu search mechanism was introduced. A Tabu list records the previous moves performed. A potential move is considered Tabu if it is in the Tabu list. Moreover, a move is “aspired” if the resultant cost is lower than the cost of the best solution encountered. If the best move selected by the steepest decent approach is Tabu and not aspired, then the next best move in the neighborhood of the current solution would be considered; otherwise, the selected move is made. The improvement process in this phase continues until a preset maximum number of iterations (maxIter) or a pre-set maximum computation time (maxTime) has been reached. The key steps of the improvement phase are as follows:

1. Let the current solution $X$ be the feasible solution generated in the construction phase, and set the solution of “best so far” $z^* = \infty$.

2. Choose the best move $\text{bestMove}$ from the neighborhood of the current solution.

3. If $\text{bestMove}$ is Tabu and not aspired, repeat from Step 2; otherwise, accept $\text{bestMove}$ and update the solution $x$ and cost $z(x)$. 
4. If $z(x) < z^*$, then $x^* = x$ and $z^* = z(x)$.

5. Repeat steps 2–4 until the number of iterations equals $maxIters$ or until $maxTime$ computation time has been performed.

6. Output $x^*$ and $z^*$.

**Simulation Experiment**

This section describes the experiment conducted to test the proposed two-phase solution approach for the STAR problem. A customized microscopic simulation model, PARAMICS (Quadstone 2009), was adopted to generate time-dependent link travel times for the experiment. A portion of the Central Business District (CBD) area in Singapore, which is bounded by the Electronic Road Pricing (ERP) gantries and covers an area of approximately 3.0 km by 2.5 km, was used for the simulation.

For network coding, the details of the geometry and physical layout of the roads were collected via field surveys. The coded network features included the number of lanes (mid-block and at intersections), turn restrictions, posted speed limit, etc. Signal timing plans, O-D matrices of background traffic, and boundaries of traffic analysis zones in the CBD area were collected from the Land Transport Authority of Singapore.

The coded CBD network in PARAMICS consisted of a total of 894 nodes and 2,558 links. The 100 traffic analysis zones in this network were defined according to the traffic demands of each zone, which were allocated according to the acquired hourly O-D data. Figure 1 is a screen shot of the CBD network coded in PARAMICS.

**FIGURE 1.**
Simulated CBD network of Singapore
A customized program developed through PARAMICS’ Application Programming Interface (API) was developed to collect the time-dependent travel time of each link in the CBD network as the simulation progressed. These travel times were used to construct the link-to-link travel time between each pickup and drop off locations.

As there are ERP gantries to separate the CBD area from other parts of Singapore, a fleet of taxis may always do their business within the CBD to avoid the ERP toll. Based on the data provided by taxi companies in Singapore, approximately 3,000 advance bookings are made during the day time (from 8:00 AM to 6:00 PM) across the whole island of Singapore. We assume that one-third of the above demands (pick-up and drop-off locations) are within the CBD area.

In this study, 1,000 pairs of taxi pick-up and drop-off locations were randomly generated from among 100 major trip generators (e.g., major office buildings, shopping malls, hospitals, hotels, and convention centers) to form a demand set. The pick-up times were from 8:00 AM to 6:00 PM (see Table 2). For each demand set, the average pickup time deviation is defined as \[ \sum_{i=1}^{n} |T_i - \bar{T}| / n \], where \( T_i \) is the desired pickup time and \( \bar{T} \) is the average pickup time for all the \( n=1000 \) requests within a demand set. Ten sets of taxi demands were generated. The average deviation of pick-up times for each set varied from half an hour to more than two hours (see Table 3). To study the performance of the proposed heuristics, the pick-up time deviation could not be too small during the experiment. This is because an extremely small deviation means that all the pick-ups will happen at almost the same time and, thus, there is very limited opportunity to chain these trips.

**Experimental Results**

All the computation works were carried out in a personal computer with an Intel Core i3 CPU and 4 GB of RAM. To solve the STAR problem, numerical comparisons between the proposed insertion earliest time window insertion and other construction heuristics. The results are listed in Table 4. The computation times of these construction heuristics always took less than 30 seconds to arrive at the initial solution with a problem size of 1,000 trips in this study. Then, each of these initial solutions was improved by using the move operations and Tabu search procedure. The Tabu search had a pre-set maximum computation time of 30 seconds. The results at the end of the improvement phase are shown in Table 5. In the objective function, \( f(R) \) was set to the total travel time of all the routes. Intuitively, \( C \) could be set to 6 hrs \( \times \) 60 minutes/hr \( = \) 360 minutes so that the term \( C \times m \) is equivalent to the total taxi-hours available to serve customers during the 6-hour planning horizon. This will also convert \( C \times m \) to the unit of travel time in minutes used in \( f(R) \). However, in our experiment, \( C \) was set to a very high value so that the objective function forced the solution to converge to the minimum number of taxi used. This was done deliberately so that the different heuristics could be evaluated by comparing the number of routes or taxis.
### TABLE 2.
Example of Randomly-Generated Demand Set with 1,000 Trips

<table>
<thead>
<tr>
<th>Reservation Request</th>
<th>Pick-up Location</th>
<th>Destination Location</th>
<th>Pick-up Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Paragon Tower</td>
<td>Parco Bugis Junction</td>
<td>9:30 AM</td>
</tr>
<tr>
<td>2</td>
<td>Cairnhill Place</td>
<td>Bank of China</td>
<td>9:55 AM</td>
</tr>
<tr>
<td>3</td>
<td>Sunshine Plaza</td>
<td>People’s Park Complex</td>
<td>11:40 AM</td>
</tr>
<tr>
<td>4</td>
<td>Sin Tai Hin Building</td>
<td>Centennial Tower</td>
<td>8:35 AM</td>
</tr>
<tr>
<td>5</td>
<td>Parco Bugis Junction</td>
<td>Maxwell Road Food Center</td>
<td>8:25 AM</td>
</tr>
<tr>
<td>6</td>
<td>Bugis Village</td>
<td>UIC Building</td>
<td>1:25 PM</td>
</tr>
<tr>
<td>7</td>
<td>Golden Mile Complex</td>
<td>Air View Building</td>
<td>4:35 PM</td>
</tr>
<tr>
<td>8</td>
<td>Keypoint Building</td>
<td>People’s Park Complex</td>
<td>10:30 AM</td>
</tr>
<tr>
<td>9</td>
<td>Ngee Ann City</td>
<td>OUB Center</td>
<td>8:25 AM</td>
</tr>
<tr>
<td>10</td>
<td>Singapore Power Building</td>
<td>Centennial Tower</td>
<td>5:10 PM</td>
</tr>
<tr>
<td>11</td>
<td>Suntec City Tower</td>
<td>Sunshine Plaza</td>
<td>8:50 AM</td>
</tr>
<tr>
<td>12</td>
<td>Centennial Tower</td>
<td>Air View Building</td>
<td>4:45 PM</td>
</tr>
<tr>
<td>13</td>
<td>People’s Park Complex</td>
<td>Ngee Ann City</td>
<td>8:05 AM</td>
</tr>
<tr>
<td>14</td>
<td>Ministry of Manpower</td>
<td>Golden Mile Complex</td>
<td>10:00 AM</td>
</tr>
<tr>
<td>15</td>
<td>OUB Center</td>
<td>The Paragon Tower</td>
<td>9:45 AM</td>
</tr>
<tr>
<td>16</td>
<td>Bank of China</td>
<td>Golden Mile Complex</td>
<td>8:10 AM</td>
</tr>
<tr>
<td>17</td>
<td>Maxwell Road Food Center</td>
<td>CPF Building</td>
<td>8:05 PM</td>
</tr>
<tr>
<td>18</td>
<td>Air View Building</td>
<td>Sin Tai Hin Building</td>
<td>3:30 PM</td>
</tr>
<tr>
<td>19</td>
<td>CPF Building</td>
<td>Ngee Ann City</td>
<td>2:10 PM</td>
</tr>
<tr>
<td>20</td>
<td>UIC Building</td>
<td>Bugis Village</td>
<td>4:50 PM</td>
</tr>
<tr>
<td>.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>999</td>
<td>The Paragon Tower</td>
<td>Centennial Tower</td>
<td>11:15 AM</td>
</tr>
<tr>
<td>1000</td>
<td>Suntec City Tower</td>
<td>Golden Mile Complex</td>
<td>3:45 PM</td>
</tr>
</tbody>
</table>

Average deviation of pick-up time: \( \frac{\sum_{i=1}^{n}|T_i - \bar{T}|}{n} \) 62.7 minutes

### TABLE 3.
Average Pick-up Time Deviation within Each Demand Set

<table>
<thead>
<tr>
<th>Demand Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average deviation of pick-up time (min)</td>
<td>36.7</td>
<td>45.8</td>
<td>54.5</td>
<td>62.7</td>
<td>71.9</td>
<td>82.0</td>
<td>91.2</td>
<td>101.5</td>
<td>112.1</td>
</tr>
</tbody>
</table>

*Journal of Public Transportation, Vol. 17, No. 3, 2014*
TABLE 4.
Initial Solutions after Construction Phase

(a) Initial solutions by nearest neighbor insertion heuristic

<table>
<thead>
<tr>
<th>Demand Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxis used</td>
<td>160</td>
<td>149</td>
<td>146</td>
<td>136</td>
<td>128</td>
<td>121</td>
<td>123</td>
<td>119</td>
<td>119</td>
<td>117</td>
<td>131.8</td>
</tr>
<tr>
<td>Total travel time (min)</td>
<td>5450.1</td>
<td>5430.7</td>
<td>5420.7</td>
<td>5533.4</td>
<td>5527.5</td>
<td>5562.2</td>
<td>5538.7</td>
<td>5548.0</td>
<td>5558.2</td>
<td>5510.2</td>
<td></td>
</tr>
</tbody>
</table>

(b) Initial solutions by sweep insertion heuristic

<table>
<thead>
<tr>
<th>Demand Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxis used</td>
<td>136</td>
<td>116</td>
<td>112</td>
<td>96</td>
<td>91</td>
<td>90</td>
<td>93</td>
<td>87</td>
<td>91</td>
<td>90</td>
<td>100.2</td>
</tr>
<tr>
<td>Total travel time (min)</td>
<td>8383.1</td>
<td>8609.9</td>
<td>8597.9</td>
<td>8665.2</td>
<td>8819.2</td>
<td>8769.5</td>
<td>8780.6</td>
<td>8837.1</td>
<td>8858.3</td>
<td>8714.9</td>
<td></td>
</tr>
</tbody>
</table>

(c) Initial solutions by earliest time window insertion heuristic

<table>
<thead>
<tr>
<th>Demand Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi used</td>
<td>73</td>
<td>56</td>
<td>54</td>
<td>53</td>
<td>42</td>
<td>40</td>
<td>34</td>
<td>32</td>
<td>32</td>
<td>28</td>
<td>44.4</td>
</tr>
<tr>
<td>Total travel time (min)</td>
<td>6951.7</td>
<td>6977.6</td>
<td>7015.4</td>
<td>7191.3</td>
<td>7164.9</td>
<td>7252.1</td>
<td>7325.3</td>
<td>7416.0</td>
<td>7349.4</td>
<td>7203.2</td>
<td></td>
</tr>
</tbody>
</table>

From Table 4, it can be observed that the initial solution from the proposed earliest time window insertion heuristic was significantly better than the other two heuristics (nearest neighbor insertion and sweep insertion) in terms of the number of taxis required. However, a smaller number of routes (or taxis) could increase the total travel time (for example, see the total travel times for demand set 1 in Tables 4(a), 4(b) and 4(c)). This is because the calculation of travel time of each route involved in this study began with the origin of the first booking demand and ended with the destination of the last trip and included all the travel times between these connected trips (between drop-offs and pick-ups). Therefore, using fewer routes may force taxis to travel a longer distance or time between last drop-offs and next pick-ups, i.e., vacant or empty cruising between jobs.

In the improvement phase, the Tabu search has proven to be so efficient that even fairly poor initial solutions (in Table 4(a),4(b)) can be improved into solutions (in Table 5[a],5[b]) which are comparable to those of good initial solutions.
TABLE 5.
Solutions after Improvement Phase

(a) Improved solutions by nearest neighbor insertion heuristic

<table>
<thead>
<tr>
<th>Demand Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxis used</td>
<td>73</td>
<td>58</td>
<td>59</td>
<td>55</td>
<td>50</td>
<td>40</td>
<td>36</td>
<td>34</td>
<td>33</td>
<td>33</td>
<td>47.1</td>
</tr>
<tr>
<td>Total travel time (min)</td>
<td>7233.8</td>
<td>7286.8</td>
<td>7402.2</td>
<td>7062.4</td>
<td>6891.3</td>
<td>7420.7</td>
<td>7651.0</td>
<td>7769.8</td>
<td>7696.0</td>
<td>7587.5</td>
<td>7400.2</td>
</tr>
</tbody>
</table>

(b) Improved solutions by sweep insertion heuristic

<table>
<thead>
<tr>
<th>Demand Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxis used</td>
<td>59</td>
<td>62</td>
<td>55</td>
<td>46</td>
<td>40</td>
<td>36</td>
<td>32</td>
<td>33</td>
<td>32</td>
<td>32</td>
<td>46.9</td>
</tr>
<tr>
<td>Total travel time (min)</td>
<td>7525.7</td>
<td>7518.2</td>
<td>7641.2</td>
<td>7608.5</td>
<td>7664.6</td>
<td>7695.3</td>
<td>7744.4</td>
<td>7738.5</td>
<td>7654.4</td>
<td>7613.1</td>
<td>7660.4</td>
</tr>
</tbody>
</table>

(c) Improved solutions by earliest time window insertion heuristic

<table>
<thead>
<tr>
<th>Demand Set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxis used</td>
<td>71</td>
<td>54</td>
<td>53</td>
<td>52</td>
<td>42</td>
<td>37</td>
<td>33</td>
<td>31</td>
<td>32</td>
<td>27</td>
<td>43.2</td>
</tr>
<tr>
<td>Total travel time (min)</td>
<td>6327.6</td>
<td>6370.0</td>
<td>6357.6</td>
<td>6486.1</td>
<td>6444.6</td>
<td>6496.6</td>
<td>6538.0</td>
<td>6709.0</td>
<td>6538.8</td>
<td>6692.8</td>
<td>6496.1</td>
</tr>
</tbody>
</table>

Overall, the larger the booking time deviation, the fewer the taxis required. However, the deviation defined as $\sum_{i=1}^{n}|T_i - \bar{T}|/n$ indicates only the average deviation from the average pick-up time. A large value of deviation does not necessarily mean that the pick-up times are evenly distributed that could lead to a solution in which fewer taxis are necessary.

Through the customized two-phase approach, a practical routing plan for a batch of 1,000 advance reservations could be generated quickly to provide real-time dispatch decisions. Under the existing taxi dispatch system, these 1,000 advanced reservations may be taken up by up to 1,000 different taxis. However, through our proposed trip-chaining strategy, these 1,000 trips may be grouped into fewer than 80 routes and assigned to a fleet with fewer than 80 taxis (see Table 5). The reduction of fleet size involved in reservation service is significant.

The authors caution that the above reduction in fleet size is computed for taxis that respond to advance reservations. This is because, although only a small fleet of taxis is necessary to cater to the advance reservations, the other taxis are free to pick up customers who make current reservations or are on the streets at any time. Having two different groups of taxis, each specializing in different types of customers or trips, will most likely lead to better utilization of taxis and increased revenue for the drivers. However, this scenario is much more complex to analyze and will be the direction of future research.
Conclusion
This research has identified the STAR taxi dispatch problem and proposed a two-phase solution approach. The two-phase approach consists of an earliest time window insertion heuristic to construct an initial solution followed by move operations cum Tabu search to improve the solution. Experimental results have showed that the two-phase approach is efficient in providing an instantaneous solution. The numerical results also show that by chaining advance-reservation rips, the taxi fleet could be reduced significantly.

The main contribution of this study is that a revolutionary system has been proposed for a real-life problem of advance taxi reservation in Singapore that would reduce operating costs and empty cruising time and could be deployed by taxi companies without any extra devices or facilities. Under the proposed system, the benefits for taxi drivers, taxi companies, and customers are summarized as follows:

• For taxi drivers, there will be an increase in productivity since they can serve more customers with less empty cruising, thus reducing operating cost. The system might also increase taxi driver income by (1) accepting a planned route with multiple advance-reservation trips and (2) having an increase in taxi occupancy time.

• For taxi companies, the most attractive part is that an increase in resource utilization would be expected. With the same vehicle resource, a taxi company will be able to handle a higher number of advance reservations. In other words, with the same demand level, a taxi company could reduce the number of vehicles in use, which translates into a reduction in inventory cost.

With a reduced fee for advance reservations, customers may be more willing to make reservations in advance, thus reducing their transportation expenses and improving travel time reliability.

Acknowledgments
The authors express their appreciation to the Land Transport Authority of Singapore for providing the O-D data of the CBD area in Singapore. Special thanks are also due to ComfortDelgro Corporation for its assistance in verifying the detailed information about existing taxi operations and dispatch systems in Singapore.

References


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A Transit-Based Evacuation Model for Metropolitan Areas

Xin Zhang, Gang-ilen Chang
University of Maryland

Abstract

This paper develops a decision-support model for transit-based evacuation planning occurring in metropolitan areas. The model consists of two modules executed in a sequential manner: the first deals with determining pick-up locations from candidate locations based on the spatial distribution of the evacuees, and the second plans for the route and schedule for each transit vehicle based on vehicle availability and evacuee demand pattern. An overlapping clustering algorithm is first adopted in allocating the demands to several nearby clusters. Then, an optimization model is proposed to allocate available buses from the depots to transport the assembled evacuees between the pick-up locations and different safety destinations and public shelters. A numerical example based on the city of Baltimore demonstrates the applicability of the proposed model and the advantages compared to state-of-the-art models with overly strict and unrealistic assumptions.

Introduction

Under potential terrorist attack, harmful substances released from transportation and industrial accidents, fires, floods, and other emergencies require immediate evacuation from hazardous areas. In congested metropolitan areas, commuters are likely to depend on either transit or other modes for their daily commute and, thus, may not have access to their private vehicles. Once an incident occurs, responsible agencies, such as city transportation administration and emergency units, should quickly devise a plan to dispatch available public transit resources to evacuate carless populations.

Although aiding the carless during evacuations has been presented in recent research, planning details such as how to identify available buses and drivers, how to determine potential pick-up locations, how to allocate bus routes to collect evacuees, and how to provide a timetable for the drivers (USDOT and USDHS 2006) are not well studied. Litman (2006) and Renne (2008) highlighted the needs for transit-dependent people during evacuation planning based on their experience with hurricanes Katrina and Rita. Wolshon (2001) mentioned that about 15–30 percent of the evacuation population in New Orleans during the hurricanes was transit-dependent. Fittante (2012) demonstrated community transit’s value in response to Hurricane Sandy. Transit agencies should be in a position
to render valuable assistance during emergencies. During the 9/11 terrorist attack, the transit system in New York City allowed free entry and led evacuees to safe locations. In Washington DC, buses contributed to the response effort, and additional buses were provided to the DC police to move officers to key locations. The Federal Transit Administration (FTA) and other agencies have issued many security guidelines for response before, during, and after a threat to ensure a quick recovery (FTA 2002; USDOT 2006). It is suggested that transit agencies to perform their own review on performance indicators for assessing emergency preparedness (Nakanishi 2003).

The transit evacuation model developed in this paper concerns the evacuation scenario occurring in metropolitan areas—for example, under a no-notice threat during a football game. The model consists of two modules executed in a sequential manner: the first deals with determining pick-up locations from candidate locations based on the spatial distribution of the evacuees. Once the pick-up locations are set, the evacuees are allocated accordingly, and the arrival pattern of each pick-up location is obtained. Fuzzy c-means (FCM), developed by Dunn (1974) and improved by Bezdek (1984), is applied to allow people at one location to be assigned to multiple clusters. The second module develops an integer-linear optimization module and plans the route and schedule for each transit vehicle based on vehicle availability and evacuee demand patterns.

Literature Review
Various studies have focused on different aspects of evacuation planning, such as demand modeling (Mei 2002; Wilmot 2004; Fu 2007), departure scheduling (Malone 2001; Mitchell 2006; Sbyati 2006; Chien 2007; Chen 2008), route choice (Cova 2003; Afshar 2008; Chiu 2008; Yazici 2010; Zheng 2010; Xie 2011; ), contra-flow operation (Theodoulou 2004; Wolshon 2005; Tuydes 2006; Xie 2010) and relief operation (Haghani 1996; Barbarosoglu 2004; Ozbay 2007; Xie 2009). Most of these are specific to the control and management of passenger car flows. Compared to these evacuation research efforts, there are only a limited number of studies on modeling transit-based evacuation. Elmitiny (2007) simulated different strategies and alternative plans for the deployment of transit during an emergency situation. Chen (2009) proposed a bi-level optimization model to determine waiting locations and corresponding shelters in a transit-based evacuation; the model was applied on the network within the University of Maryland. Song (2009) formulated transit evacuation operation during a natural disaster as a location-routing problem aiming to minimize total evacuation time; the problem identified the optimal serving area and transit vehicle routings to move evacuees to safety shelters. Abdelgawad (2010) developed an approach to optimally operate the available capacity of mass transit to evacuate transit-dependent people during no-notice evacuation of urban areas; an extended vehicle routing problem was proposed to determine the optimal scheduling and routing for the buses to minimize the total evacuation time. Sayyady (2010) proposed a mixed-integer linear program to model the problem of finding optimal transit routes during no-notice disasters; a Tabu-search algorithm was designed and an experiment was conducted using the transportation network of Fort Worth, Texas. Naghawi (2010) systematically modeled and simulated transit-based evacuation strategies applying the TRANSIMS agent-based transportation simulation system to the assisted evacuation plans of New Orleans.
(2012) addressed the optimal allocation of bus stops for the purpose of evacuating special needs populations; to evaluate the solution quality, a microscopic traffic simulation model was developed to represent the downtown Washington DC area in an evacuation scenario.

In carefully examining the similar study efforts, it can be concluded that most of the above models assumed one or several of the following:

- The pick-up locations serving as convening points are given and known in advance.
- All evacuees are present at the pick-up locations shortly after the evacuation starts.
- The loading and unloading times at pick-up locations are negligible or are assumed to be a constant value.
- Each vehicle is assigned a fixed route and runs in a cycle.
- The destinations have infinite holding capacities for evacuees.

Most of these assumptions are over-restrictive and, thus, prevent the application of the model outcome to real-world evacuation scenarios. To overcome these restrictions, our model tries to relax these assumptions and has the following unique characteristics that distinguish it from the previous studies:

- Both pick-up location allocation and transit bus scheduling are considered. During evacuations, the massive number of evacuees first needs to be coordinated and guided to nearby convene points, and then the transit vehicles are scheduled depending on the time-dependent arrival patterns of the evacuees at these pick-up points.
- The demand pattern is treated as time-dependent. Most prior research assumes that all evacuees are queued at pick-up locations at the beginning of the evacuation. This is almost never true because the evacuees may begin to evacuate at different times and it takes time for them to walk to the designated pick-up locations, and also because the pick-up locations, such as bus stops, have limited holding capacities, thus accumulating crowds and causing a huge bottleneck at that location.
- The loading/unloading times depend on the actual boarding/deboarding times. Negligence of this will overestimate the transport efficiency in generating the bus route and scheduling the timetables.
- Although pick-up locations are determined beforehand, the bus route is more flexible than the daily fixed route, servicing different pick-up locations at different runs based on actual need. Sometimes it is inefficient for a bus route to service fixed pick-up locations back and forth during evacuations. Instead, once a bus drops off evacuees at a safety area, it will be dispatched to the most-needed pick-up location.
- Capacity constraint is incorporated into destinations that are commonly public shelters, such as stadiums, schools, parks etc. Without such constraint, the model is subject to generate solutions in which all evacuees are sent to one or two nearest shelters and may cause overcrowding problems.
Modeling Pick-Up Location Selection

The set of pick-up locations should cover all carless evacuees and limit their total walking distance, as per FTA requirements. This study grouped all evacuee generation points into several clusters of demand zones, and then allocated a pick-up location within each zone. For each demand point, the evacuees were distributed based on the proximity of the nearby pick-up location within walking range. An overlapping clustering algorithm to tie a particular demand point to several nearby clusters was adopted. Developed by Dunn (1974) and improved by Bezdek (1984), Fuzzy c-means (FCM) allows one piece of data to be assigned to multiple clusters, which is based on the following objective function:

\[
J = \sum_{i=1}^{N} \sum_{j=1}^{C} u_{ij} \left\| x_i - c_j \right\|^2
\]

(1)

where,

- \( x_i \) = the ith measured data
- \( c_j \) = the center of the cluster
- \( u_{ij} \) = the degree of membership of \( x_i \) in the cluster \( j \)
- \( \left\| \cdot \right\| = \) the second-norm expressing the similarity between measured data and the center

In the context of determining bus pick-up locations, \( x_i \) is the ith evacuee’s position, \( c_j \) is the jth pick-up location, \( \left\| \cdot \right\| \) is the distance between the evacuee and the pick-up location, and \( u_{ij} \) measures the likelihood the evacuee \( i \) will move to the pick-up location \( j \).

The entire algorithm for determining the pick-up locations and the evacuee’s allocation plan is composed of the following steps:

1. Initialize \( c_j \) and \( u_{ij} = \frac{1}{\sum_{k=1}^{C} \left\| x_i - c_k \right\|} \).
2. Calculate \( c_j = \frac{\sum_{i=1}^{N} u_{ij} x_i}{\sum_{i=1}^{N} u_{ij}} \).
3. Calculate \( u_{ij} = \frac{1}{\sum_{k=1}^{C} \left\| x_i - c_k \right\|} \).
4. If \( \Delta U = \max(\Delta u_{ij}) \leq \varepsilon \), go to step 5; otherwise, go to step 2.
5. If \( \left\| x_i - c_j \right\| > \xi \), set.
Note if any of the final pick-up locations is geographically feasible (e.g. river, rail-road, and building), then it needs to be adjusted to the closest geographically location, which can serve the pick-up purpose.

**Transit Vehicle Routing and Scheduling**

*Define Pick-Up Request and Vehicle Route*

Each pick-up request is associated with the following parameters: pick-up location, number of evacuees (usually equal to load capacity), and time-window with an upper and lower bound. The bound for the time window can ensure people being picked up on time and prevent intolerably long waiting times. For each pick-up location $i$, we divide the time horizon into time segments with lengths $t_{ij}, j = 1, 2, 3\ldots$ and let $d_{ij}$ be the demand reaching pick-up location $i$ during time interval $t_{ij}$, then $t_{ij} = \arg \min(d_{ij} = C, t_{ij} = W)$, where $C$ is the bus capacity and $W$ is the maximum waiting time. For each time segment $t_{ij}, j = 1, 2, 3\ldots$, a pick-up request node is created with a time window $a_{ij} = \sum_{0<k<j} t_{ik}, b_{ij} = a_{ij} + W$.

For example, given the capacity and the maximum waiting time to be 20 passengers and 2 minutes, Figure 1 and Table 1 show the pick-up requests I to VI created from the cumulative arrival curves at a particular pick-up location $i$.

---

**FIGURE 1.** Pick-up requests generated from cumulative arrival curve

**TABLE 1.** Details of Pick-Up Requests

<table>
<thead>
<tr>
<th>Pick-up Request</th>
<th>Time Window</th>
<th>Pick-up Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0–120s</td>
<td>20</td>
</tr>
<tr>
<td>II</td>
<td>40–160s</td>
<td>20</td>
</tr>
<tr>
<td>III</td>
<td>80–200s</td>
<td>20</td>
</tr>
<tr>
<td>IV</td>
<td>120s–240s</td>
<td>20</td>
</tr>
<tr>
<td>V</td>
<td>240–360s</td>
<td>10</td>
</tr>
<tr>
<td>VI</td>
<td>360–480s</td>
<td>10</td>
</tr>
</tbody>
</table>
Define $N^p$ be the set of pick-up request nodes, $N^O$ be the set of origin nodes for buses, $N^D$ be the set of destination nodes for drop off, and $N^E$ be the set of the end depot nodes where the bus mission is completed upon arrival. Each pick-up request node $i$ is associated with a time window $[a_i, b_i]$. Herein we consider the hard time window so that $i$ must be visited by a bus before $b_i$. Let $V$ be a set of homogenous buses to be used in evacuation. The route for each bus is designed in the following manner: pull out of $N^O$; visit several (no more than two in this study) pickup-request nodes, satisfying their time windows, and go to a destination node to drop off; come back to visit another pick-up request node within the time window; go to another destination node to drop off, and so on, until no pickup-request can be satisfied within allowed time window; finally, go to the end-depot. Each bus is dispatched in such a manner until all pickup-requests are visited exactly once.

Figure 2a shows the typical route for one bus, which consists of multiple runs. Each run includes one or two pick-up request nodes and one drop off node. Figure 2b illustrates two example bus routes. We tried to assign buses starting from $N^O$ and visiting nodes in $N^p$ and $N^D$ alternately and continuously.

FIGURE 2.
Illustration of bus routes

(a) Typical route for one bus

(b) Bus routes
Variable Definition
The decision variables employed in this model are defined below. The indicator variables represent the sequence of the bus routes, and the other integer variables represent the arrival times, departure times, and the bus loads.

\[ b_{i,j,k} = \text{indicator whether bus } k \text{ moves from node } i \text{ to } j \]
\[ b_{i,j,m,k} = \text{indicator whether bus } k \text{ moves from node } i \text{ to destination } j \text{ and then to node } m \]
\[ w_{i,k,l} = \text{indicator whether node } i \text{ is routed by the } k\text{th vehicle at } l\text{th run} \]
\[ t_{i,k}^A = \text{the time bus } k \text{ arrives at request node } i \]
\[ t_{i,k}^D = \text{the time bus } k \text{ departs from request node } i \]
\[ t_{i,j,m,k}^A = \text{the time bus } k \text{ arrives at destination node } j \text{ following node } i \text{ and preceding node } m \]
\[ t_{i,j,m,k}^D = \text{the time bus } k \text{ departs from destination node } j \text{ following node } i \text{ and preceding node } m \]
\[ l_{k,l} = \text{the load for bus } k \text{ at run } l \]
\[ l_{i,k,l} = \text{the load to destination } i \text{ for bus } k \text{ at run } l \]

The known variables are defined as follows:

\[ NO = \text{the set of origin nodes for buses, e.g. bus depots} \]
\[ ND = \text{the set of destination nodes for evacuees, e.g. shelters} \]
\[ NP = \text{the set of pick-up request nodes for evacuees, e.g. shelters} \]
\[ NE = \text{the set of virtual end depots} \]
\[ TT_{i,j} = \text{the travel time from node } i \text{ to node } j \]
\[ n_i = \text{the number of pedestrians for request } i \]
\[ L_{\text{max}} = \text{the maximum load of each bus} \]
\[ C_i = \text{the capacity of destination } i \]
\[ a_i = \text{the lower bound of the time window of node } i \]
\[ b_i = \text{the upper bound of the time window of node } i \]

Mathematical Formulation

Objective Function
The objective of the model in equation (2) is to minimize the time for the last evacuees to arrive at safe destinations. The definition of the time window for the pick-up request guaranteed that the evacuees would not wait more than the maximum waiting time to board the bus.

Minimize \[ \max(t_{m,k}^A), \forall m \in NE, \forall k \in K \]
The model formulation also includes travel time constraints, time window constraints, pick-up requests constraints, bus load constraints, and destination capacity constraints, which are detailed in the following sections.

**Travel Time Constraints**

\[
t_{i,k}^4 - t_{i,k}^D \leq TT_{i,j} + M(1-b_{i,j,k}), \forall i \in N^P \cup N^O, j \in N^P, \forall k \in K
\]

\[
t_{i,k}^4 - t_{i,k}^D \geq TT_{i,j} - M(1-b_{i,j,k}), \forall i \in N^P \cup N^O, \forall j \in N^P, \forall k \in K
\]

\[
t_{i,j,m,k}^4 - t_{i,k}^D \leq TT_{i,j} + M(1-b_{i,j,m,k}), \forall i \in N^P, \forall j \in N^D, \forall k \in K
\]

\[
t_{i,j,m,k}^4 - t_{i,k}^D \geq TT_{i,j} - M(1-b_{i,j,m,k}), \forall i \in N^P, \forall j \in N^D, \forall k \in K
\]

Constraints (3) and (4) set the travel time needed from the pick-up node i to j, constraints (5) and (6) set the travel time from the pick-up node i to destination node j, and constraints (7) and (8) set the travel time from destination node j to pick-up node m.

**Time Window Constraint**

\[
t_{i,k}^D - t_{i,k}^A \geq n_i \Delta t, \forall i \in N^P, \forall k \in K
\]

\[
t_{i,j,m,k}^D - t_{i,m,k}^A \geq l_{i,k} \Delta t - M w_{j,k,j}, \forall i, j, m \in N, \forall k \in K, \forall l \in L
\]

\[
t_{i,k}^A \leq b_j, \forall i \in N^P
\]

\[
t_{i,k}^D \geq a_i, \forall i \in N^P
\]

Constraint (9) considers the loading time at the pick-up request node i. Constraint (10) calculates the unloading time needed at the destination node j based on the bus load. Constraints (11) and (12) force the arrival time to be earlier than the upper bound of the time window and the departure time to be later than the lower bound of the time window at the pick-up request i.

Each pickup request can be served by only one bus:

\[
\sum_i \sum_k b_{i,j,k} = 1, \forall j \in N^P
\]

\[
\sum_j \sum_k b_{i,j,k} = 1, \forall i \in N^P
\]

\[
\sum_j b_{i,j,k} = 1, \forall i \in N^O, \forall k \in K
\]
\[
\sum_{m,j,k} b_{i,j,m,k} = 1, \forall i \in N^p, \forall j \in N^D, \forall k \in K
\] (16)

\[
\sum_{i \in N^p} b_{i,j,m,k} = 1, \forall m \in N^p, \forall j \in N^D, \forall k \in K
\] (17)

\[
b_{i,j,m,k} = 0, \forall j \in N^E
\] (18)

\[
\sum_k \sum_l w_{i,k,l} = 1, \forall i \in N^p
\] (19)

\[
b_{i,j,m,k} \leq b_{i,j,k} + b_{j,m,k} - 0.95
\] (20)

\[
b_{i,j,m,k} \geq b_{i,j,k} + b_{j,m,k} - 1.01
\] (21)

\[
w_{i,k,l} - w_{j,k,l} \leq M (1 - b_{i,j,k})
\] (22)

\[
w_{i,k,l} - w_{j,k,l} \geq M (b_{i,j,k} - 1)
\] (23)

Constraints (13) and (14) ensure each pick-up request is serviced exactly once. Constraint (15) ensures that the bus from the depot can head to only one pick-up location. Constraints (16) and (17) ensure only one preceding and following node for the destination node at each bus run. Constraint (18) dismisses the bus mission once it reaches the end depot. Constraint (19) ensures that each pick-up request be serviced exactly once. Constraints (20) and (21) ensure that the value of \( b_{i,j,m,k} \) can be 1 only if \( b_{i,j,k} \) and \( b_{j,m,k} \) are both 1. Constraints (22) and (23) establish the relationship between the indicator variables \( b \) and \( w \), which means that if pick-up request \( j \) is serviced by one bus followed by pick-up request \( i \), then the indicator variable \( w \) value should be identical for pick-up requests \( i \) and \( j \) for the same bus run.

**Bus Capacity Constraints**

\[
l_{k,l} = \sum_i n_{i,k,l}, \forall k \in K, \forall l \in L
\] (24)

\[
l_{k,l} \leq l_{\text{max}}, \forall k \in K, \forall l \in L
\] (25)

Constraint (24) calculates the total load for the bus \( k \) at the \( l \)th run, and constraint (25) limits the load to be less than the maximum load for each bus.

**Destination Capacity Constraints**

\[
l_{i,k,l} \geq l_{k,l} - M (1 - w_{i,k,l}), \forall i \in N^K, \forall k \in K, \forall l \in L
\] (26)

\[
l_{i,k,l} \leq l_{k,l} + M (1 - w_{i,k,l}), \forall i \in N^K, \forall k \in K, \forall l \in L
\] (27)

\[
l_{i,k,l} \leq M w_{i,k,l}, \forall i \in N^K, \forall k \in K, \forall l \in L
\] (28)

\[
l_{i,k,l} \geq -M w_{i,k,l}, \forall i \in N^K, \forall k \in K, \forall l \in L
\] (29)

\[
\sum_k \sum_l l_{i,k,l} \leq C_i, \forall i \in N^K
\] (30)
Constraints (26)–(29) calculate the number of evacuees unloaded at the destination $i$ at the 1st run for bus $k$. Constraint (30) limits the total unloaded evacuees at each destination node to be less than its holding capacity.

**Further Simplification**

Note that, during evacuations, the evacuee volumes are high, especially at beginning. The number of evacuees at a single pick-up request is very likely to be close to or reach bus capacity. In addition, some pick-up requests may have restrictive time windows, such that the bus serving one of these types of request nodes will not have enough remaining capacity or time to service any other pick-up request at that run. Thus, we can divide the pick-up request nodes into two groups: $N_1^p$ and $N_2^p = N^p \setminus N_1^p$. Any node $i$ in the group $N_1^p$ and any node $j$ in $N^p$ satisfies at least one of the following criteria:

1. $n_i + n_j > L_{\text{max}}$
2. $[a_i + n_i \Delta t + TT_{ij}^i, b_i + n_i \Delta t + TT_{ij}^i] \cap [a_j, b_j] = \emptyset$ and $[a_j + n_j \Delta t + TT_{ji}^j, b_j + n_j \Delta t + TT_{ji}^j] \cap [a_i, b_i] = \emptyset$

The pick-up request in $N_1^p$ either has a close-to-capacity number of pick-ups or an inflexible time window, which cannot accommodate other requests and thus should be serviced exclusively by one run. Constraint (31) excludes the possibility of servicing any two pick-up requests within $N_1^p$, which simplifies the formulation and, in turn, improves the computation speed.

$$b_{i,j,k} = 0, \forall i, j \in N_1^p, \forall k \in K$$

**Numerical Example**

The model was tested on the city of Baltimore’s downtown road network. A hypothetical evacuation after a sudden incident such as a terrorist attack was assumed. Figure 3 shows the spatial distribution of the demand points, bus depots, and safety destinations based on the aggregated 2010 MPO data from Baltimore County. There were around 40 pedestrian demand points, 2 transit depots, and 10 safety shelters in the vicinity area of the downtown area. The sizes of the demand points indicate the levels of the evacuee numbers at the locations and were estimated based on the traffic analysis data provided by Baltimore County. The two bus depots were the Bush Bus Division in the southwest and the Kirk Bus Division in the northeast and included high schools, community colleges, recreation centers, etc. For illustrative purposes, a constant evacuation rate every 10 minutes for the first 30 minutes was assumed at any given demand location. CPLEX 12.4 was adopted to solve the mixed-integer programming problem on a Windows7 computer with an Intel i-7 3770 CPU and 8GB of memory.
Table 2 lists the rate ranges in terms of pedestrian level, the capacities of the shelters, and the availability of buses in the depots. Figure 4 depicts the 11 candidate pick-up locations after the fuzzy clustering on the evacuee demand points. The average walking time for the evacuees to the pick-up locations was 3.1 minutes; the farthest was 9.8 minutes. Table 3 shows the cumulative arrival curve for the 11 pick-up locations based on the pedestrian levels and the degrees of membership of their nearby demand locations. Figure 5 shows two among the generated bus routes, and Table 4 lists the corresponding time and pick-up schedules.
TABLE 2. Shelter Capacities, Bus Availabilities, and Demand Levels

<table>
<thead>
<tr>
<th>Shelter ID</th>
<th>Capacity (person)</th>
<th>Depot ID</th>
<th>Bus Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1,500</td>
<td>I</td>
<td>50</td>
</tr>
<tr>
<td>b</td>
<td>1,000</td>
<td>II</td>
<td>50</td>
</tr>
<tr>
<td>c</td>
<td>1,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>2,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>1,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>1,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>1,000</td>
<td>Pedestrian level</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>1,000</td>
<td>High</td>
<td>30</td>
</tr>
<tr>
<td>i</td>
<td>1,000</td>
<td>Medium</td>
<td>20</td>
</tr>
<tr>
<td>j</td>
<td>1,000</td>
<td>Low</td>
<td>10</td>
</tr>
</tbody>
</table>

FIGURE 4. Pick-up locations after fuzzy clustering
TABLE 3.
Time-Dependent Arrivals to Pick-Up Locations

<table>
<thead>
<tr>
<th>Pick-up Location</th>
<th>0–10 (min)</th>
<th>10–20 (min)</th>
<th>20–30 (min)</th>
<th>30–40 (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>269</td>
<td>211</td>
<td>105</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>353</td>
<td>271</td>
<td>136</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>353</td>
<td>272</td>
<td>135</td>
<td>31</td>
</tr>
<tr>
<td>4</td>
<td>362</td>
<td>265</td>
<td>130</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>265</td>
<td>200</td>
<td>106</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>363</td>
<td>268</td>
<td>133</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>450</td>
<td>355</td>
<td>180</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>628</td>
<td>478</td>
<td>256</td>
<td>45</td>
</tr>
<tr>
<td>9</td>
<td>639</td>
<td>415</td>
<td>208</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>365</td>
<td>261</td>
<td>135</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>451</td>
<td>352</td>
<td>176</td>
<td>34</td>
</tr>
</tbody>
</table>

FIGURE 5.
Two examples of generated bus routes.
As indicated previously, the improvements of this model compared to the previous studies are as follows:

- The time window of the pick-up request was used to restrict the maximum waiting time for evacuees.
- Pick-up nodes and targeted destinations do not have to be fixed in different runs.
- A time-dependent arrival curve at the pick-up locations is considered rather than assuming all evacuees are present at the location at the start.

To show the advantage of adopting the above improvements, we designed the following experiments:

- Use maximum waiting times of 2, 5, and 10 minutes.
- Fix the route in each bus run.
- Assume a full-demand start at pick-up locations.

Table 5 shows the minimum number of buses needed for the combination of the experiment settings. It can be seen that the longer the waiting time toleration, the fewer the number of buses are needed to service all evacuees. The strategy of fixing the route requires more vehicle resources than that of the flexible route. Assuming a full demand start, the number of buses needed is much higher, and most of the buses are scheduled simultaneously at the start of the evacuation, which may create a great burden on vehicle road traffic. The fixed and flexible route strategies under the full demand scenario do not make much difference, simply because most of the vehicles will be scheduled only for one run to meet the time window constraints.

### Table 4.
<table>
<thead>
<tr>
<th>Bus</th>
<th>Run</th>
<th>Depot</th>
<th>Pick-up Node</th>
<th>Destination</th>
<th>Bus load (persons)</th>
<th>Travel Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>II</td>
<td>10</td>
<td>g</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>8</td>
<td>i</td>
<td>50</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>2, 1</td>
<td>b</td>
<td>40</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>I</td>
<td>3</td>
<td>d</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>5</td>
<td>d</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>9</td>
<td>e</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>7</td>
<td>j</td>
<td>50</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>1</td>
<td>b</td>
<td>30</td>
<td>12</td>
</tr>
</tbody>
</table>

### Table 5.
<table>
<thead>
<tr>
<th>Max Waiting</th>
<th>Arrival Curve</th>
<th>Full Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed Route</td>
<td>Flex Route</td>
</tr>
<tr>
<td>2 min</td>
<td>87</td>
<td>73</td>
</tr>
<tr>
<td>5 min</td>
<td>73</td>
<td>53</td>
</tr>
<tr>
<td>10 min</td>
<td>46</td>
<td>31</td>
</tr>
</tbody>
</table>
Table 6 shows the distribution of evacuees to safety areas with and without destination capacity constraints. It can be seen clearly in the latter case that a few shelters closest to the pick-up locations become overcrowded and exceed their actual capacity. With the capacity constraints in the model, the evacuees are distributed more evenly among the destinations.

**TABLE 6.**
Minimum Buses Required for Different Combination of Settings

<table>
<thead>
<tr>
<th>Destination ID</th>
<th>Capacity Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With</td>
</tr>
<tr>
<td>a</td>
<td>1,388</td>
</tr>
<tr>
<td>b</td>
<td>790</td>
</tr>
<tr>
<td>c</td>
<td>1,414</td>
</tr>
<tr>
<td>d</td>
<td>2,000</td>
</tr>
<tr>
<td>e</td>
<td>1,000</td>
</tr>
<tr>
<td>f</td>
<td>297</td>
</tr>
<tr>
<td>g</td>
<td>388</td>
</tr>
<tr>
<td>h</td>
<td>800</td>
</tr>
<tr>
<td>i</td>
<td>1,000</td>
</tr>
<tr>
<td>j</td>
<td>790</td>
</tr>
</tbody>
</table>

**Conclusions**

This paper proposed an optimization approach to determine pick-up locations for evacuees and allocate trips for buses for rescue purposes in transit-based evacuation planning. The proposed model was formulated as an integer linear program. In the model, evacuee demand points were clustered, and the center was defined as the pick-up location. Evacuees at each demand point were guided to nearby pick-up locations according to their proximity. The buses started from the bus depot to pick up evacuees and dropped them off at the safety area; after unloading, they headed towards other pick-up locations until all evacuees were picked up. An example using the Baltimore downtown area showed that the proposed model was more realistic and yielded better results compared to previous models under some given assumptions.

This research should be useful to planners, transit agencies, and emergency management officials, as effective and reliable transit evacuation planning is imperative and critical based on experiences from the past. For emergency management agencies, how to efficiently use available public transit resources without keeping citizens waiting too long is critical. The paper offers an analytical approach to provide answers to some of the issues for transit-based evacuation, such as the following: How many transit vehicles are needed and should be reserved in case of an emergency situation? How can a flexible rather than a fixed route for drivers be scheduled to increase evacuation efficiency? How can reasonable dispatch schedules for transit vehicles be generated to prevent unnecessary road congestion by sending all vehicles at once? How can pick-up points for emergency purposes be reasonably selected? In addition, since this model adopts a generalized approach and is based on a few location-specific assumptions, it can be applied to other cities as long as the input demand, road network, and transit data are present.
Although much has been done in this paper regarding transit evacuation modeling, the study is still exploratory and can be further improved. The limitations of this model include the following:

- The separation of the two modules (pick-up location selection and transit route optimization) may render non-optimality of the entire system. However, the current difficulty of combining these two lies in over-complexity of the model.

- Without distinguishing the categories and groups of evacuees, it is hard to preclude the possibility that people without special needs may occupy spaces reserved for special-needs groups, such as persons with disabilities and children.

- Although the computation speed is acceptable on a citywide transit network for evacuation within a reasonable time window, the NP-hardness of the integer-linear formulation may have an impact on the computation efficiency in the application of statewide networks and time windows in days and weeks.

- The model inputs currently rely on planning MPO data. However, there are numerous daily visitors in study areas that may not be captured by the data. Moreover, the actual number of evacuees at the time of evacuation is somewhat unpredictable. All these factors may impact the optimal solutions.

- Current travel estimation is not based on real-time traffic information during evacuation. Few previous studies have tried to combine passenger car and transit evacuation modeling under a unified framework. Thus, the capability of estimating travel time during evacuations will affect the solution quality of this model.

To address these modeling limitations, future studies could focus on directions such as integrating the two decision modules, paying attention to special group needs, designing an efficient algorithm to expedite the computation process, performing sensitivity analyses, and receiving real-time input data feeds and integrating them with the passenger car evacuation model.

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**Xin Zhang** (leadaming@gmail.com) received an M.Sc. in Geographic Information Science from Peking University, China, and a Ph.D. in Civil Engineering from the University of Maryland, with a dissertation on developing an integrated model for coordinating mixed pedestrian-vehicle flows in metropolitan areas under emergency evacuation situations. His research interests include operational research modeling application in transportation, traffic simulation modeling, machine learning analysis on traffic data, and evacuation planning modeling. His current work is focused on operational research modeling on logistics and transit systems such as railways and public transportation.

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