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Incorporating equity into the transit frequency-setting problem

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ABSTRACT

This paper and the proposed formulation contribute to an apparent gap in transit research design by integrating equity considerations into the transit frequency-setting problem. The proposed approach provides a means to design transit service such that equitable access to basic amenities (e.g., employment, supermarkets, medical services) is provided for low-income populations or disadvantaged populations. The overarching purpose is to improve access via transit to basic amenities to: (1) reduce the disproportionate burden faced by transit dependent populations; and (2) create a more feasible transportation option for low-income households as an opportunity to increase financial security by reducing dependence on personal autos. The formulation is applied to data from a mid-sized US metropolitan area. The example application illustrates the formulation successfully increases access to employment opportunities for residents in areas with high percentages of low-income persons, as well as demonstrates the importance of considering uncertainty in the locations of populations and employment.

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1. Introduction

The objectives of this paper are to: (1) illustrate the need for a new methodology to consider issues of equitable access and mobility in transit route and service design; (2) present a new methodology for addressing equitable access from a transit route and service design perspective; and (3) demonstrate the proposed approach by applying the methodology to transit service in a mid-sized metropolitan area.

1.1. Problem motivation

Public transportation is called upon to fulfill many roles from decreasing pollution levels and reducing United States' dependence on foreign oil to sparking economic development and redevelopment in urban areas (Bailey, 2007; CCAP, 2009; CTOD, 2009). One of transit's original roles and a motivation for transit subsidies has been to serve individuals who are unable to travel by private auto. This role is increasing in importance in light of recent volatility of gasoline prices and a rise in household expenditures on transportation. Transportation expenditures recently reached the second highest

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share in American household budgets (Haas et al., 2008). Coupled with the increase in transportation costs is an increase in housing prices, which is compounded by inadequate growth of the average American household income. From 2000 to 2005, average household income rose 10.3% with transportation costs increasing by 13.4% and housing costs increasing 15.4% (Lipman, 2006). As a result, the percent of the population facing the real possibility of no longer being able to afford travel by personal auto is on the rise, particularly with the national unemployment rate reaching 9.5% in June 2009 (BLS, 2009).

One opportunity for households to improve their financial security is by relying more on transit for access to basic needs (e.g., employment, supermarkets, medical service). Bailey (2007) found households in proximity to transit service that choose to get rid of a personal auto saved on average $6251 annually. However, this elevates an existing issue facing many US metropolitan areas and transit agencies: regular transit users, partially or fully dependent on transit, experience the lowest levels of mobility among US population segments (Giuliano, 2005). Therefore, to make transit service an attractive and feasible mode to reach basic amenities, and in-turn a reasonable option for low-income households to become more financially secure, the levels of accessibility and mobility experienced by regular transit users needs to be improved.

Currently, regular transit users (individuals partially or fully dependent on transit) carry an inequitable burden in satisfying basic needs and in some instances forgo needs, such as medical services, due to the absence of feasible transportation options, or cut expenditures on other necessities, such as food, to make travel by auto financially possible (Gicheva et al., 2007; Giuliano, 2005; Wallace et al., 2005). Previous research has illustrated workers from low-income households dependent on transit are also disproportionately limited in employment opportunities with reduced access to their regional economy (CCAP, 2009). Land use patterns, segregated by type and distributed inequitably across neighborhoods, contribute to the burden of reduced access experienced by transit dependent populations. For example, the distribution of supermarkets has been found to vary based on socio-demographics with low-income and minority neighborhoods home to 25–70% fewer supermarkets than middle income and predominantly white neighborhoods (Powella et al., 2007), requiring some residents to travel on average an additional 1.1 miles to reach a grocery store (Zenk et al., 2005).

Collectively, these studies and recent events point to the need for improved transit and land use planning considering equitable levels of access to basic amenities via different transportation modes. This paper focuses on providing equitable levels of access from a transit service design perspective; it is applicable under current and evolving land use patterns (by treating the size of the protected population and the number of destinations as uncertain). The proposed methodology applies network optimization and design principles to produce transit service resulting in equitable opportunities for at-risk or protected populations (e.g., low-income) to access basic needs.

The following section discusses traditional transit route and service design methodologies and the degree to which equity and accessibility have been considered. Subsequent sections present the formulation and solution method for the equitable access transit service design problem, numerical analysis with the formulation applied to data from a mid-sized US metropolitan area and a conclusion noting potential future research and applications to current planning practices.

1.2. Background

>Equity entered the public transport dialogue as early as the 1970's focusing on fiscal equity in funding public and mass transit systems through government subsidies (Hodge, 1988; Kain and Meyer, 1970; Wachs, 1989). Executive Order 12898 entitled Federal Actions to Address Environmental Justice (EJ) in minority populations and low-income populations helped ignite awareness regarding the potential disproportionate impacts transportation projects could have on disadvantaged populations. Executive Order 12898 brought about the need for EJ analysis methodologies capable of determining whether an action or project would cause disproportionately high and adverse human health or environmental impacts on minority or low-income populations. Research studies and papers aimed at formulating methods to identify at-risk or disadvantaged populations, define disproportional impacts, quantify impacts, and explore potential appropriate mitigations followed (see Dixon et al., 2001; Duthie et al., 2007; Forkenbrock and Sheeley, 2004; Lane et al., 1998; Purvis, 2001; Sanchez, 1998). These EJ and equity considerations helped raise awareness and foster a climate for discussing and exploring transport as a social issue with respect to public transportation provision and land use patterns.

The attention of the urban planning and transportation profession has been widening to consider the social implications of transportation, specifically levels of access and mobility experienced by low-income, minority, and transportation disadvantaged population groups. Researchers are exploring the possible existence of and finding relationships between individuals' levels of mobility and accessibility and their employment rates and personal health (Cervero et al., 2002; Sanchez, 1999, 2002; Wallace et al., 2005). The prominence of case studies considering low-income and/or minority communities' levels of access and mobility is also increasing. For example, Lucas et al. (2009) evaluate the United Kingdom's Urban Bus Challenge Fund's effectiveness at improving economic opportunities and quality of life in four low-income neighborhoods. Curriea et al. (2009) and Lucas and Fuller (2005) also use case studies to understand and investigate impacts varying levels of accessibility and mobility have on disadvantaged populations. Karlstrom and Franklin (2009) evaluate the horizontal and vertical equity effects of the Stockholm congestion pricing. Finally, researchers and practitioners are reviewing policy and planning processes from a social equity perspective looking for effective existing policies and opportunities to develop new strategies through continued applied research (see Lucas, 2006; Lucas et al., 2007; Lucas and Stanley, 2008; Sanchez, 2008; Sanchez and Wolf, 2005; Ward, 2009).

The above research has set the stage for explicitly incorporating equity into transit network design problems. Equity objectives and constraints are already being integrated into road network design problems with applications to spatial allocation of road improvements, highway investment, intergenerational equity, toll prices, congestion pricing, and cordon pricing (see Antunes et al., 2003; Chen and Yang, 2004; Connors et al., 2005; Duthie and Waller, 2008; Eliasson and Mattsson, 2006; Maruyama and Sumalee, 2007; Meng and Yang, 2002; Santos et al., 2008; Szeto and Lo, 2006; Yang and Zhang, 2002). In contrast, researchers focused in the area of transit network design do not appear to have explicitly incorporated issues of equity and access.

Transit network design problems have predominantly focused on minimizing user and operator cost without considering equity or access for disadvantaged populations (Kepaptsoglou and Karlaftis, 2009). For example, Pattnaik et al. (1998) select routes for a transit network with the objective of minimizing cost to the operator and total travel time experienced by the user with constraints on total operating costs and vehicle fleet size. Zhao et al. (2005) focus on minimizing transfers and maximizing service coverage to develop routes for a public transportation network. Borndorfer et al. (2007) consider line planning in public transportation focusing on finding lines and frequencies such that a given travel demand is satisfied while minimizing operating costs for agencies and minimizing travel times for passengers. Schobel et al. (2009) address public transit stop locations, formulating an objective to cover all given demand points with minimal additional travel time. These problem definitions and solution approaches reflect the pervasive attention allocated to maximizing operating efficiencies to benefit the user and transit agency. While operating efficiencies are beneficial and critical to consider, equity issues are also pertinent to address in transit network design. This is particularly valid given the reduced mobility and accessibility experienced by the transportation disadvantaged and the resulting burden they experience meeting their basic needs.

Historically, some transit route and service network design problem formulations and solution approaches have included access to the transit system, but not the level of access the system provides to users. For example, Wu and Murray (2005) consider the quality of service provided based on transit travel time, frequency of stops, and access to the transit system based on stop frequency; they focus on optimizing the balance between service quality and access to the transit system via stop placement. While such formulations address the trade-off between public transit service quality and access to the system, they do not explicitly consider access to basic amenities nor do they address equity in the levels of access provided.

1.3. Proposed methodology

Recent and expected increases in the cost of transportation and energy, enhanced awareness of transportation as a social equity issue, and the review of transit network design problems, collectively illustrate an opportunity and need to introduce equity and access into transit network design. As a result, this paper proposes a methodology incorporating access equity into transit network service design.

The methodology compares access via transit to access via personal auto for selected origins and destinations. In the context of this paper, accessibility is defined in terms of transit service frequency, number of potential bus or rail lines available for a trip, and the attractiveness of the destination based on travel time and concentration of amenities (e.g., number of supermarkets). The objective function in the problem formulation minimizes the difference between access via transit and access via personal auto across the selected origins and destinations. During this process, access by transit is improved using access by personal auto as a yardstick for a base level of travel convenience and flexibility necessary to meet basic needs in an auto-oriented society. The result is transit service designed to provide an equitable difference between access via transit and access via personal auto across the selected origins and destinations within a given set of operating constraints. Routes can be current transit routes in operation, generated by one of the formulations noted above, or the proposed formulation could be integrated into a multiobjective optimization transit design problem as an objective (e.g., maximizing access equity) or design constraint (e.g., specifying a minimum level of equity that must be met).

The proposed formulation also accounts for demand uncertainty. Research by Waller et al. (2001) and Lam and Tam (1998) have illustrated accounting for demand uncertainty can influence the solutions of network design problems. Given these findings and the construct of the proposed formulation, demand uncertainty is incorporated by applying a uniform distribution to the number of protected individuals and concentration of amenities. This helps capture the variability in the number of potential transit riders and locations of amenities (e.g., employers, grocery stores), which is likely to occur due to circumstances unobservable to the analyst and infeasible to capture in a single data point.

The overarching idea of the formulation is to improve service frequency to achieve equitable access to the given destination compared to travel by personal auto. The following section explains the formulation in additional detail.

2. Material and methods: problem formulation

Starting from a study area divided into sub-areas (e.g., traffic analysis zone, Census Block), the formulation in this section can be applied to find the frequencies for each bus route that maximize equity given fixed capital and operating budgets. For each sub-area pair, the difference between measures of accessibility by transit and accessibility by automobile is calculated. The difference between this accessibility difference and the mean of all accessibility differences, across all sub-area pairs, is then calculated for each sub-area. The goal of the model is to make these differences as close to equal as possible for all sampled realizations of uncertain attractiveness and number of protected persons, with more weight given to the sub-area pairs with higher numbers of protected persons living in the origin sub-area.

The objective function is defined in Eq. (1) and is based on the concept of coefficient of variation, which acts to minimize the standard deviation of the accessibility measures, defined as A_{ij}^w for each sub-area pair and each realization of the uncertain parameters, divided by the mean of these measures $\overline{A}^w = \frac{1}{|I||J|}\sum_{i\in I}\sum_{j\in J}A_{ij}^w$ where I is the set of all origin sub-areas in the study area, J is the set of all destination sub-areas, and w (where $w = 1, \ldots, W$) is used to denote a result based on the wth realization of the uncertain parameters. When calculating the standard deviation, the squared terms are weighted according to P_i^w, the proportion of all protected persons in the study area that reside in origin sub-area i $\left(\sum_{i\in I}P_i^w = 1\right)$.

$$\min \frac{1}{W}\sum_{w=1}^{W}\left[\frac{1}{\overline{A}^w}\left[\frac{1}{|I||J|}\sum_{i\in I}\sum_{j\in J}P_i^w(A_{ij}^w-\overline{A}^w)^2\right]^{1/2}\right] \tag{1}$$

The accessibility measure, A_{ij}^w is calculated as the difference between accessibility by car, $A_{ij}^{w,c}$, and accessibility by bus, $A_{ij}^{w,b}$, which are defined in Eqs. (2) and (3). Both measures are based on the area-wide accessibility measure and network connectivity index defined in Kittelson and Associates, Inc. et al. (2003). Area-wide accessibility measures travel attractiveness based on the concentration of amenities at the destination and the travel time for the trip. The connectivity index is a ratio of the number of bus or car routes to the number of intersections in the origin sub-area. This ratio is a means to measure the ease with which travelers' can reach the bus or car routes for a given origin–destination (O/D) pair.

Accessibility by bus is an increasing function of R^b – the number of bus routes that service a given sub-area pair, F – the total frequency of bus routes between sub-areas (the decision variable in this problem), S – the (uncertain) number of employment opportunities in the destination sub-area; a decreasing function of N – the number of intersections in the origin sub-area and t^b – travel time by bus between sub-areas; and constants α and β. Values of α are one or greater; larger values indicate a great attraction per unit of the amenity, S. Values of β indicate travelers' tolerance for increased travel time. Both α and β can be calibrated to fit local conditions.

$$A_{ij}^{w,b} = \frac{R_{ij}^b}{N_i}F_{ij}(S_j^w)^{\alpha}e^{-\beta t_{ij}^b} \quad \forall i,\ j\in I,\ \ w=1,\ldots,W \tag{2}$$

Accessibility for automobiles is an increasing function of R^c – the number of car routes between a pair of sub-areas, D – the number of potential departure times, and S defined in the above paragraph; a decreasing function of t^c – travel time by car between sub-areas, and N (defined above); and constants α and β.

$$A_{ij}^{w,c} = \frac{R_{ij}^c}{N_i}D_{ij}(S_j^w)^{\alpha}e^{-\beta t_{ij}^c} \quad \forall i,\ j\in I,\ \ w=1,\ldots,W \tag{3}$$

The objective is constrained by a fixed capital budget and a fixed operating budget. The two budgets are considered separately since they typically come from different funding sources and also operate on different time scales (i.e., capital investments incur one-time costs whereas operating costs are recurring) (Cambridge Systematics, Inc. et al., 2009). Shown in Eq. (4), the cost of purchasing buses to service all routes k in the set of routes K is constrained by *CapitalBudget*, where C_{bus} is the cost to purchase one bus and B_k is the number of buses assigned to route k.

$$C_{bus}\sum_{k\in K}B_k \leqslant CapitalBudget \tag{4}$$

Shown in Eq. (5), the weekly cost of operating the buses assigned to each route is constrained by a constant weekly *OperatingBudget*, where C_{fuel} is the fuel cost per mile, C_{wage} is the hourly wage paid to each bus driver, L_k is the length of route k, and H is the number of hours per week each bus is operated.

$$C_{fuel}\sum_{k\in K}\frac{L_kB_kH}{t_k} + C_{wage}\sum_{k\in K}B_kH \leqslant OperatingBudget \tag{5}$$

The number of buses assigned to route k is completely determined by the frequency for that route as shown in Eq. (6). All routes are assumed to be line routes, meaning they run from endpoint to endpoint, and then back again along the same route, which is why a multiple of two is used in the equation.

$$B_k = 2\lceil F_k t_k^b \rceil \tag{6}$$

The variables for frequency and travel time indexed by route are related to frequency and travel time indexed by sub-area pair as shown in Eqs. (7) and (8), respectively, where $\delta_{k,ij}$ is an indicator variable for whether or not route k connects sub-area i to sub-area j.

$$F_{ij} = \sum_{k\in K}F_k\delta_{k,ij} \quad \forall i\in I,\ \ j\in J \tag{7}$$

$$t_{ij} = \min_{\substack{k\in K\\ s.t.\,\delta_{k,ij}=1}} t_k \quad \forall i\in I,\ \ j\in J \tag{8}$$

3. Calculation: solution method

The consideration of uncertainty in the formulation as well as the nonlinear objective function necessitates the use of a heuristic solution method. A genetic algorithm (GA)-based method is proposed due to the successful applications of GA to other related problems (Fan and Machemehl, 2006). Unlike random search heuristics, GA also takes advantage of any existing neighborhood effects, which in this research means considering frequencies similar to those that have been shown to perform well. The complexity of the objective function does not significantly increase the problem difficulty since its fitness is assessed through a simple function evaluation.

The notation used to describe a GA as applied to the current problem is as follows. There is one "chromosome" per bus route. "Chromosome" refers to a vector of length *chrom* such that $\sum_{a=0}^{chrom/R^b-2} 2^a < F^{\max} \leqslant \sum_{a=0}^{chrom/R^b-1} 2^a$ where $F^{\max}$ is the maximum bus frequency allowed and R^b is the total number of bus routes. For example if $F^{\max}$ is set to six buses per hour and R^b is set to 4, then *chrom* equals twelve. Each chromosome is composed of sub-strings, one for each bus route (e.g., | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 |, where shading is used to separate the sub-strings of the chromosome). Since each entry (or "gene") in the chromosome takes a binary value, zero or one, a sub-string of length three can be used to represent frequencies from zero to seven. A "population" is a set of *c* chromosomes in the same "generation"; and "fitness" is an equivalent term for objective function value. A thorough discussion of GA approaches is given by Holland (1975) and Goldberg (1989).

Step 1. Initialization of population. Set the index for the current generation, $n = 1$. Randomly set each gene in each of the *c* chromosomes equal to zero or one. Let F_k equal the base 10 transformation of the *k*th binary sub-string in a given chromosome. This first set of chromosomes represents the initial population, pop_n.
Step 2. Calculate objective. Solve for the objective function value of each chromosome in pop_n. Check for convergence (i.e., whether $n = n_{\max}$). If convergence is not reached, go to Step 3.
Step 3. s-tournament selection. For each group or "tournament" of *s* chromosomes, keep the best chromosome as a parent for generation $n + 1$.
Step 4. Crossover. Let $n = n + 1$. Generate *K* uniform(0, 1) random numbers for each pair of "parent" chromosomes. If the *k*th random number is less than the probability of crossover, p_c, perform a single-point crossover operation on the *k*th sub-strings in the pair to create two new "child" chromosomes. The set of children chromosomes is pop_n.
Step 5. Mutation. Mutate each gene of each chromosome in pop_n with probability p_m.

The three basic parameters that can be varied in applying the above solution method is the number of "generations", the GA "population", and the number of realizations used in accounting for uncertainty.

4. Results and discussion of numerical analysis

Numerical analysis was conducted to demonstrate the proposed methodology. The formulation focuses on setting the frequency of bus service working within the context of pre-established routes. The numerical analysis presented here uses a set of existing bus routes in a mid-sized metropolitan area. This application focuses on low-income individuals' access to employment opportunities during the weekday morning commute to work. The data assembly process and numerical analysis results are presented and discussed below.

4.1. Data assembly

Nine sets of information need to be gathered and assembled in tabular form to apply the proposed formulation. These sets are: (1) residential locations of the protected population (to serve as trip origins); (2) number of protected persons in each origin area; (3) destinations of interest (e.g., location of supermarkets); (4) concentration of amenities in each destination area; (5) bus routes connecting origins and destinations and corresponding travel time; (6) number of alternative routes by auto connecting origins and destinations and corresponding travel time; (7) number of intersections in the origin area; (8) measures of uncertainty for protected population and concentration of amenities; and (9) transit operation characteristics (e.g., cost of fuel). For the purpose of demonstrating the formulation, the number of sub-areas under consideration was limited to 15 origins and 10 destinations. Focusing on a limited study area allows for a more thorough understanding and discussion of the results produced. The process used to gather data is summarized in Table 1.

For all numerical analyses, the GA parameters (based on initial test results) were set at 60 "generations" and a "population" of 100; and the number of sampled uncertain realizations is set to 20. In the context of this paper, *D*, is set to 60 indicating auto travelers can depart any minute of a given hour.

4.2. Context

As discussed above, the 15 census tracts with the highest poverty rates and the 10 census tracts with the highest number of employment opportunities were selected as the origins and destinations, respectively. The poverty rates in the origin sub-

Table 1
Data assembly.

Data needs	Source	Comments
Location of protected population	2000 US Census Bureau Data	Defined low-income as those at or below the poverty line.[a] Used the 15 census tracts with highest percent of population at or below poverty line as the origin sub-areas
Number of protected persons	2000 US Census Bureau Data	Poverty rates and total population used to obtain number of protected persons per census tract
Destinations of interest	2005 Data from Local MPO	Focused on access to employment opportunities; used top 10 census tracts based on number of employment opportunities
Concentration of amenities	2005 Data from Local MPO	Number of employment opportunities in selected census tracts
Bus routes and transit travel time	Existing Bus Routes, Google Maps	Used the transit agency's online Trip Planner tool to identify direct routes (no transfers) for each origin–destination (O/D) pair and transit travel time.[b,c] Identified three new routes to provide direct service for 85 O/D pairs currently without direct service. Google Maps was used to find distance along new routes between these 85 O/D pairs. Distance converted to travel time using assumed average travel speed of 12 miles per hour[d]
Possible auto routes and auto travel time	Google Maps	Identified number of possible routes with similar travel times between each O/D pair. Travel times do not account for traffic congestion
Number of intersections in origin sub-area	2000 Census Tract Boundaries and Street Network	Overlaid tract boundaries and street network to determine number of intersections
Measures of uncertainty	–	Assumed uniform distribution for protected population and number of employment opportunities
Transit operating constraints	FTA Report[d]	Cost of purchasing a bus set at $350,000. Cost of fuel per mile set at $6. Hourly wage for bus operator set at $10

[a] Poverty line calculated by US Census Bureau based on number of adults and children (under 18 years old) in household. In 2000, poverty threshold for single adult was annual income of $8795; for a two adult, two children household it was $17,463 (USCB, 2006).
[b] Tranist agency's online Trip Planner tool used to identify bus route options for weekday morning commutes to work (arriving by 8:00 a.m.).
[c] Cross-streets were selected in each sub-area to serve as specific trip origin and destinations; kept consistent throughout data collection for bus and auto route options as well as bus and auto travel times.
[d] *Source*: Nigel et al. (2007).

areas range from 27.8% to 53.5%, well above the 2007 nationwide average of 13.0% (USCB, 2009). The number of employment opportunities in the selected tracts ranged from 9023 to 43,636 opportunities; collectively the selected tracts account for approximately 35% of the employment opportunities in the metropolitan area. The highest concentration in a single census tract occurs in a downtown census tract, which contains 8.4% of employment opportunities. Fig. 1 illustrates the relative locations of the origin and destination sub-areas identified for the numerical analysis.

The origin sub-areas are numbered R1–R15 (seen in a solid dark shade) and the destination sub-areas are numbered 1–10 (a lighter hatched pattern). Two census tracts serve as both origin and destinations these are labeled as 3/R3 and 2/R1. The origin sub-areas are relatively close together in spatial proximity. In contrast, the employment sub-areas are dispersed across the metropolitan area. There are 26 existing bus routes providing direct connections between the origins and destination pairs. As noted above, these routes are supplemented with three new routes identified to directly connect 85 O/D pairs currently without direct transit service.

4.3. Results

Discussed below are the influence different parameters have on the solution (i.e., set of bus frequencies) as well as the results from comparing existing bus service to the bus service produced by the proposed formulation.

The results of a sensitivity analysis were as expected. Increasing the values of α and/or β increased the gap between transit and auto accessibility, leading to a higher objective value. Increasing the capital and operating budgets results in a lower objective function value indicating that a higher degree of equity is achievable as these constraints are relaxed. Finally, results indicate the degree of uncertainty associated with the protected population and employment opportunities influences the consistency of bus route frequencies provided. Higher values of uncertainty tend to result in more variation in service frequency. An uncertainty of plus or minus 25% of the parameter value appears to be the threshold at which higher uncertainty values result in more variation in the solution set. However, it appears there are 14 bus routes whose frequencies remain the same for uncertainty values ranging from 0 to plus or minus 75%. Fig. 2 illustrates two bus routes whose frequencies are consistent across levels of uncertainty (see Bus Route 7 and 28) and two bus routes whose frequencies vary based on the level of uncertainty (see Bus Route 4 and 2).

The results illustrated in Fig. 2 indicate the higher the level of uncertainty, the more important its consideration is in order to achieve the frequencies that are most robust in serving the uncertain locations of protected populations and employment.

O/D pair accessibilities for the existing bus systems (calculated using existing service frequencies and routes) were compared to accessibility values resulting from the transit service produced by the proposed formulation. The following parameter values were assumed: $\alpha = 1.00$, $\beta = 0.85$, uncertainty values of plus or minus 15% for the protected population and employment opportunities, a capital budget of $27,300,000 and an operating budget of $537,264. The capital and operating

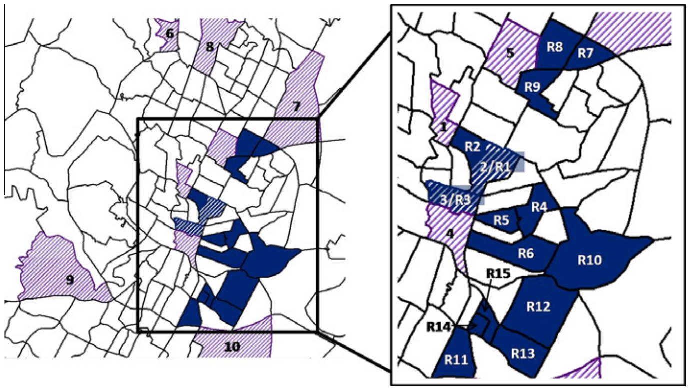

Fig. 1. Origin and destination sub-areas selected for selected US metropolitan area.

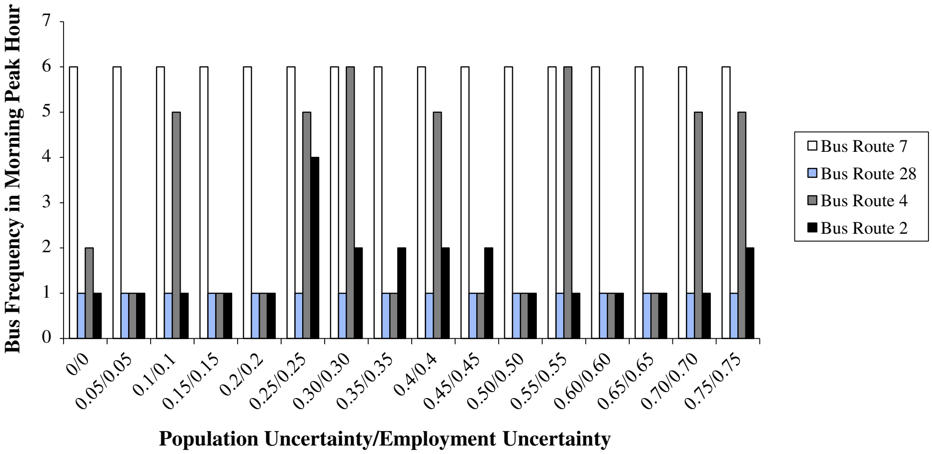

Fig. 2. Influence of uncertainty parameters on solution set.

budgets were set such that they are approximately equivalent with the costs incurred by the transit agency providing the existing service.

Table 2 summarizes a comparison between the transit access provided by existing service (see column "existing") and the transit access provided by the model (see column "model results"). The results shown are for census tracts R12, R8, and R15 to reach each of the employment tracts. (Tracts R12, R8, and R15 have the highest percent of protected population in the metropolitan area with 53.5%, 34.2%, and 37.7% of their respective populations living below the poverty line.)

Tracts 4, 2, 3, and 8 are the four census tracts with the highest percent of employment opportunities in the metropolitan region at 8.39%, 4.59%, 4.53%, and 4.40%, respectively. Noticeable improvements can be seen for access to these tracts. Among the three residential tracts summarized in Table 2, there are two instances in which access slightly decreases. This occurs for residential tract R12's access to employment tract 10 and residential tract R15's access to employment tract 5. These slight decreases reflect the problem's financial constraints. Limited resources are being reallocated to provide equitable access across 150 origin–destination pairs, which means, in some instances, access will be slightly reduced to enable improvements elsewhere. Under the given financial constraints, the decrease in R12's access to employment tract 10 occurs because employment tract 10 has the lowest number of employment opportunities of the 10 tracts considered making it relatively unattractive compared to the other employment tracts. The decrease in R15's access to employment tract 5 occurs because, of the five tracts served under existing service, tract 5 is least attractive to residents in R15 (based on the travel time by transit and number of employment opportunities). The formulation reduces access to these tracts to provide improved access to the remaining employment tracts that are more attractive due to travel time and/or the number of employment opportunities.

The success in the proposed formulation can be seen in the clear access improvements provided to the residents in the most at-risk residential areas. Particularly notable, access for the most at-risk residential tracts to the employment tracts with the highest concentration of employment opportunities is consistently improved.

Table 2
Existing service vs. results for access provided for residents.

Destination census tract	Transit accessibility		Auto accessibility	Bus frequency	
	Existing	Model results		Existing	Model results
Access provided for residents in tract R12					
1	0.00	66.36	18930.62	0.00	1.00
2	554.94	3107.65	54239.16	2.86	8.00
3	0.00	426.25	54280.52	0.00	2.00
4	4697.93	8833.20	97704.94	5.58	7.00
5	342.04	684.07	32119.84	2.00	2.00
6	0.00	51.10	12643.40	0.00	1.00
7	0.00	61.06	26830.82	0.00	1.00
8	0.00	71.02	30935.97	0.00	1.00
9	0.00	71.11	7206.00	0.00	1.00
10	430.90	186.72	7542.60	4.62	2.00
Access provided for residents in tract R8					
1	0.00	739.19	20569.49	0.00	4.00
2	500.30	6003.61	53370.84	2.00	6.00
3	0.00	2653.92	33646.03	0.00	5.00
4	0.00	915.66	58870.98	0.00	3.00
5	4885.30	5066.24	25692.61	7.71	6.00
6	0.00	569.80	13354.18	0.00	4.00
7	0.00	1277.49	20568.91	0.00	4.00
8	0.00	1583.78	50421.24	0.00	4.00
9	0.00	32.10	18725.52	0.00	1.00
10	0.00	344.42	12002.03	0.00	4.00
Access provided for residents in tract R15					
1	0.00	1003.45	73414.50	0.00	3.00
2	4013.95	26784.35	136311.85	2.86	10.00
3	19010.42	62256.67	146429.04	6.86	16.00
4	35202.15	90785.38	389796.97	6.86	15.00
5	14492.24	13962.68	116045.36	8.00	10.00
6	0.00	337.71	70487.87	0.00	3.00
7	0.00	790.02	99722.54	0.00	3.00
8	0.00	932.05	177426.87	0.00	3.00
9	0.00	341.04	55104.69	0.00	1.00
10	2449.68	2937.83	57678.74	4.62	4.00

5. Conclusion

The need to incorporate equitable access in transit service design was demonstrated by documenting current and anticipated continued rise in transportation and energy expenditures, awareness of transportation as social equity issue, and a review of transit network design problems. The purposes of improving equity in transit access to basic amenities are to (1) reduce the disproportionate burden faced by transit-dependent populations; and (2) increase the financial security of low-income households by giving them the option to reduce their dependence on autos. This paper contributes to the transit design literature by integrating equitable access into the transit frequency-setting problem. The formulation was shown to be successful at increasing access to employment opportunities for residents in areas with the high percentages of protected persons by applying it to a mid-sized metropolitan region. The example application also reflects the financial constraints and inherent tradeoffs necessary in reaching equitable access across multiple origin–destination pairs. Finally, results in Fig. 2 indicate the higher the level of uncertainty, the more important its consideration is in order to achieve the frequencies that are most robust in serving the uncertain locations of protected populations and employment.

There are many opportunities for integrating the proposed formulation into different planning contexts and future research. First, the proposed formulation can be used to address access to needs other than employment opportunities such as supermarkets and medical services. Second, it could also be applied in the context of evaluating alternative future land use scenarios for a region. Agencies could consider the levels of access and mobility experienced by transit dependent populations in multiple land use scenarios under a fixed transit budget. Such planning analysis would bring awareness to which land use patterns and transit service designs provide the most equitable levels of access and mobility. This would be particularly valuable for coordinating land use and transit planning that explicitly considers equity in access and mobility. Finally, the current formulation could be incorporated into multiobjective transit design formulations, which would allow analysts to consider access equity in concert with travel demand, user cost and operator costs when designing routes as well as setting frequencies for a transit network. It is important to note that the formulation provided here is not intended for use as a "black box" model. As with all models, results should be used to inform decisions and should be considered within the context of all other factors not present in the model.

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Glossary terms

Accessibility: Accessibility and access refer to the ease with which individuals are able to reach desired or necessary destinations (e.g., employment, medical services, grocery stores)

Attractiveness: Attractiveness measures the significance of a destination based on the concentration of amenities at the destination (e.g., number of employment opportunities) and the travel time required to reach the destination

Disadvantaged populations: Disadvantaged populations are populations whose financial and/or environmental circumstances limit their resources and/or ability to meet their basic needs

Environmental Justice: Environmental Justice in the context of transportation refers to the three following principles (definition is from the Federal Highway Administrations webpage regarding Environmental Justice: http://www.fhwa.dot.gov/environment/ej2000.htm): (1) to avoid, minimize, or mitigate disproportionately high and adverse human health and environmental effects, including social and economic effects, on minority populations and low-income populations; (2) to ensure the full and fair participation by all potentially affected communities in the transportation decision-making process; and (3) to prevent the denial of, reduction in, or significant delay in the receipt of benefits by minority and low-income populations

Equity: Equity is the concept of providing equal opportunities

Genetic algorithm (GA): Genetic algorithm (GA) is a heuristic solution method used to help solve optimization problems with nonlinear objective functions and incorporating measures of uncertainty

GA chromosome: GA chromosome is a representation of a feasible solution to the mathematical program. A GA chromosome comprises ***genes***. In the problem studied in this paper, GA chromosomes are binary representations of the feasible solutions and genes take binary 0 or 1 values

GA population: GA population is a set of chromosomes

GA crossovers and mutation: GA crossovers and mutation are operations to generate new feasible solutions from existing solutions. In GA mutation, each gene in a chromosome is mutated (0's changed to 1's and vice versa) based on a mutation probability. If the mutation probability is too high, GA search turns into a random search. Appropriate choice of the mutation probability ensures that the GA search does not get trapped in a local optima. In the GA single point crossover mechanism adopted in this work, pairs of child chromosomes are generated from pairs of parent chromosome based on the crossover probability. Usually in a single point crossover, parent chromosomes are sliced at random points and the genes are exchanged to create two new child chromosomes

GA fitness functions: GA fitness functions are functions used to evaluate the "attractiveness" of each chromosome. Generally fitness functions correspond to the objective function being optimized

Objective function: Objective function is the mathematical function that is either minimized or maximized within a network design problem

Optimization constraints: Optimization constraints are the equations, which set the problem boundaries. They often reflect real-world constraints related to budgets, flow conservation, and other similar characteristics

Poverty rate: Poverty rate is the percentage of the population living below the poverty line

Protected populations: Protected populations are typically low-income, minority, or those characterized as disadvantaged populations. The term protected means they are protected from a disproportionately adverse impact or burden under the concept of Environmental Justice

Transit network design problems: Transit network design problems are optimization problems formulated such that their solutions are an optimal set of routes or transit service frequencies for a given demand and set of constraints. Constraints are often related to transit agency budgets and other transit operating characteristics

Road network design problems: Road network design problems are optimization problems formulated such that their solutions are an optimal set of road improvements for a given demand and set of constraints. These problems can be discrete network design problems in which new roadway links are added, continuous problems in which capacity is added to existing links, or a mixture of both. Constraints are often related to the cost of the improvements and corresponding budget