Transit Design: A Holistic Approach Considering Equity and Efficiency

Sophie Pavia
Department of Computer Science
Vanderbilt University, Nashville, TN
sophie.r.pavia@vanderbilt.edu

Shadi Omidvar Tehrani
Department of Human and Organizational Development
Vanderbilt University, Nashville, TN
shadi.omidvar.tehrani@vanderbilt.edu

Danushka Edirimanna
Department of Engineering
Cornell University, Ithaca, NY
ke233@cornell.edu

Rishav Sen
Department of Electrical Engineering
Vanderbilt University, Nashville, TN
rishav.sen@vanderbilt.edu

Michael Wilbur
Department of Computer Science
Vanderbilt University, Nashville, TN
michael.p.wilbur@vanderbilt.edu

Chandra Ward
Department of Social, Cultural, and Justice Studies
University of Tennessee at Chattanooga, Chattanooga, TN
chandra-ward@utc.edu

Paul Speer
Department of Human and Organizational Development
Vanderbilt University, Nashville, TN
paul.w.speer@vanderbilt.edu

Philip Pugliese
Chattanooga Area Regional Transportation Authority
CARTA, Chattanooga, TN
philippugliese@gocarta.org

Ayan Mukhopadhyay

Department of Computer Science
Vanderbilt University, Nashville, TN
ayan.mukhopadhyay@vanderbilt.edu

Aron Laszka
College of Information Sciences and Technology
Pennsylvania State University, State College, PA
laszka.aron@gmail.com

Samitha Samaranayake
Department of Civil and Environmental Engineering
Cornell University, Ithaca, NY
samitha@gmail.com

Abhishek Dubey
Department of Computer Science
Vanderbilt University, Nashville, TN
abhishek.dubey@vanderbilt.edu

Word Count: 5680 words + 1 table(s) $\times$ 250 = 5930 words

Submission Date: February 12, 2024

ABSTRACT
Public transit is an essential infrastructure enabling access to employment, healthcare, education, and recreational facilities. However, transportation systems often face the dilemma of concentrating their service into high-utilization routes that serve large numbers of people and spreading out service to ensure that people everywhere have access to at least some service. The regional transit agency of Chattanooga, Tennessee, exemplifies the challenges that many transit agencies face throughout the U.S., especially the issues encountered in mid-sized southern cities. The primary challenge is balancing the tension between service coverage and ridership, all while considering who needs transit most. By adapting a holistic approach, this study considers public transportation as a necessary infrastructure in the current urban transportation ecosystem. We determine the demand for transit with a data collection survey to understand the needs of Chattanooga and the broader Hamilton County, Tennessee, as a community, analyze the current public transit infrastructure for bus lines, and finally propose two methods that can be used together for network design and the creation of an on-demand integrated system.

Keywords: Transit Design, Equity, Accessibility, Community, Public Transportation

INTRODUCTION

Chattanooga is a mid-size city in eastern Tennessee with a population of approximately 180,000. It is often considered to be a gateway to the Deep South, Midwest, and Northeast for travelers from Alabama, Florida, and Georgia. Therefore, transportation infrastructure is vital for this mid-size city. However, it has been ranked as having some of the worst traffic congestion among cities that are similar in size, and therefore, there is an immediate need for efficient transportation (*1*). The public transit agency of Chattanooga, CARTA aims to provide solutions to combat traffic congestion by providing efficient public transit options, and currently spends more than $1.1 million annually on fuel through offering several different transportation modalities. These include fixed-route service, demand-response service (using neighborhood shuttles), and paratransit service. With these three service options, CARTA serves over 3 million passenger trips per year. We use CARTA as a use-case to determine the community's public transit needs, and propose an equitable integrated approach to serve the city with the goal of increasing efficiency.

Improving the efficiency of an existing system while enhancing accessibility and coverage is challenging. CARTA exemplifies these efficiency challenges that transit agencies face throughout the U.S., especially in mid-size southern cities, where agencies have to balance the tension between improving service coverage and improving ridership. When discussing the ridership versus coverage debate, it is also important to consider that transit is a more critical need for some people than others, i.e., some segments of the population depend on public transit for their basic mobility needs (e.g., access to employment) more so than other segments (*2*). This consideration of equity is often absent from traditional network design literature, however creating equitable transit systems is an identified goal for the Department of Transportation's (DOT) most recent strategic plan (*3*). The DOT established a goal of supporting and engaging people and communities to promote safe, affordable, accessible, and multi-modal access to opportunities and services while reducing transportation-related disparities, adverse community impacts, and health effects (*3*). In this study, we aim to address how we can incorporate fairness within network design through a holistic approach to achieve this goal.

Our community engagement team, collaborating with our local partner CARTA, utilized three methodologies to capture transit needs and perceptions among residents of Chattanooga, between 2021 and 2022. We will outline these data collection efforts which include focus groups, community surveys, and archival data (i.e., census, LODES, safegraph datasets), the findings, and future directions for research. The results reported here seek to succinctly reflect this project's efforts to understand Chattanooga transit needs. Together, we are using findings findings from this data to support efforts to design responsive and equitable transit systems based on needs and priorities of Chattanooga residents.

Contributions and Key Findings

Our contributions are four-fold:

1. We evaluate the current network design of Chattanooga, TN, through data collection efforts. We use the results to determining which segments of the population 'need' transit more than others. The results suggested that low-income Black residents, many of which were found to have high levels of ridership, may be increasingly displaced to outside areas of the city. These insights indicate that expansion into surrounding areas may be necessary to maintain and maximize ridership.
2. We introduce an mixed-integer linear programming (MILP) formulation for the design

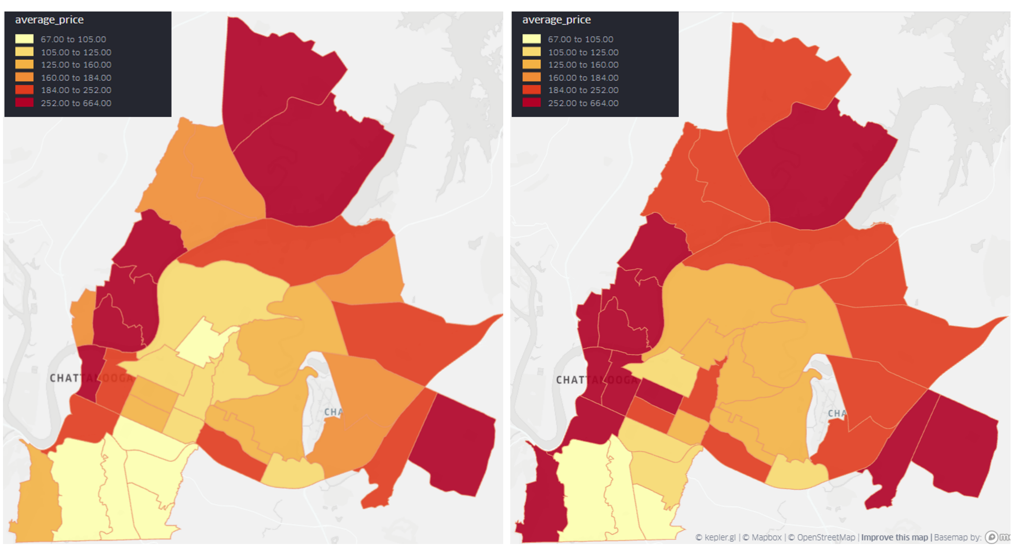
of transit networks with the consideration of equity and fairness. We identify the effects on a network when equity is integrated by construction. We find that a Rawlsian view of welfare can be used to ensure that all regions are served, prioritizing those who are in more ‘need’ of transit.

3. To address the possible need of expansion to surrounding areas, we present an integrated system that can modify existing transit networks by utilizing a fleet of on-demand vehicles. A maximum service-rate gain of 20.19% is achieved when using the new transit system in conjunction with on-demand vehicles.
4. We evaluate an integrated system showcasing both network design and multi-modal transit using real-world data from Chattanooga. Using the data collection results, we propose a flexible, equitable, and efficient transit network design process for the city of Chattanooga.

Organization The rest of this paper is organized as follows. In Section 3, we give an overview of Chattanooga and the city’s need for equitable, efficient transit. In Section 4, we present and analyze results from the survey data. We then discuss an approach to consider fairness with network design in Section 6 and insights we can take away from those results. In Section 7, we present our method for an integrated system using insights gathered from previous analysis. We present related transit studies in Section 8. Finally, in Section 9, we give our conclusions. We expect that this study will serve as a starting point to make public transit design more equitable and fair for sections of society that need it the most.

STORY OF CHATTANOOGA

Transportation and Gentrification



(a) (b)

FIGURE 1: Average household value in Chattanooga at the Census Tract Level in (a) 2010 and (b) 2020. Where spectrum of yellow to red demonstrates low to high value homes

Over time, the city of Chattanooga has undergone changes in network design as well as

	African American			White		
Tract	2017	2000	Net Change	2017	2000	Net Change
20	396	1516	-1120	703	99	604
124	1134	1639	-505	4863	1553	3310
14	778	1113	-335	898	1082	-184
26	872	1045	-173	790	689	101
11	1073	1412	-339	439	257	182
6	58	154	-96	3113	2539	574
8	409	563	-154	1108	613	495
4	3291	3265	+26	260	90	170
13	1135	1261	-126	543	623	-80
16	2258	2101	+517	279	759	-480
31	530	457	+73	1221	847	374
TOTAL	11934	14526	**-2592**	14217	9151	**5066**

TABLE 1: Population change by race between 2000 and 2017. Red denotes Opportunity Zone Census Tract

changes in housing and population. Gentrifying processes appear to be operating in Chattanooga and Hamilton County, with large increases in housing process in neighborhoods with close proximity to lower income areas, and associated decreases in non-white populations in or near those neighborhoods. Figure 1 highlights the change in housing prices in census groups over-time (spectrum of yellow to red demonstrates low to high value homes), showing the areas where gentrification is present. Figure 1 shows, over-time, how Hamilton county has shown disproportionate increases in housing value for neighborhoods in proximity to the downtown area. The changes in data regarding housing value, and the unevenness of value changes across the geography of Chattanooga, are consistent with gentrifying processes.

The latest Census data also shows a decrease in the Black population in Chattanooga. Specifically, inner city neighborhoods are declining in Black population as shown in Table 1. These shifts in Black population are consistent with gentrifying processes, and align with reports by focus group members who have had to move out of Chattanooga due to rapid housing costs. The Census reports that the African American population in Hamilton County decreased by 3,472 residents from 2010 to 2020. The Census further indicates census tracts outside the urban core such as East Ridge increasing in population as shown in Figure 2. East Ridge and areas outside the urban core such as Highway 58 are areas that also have more affordable housing. The areas seeing a decrease in Black population are predominantly Black and low-income. While not a representative sample, we will show later that the survey sample indicates that low-income Black residents are the primary riders of CARTA. Like most U.S cities, Chattanooga is facing large scale urban redevelopment and affordable housing issues that has and likely will continue to change the face of the city. Because of evolving factors like gentrification, a flexible transit network design is needed, in order to adapt with the city's needs and consider who need transit most.

Transit Score

In order to analyze public transit in the concerned region, we derived a method to assign a 'transit score' to census block groups based on a series of requests from an origin destination matrix, that

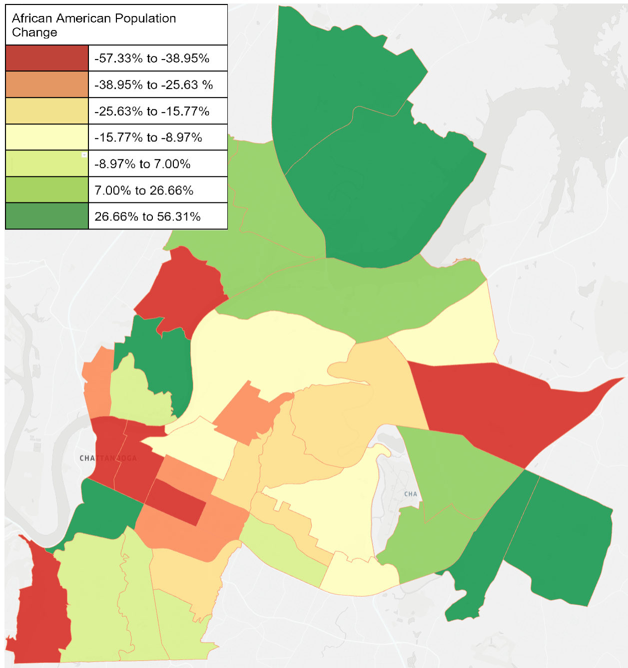


FIGURE 2: Change is Chattanooga's Black population.

(a) (b)

FIGURE 3: Transit scores for Chattanooga and its public transit agency using (a) earlier GTFS and (b) newer GTFS with increased bus frequency. (Where the transit score is from 0 to 1, following the spectrum from yellow to red)

serves as the connectivity matrix between census block groups. We use these scores to compare the city's transportation efficiency and gather insights on how to update the public transit modes and frequencies. Transit score is a metric defined as the ratio of time taken to drive to the time taken by the transit mode for the same origin-destination travel; it varies between 0 and 1 (yellow to red on the map in Figure 3). A transit score of 1 (red on the map) means a perfect public transportation system, while 0 (yellow on the map) means no transportation modes exist. The General Transit Feed Specification (GTFS) of the city's transit agency, CARTA, provides the specifications of the transit coverage and movement. The old and new GTFS are compared in Figure 3. The gray-colored regions are where data is unavailable. The new GTFS that was used was derived based on the discussions with the community engagement team. Figure 3 highlights the improvement of transit scores when using the new GTFS. We use these figures as a measure of transit security, to determine what areas currently need improvement in transit accessibility. We compare the transit scores of each census block with the data we gathered during the survey to best determine the need for transit and how to implement an equitable integrated system using the existing network.

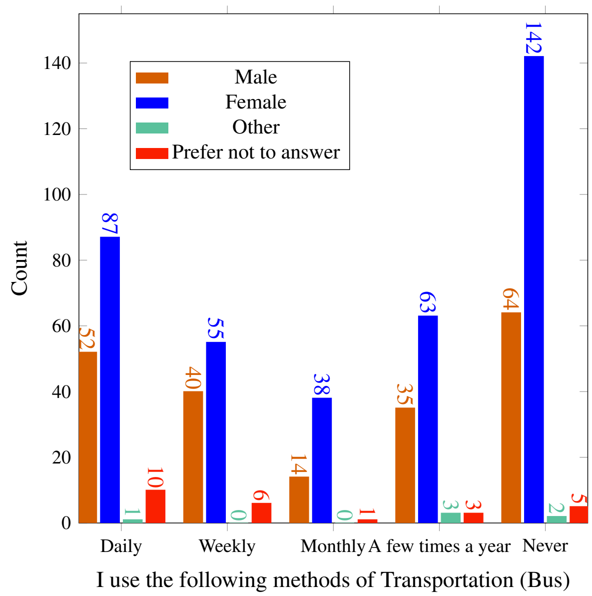


FIGURE 4: Bus rider sample groups by gender.

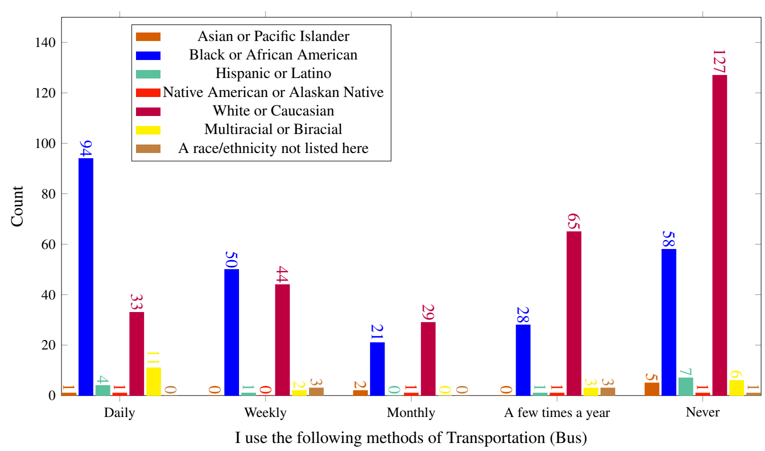


FIGURE 5: Bus Rider Sample Groups by Race

DATA SURVEY

Understanding the needs of the community through a Data-driven Approach

Data Collection

From August 2022 to November 2022, our community partner, CARTA, worked with other local agencies to disseminate surveys to the local Housing Authority residents, CARTA bus riders, CARTA's email list, and targeted organizations. The surveys were available both online, using survey monkey (*4*), and in paper format. Participant recruitment was conducted via word of mouth, fliers at bus shelters, and having CARTA workers at some of the more populous bus stops. Other local agencies assisting in promoting survey participation include local media outlets such as *The*

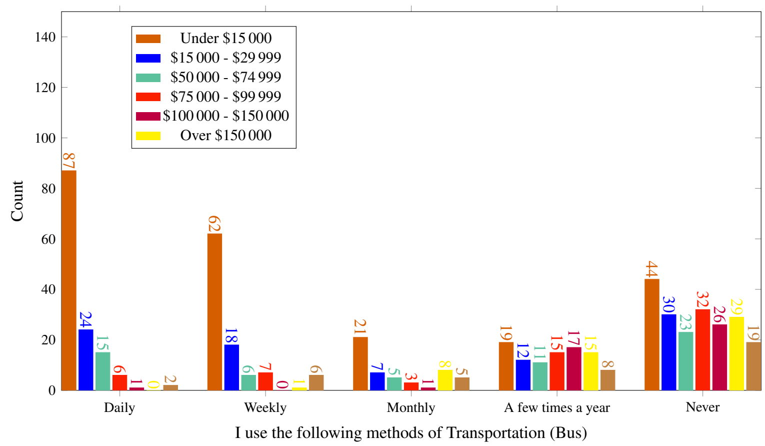


FIGURE 6: Bus rider sample groups by income.

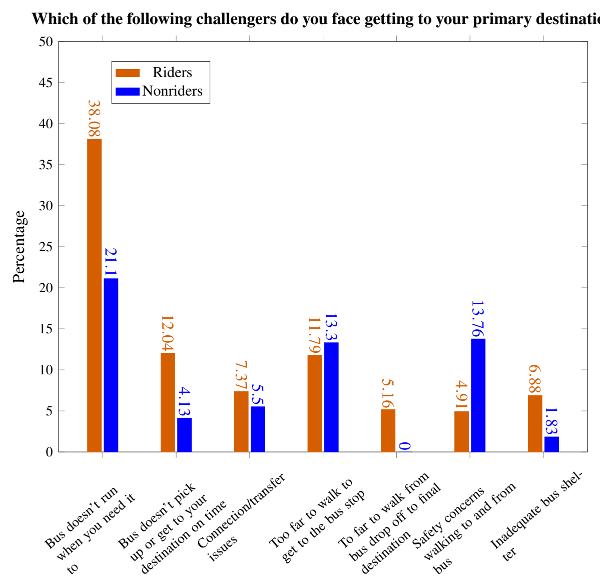


FIGURE 7: Challenges faced reaching primary destination.

Chattanoogan and Nooga Today, the Chattanooga Library, the Chattanooga Housing Authority (from now referred to as CHA), Chattanooga's Therapeutic Recreation Center, Green|Spaces, and Outdoor Chattanooga. This effort represents a convenience sample, as the sample were not randomly selected and often were selected due to their relationship with one of our many community partners.

Sample

A total of 673 surveys were collected. The largest number of survey participants were from Chattanooga Housing Authority (34%) and other targeted organizations mentioned above (43%). The remaining respondents came from CARTA bus riders (10%) and the CARTA email list (12%). The majority of the respondents in the study used the bus (47%) as their primary form of transportation, while roughly 38% of respondents indicated they used other modes of transportation to get around (ie., personal vehicle, bike, ride-sharing, or bike-sharing. Women (62.3%) constituted the majority

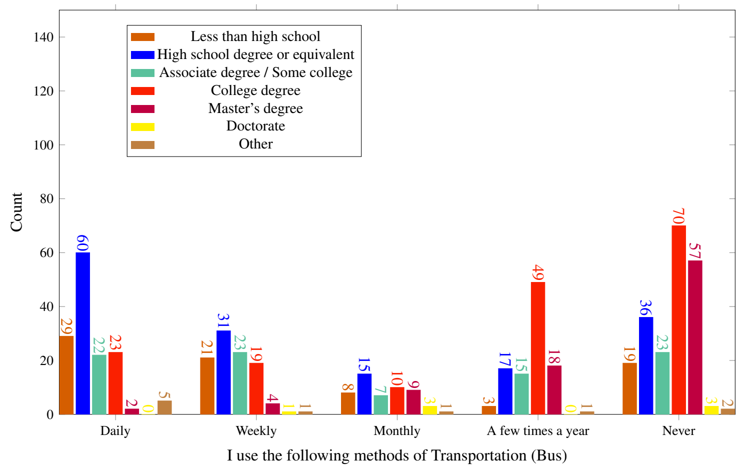


FIGURE 8: Bus rider sample groups by education.

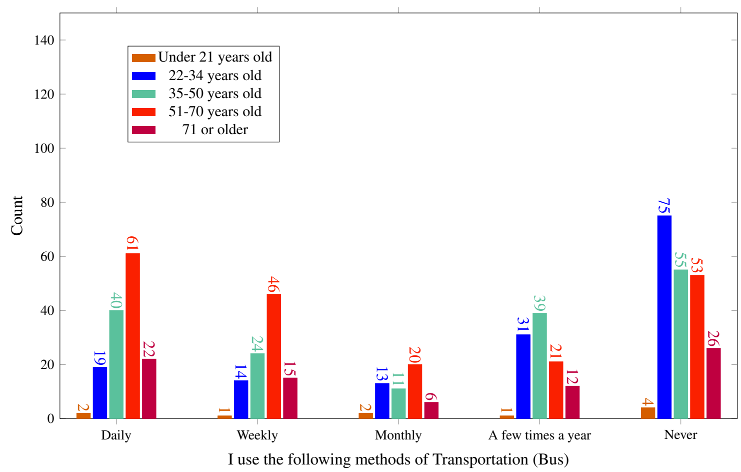


FIGURE 9: Bus rider sample groups by age.

of the sample. The sample in Figure 4 shows that women also made up the majority of riders, in this sample (34%) The majority of regular bus riders surveyed were between the ages of 51-70 (20%), followed closely by the 35-50 age category (18%), and the majority of those who were not bus riders skewed younger, between 22-34 (14.8%). Figure 5 shows the racial distribution highlighting that the majority of bus riders were Black (27%), whereas the majority of non-bus riders sampled were White (29%). Non-bus riders had a more even income distribution compared to those who were regular bus riders. Figure 6 shows that the majority of regular bus riders reported an annual income of under $15,000 (24%) Not surprisingly, the majority of bus riders would be considered low-income.

Study Population

We saw that women (14%) were almost twice as likely to report riding the bus daily compared to men (8.5%). Figure 8 shows that the majority of daily bus riders had earned at least a high school diploma. Not surprisingly, those with the lowest income, $15,000 or less, were most likely to report daily bus use (15%). Those making less than $15,000 a year were more likely than not to ride the bus daily. Riders indicated that they primarily use the bus to get to work (14%), run errands (12%), and to health care services (6%).

FINDINGS

Challenges to Accessing Transit

Figure 7 shows that the greatest challenge facing both riders and non-riders in getting to their primary destination, overwhelmingly had to do with the time. Twenty-nine percent of bus riders reported the bus not running when they need it to, followed by twenty-one percent reporting the bus either not getting to or picking up on time as the greatest challenges in getting to their primary destination. The majority of bus riders (22%) indicated that they would be more likely to take a rideshare option, compared to any other mode of travel to make a connection.

Responses to changes to existing system

The majority of the sample, when given a choice, preferred transit that had more stops, and shorter walks to stops, even though it would make the overall trip slower. The majority of survey respondents were likely to use a dial-a-ride service if offered. A majority of the survey respondents were also likely to pay a higher price for a dial-a-ride service. Non-bus riders preferred to arrange the service by computer or mobile app, while bus riders preferred to use a phone to call and arrange the service. This is not surprising given that the age of bus riders in this sample skewed older, while the non-bus riding sample skewed younger as shown in Figure 9. A slight majority of both riders and non-riders preferred to arrange for the service in advance. We use these findings to motivate our work with a multi-modal, integrated approach that we present in Section 7.

Takeaways

Combining ridership preferences, demographic trends, and the gentrification analysis, the results suggest that some of CARTA's most reliable customers, low-income Black residents may be increasingly displaced to more affordable areas outside the city. These are areas often with a lower transit score, with the majority of the areas not being currently serviced by CARTA. These insights and the data suggest that expansion into surrounding areas may be necessary to *maintain and maximize ridership*. As well as for areas currently served that in order to attract new riders, transit needs to be safer or change the perception about the safety of public transit to non-riders.

DESIGNING EQUITABLE TRANSIT

The results from the data collection and transit score analysis are useful to help understand which sections of the city need public transit critically, We can use the results to account for such priorities during planning, which can improve accessibility for residents who depend on transit more than others, or for areas where residents have a new need for transit due to gentrification and displacement. We saw in Section 4, that the current system will not adequately support low-income Black residents if the city continues to follow the demographic trends seen in Section 3. By taking into consideration these groups, we can maintain and maximize ridership, which preservers the transit budget. We will now present a simplified abstraction for transit network design that explicitly considers different notions of equity, welfare, and priority that can help use achieve an equitable and efficient transit system.

Formulation

Our formulation is an integer linear program based on a piece-wise linear utility function that quantifies the utility of a passenger from the installed transit network compared to the use of personal vehicles. We adopt a traditional line planning formulation with the addition of the defined utility function. We also follow standard constraints on flow-based line planning (*5*). We focus on this simplified abstraction to capture the basic nature of network design—while simultaneously connecting various pairs of nodes in a network—without the level of domain detail reserved for full-blown transit planning (e.g., capacities, frequencies, number of transfers). This choice enables us to run comprehensive experiments shedding light on fundamental efficiency versus coverage trade-offs in a way that is more tractable and involves fewer model parameters.

We utilize two social welfare objective functions in our formulation; Utilitarian and Rawlisan. A priority-adjusted utilitarian social welfare function computes the sum of priority-adjusted utilities for each origin-destination pair in our underlying network. Therefore, the *maximum priority-adjusted ridership* problem is

$$\max_{(x,y,f,\ell,u)\in P} \sum_{(o,d)\in\mathscr{D}} b_{od}\cdot(p_{od}\cdot u_{od}). \tag{1}$$

Note that the objective function in (1) is monotonic increasing.[1] Similarly, the *maximum priority-adjusted coverage* problem is

$$\max_{(x,y,f,\ell,u)\in P} \min_{(o,d)\in\mathscr{D}} (1-p_{od})\cdot u_{od}. \tag{2}$$

The max-min nature of the formulation is based on the Rawlsian view of egalitarianism, i.e., we seek to maximize the utility of the least advantaged population group. While the objective function in (2) is not monotonic increasing, we can make it so by including a small multiplicative factor of the objective function of (1). Where b_{od} corresponds to the demand, p_{od} refers to the priority score, u_{od} is the utility at the origin-destination level. We acknowledge there are many definitions of equity and welfare that can be relevant for this problem, e.g., Nash Social welfare. We look at the ones which we consider to be at the two ends of the spectrum, serving everyone with at least some utility versus serving the worst-off to the best ability. See section 6.2 for details on how priority scores are calculated. Further technical details are excluded from this report as our main focus is demonstrating a introductory approach to considering fairness in transit design.

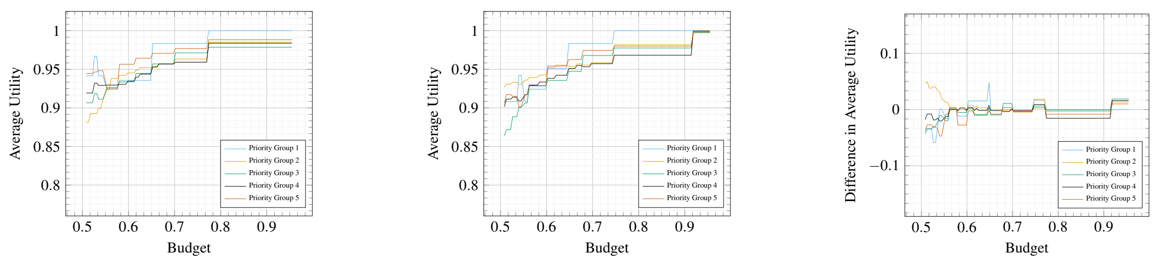
Priority Scores

We use the notion of priority scores to capture the *need* for transit, i.e., some sections of the community depend on transit more than others. As we saw in the data collection efforts in the previous section, there are parts of the population where transit needs are higher for some. Because of Chattanooga rapid change in housing values across Hamilton county, which is consist with the gentrifying process, we use car ownership and household income as proxies for priority in this analysis. However, any viable demographics and statistics can be used to calculate a priority distribution to capture different community needs.

First, we gather data pertaining to average household income and for all census tracts from the American Community Survey Data (ACS) (*6, 7*). We divide the spread of each attribute (e.g., income) into bins and assign a score (between 0 and 1) based on the percentile of the bin, i.e., the lowest bin is assigned a score of 0.1, and the highest bin is assigned a score of $1-\varepsilon$ for some small $\varepsilon > 0$. Then, for each census tract, we compute the sum of its car ownership score and income

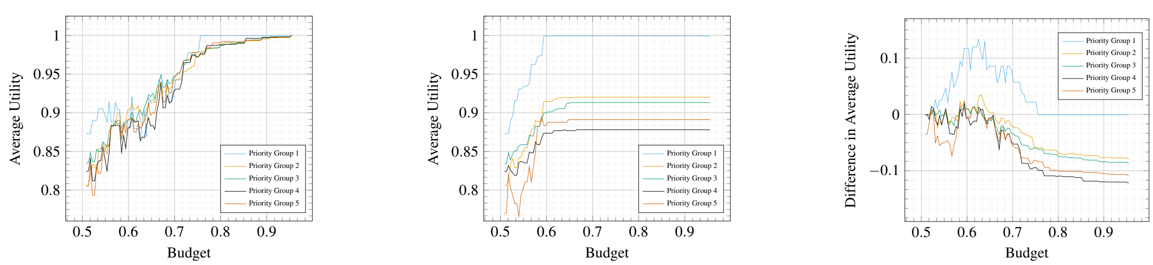
[1] We assume without loss of generality that $b_{od}, p_{od} > 0$ for all $(o,d)\in\mathscr{D}$.

score. For example, assume that a tract falls in the second lowest bin concerning car ownership (i.e., a score of 0.2) and the lowest bin concerning income (i.e., a score of 0.1). The cumulative score for this census tract would be 0.3. Finally, we normalize the resulting scores across all tracts to create our proxy for priority. While this process gives us a priority score for each census tract, we still face two challenges. First, recall that our model captures priority at the origin-destination level. Second, analyzing the effect of network design on a large number of tracts (each with its own priority score) is cumbersome. To tackle these challenges, we label each origin-destination pair with the priority score of the origin. This assignment is based on the notion that we want to capture the need for transit at when residents travel *to* the place of employment. Second, we create a set of k priority classes by uniformly binning the range of priority scores; we refer to these partitions as priority groups. Each origin-destination pair, therefore, falls within one of these priority groups.



(a) Equal Priorities (b) Unequal Priorities (c) Utility Gain

FIGURE 10: Average utility and gain based on the utilitarian formulation in Chattanooga, Hamilton County, TN.



(a) Equal Priorities (b) Unequal Priorities (c) Utility Gain

FIGURE 11: Average utility and gain based on the Rawlsian formulation in Chattanooga, Hamilton County, TN.

Results

Our experimental results shown in Figures 10 and 11 demonstrate that considering the various degrees of need of the residents is critical to serving people who need transit the most.

In Figures 10 and 11, all requests are served for the selected budget range. However, for the lower end of the budget range, lower priority groups' (groups 3,4,5) origin-destination requests are served by a longer path, thus receiving a lower average utility. Based on a transit agency's needs, the agency can analyze results shown and choose the social welfare function that best aligns with their needs. Our results also show that a utilitarian objective can achieve higher cumulative utility by sacrificing service to a small subset of origin-destination pairs. However, a Rawlsian view of welfare can be used to ensure that all regions are served (given at least some minimum budget), albeit at the cost of lower average utility.

When considering fair network design we started with a clean slate, i.e., we assumed that a transit designer has the scope to optimize a network from scratch. However, we point out that such optimization is typically infeasible in practice as most cities must optimize resources *given* the current network. However, we believe that this fundamental analysis of transit design that explicitly focuses on equity and fairness is critical to shaping our future understanding of the intersection of network design and equity. Serving as a stepping stone for understanding the intersection of transit network design and social welfare considerations for the city of Chattanooga, given the data analysis. We hope that this is will help us identify the effects on a network when equity is integrated by construction and use these results to inform us when adapting an existing network with an integrated approach.

MULTI-MODAL TRANSIT APPROACH

In order to modify an existing network, we focus on an on-demand and transit-integrated system that serves the daily commuters in Chattanooga fully. Our main objective is to expand the understanding of the effectiveness and properties of such a system in order to better serve the area. We can adopt this methodology, taking into consideration the needs of Hamilton County residents, to serve the area equitably and efficiently. We saw in the data analysis from the survey that expansion into surrounding areas may be necessary to maintain and maximize ridership, which could be addressed by our on-demand and multi-modal options in this integrated approach. We will first discuss the design of the integrated system, and secondly, the conducted experiments.

Design

The system utilizes a fleet of on-demand vehicles and a transit network to fulfill commuter demands. We assume an already existing transit network and the operation schedule is available. The passengers will be served using one of the following configurations:

- Transit-only option: The passenger is completely served by the transit network. The passenger may be required to walk to and from the bus stop, limited by a maximum walking distance.
- On-demand only option: An on-demand vehicle picks up the passenger from the origin and drops them off at the destination.
- Multi-modal only option: The passenger relies on the transit network for the core part of the journey while on-demand vehicles provide first and/or last leg coverage to and from the bus stops.

The Transit-only option is preferred during the assignment. Therefore, if for a given passenger, there is an available transit-only option, the passenger will be served only through the transit. However, the latter two models rely on the on-demand vehicle fleet for fulfilling the journey. Our model aims to serve as many passengers as possible while reducing the total vehicle miles traveled by the fleet. Therefore, the assignment of the option and the particular vehicle assigned depends on the current status of the on-demand fleet and total demand. Furthermore, the system relies on the following assumptions:

- The buses in the transit network are considered to be uncapacitated. We discuss the violation of the capacities in the results section.

- A passenger is limited to at-most one bus-to-bus transfer. This is to ensure the quality of service as passengers are unlikely to make multiple transfers.
- We assume that all the travel times are deterministic.

Since the system is expected to be operated online in practice, similar to the existing ride-hailing systems, we queue passenger requests for a brief period (ex: 30 seconds) and process them as a batch. We first determine the potential service choices, such as buses and on-demand automobiles, for each passenger request. Second, we solve an Integer Linear Problem to find the best solution considering the whole batch. The optimal solution to the assignment problem might opt to refuse service to some passengers. In accordance with the requirements of each travel option, a bus and/or an on-demand vehicle will be assigned to each passenger to be served.

Experiments

Setup

In this experiment, we utilize synthetic commuter trips in the Chattanooga area. There are 31528 commuters, resulting in 63056 total commuter trips after splitting each commuter into 2 trips (trip to work and home). All the morning commuter trips belong to the 7.00 am to 9.00 am time window and the evening trips belong to the 4.00 pm to 6.00 pm time window. The following figure shows the temporal distribution of travel demand.

We consider two different transit networks to work along the on-demand vehicle fleet: 1) the current (existing) CARTA bus network and 2) the new (proposed) bus network. In addition to evaluating the performance of the integrated system, we compare the effectiveness of each bus network for the integration.

We conduct all the experiments in 3 different settings.

- Old transit+on-demand setting: Passengers are served via both the on-demand fleet and the old bus network
- New transit+on-demand setting: Passengers are served via both the on-demand fleet and the new bus network
- On-demand only setting: Passengers are served only via the on-demand fleet

Results

Figures 12 and 13 show that compared to the on-demand-only setting, transit-integrated settings deliver a higher service rate while attaining lower total vehicle miles traveled (VMT). The maximum service rate gain (20.19%) is achieved with the new transit when relying on a 1000-vehicle fleet of capacity 5. Furthermore, the results suggest that the new-transit fleet consistently outperforms the old-transit network by yielding higher service rates. Integrated-system with the new-transit network also dominates the old-transit network in terms of reduced VMT. As expected the average VMT remains lower with higher capacities as it facilitates more sharing.

Figure 14 describes the distribution of the service options assigned in each setting. The new-transit integration system serves 40% of the requests via the multi-modal options across all the settings. On the other hand, the multi-modal proportion in the old-transit system always remains below 30%. Similarly, the new-transit system serves more trips via only the transit network. This suggests that the new-transit system is better suitable for a transit and on-demand integrated system. Note that the number of transit trips remains constant with different vehicle fleets but the proportion reduces as the number of trips served by the other two service options increases with the increased fleet sizes.

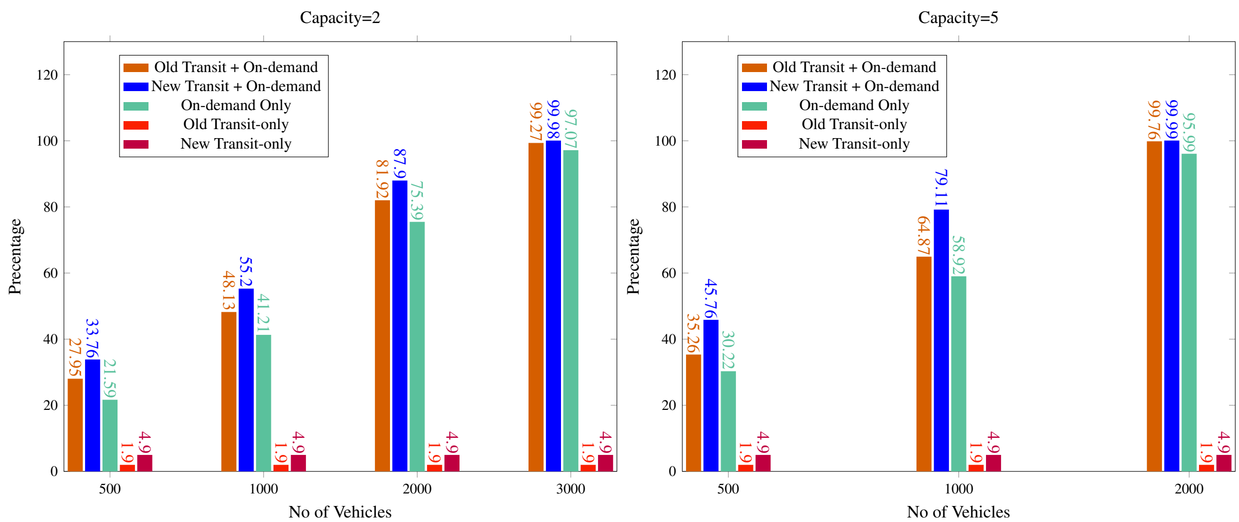


FIGURE 12: Service Rate: Comparison of service rate for varying vehicle capacities (2 and 5) and fleet sizes (500, 1000, 2000, 3000).

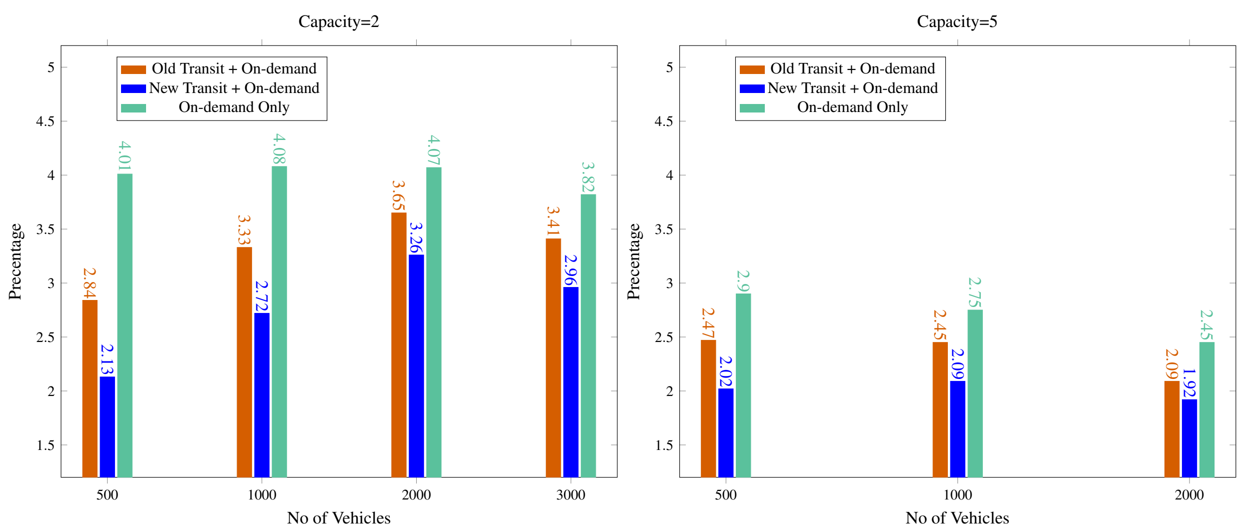


FIGURE 13: VMT: Comparison of Vehicle Miles Traveled (VMT) for varying vehicle capacities (2 and 5) and fleet sizes (500, 1000, 2000, 3000).

The distribution of buses by their maximum passenger occupancy is depicted in Figure 15, with the blue plot representing the bus occupancy in the old-transit+on-demand setting and the red plot describing the new-transit+on-demand setting. In both settings, we are using an on-demand fleet of 2000 vehicles, each with a capacity of 5 passengers. In the new transit network setting, 45.6% (152 out of 333) of the buses exceed the seating capacity of 50. However, assuming a total capacity of 100 passengers per bus, including standing passengers, only 18.3% (61 out of 333) of buses exceed their capacity. Similar violations are observed in the old transit network setting, with 42% (78 out of 186) of buses exceeding seating capacity and 18.8% (35 out of 186) of buses exceeding total capacity. Nevertheless, the maximum occupancy of any bus in the new transit network is 274, while in the old transit network, it is 473.

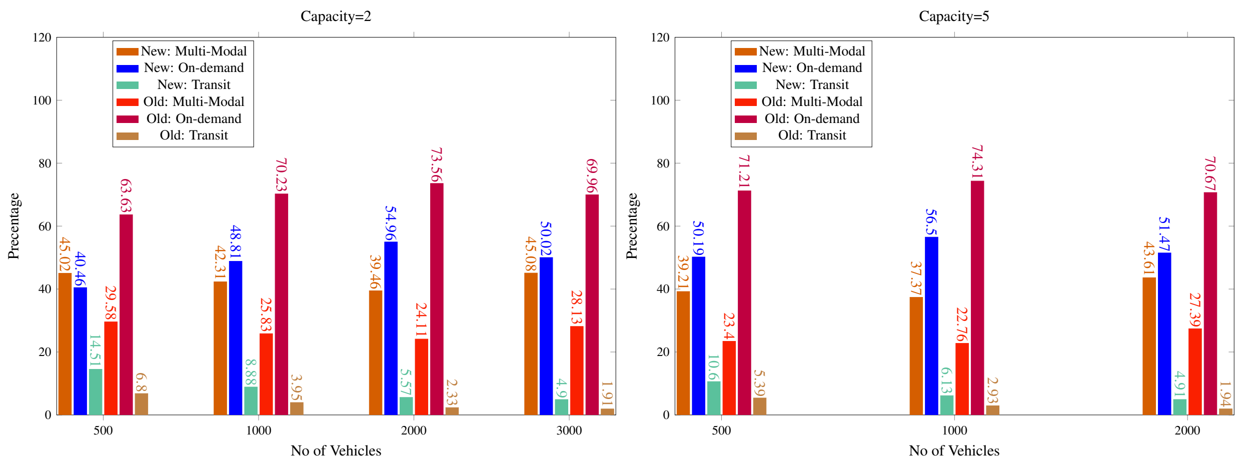


FIGURE 14: Service option composition for varying vehicle capacities (2 and 5) and fleet sizes (500, 1000, 2000, 3000).

Takeaways

We can adopt this integrated system to Chattanooga's existing network to serve passengers in 3 different settings; old transit network + on-demand setting, new proposed transit network + on-demand setting, and on-demand only setting. We are able to combine works with using the proposed transit network from the fairness work in combination with on-demand. This allows us to create a flexible, equitable, and efficient transit network for the city of Chattanooga as well as reach areas of the community not currently served by transit.

RELATED WORK

Equitable Transit Design

When tackling transit design, agencies often have to consider how to combat the ridership versus coverage debate, while maintaining efficiency. Current transportation literature is a well-studied topic in transportation optimization. However, because of the complexity of real-world transit operations there is no single transit system design problem that considers efficiency, ridership, coverage, and equity. Works often focus on one of the listed aspect and leave others as an afterthought (*8–11*). We strive to incorporate all elements in a holistic, integrated approach that considers transit design from start to finish by utilizing a data collection survey, mathematical optimization, and multi-modal approach. Previous works decompose the design of transit systems into a sequence of problems to be solved incrementally (*12–14*). Other works aim to consider equity with network design, but it is an afterthought instead of at the center of the design or no exact formulation is given (*14–16*).

Multi-modal Transit Systems

A few recent studies have explored the value of integrating on-demand systems with public transit. For example, Salazar et al. (*17*) argued that an integrated system with coordination between on-demand fleets and mass transit could lead to reduced travel times and emissions. Stiglic et al. (*18*) showed that integration of carpooling with public transit could lead to an increase in the service rate and transit usage. Vakayil et al. (*19*) proposed an integrated system in which the on-demand fleet provides first-and-last mile coverage for the transit system. However, they do not permit ride-

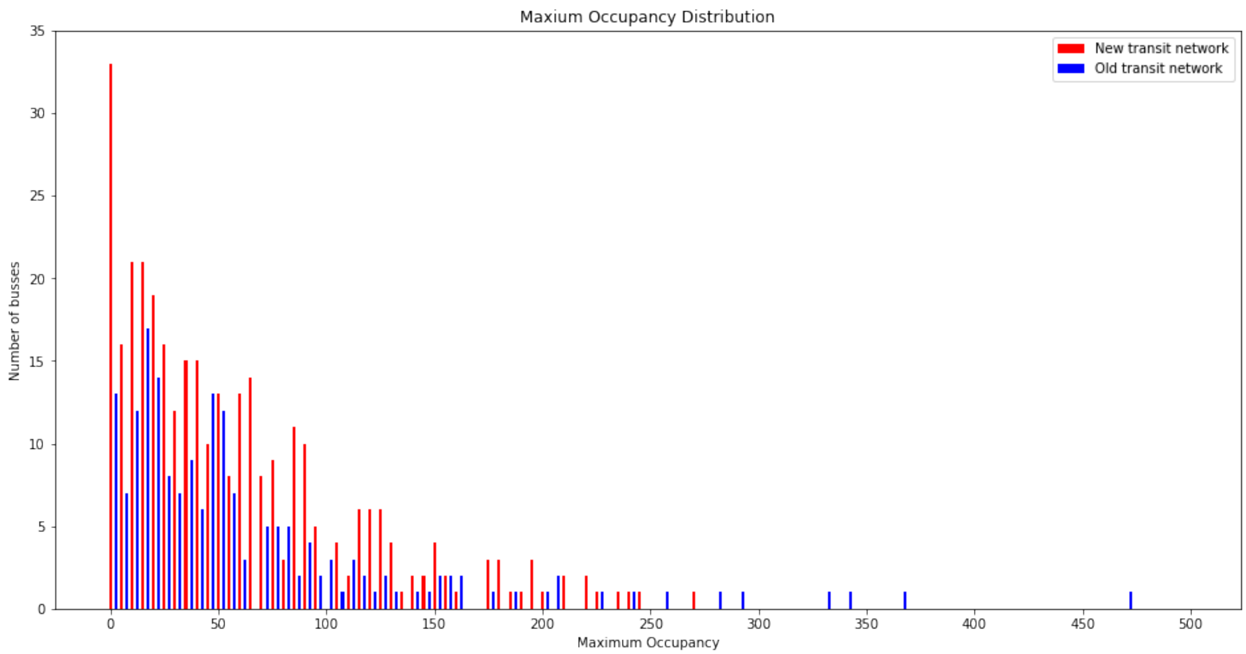


FIGURE 15: Distribution of maximum bus occupancy.

sharing and myopically assign the passengers to the nearest bus stop without considering the state of the on-demand fleet. Periver et al. (*20*) provide an efficient approximation algorithm for the integrated design problem, but ignore the operational optimization of the integrated on-demand service.

Transit Network Design

The design of transit systems is a complex process that cannot be solved in a single step. Instead, it must be broken down into a series of smaller problems that can be solved one at a time, taking into account the operational considerations of each step. (*12, 13*) The steps of transit network design is commonly broken down into first; the designing of the physical infrastructure network, for example where to install bus lines. Second; the designing of the operation network, or in other words, line planning (*13, 21*). From there, frequency setting and pricing problems (*22*) can be applied as well as crew and fleet scheduling problems (*23*). Often, transit system design literature's goal is to maximize ridership. There are a few works that deviate from a utilitarian view (*8–11*), however the efficiency and equity trade-offs of the design of transit networks is largely unexplored.

CONCLUSION

We present results from a data collection effort on public transit for the city of Chattanooga, Hamilton County, Tennessee. From the results we motivate our approach to consider fairness when designing and deploying transit networks. This is done through a mathematical formulation for transit network design that explicitly considers different notions of equity, welfare, and priority. Informing our priority score calculations with results from the data survey. To solve the problem further, without having to change the existing network, we propose a multi-modal approach that considers an on-demand and transit-integrated system to serve the daily commuters in Chattanooga. Because of the gentrification process taking place in Chattanooga over the years, with this multi-modal approach we can expand our services to areas that do not have access to transit under the current transit network. We can also combine a proposed network from the fairness design with the integrated system to fulfill the new transit network + on-demand setting to create a flexible, equitable, and efficient transit network for the city of Chattanooga, while addressing the concerns and challenges discovered in the data survey.

FUNDING

This work was supported in part by National Science Foundation through award number 1952011. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: S. Pavia, S. Tehrani, D. Edirimanna, and R. Sen provided technical guidance and management for the research, helped run data analyses, and helped write the manuscript. S. Tehrani, C. Ward, P. Speer, and P. Pugliese helped with data collection efforts, data processing, ran analyses, as well as helped write the manuscript. M. Wilbur helped with data processing, literature review and editing of the manuscript. A. Mukhopadhyay, A. Laszka, S. Samaranayake, A. Dubey supervised the research and assisted with the manuscript editing and writing. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Pare, M., *Chattanooga traffic gridlock sets new records: Chattanooga Times Free Press*, 2015.
2. Tan, S., A. Fowers, D. Keating, and L. Tierney, Amid the pandemic, public transit is highlighting inequalities in cities. *The Washington Post*, 2020.
3. of Transportation, U. D., *U.S. Department of Transportation Strategic Plan FY 2022-2026*, 2022.
4. *SurveyMonkey Inc.* Online, ????
5. Pavia, S., J. C. M. Mori, A. Sharma, P. Pugliese, A. Dubey, S. Samaranayake, and A. Mukhopadhyay, *Designing Equitable Transit Networks*, 2023.
6. U.S. Census Bureau, *INCOME IN THE PAST 12 MONTHS (IN 2020 INFLATION-ADJUSTED DOLLARS)*, 2020.
7. U.S. Census Bureau, *COMMUTING CHARACTERISTICS BY SEX)*, 2020.
8. Camporeale, R., L. Caggiani, A. Fonzone, and M. Ottomanelli, Quantifying the impacts of horizontal and vertical equity in transit route planning. *Transportation Planning and Technology*, Vol. 40, No. 1, 2017, pp. 28–44.
9. Jiang, Y., Reliability-based equitable transit frequency design. *Transportmetrica A: Transport Science*, 2021, pp. 1–31.
10. Rumpf, A. and H. Kaul, A public transit network optimization model for equitable access to social services. In *Equity and Access in Algorithms, Mechanisms, and Optimization*, 2021, pp. 1–17.
11. Camporeale, R., L. Caggiani, and M. Ottomanelli, Modeling horizontal and vertical equity in the public transport design problem: A case study. *Transportation Research Part A: Policy and Practice*, Vol. 125, 2019, pp. 184–206.
12. Desaulniers, G. and M. D. Hickman, Public transit. *Handbooks in operations research and management science*, Vol. 14, 2007, pp. 69–127.
13. Schöbel, A., Line planning in public transportation: models and methods. *OR spectrum*, Vol. 34, No. 3, 2012, pp. 491–510.
14. Wei, Y., M. Mao, X. Zhao, J. Zou, and P. An, City Metro Network Expansion with Reinforcement Learning. In *Proceedings of the 26th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, Association for Computing Machinery, New York, NY, USA, 2020, KDD '20, p. 2646–2656.
15. Camporeale, R., L. Caggiani, A. Fonzone, and M. Ottomanelli, Better for Everyone: An Approach to Multimodal Network Design Considering Equity. *Transportation Research Procedia*, Vol. 19, 2016, pp. 303–315, transforming Urban Mobility. mobil.TUM 2016. International Scientific Conference on Mobility and Transport. Conference Proceedings.
16. Behbahani, H., S. Nazari, M. Jafari Kang, and T. Litman, A conceptual framework to formulate transportation network design problem considering social equity criteria. *Transportation Research Part A: Policy and Practice*, Vol. 125, 2019, pp. 171–183.
17. Salazar, M., F. Rossi, M. Schiffer, C. H. Onder, and M. Pavone, On the Interaction between Autonomous Mobility-on-Demand and Public Transportation Systems. In *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, 2018, pp. 2262–2269.
18. Stiglic, M., N. Agatz, M. Savelsbergh, and M. Gradisar, Enhancing urban mobility: Integrating ride-sharing and public transit. *Computers '1&' Operations Research*, Vol. 90, 2018, pp. 12–21.

19. Vakayil, A., W. Gruel, and S. Samaranayake, *Integrating shared-vehicle mobility-on-demand systems with public transit*, 2017.
20. Périvier, N., C. Hssaine, S. Samaranayake, and S. Banerjee, Real-Time Approximate Routing for Smart Transit Systems. *Proc. ACM Meas. Anal. Comput. Syst.*, Vol. 5, No. 2, 2021.
21. Borndörfer, R., M. Grötschel, and M. E. Pfetsch, A column-generation approach to line planning in public transport. *Transportation Science*, Vol. 41, No. 1, 2007, pp. 123–132.
22. Bertsimas, D., Y. Sian Ng, and J. Yan, Joint frequency-setting and pricing optimization on multimodal transit networks at scale. *Transportation Science*, Vol. 54, No. 3, 2020, pp. 839–853.
23. Haase, K., G. Desaulniers, and J. Desrosiers, Simultaneous vehicle and crew scheduling in urban mass transit systems. *Transportation science*, Vol. 35, No. 3, 2001, pp. 286–303.