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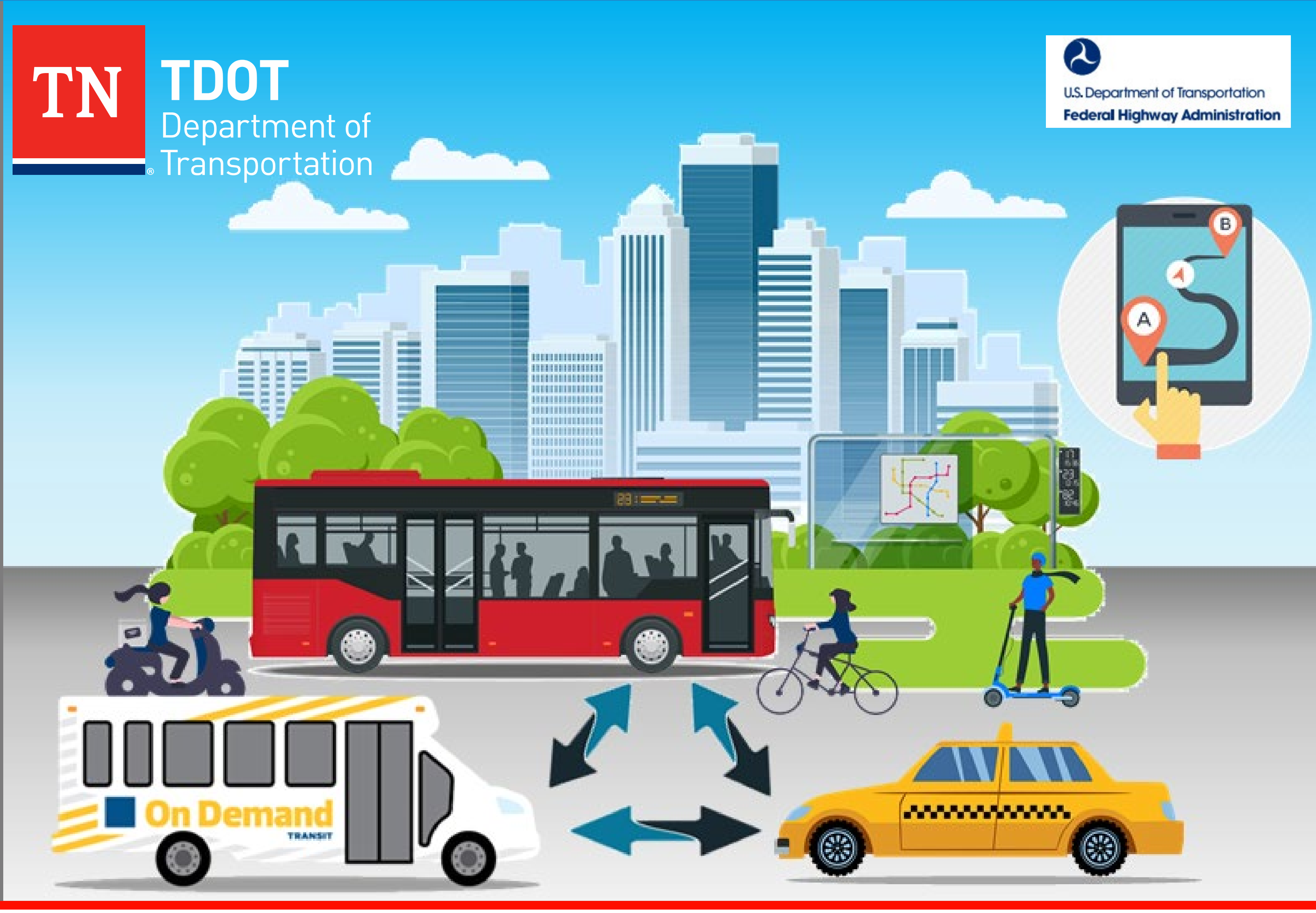

Connecting Demand Response Transit with Fixed Service Transit

Research Draft Report from the University of Memphis | Sabyasachee Mishra, Candace Brakewood, Mihalis M. Golias, Avani Aravind, Suvin P. Venthuruthiyil, Ishant Sharma| May 31, 2022

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16. Abstract
Public transportation providers are constantly striving to maximize available resources in terms of cost and vehicle fleet to deliver high-quality services that allow passengers to finish their trips between origins and destinations in the time allotted. Even though buses and metro systems serve a vast number of people, some passengers may find them inconvenient due to their lack of flexibility. Because of its capacity to combine flexible or customizable service with cost-efficiency, demand responsive transit (DRT) captures the demands of rural populations, especially in dispersed locations, while Fixed Route Transit (FRT)can capture the urban demand. Although FRT and DRT function well in many areas, their integration is often overlooked. Therefore, by connecting FRT and DRT, transit agencies can potentially minimize the overall system cost while maximizing the coverage in the low population density areas. This study intends to cover this gap by proposing a methodology to improve the existing FRT system in Morristown, Tennessee by connecting FRT with the DRT system and assessing possible collaboration with transportation networking companies. In this study, different scenarios with multiple modes and multiple legs are modeled using agent-based simulation, integrating the Transportation Network Companies (TNC) along with, FRT, and DRT, and the best performing scenario in terms of the total system cost for every Origin-Destination pair is calculated. The results indicate how the integrated system can serve as a feeder service for the conventional fixed route transit system, with 60% of trips preferring an integrated scenario based on simulation.

17. Key Words **FIXED ROUTE TRANSIT** **DEMAND-RESPONSIVE TRANSIT** **TRANSPORT NETWORK COMPANY** **AGENT-BASED MODELING**	18. Distribution Statement No restriction. This document is available to the public from the sponsoring agency at the website http://www.tn.gov/.

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Executive Summary

What was the research need?

Travel behavior has changed because of sociodemographic and recent market development trends, prompting the adoption of more flexible and accessible public transportation solutions (Grahn et al., 2021). This is especially true in low and medium-density areas, where fixed-route transit may not be cost-effective nor provide a sufficient degree of service to its dependents. According to Potts et al., 2010a, around 40% of transit agencies in the United States provided some type of flexible transit service to meet the growing demand for more flexible transit service alternatives. Effective integration of traditional transit with demand responsive services has been considered as a viable approach for avoiding unfavorable scenarios, as it combines the efficiency of public transportation with the ease and flexibility of demand responsive services. As a result, the operation and design of such an integrated system have received a lot of attention, and emerging technologies have been deployed to enhance their operational efficiency.

The purpose of this study is to advise the Tennessee Department of Transportation (TDOT) on feasible integration policies for conventional Fixed Transit (FRT) and Demand Responsive Transit (DRT) services including the possibility with Transportation Network Companies (TNCs), as well as to determine how the cost aspect of integration affects users and agencies. The study also identifies the beneficial candidate scenarios for the integration. The study assists in identifying the most effective evaluation strategies for assessing the newly created scenarios and the existing transportation system, as well as how the new multimodal scenarios can be implemented in the future. Additionally, the research presented here will aid agencies in assembling appropriate information before implementing and evaluating any FRT-DRT integration project. The study can be summarized in three sections. First is a review of published literature on existing public transit integration projects and proposed methodologies. The second section presents the proposed methodology for the study. Finally, an evaluation of the proposed framework and the resulting data is conducted, as well as an assessment of integration viability.

What were the research objectives?

The main objectives of this project were as follows:

- To provide a comprehensive review of previous literature and studies available on connecting DRT with FRT;
- To conduct case studies of connections between DRT and FRT in cities with similar geographic or transportation systems, with a focus on new and innovative partnerships such as those with TNCs;
- To identify areas with low transit coverage and potential areas for a demand responsive connector (DRC);
- To develop a sketch tool for connecting DRT with FRT either introducing a dedicated demand responsive service, collaborating with transportation networking companies to serve as DRT, or converting additional low frequency and low demand FRT services to a DRC;
- To analyze the operational aspects associated with DRT-FRT coordination;

- To develop an equity-based toolbox to identify the target population for DRT-FRT service; and
- To develop an implementation plan for connecting DRT with FRT under various scenarios.

What was the research approach?

In this project, Morristown city in Hamblen County was chosen as the research area because it had an established DRT service and recently launched a fixed-route service. In this regard, comprehensive data corresponding to individual trips (from ticket data) was collected from East Tennessee Human Resource Agency (ETHRA), which included the characteristics of those who purchased the tickets, as well as information on the trip purpose. To create distinct scenarios that represent various combinations of the FRT, DRT, and TNC systems to complete a trip (Integrated Scenario), an agent-based simulation modeling technique was used, reproducing current field conditions using the obtained data. The model creates multiple scenarios in which users were presented with multiple mode options and legs to complete the journey. In each case, the cost borne by users, transit agencies, and the system as a whole was computed, and the most viable scenario for each origin and destination was determined that resulted in the lowest system cost. The costs were calculated not only in monetary terms, but also in terms of the value of travel time for each user, taking into account the travel time, waiting periods, and transfer times for the various scenarios.

An evaluation of the whole system was done in terms of cost, time, and equity to assess the effectiveness of each scenario in terms of accessibility and serving the demand. The algorithm for the aforementioned analyses was developed in the MATLAB®R2021b platform, which can be extended to any city with a defined road network structure.

What were the findings?

The key findings of the project are as follows:

- The study successfully analyzed the possibilities of the integration of FRT, DRT, and TNCs from both user and agency perspectives.
- 60% of the trips preferred the "Integrated Scenario" compared to the base case scenario of DRT-DRT given the economic viability.
- Utilizing DRTs and TNCs as a feeder system to FRT is feasible in terms of the total system cost.
- In terms of equity, the integrated scenarios are more equitable than the FRT network in catering to the demand and the system cost.
- Integration is advisable for both the users and agencies for a more equitable and low-cost public transit system.

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Glossary of Key Terms and Acronyms

Acronym	Description
APTA	American Public Transportation Association
DRT	Demand Response Transit
DRC	Demand Responsive Connector
ETHRA	East Tennessee Human Resource Agency
FRT	Fixed Route Transit
GTC_{TOTAL}	Generalized Travel Cost Ratio
GTFS	General Transit Feed Specification
TL_{FRT}	Trip Length by FRT
TNC	Transportation Network Companies
TPTA	Tennessee Public Transportation Association
VOR	Value of Reliability
VOT	Value of Travel Time

Chapter 1 Introduction

Fixed route transit (FRT) and demand responsive transit (DRT) are the major services offered by transit agencies (Potts et al., 2010b) to meet varying demands (temporal and spatial) and optimize the available vehicle fleet and budget to provide mobility to the general population. FRT in terms of buses and metro systems serves a large number of passengers but such services might be inconvenient for a significant proportion of the population because of the associated inflexible route and schedule (Li & Quadrifoglio, 2010). Due to their high dependence on demand, FRT operates in urban and suburban or medium to high-density areas and hence often leaves out the population living in low-density areas (rural). DRT, with its ability to provide on-demand cost-effective service to the passengers (Davison et al., 2014; Koffman, 2004), typically serves the population living in low-density areas. But DRT functioning is usually at the expense of high operating costs for the agency as they also include subsidies in addition to the operational costs. DRT may also resemble on-demand taxi services often operated by Transportation Networking Companies (TNCs) or local taxi operators. However such services are more expensive than DRT (Ho et al., 2018) and have limited service coverage areas. Hence these services are often unaffordable for low-income communities and inaccessible to rural populations.

The population living in low-density areas typically travels to the nearest suburban area to complete their daily needs including medical, shopping, and recreational trips, and rely on private cars and public transit to travel. Carless inhabitants generally rely only on DRT, assuming it is available, due to limited FRT coverage and the lack of taxi services. Flexible/hybrid transit service, which combines DRT and FRT, has the potential to mitigate the above-mentioned drawbacks while maximizing their benefits. Table 1-1 shows a comparison of different aspects of FRT, DRT, TNC, and Flexible/Hybrid Transit Services.

Table 1-1 Comparison of FRT, DRT, taxi, and flexible transit services (Ho et al., 2018)

	FRT	DRT	Taxi services	Flexible/hybrid transit service
Route	Fixed	Flexible	Customized	Fixed and flexible
Schedule	Fixed	By request	By request	Fixed and by request
Speed	Slow to fast	Medium	Fast	Reasonably fast
Cost	Low	Medium	High	Low to Medium
Mode	Shared	Shared	Non-shared	Shared
Capacity	High	Medium	Low	Low to Medium
Reservation	Not needed	Often needed	Not needed	Needed for flexible routes

In Tennessee, 25 transportation organizations service 95 counties with a fleet of over 1800 vehicles (*TPTA*, n.d., 2019). Because of the rigid schedules and limited coverage area associated with present FRT services in Tennessee, the Nashville Metropolitan Transit Authority's strategic plan recommends boosting bus frequency and making public transportation competitive with private vehicles (*Sustainable Community Development Group*, n.d.). By combining FRT and DRT, transportation agencies may be able to reduce overall system costs while increasing coverage in low-density areas. By proposing a strategy for integrating FRT to DRT and TNCs, this study hopes to give a methodology for reinforcing the existing FRT infrastructure in Morristown, Tennessee.

1.1 Objectives

The major research objectives of the project are:

1. To provide a comprehensive review of previous literature and studies available on connecting DRT with FRT;
2. To conduct case studies of connections between DRT and FRT in cities with similar geographic or transportation systems, with a focus on new and innovative partnerships such as those with TNCs;
3. To identify areas with low transit coverage and potential areas for a demand responsive connector (DRC);
4. To develop a sketch tool for connecting DRT with FRT either introducing a dedicated demand responsive service, collaborating with transportation networking companies to serve as DRT, or converting additional low frequency and low demand FRT services to a DRC;
5. To analyze the operational aspects associated with DRT-FRT coordination;
6. To develop an equity-based toolbox to identify the target population for DRT-FRT service; and
7. To develop an implementation plan for connecting DRT with FRT under various scenarios.

1.2 Organization of the report

The report is organized into a total of six chapters. The first chapter is the introduction which gives a general background of the study topic, the objectives of the study, and the organization of the report. The second chapter is the literature review wherein literature regarding FRT-DRT coordination, their merits, and economic feasibility, and case studies with the incorporation of TNCs to the public transit networks are discussed. The chapter also discusses the different coordination problems faced. The third chapter discusses the methodological framework for the study; it includes the methodology for data collection, analysis, and the generalized cost calculation of the multiple scenarios developed for the study. The fourth chapter gives background information about the study area and the network and routes used for the study and the various data collection. This chapter explains detailed steps of the data collection procedure for this study from different agencies and how it is consolidated into a workable format. It also discusses the demand data and how it is distributed within the different socioeconomic groups. The sixth chapter discusses the various results of the study, and they are then interpreted, including how the scenarios are beneficial according to different performance measures. The sixth chapter also gives the conclusions of the study and recommendations for future work and limitations of the study. The last section lists the references used in the study.

Chapter 2 Literature Review

DRT services come with reduced perceived travel time compared to conventional transit services and come with no overly substantial additional cost depending upon the demand (Navidi et al., 2018). The frequency of DRT services increases with decreases in population indicating its use for low-density areas and preferred for work-related trips (C. Wang et al., 2015). The previous literature and studies on DRT services are vast and the first trial of DRT services, also known as dial-a-ride services, dates back to 1970 in Mansfield, Ohio, the US which was followed by City of Oxford Motor services in Abingdon (United Kingdom) in 1972 (Ho et al., 2018). For the sake of brevity, the literature on DRT implementation is bypassed in this report and instead focus on the literature about the connection between FRT and DRT or other on demand services, such as TNCs.

2.1 Integration of FRT and DRT

Transit service that is flexible/hybrid in nature, which combines DRT and FRT to complete trips, dates back to 1984 when they were first proved better than FRT in areas with low trips densities (Daganzo, 1984). Most of the studies focus on comparing flexible services with FRT, DRT, and taxi services (Atasoy et al., 2015; Chen & Nie, 2017; Frei et al., 2017; Kim & Schonfeld, 2014; Kim & Schonfeld, 2015; Li & Quadrifoglio, 2010; Nourbakhsh & Ouyang, 2012; Feng et al., 2015; Zhang et al., 2018). Many studies are either based on optimization frameworks (minimizing cost & travel time or maximizing benefits) or statistical models to identify factors affecting the use of flexible transit services. In all these studies, flexible services generally proved better with higher user cost savings (Chen & Nie, 2017), especially for low-density population areas. The value of waiting time for flexible transit systems is typically less than the FRT because of the at-home pickup feature of flexible transit services (Frei et al., 2017). Flexible services are often used more than FRT by both young and older people (Broome et al., 2012). Flexible transit services can result in increased operator profit and passenger satisfaction, which highlights its potential in making public transit more competitive than private cars (Atasoy et al., 2015). Flexible transit services can provide more social welfare than park and ride and are befitting for cities with insufficient infrastructure to serve long trip passengers (Zhang et al., 2018).

Many prior studies considered timed transfers between DRT and FRT services (Bakker et al., 1988; Knoppers & Muller, 1995; Kyte et al., 1982; Muller & Furth, 2010; Ting & Schonfeld, 2005). Timed transfers can increase annual ridership (Kyte et al., 1982), applicable for low-density cities or suburban areas (Bakker et al., 1988), and decrease waiting time if one bus is held to wait for another (Muller & Furth, 2010). Past studies have shown that the coordinated transfers outperform uncoordinated transfers (Ting & Schonfeld, 2005).

Some of the studies focus on DRT or flexible transit services serving the role of paratransit services (Gupta et al., 2010; Neven et al., 2015; Rahimi et al., 2018; Ryley et al., 2014). Flexibility in fixed transit services will minimize the resources required to provide mobility for persons with disabilities (Neven et al., 2015). The use of non-dedicated services, such as taxis, can reduce costs and increase the efficiency of paratransit services (Gupta et al., 2010). Taxis can also help in reducing DRT operating costs (Rahimi et al., 2018). DRT services are used primarily for recreational and medical trips but face cost challenges (Ryley et al., 2014).

From the past literature considered here, it can be concluded that flexible transit services (connecting DRT and FRT) have the potential to provide efficient mobility services in low-density population areas, can reduce transfer waiting times, potentially save user and operating costs, act as paratransit service, and coordinate with taxi service to reduce the operating cost further in areas with very low transit demand.

The Flexibility in fixed transit services will minimize the resources required to provide mobility for persons with disabilities (Neven et al., 2015)

2.2 FRT-DRT Coordination problems

The majority of coordination between DRT and FRT fails due to complex scheduling conditions (Potts et al., 2010b). As per Potts et al., 2010b, "Problems with scheduling—can't make time points when demand for flexible trips is high or have too much extra time when demand for flexible is low." Nelson et al., 2010 reviewed the state of flexible transport systems in 2010 and proposed a solution: a Flexible Agency for Collective Mobility Services, which establishes an organizational structure and economic model for flexible transit services while also incorporating necessary supporting technologies. Mulley & Nelson, 2009 highlight the potential of flexible transit systems to revolutionize existing FRT services in increasing the public transport coverage to a wider population. Velaga, Nelson, et al., 2012 and Velaga, Rotstein, et al., 2012, provide an overview of such services in the context of rural areas while providing different challenges and opportunities.

Koffman, 2004 surveyed 24 different transit agencies in North America to explore the current status of flexible transit services among these agencies. According to the study, transit agencies operate flexible services to (1) cover spread-out, low-density areas cost effectively; (2) serve low-demand time periods; (3) balance customer access and routing effectiveness; (4) reduce or eliminate the cost of separate paratransit for people with disabilities; (5) lay the groundwork for future fixed-route transit; and (6) respond to community preferences and geography. However, established planning or design criteria were unavailable to assist transportation planners, and developing flexible services needs a willingness to experiment.

Higgins & Cherrington, 2005, studies the operational experience with flexible transit services in Texas and concluded that such service is more complicated than FRT and outperformed FRT in the total cost of transit in the area despite the high operational costs

Higgins & Cherrington, 2005, studied the operational experience with flexible transit services in Texas and concluded that such service is more complicated than FRT and outperformed FRT in the total cost of transit in the area despite the high operational costs. Later that year, Potts et al., 2010b surveyed 1100 transit agency managers to evaluate the current state of flexible transit services in the United States. Among the significant findings was the dominance of route deviation, which is primarily used by senior citizens and physically disabled individuals. The study found that rural areas have a lower reliance on technology (radio-dominated), for coordination with other services, require advance bookings, and require no driving training. The authors then considered 10 different transit agencies to identify the best practices for flexible transit service. Goodwill & Staes, 2013 provided an overview of flexible transit agencies in Florida after including six transit studies. Such services expanded the transit coverage to low-density areas and complemented existing FRT services.

2.3 How can FRT be well supported by TNC?

The emergence of TNCs like Uber and Lyft has spawned a range of disputes about their impact on urban mobility. These include whether TNCs contribute to congestion, vehicular miles traveled (VMT), or greenhouse gas emissions (Greenblatt & Shaheen, n.d.) whether they directly compete with taxi services (Contreras & Paz, 2018), and whether they provide additional mobility options primarily for younger, higher-income commuters (Rayle et al., 2016: Rodier, 2018). Many studies have examined TNCs' impact on public transportation (Hall et al., 2018: Yan et al., 2019), with results varying. On one hand, TNCs help public transport users reach stops that are not within walking distance or to locations that are not served by public transit. TNCs may also allow riders to take Uber or Lyft to transit stations, especially those with park-and-ride lots. TNCs' quantitative and qualitative consequences have been studied, but their spatial variance has not. Statistics have identified wide TNC effects across several urban areas, without completely accounting for spatial variance or interconnectivity. While surveys and interviews can provide information on user preferences and travel patterns, they cannot show how TNC effects or user characteristics vary across neighborhoods. Examining how different spaces within a city interact with TNCs and public transit network may provide context beyond the substitute/complement debate. Rather than focusing on whether TNCs complement or replace public transit, existing TNC research can benefit from focusing on potential links.

The existing literature on the successful coordination of TNCs with FRT like the Schwieterman et al., 2018 and from the website of the *American Public Transportation Association*, n.d. (APTA) about the transit and TNC partnership, show that the majority of coordination occurs as a result of either insufficient transport service or insufficient parking. The main objective of such coordination is to:

- Fill gaps in the transit system while encouraging the public to use transit and improving transit services.
- Develop smartphone apps for using multiple modes for a single trip.
- Parking space management (mitigate or forestall).
- Provide mobility for disabled and other transportation disadvantaged populations.

The studies focus on improving or complimenting existing public transit services. Such studies majorly fall under two principal categories i.e., financial incentives to use TNC or public transit and integration FRTs in TNCs' smartphone apps.

Financial incentives: The case studies include financial incentives by either providing transit user subsidized TNC fares during off-peak hours (night times) or within city limits also include TNCs replacing existing DRT/FRT services and TNCs providing first and last-mile connectivity to and from FRT bus stops. Some examples of the case studies are provided below.

Table 2-1 Transit and TNC Partnership (source: *Transit and TNC Partnerships - American Public Transportation Association*, n.d.)

Service Type	Example
Subsidized TNC fare during off-peak hours	Pinellas County (FL), Miami-Dade Transit, Pace (Chicago, IL), Detroit (MI)
Subsidized TNC fare within city limits, TNC replacing FRT/DRT	Monrovia (CA), Innisfil (ON), Multiple communities in FL, Dayton (OH), Marin County (CA), San Clemente (CA), Philadelphia (PA)
First and last-mile connectivity	Flex-Connect (DART, IA), MetroLink (MO), CapMetro (TX), Dublin (CA), Charlotte (NC), Centennial (CO), Tacoma (WA)

2.4 Cost Models- Coordinated FRT-DRT Systems

The following are some recent studies that led to the development of cost models for FRT-DRT integration: Sipetas & Gonzales, 2021 simulated a hybrid transit system to model and optimize stop spacing on a fixed route corridor, as well as the flexible region borders inside a corridor. The model employed continuous approximation techniques to determine the fixed-route system's running cost. The proposed optimized hybrid system provides anticipated user benefits of up to 35% when compared to fixed-route systems. While Mehran et al., 2020, for fixed route bus service and semi-flexible transit, developed appropriate cost models based on basic assumptions and are created to represent operating costs as a function of yearly ridership. Turmo et al., 2018 developed an algorithm for efficiently allocating paratransit demand for Americans with Disabilities Act eligible passengers between regular paratransit services and taxis. The gain stems from optimizing the subsidy threshold for taxi fares in order to account for time-varying demand.

2.5 Research Gap

Despite substantial research on DRT and FRT operations independently in public transportation studies, there is limited research on their combined operation. Furthermore, only a few studies have looked into the possibility of including TNCs in such a system. As a result, more in-depth research about the actual joint planning between FRT, DRT, and TNC should be done, considering their potential interactions. Few studies have allowed customers to select flexible first/last mile services between their origin and destination, which is something that should be emphasized. This study develops and implements a feasible integration strategy for FRT, DRT, and TNC systems, as well as a decision support system that allows all stakeholders to accurately assess the costs and benefits of the mobility paradigm.

Chapter 3 Methodology

3.1 Project Overview

The entire study is divided into different tasks (Figure 3-1). It includes the collection of passenger data, creating a sketch planning a tool for connecting FRT with DRT and TNC, and determining the operational and economical aspects of coordination.

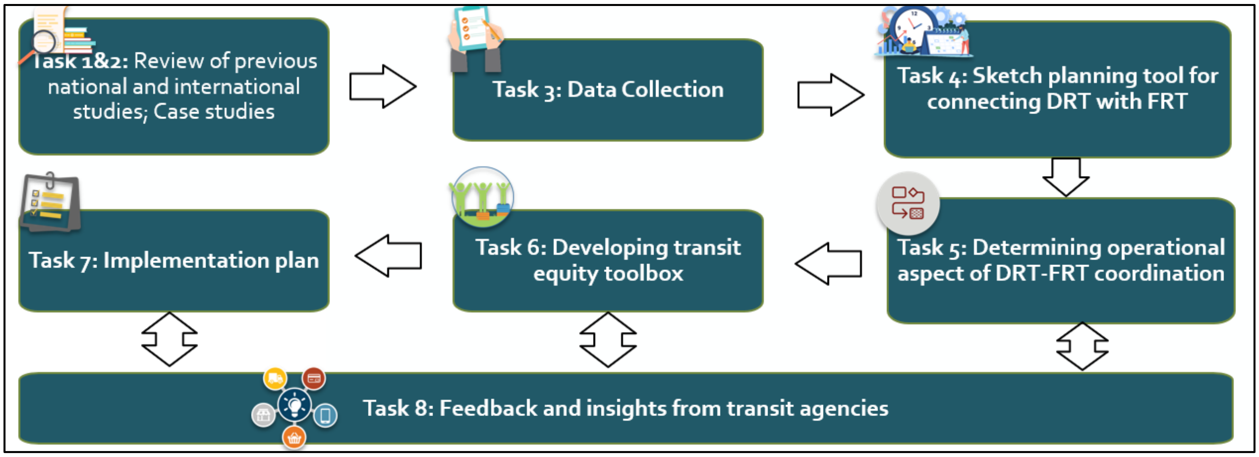

Figure 3-1 Schematic Representation of Project Tasks

The framework of the methodology for the study is shown in Figure 3-2. The demand data is collected from the transit agency and cost and travel matrices are created for every origin-destination pair, route assignment for each trip, and the study is done for multiple scenarios.

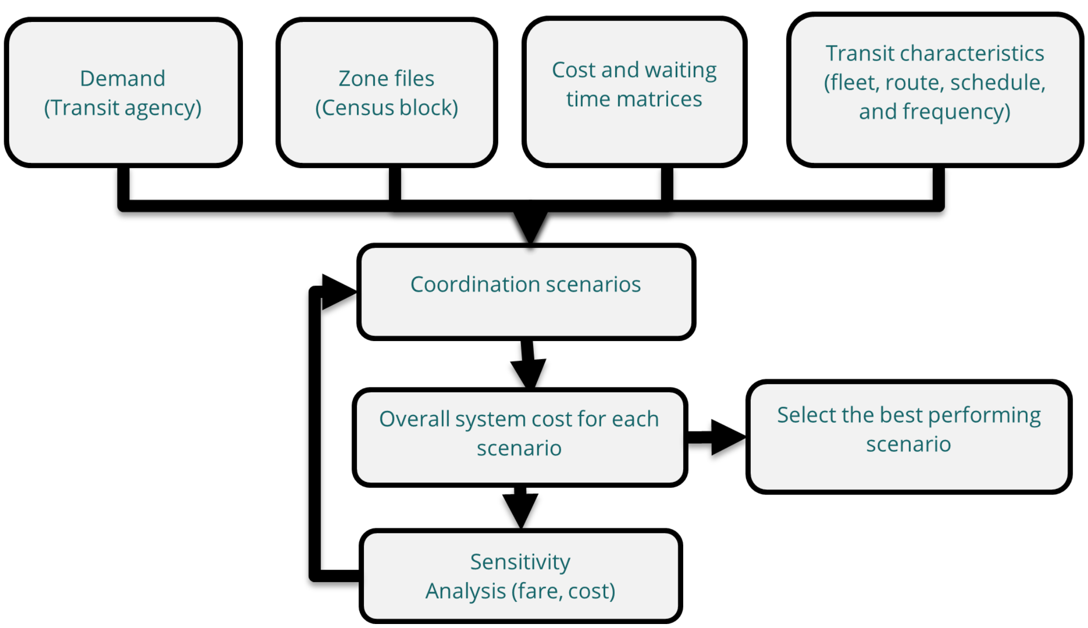

Figure 3-2 Methodology

3.2 Coordination Scenarios

For developing a sketch planning tool for connecting DRT with FRT and determining the operational aspects of DRT-FRT coordination, different scenarios are developed integrating DRT, TNC, and FRT in the local network. The simulation of creating different scenarios is done using agent-based simulations. Agents are assigned with certain personal attributes in the model, to be able to model realistic behaviors of the heterogeneous population. The total system, user, and agency costs are estimated in such a way that they account for variations in surge pricing and travel speeds at various times of the day to more accurately reflect real-world traffic. Each scenario is analyzed for every possible origin-destination (O-D) pair and the different operational and economical aspects are compared to find the best-performing alternative.

The total system, user, and agency costs are estimated in such a way that they account for variations in surge pricing and travel speeds at various times of the day to more accurately reflect real-world traffic.

3.2.1 Vehicle Modes

The modes considered are the conventional FRT buses, vehicles for DRT, and vehicles by TNCs. All the vehicles are assumed to have freedom in the model to expand the service configuration area. Model inputs include their carrying capacity, running speed, and route selection techniques. The model assumes a homogeneous fleet, with vehicles having the same inputs (capacity, speed, route choice, etc.). The FRT vehicles use fixed predefined routes, and DRT vehicles in this study are being modeled as a fleet of vehicles operated by a central dispatching unit that assigns travel requests to vehicles that offer door-to-door services to passengers. All modes are defined by their characteristic speed and are supposed to travel at that constant speed throughout the trip.

3.2.2 Road Network

The network data comprises the road network and the public transit network represented by a set of nodes and connecting links. The modes considered in the study share the local road network with the ordinary traffic and the FRT uses only a dedicated routing network with defined stops which is a subset of the local network for their traverse. The model does not take into account the number of vehicles on the road or delays behind another stopped vehicle. Each of these origin and destination points is then connected to the nearest node in the local network and the trip starts from there and ends at the last node nearest to the destination point. The local network and the FRT routes and stops are created as graphs in the model.

3.2.3 Stops and Schedule and Fares

The FRT system is the conventional transport system following fixed itineraries, FRT stops, and schedules obtained from ETHRA (the agency that services the study area), while the DRT system in the study resembles a conventional taxi service, thus the DRTs and TNCs are with unspecified itineraries and unspecified stops and are flexible to the demand of users. The fare structure was obtained from the agencies and literature.

3.2.4 Scenarios

Different integration possibilities for dynamic response services with regional public transit networks with varying degrees of connectivity and service levels are offered. It is vital to connect specific services to the entire transit system in order to provide the highest level of service possible to riders throughout their transit journey. Integrated public transit scenarios are those in which a user travels from one location to another using one or more public transportation modes. Thus, it may include FRT, DRT, or service provided by TNCs, either independently or in combination with other modes of transport. There are numerous scenarios, each of which is classified below, depending on the sort of service utilized throughout the trip. Each scenario is assessed for each possible O-D pair and the many operational and economic factors are compared to determine the preferred solution. The schematic depiction of the scenarios considered is shown in Figure 3-3.

Scenario 1: TNC-TNC: The agent takes a TNC from the node that is nearest to its origin and completes the trip to the destination using the same service without considering the FRT stops. The path chosen in this scenario is the path that produces the least generalized cost for the user.

Scenario 2: TNC-FRT: TNC integrated with FRT where the rider takes a TNC from origin to the nearest FRT stop and takes FRT until the destination is reached. If FRT is not available up to the destination, then the rider gets off at the FRT stop nearest to the destination and continues the journey in TNC to the destination.

Scenario 3: DRT-TNC: DRT coordinated with TNC, where it is assumed that the rider will take DRT to the next FRT stop and then a TNC to their destination, as FRT may not be accessible at that time.

Base Scenario: DRT-DRT: The agent takes a DRT from the nearest node and completes the trip to the destination utilizing the same service, disregarding the FRT stops. In these cases, the path chosen is the one that results in the lowest generalized cost for the user. The data used for the study is DRT ticket data and it is taken as the base case scenario.

Scenario-4: DRT-FRT: The coordinated scenarios of DRT with FRT, where the rider uses DRT services to reach the nearby FRT stop and completes the trip in an FRT or reaches the nearby FRT stop to the destination and continues using DRT services to reach the destination.

Scenario-5: DRT-FRT-TNC: Combinations of combining FRT, DRT, and TNC to complete a single journey, with DRT being used in the initial leg of the trip. The user boards a DRT from the nearest node and travels to the nearest FRT stop, where he or she then takes the FRT to the stop closest to the destination and completes the final leg with a TNC.

Scenario-6: TNC-FRT-DRT: Combinations of combining FRT, DRT, and TNC to complete a single trip, with TNC being utilized in the opening leg of the trip. The user boards a TNC at the nearest node and travels to the nearest FRT stop, where he or she then takes the FRT to the stop closest to the destination and completes the final leg with a DRT.

Apart from these scenarios, two additional scenarios are also analyzed:

Scenario-7: FRT-FRT: This scenario is only possible if the nearest nodes to the origin and destination are FRT stops, and the trip is completed solely by FRT.

Scenario-8: Hypothetical FRT: Scenario in which it is assumed that fixed route services are available over the entire local network.

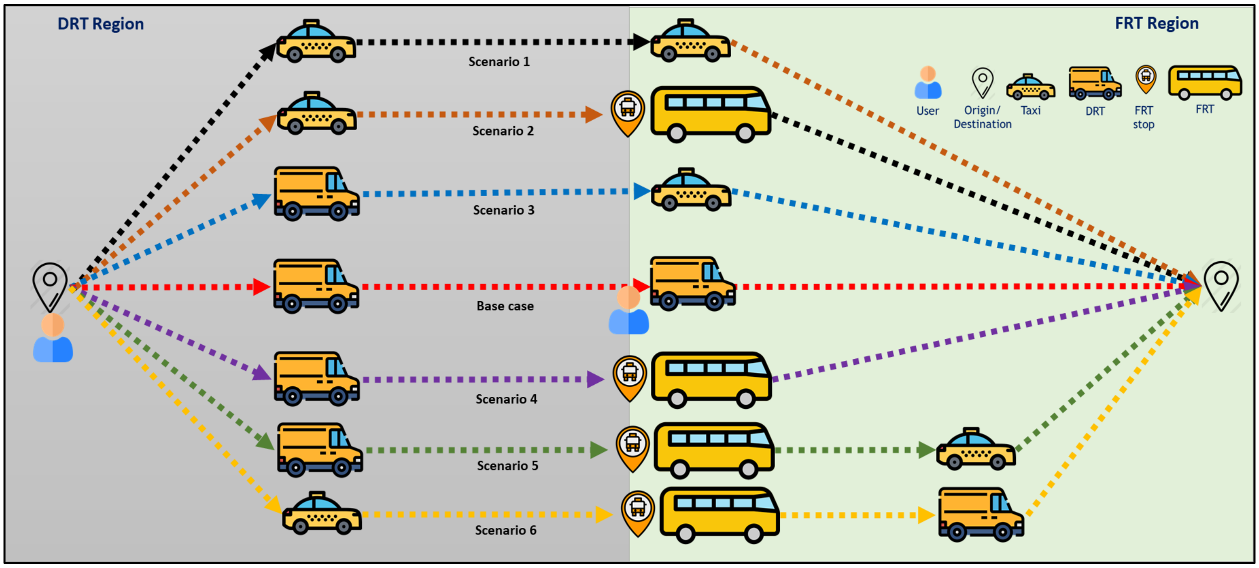

Figure 3-3 Schematic Representation of Scenarios

3.3 System Cost

The cost components are calculated for both the user and agency in every scenario and the best performing scenario based on the total cost of coordination is selected.

3.3.1 Value of Travel Time

The value of travel time (VOT) is a sort of implicit opportunity cost in which a traveler is ready to pay a certain amount of money in exchange for saving time (Kockelman Donna Chen Katie Larsen Brice Nichols et al., 2013). Because some travelers are ready to pay more than others to reduce travel time, the difference in VOT and value of reliability (VOR, detailed below) across a group of travelers can have a considerable impact on project evaluations. The concept of the value of travel time was first introduced in the 1960s after the development of the time allocation model (i.e., the consumer allocates his/her time and cost to several activities by maximizing the utility under time and budget constraints) (National Research Council (U.S.). Transportation Research Board. et al., 1976).

VOT estimates for individual travelers vary greatly based on where and how data is obtained, as well as the methods used to analyze the data. Because VOT estimations are based on willingness-to-pay considerations, better-income people tend to have higher VOTs than those with lower incomes. In this study, the average income of each census zone is used to determine the VOT of trips that are originated from the zone. Table 3 shows the VOT for different income levels taken in the study.

Table 3-1 Value of Time by Income Levels (source: (Ye, 2010))

Income level	Household Annual Income	VOT (c/min)	VOT ($/hr)	VOT ($/year)
Lower	0-20k	8.4	$5.04	$10,483
Lower-middle	20k-40k	25	$15	$31,200
Middle	40k-60k	41.7	$25.02	$52,042
Upper-middle	60k-100k	50.4	$30.24	$62,899
Higher	100k+	106.4	$63.84	$132,787

3.3.2 Generalized Cost of Travel

In transport economics, the generalized cost is the sum of the monetary and non-monetary costs of a journey. In transportation economics, the term "generalized cost" refers to the sum of a journey's monetary and non-monetary costs (Bruzelius, 1981; Cesario, 1976). The monetary costs include the fare for public transportation, the cost of fuel, wear and tear, and any parking, toll, or congestion charge associated with car travel. Non-monetary costs include the time spent undertaking the journey. Time is converted to a money value using a value of time figure, which usually varies according to the traveler's socio-economic conditions.

3.3.2.1 Generalized User Cost

The user cost is calculated in terms of time and monetary benefits. In-vehicle (travel time) and out of the vehicle (waiting times: boarding, alighting, and transfers, walking times: egress/ingress) are considered and a value of this travel time is assigned as their cost concerning their income along with the trip fare and transfer cost.

3.3.2.2 Agency Cost

Agency cost considers the operating and maintenance costs which include the cost of fleet, distance/time-based costs, the labor cost including driver, maintenance staff, and the per day procurement cost of the fleet used.

3.3.2.3 System Cost

The total system cost is the sum of User Cost and Agency Cost (Equation-1). It takes into account the variations in how users perceive each scenario in terms of their generalized cost and how much the agency has to invest in each scenario. Because it incorporates both factors, this measure can be used for the further evaluation of the performance of the Integrated system in the study.

Equation 1

$$f(c)_{total,\ i} = f(c)_{user,\ i} + f(c)_{agency,\ i}$$

$$f(c)_{user,\ i} = user\ cost\ function\ for\ scenario\ i$$

$$f(c)_{user,\ i} = transit\ agency\ \ cost\ function\ for\ scenario\ i$$

Chapter 4 Data Collection

4.1 Study area

The study area is the city of Morristown, Hamblen County. Figure 4-1 shows the Morristown area and its neighboring zip codes and its local road network. Morristown has existing DRT services and an FRT network with three different routes. In this study, data from three different sources are utilized:

Study Area: Morristown City has existing DRT services and an FRT network with three different routes

i. General Transit Feed Specification (GTFS) data for transit network characteristics,
ii. Existing DRT service areas and trip characteristics
iii. Tennessee socio-economic data and roadway network

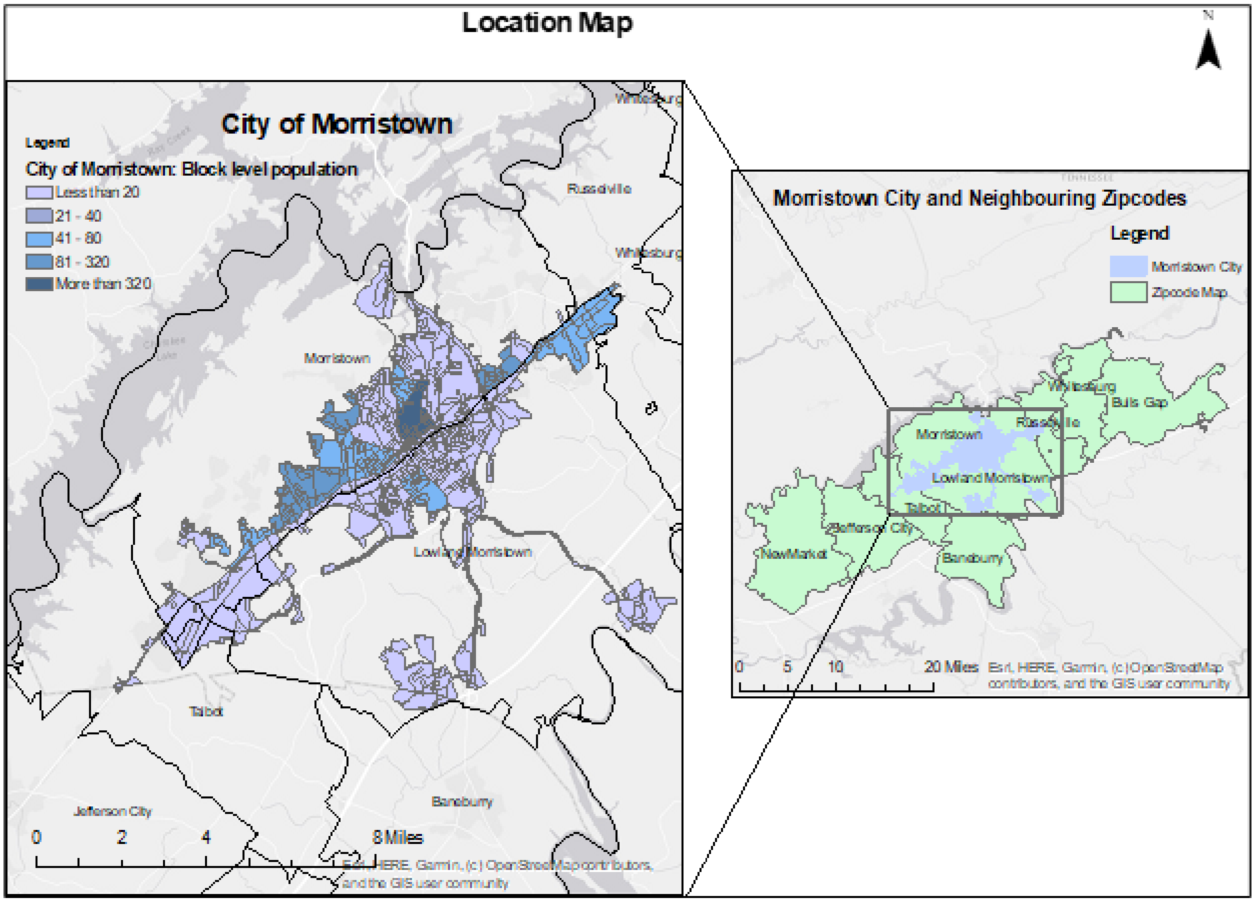

Figure 4-1 Study area of Morristown and neighboring zip codes

4.2 GTFS data

GTFS is a standardized transit dataset that includes transit characteristics (route, stops, etc.) and integrates these characteristics with public transit schedules. These datasets are used to generate shapefiles representing routes, which can be color-coded to reflect their importance in terms of transit demand. The city has recently launched FRT services with three different routes and 29 stops (as of the date of data collection) and has an already existing DRT service. Figure 4-2 shows the three different FRT routes with the stops.

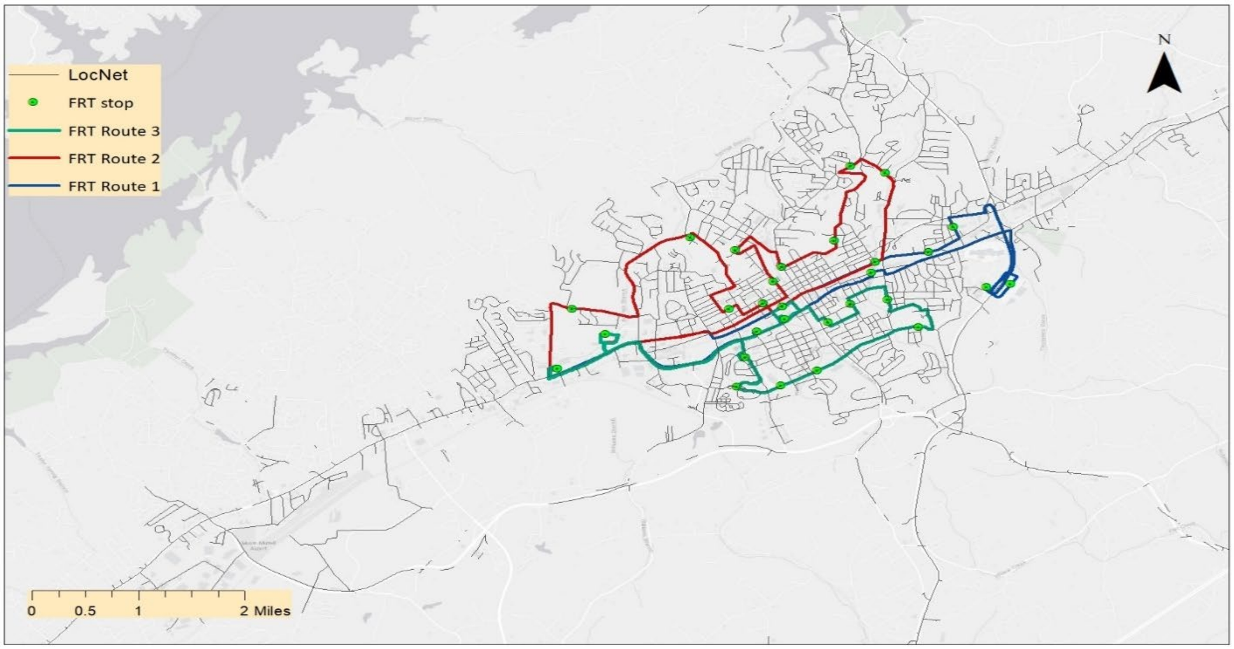

Figure 4-2 FRT Network

Route 1 runs with a 30-minute headway from 7 a.m. to 5.30 p.m., and it makes eight stops within the transit station while Routes 2 and 3 have a one-hour headway between the hours of 7 a.m. and 5 p.m. and have 12 and 13 stops, respectively (as on the date of data collection).

4.3 DRT Service Areas and Trip Characteristics

The DRT trip characteristics obtained from the ticket data give the origins and destinations of the rural area travelers and the timing of trips. The DRT trips are mapped along with GTFS to visualize the entire transit network including FRT and DRT in Morristown. The overall map will provide information about the locations where DRT and FRT services can be connected, and network spatial analysis and clustering to discover possible connectivity between DRT and FRT services. The DRT data was collected from 2019 July to 2020 June and trip distribution is shown in Figure 4-3. It's worth noting that part of the data dates from before the COVID-19 epidemic began, while others date from after. This is clear in Figure 4-3, which depicts 2020 numbers. Figure 4-4 shows the overall consolidated DRT data with the census zones and origin-destination points from DRT ticket information, the local network, and the FRT network with stops.

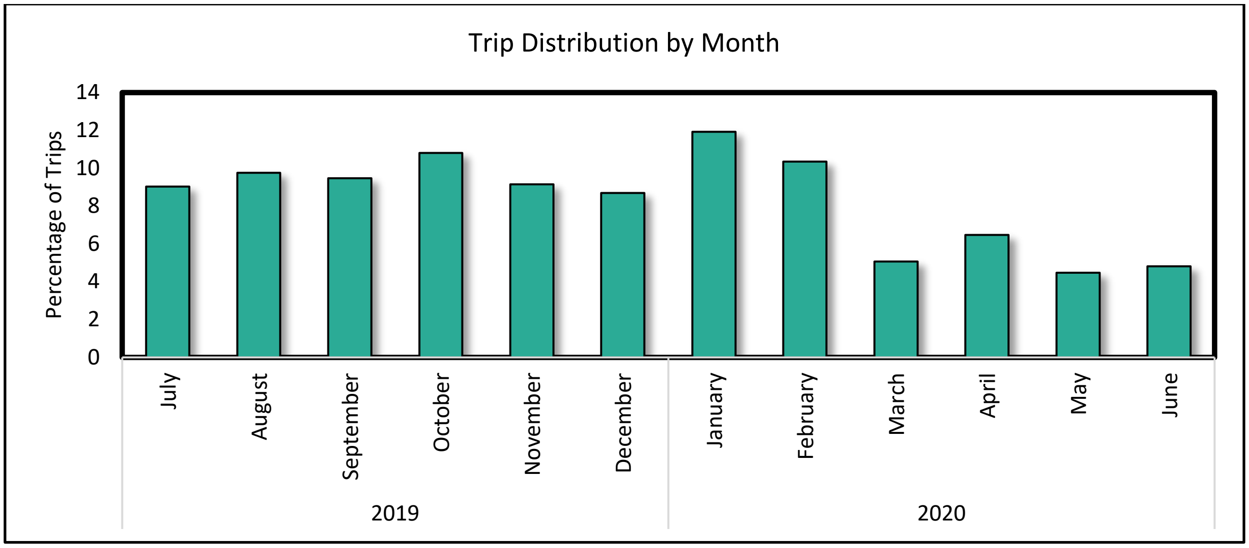

Figure 4-3 DRT Ticket data timeline

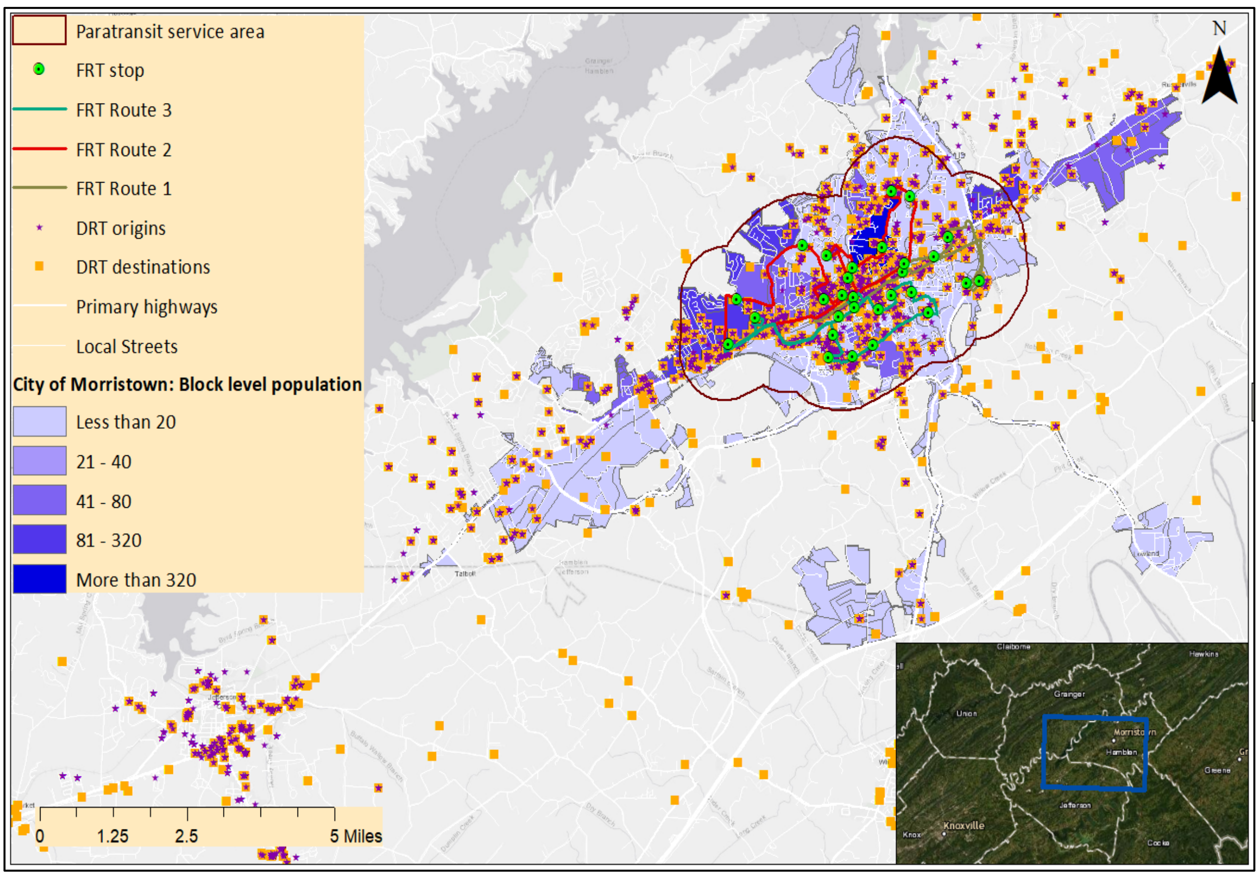

Figure 4-4 City of Morristown: DRT data

4.4 Socio-economic data

The US Census Bureau's socio-economic data was used, which includes information on age, gender, income, race, ethnicity, and other factors. Together with GTFS data, this information was used to construct a shapefile that portrayed areas with low public transportation coverage. US Census block-level data (2010) was collected and data on FRT characteristics like fare, schedule, routes, and fleet and similarly DRT characteristics of fare, schedule, routes, and fleet were collected from ETHRA (East Tennessee Human Resource Agency). The information acquired includes one-year travel data, which includes the origin, destination, age, gender, the purpose of the trip, the time of the trip, and the day of the week. Figure 4-5 depicts the distribution of journeys across different age groups and genders. It can be observed that the bulk of trips are taken by those over the age of 55, accounting for 63.3 percent of the total population that use the service. People between the ages of 35 and 54 account for 28.6 percent of all users, while people under the age of 25 accounts for only 8 percent. In terms of gender, males make up 55.6 percent of the user population, while females make up 44.4 percent.

the bulk of trips are taken by those over the age of 55, accounting for 63.3 percent of the total population that use the service

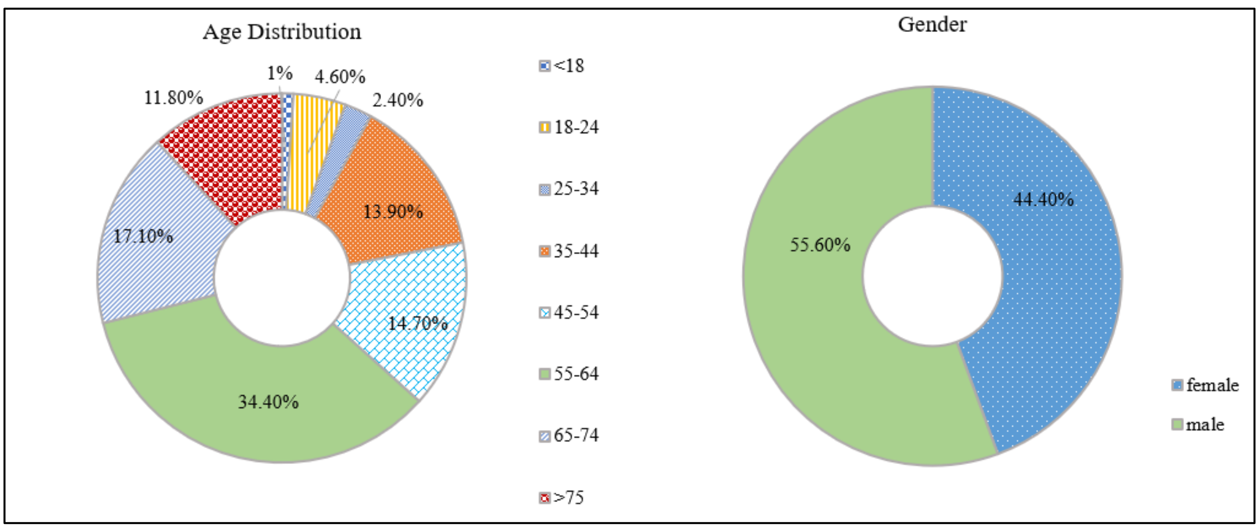

Figure 4-5 Demand data distribution for gender and age

The allocation of trips according to their purpose is depicted in Figure 4-6. The vast majority of trips are made for medical or employment reasons, with “Medical” reasons accounting for 46% of users and “Employment” accounting for 41% of users. Other than "Medical" and "Employment," the trip purposes listed include "Education," "Shopping," "Bank," "Pharmacy," "Church," "Recreation," and "Others," with each of them having the following shares: 2.9 percent, 1.9 percent, 0.48 percent,0.33 percent, 0.12 percent, 0.086 percent, and 6.8 percent, respectively, with recreation having the lowest share of users.

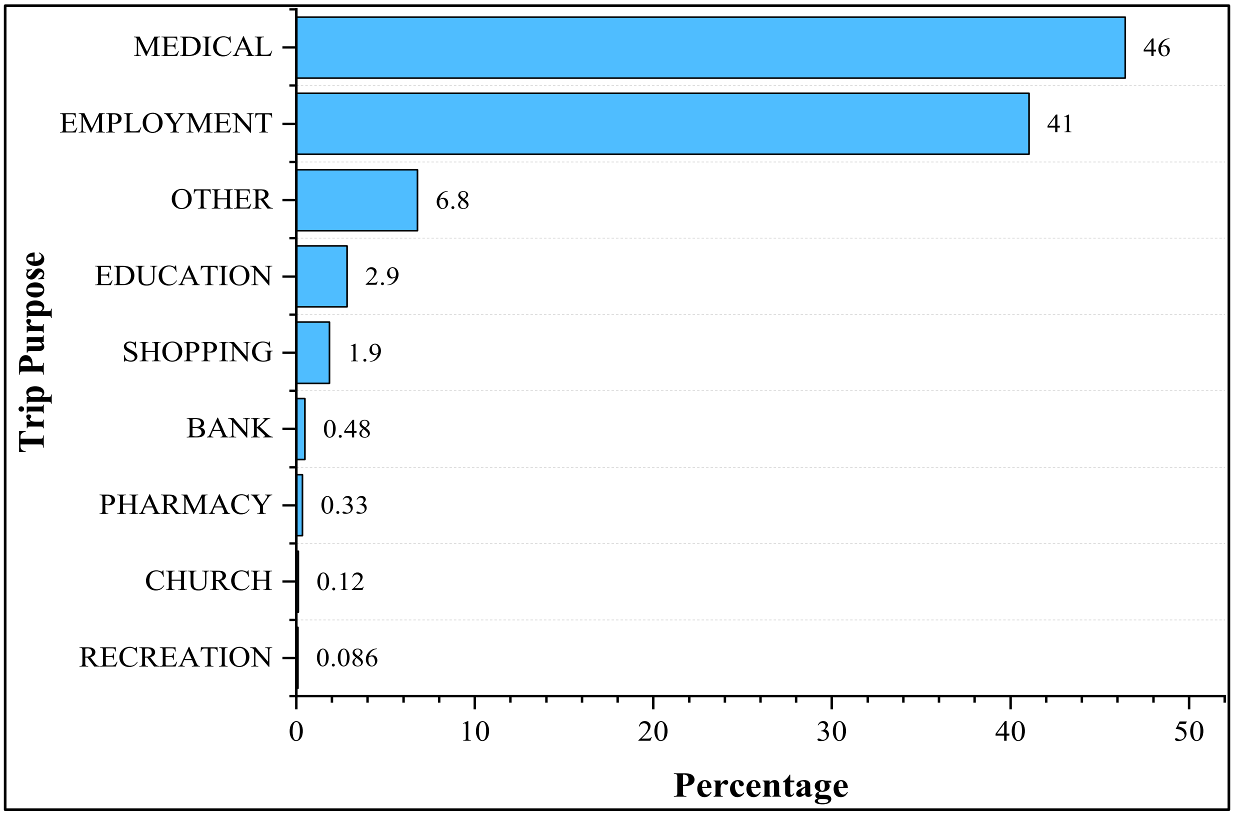

Figure 4-6 Demand data distribution: Trip purpose

4.4.1 Temporal Distribution of Trips

According to ticket data collected, the majority of journeys occurred during the week, with fewer trips occurring on weekends. Demand for DRT rides remained fairly consistent during the weekdays (Figure 4-7). Since the objective of a journey may vary from day to day, day-specific scheduling is required for FRT-DRT integration.

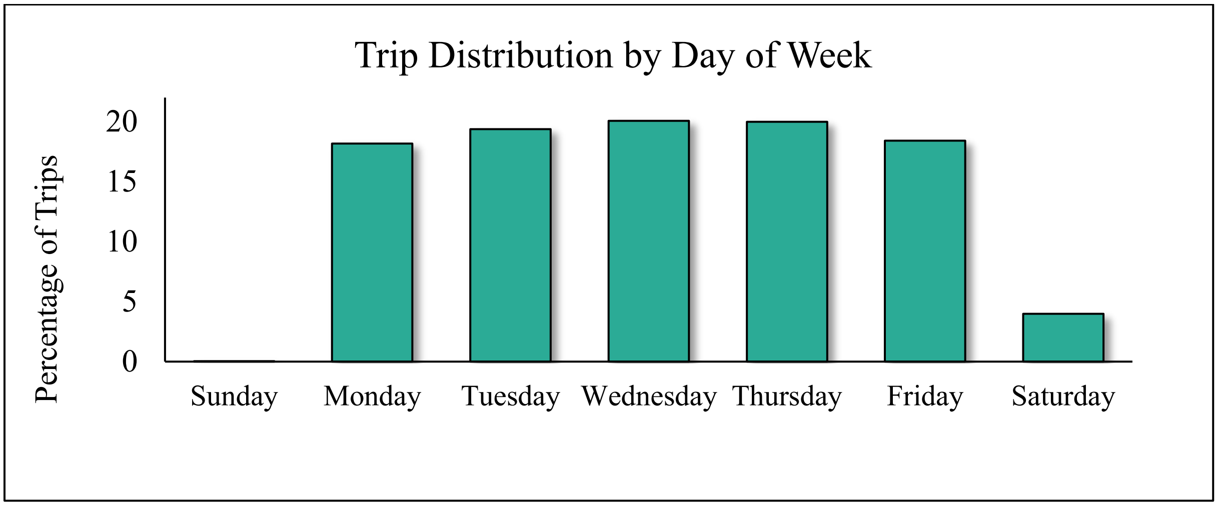

Figure 4-7 Trip Distribution by Day of Week

The distribution of trips by the time of day (Figure 4-8) reveals visible morning and evening peaks, with the biggest demand occurring in the evening. The morning high occurs between 6 AM-8 AM, and the evening peak is between 3 PM-5 PM. Peak periods may see a spike in TNC fare costs as a result of surge pricing, and total travel times for all modes tend to increase during this period due to decreased speed induced by high demand and heavy traffic.

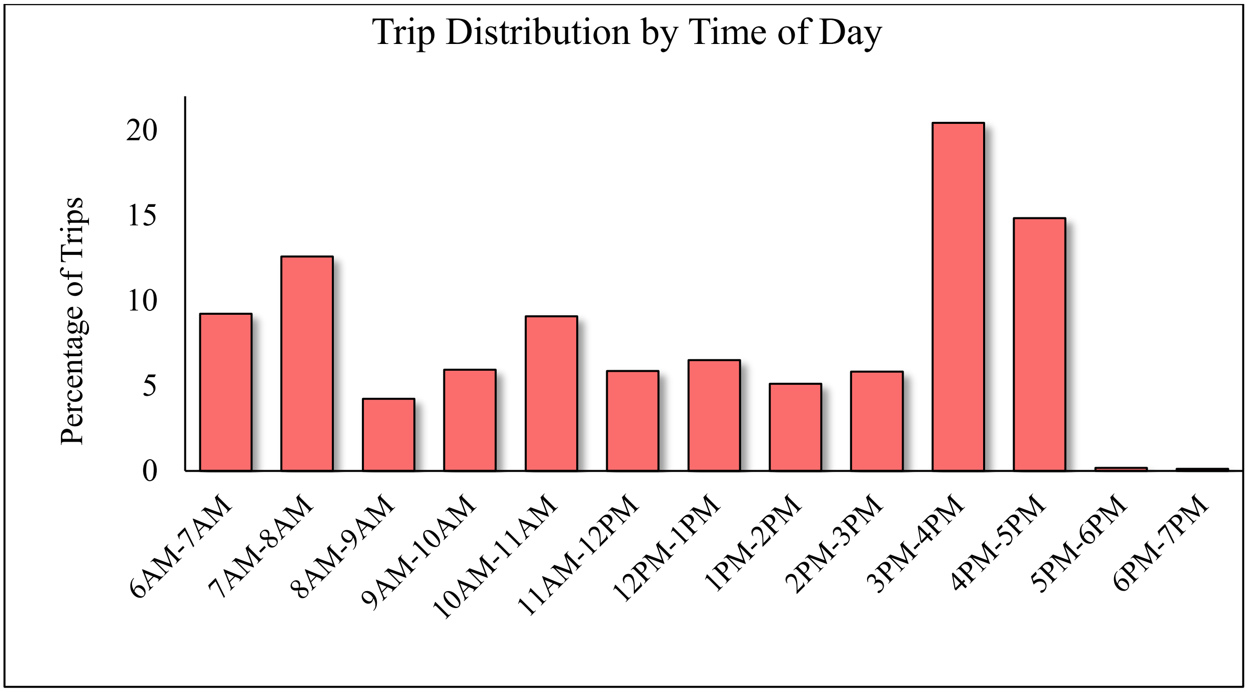

Figure 4-8 Trip Distribution by Time of Day

4.5 Demand Data

The origin and destination points collected from DRT ticket data are filtered to include only those that are located within the Morristown census zone and its bordering zip codes. The study area is made up of nine zip codes. Figure 4-9 displays the Origin-Destination demand for each zip code using a chord diagram. As can be seen, zip code 37814 (Morristown) has the highest number of origins and destinations, followed by Lowland Morristown (zipcode-38813). The overall demand data employed in the investigation yielded 381 distinct O-D combinations with varied demand, totaling 27906 trips. The zip codes included in the study are 37814 (Morristown), 37813 (Lowland-Morristown), 37760 (Jefferson City), 37860 (Russellville), 37877 (Talbot), 37891 (Whitesburg), 37711 (Bulls Gap), 37820 (New Market), 37890 (Baneberry).

The overall demand data employed in the investigation yielded 381 distinct O-D combinations with varied demand, totaling 27906 trips

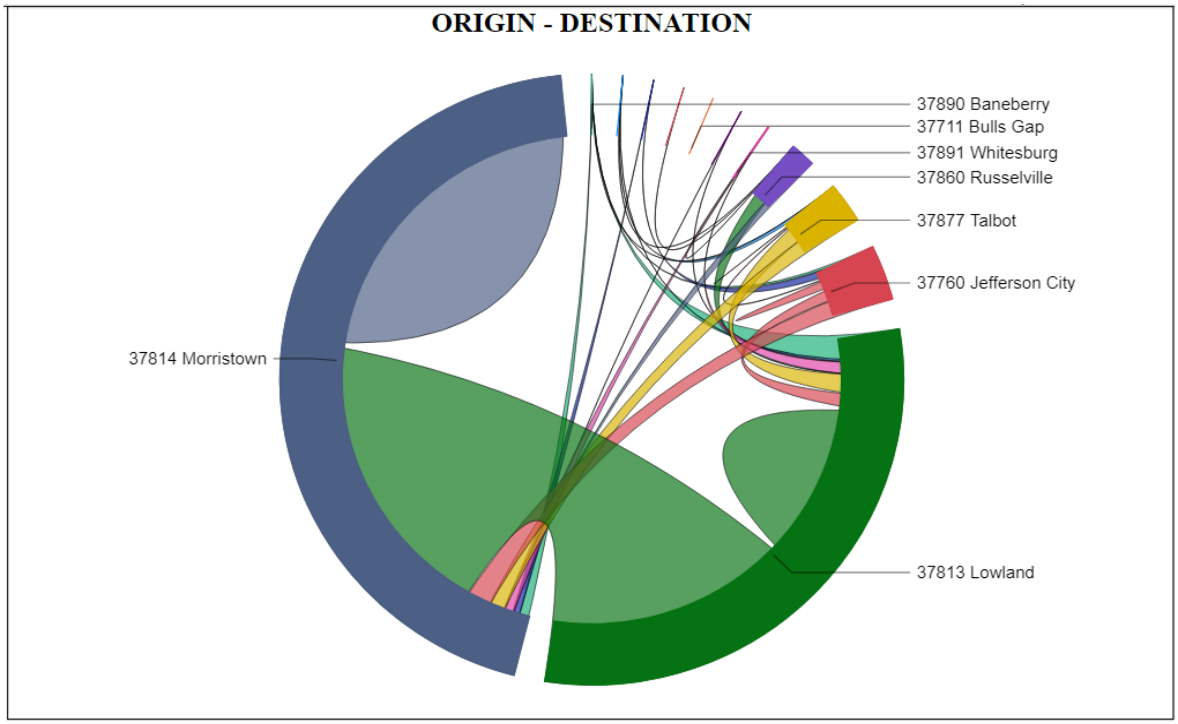

Figure 4-9 Origin – Destination Chord Diagram

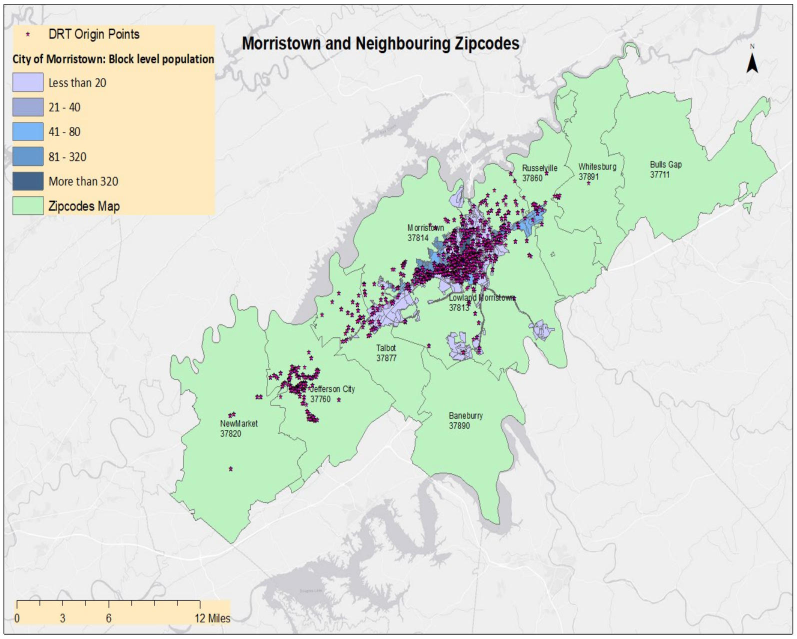

Figure 4-10 Origin Points

Figures 4-10 and 4-11 illustrate the geographic representation of the origin and destination points derived from the demand data respectively. Morristown serves as the beginning point for a large number of trips and remains a highly desirable destination. While trips to and from other zip codes are few, the lack of a permanent transit network to these locations necessitates the development of an additional public transit facility for the mobility of those in need. To ensure an egalitarian public transit system, proper integration scenarios should be supplied to every origin to destination, independent of their geographical location to maintain an equitable public transportation system.

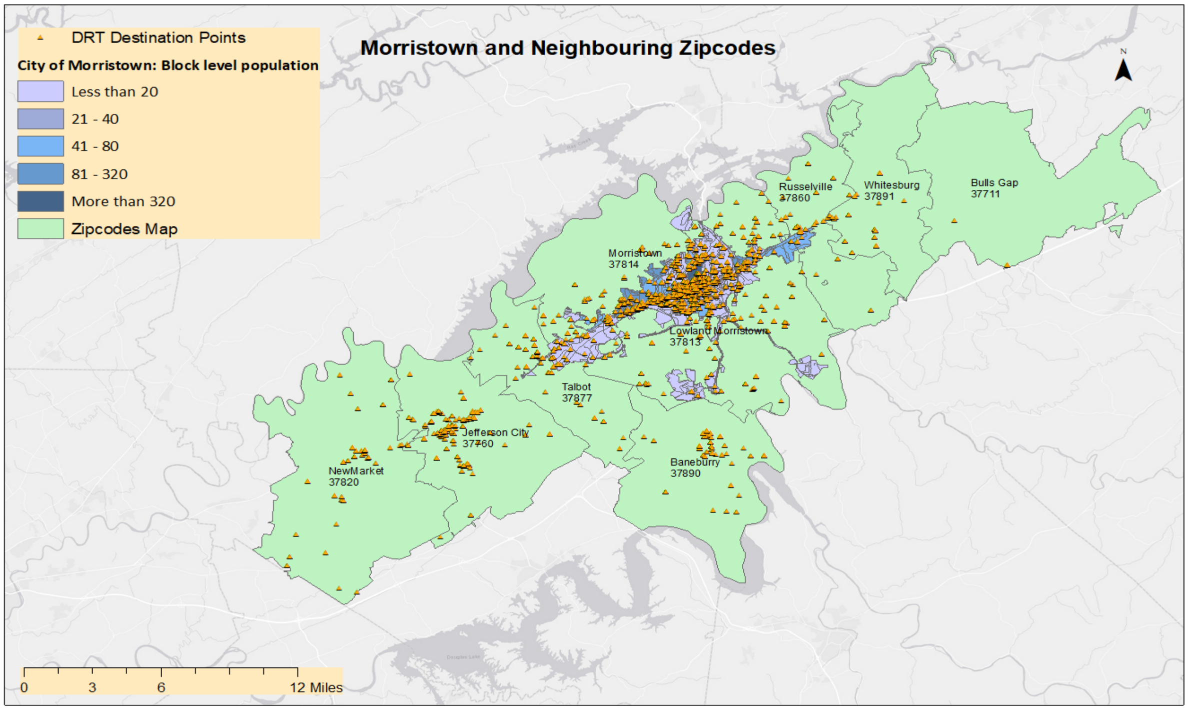

Figure 4-11 Destination Points

The origin and destination pairings with the highest demand are displayed in Figure 4-12, and it is seen that the largest demand is from W Charles St, a major educational area with numerous schools to Durham Landing Blvd. The second largest number of trips were from Union Ave (schools, churches, and residences) to E Morris Boulevard (major shopping and recreation area) with 2022 trips per analyzed year.

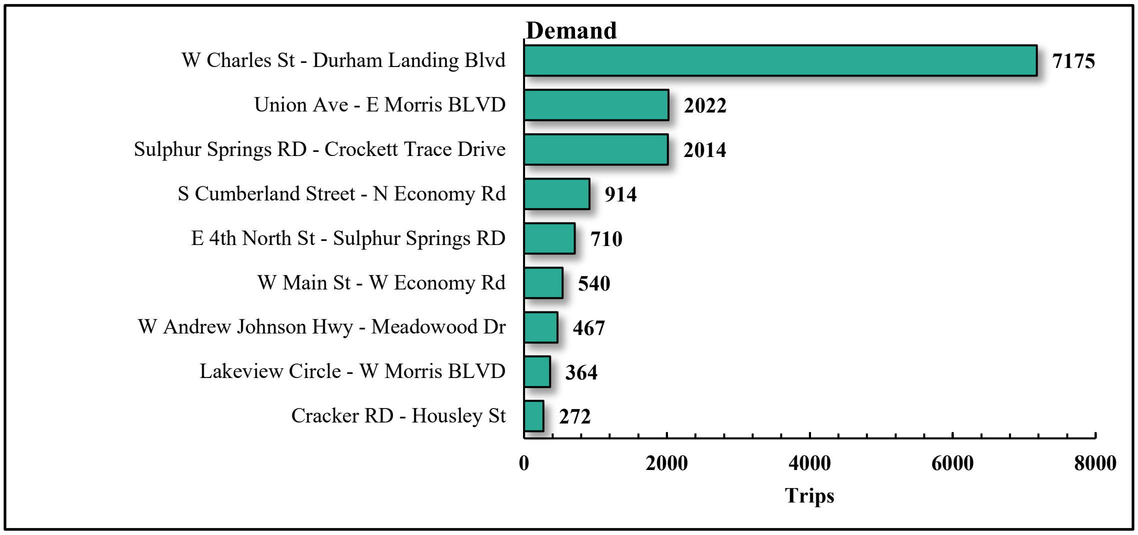

Figure 4-12 Most Frequent trips

The desire lines of the O-D pairs with more than 200 trips are depicted in Figure 4-13. In transportation, desire lines are straight lines that reflect 'origin-destination' data, which indicates the number of people that move (or could travel) between locations (points or zones) in the geographical area (*Chapter 12 Transportation | Geocomputation with R*, n.d.). The greater the line's thickness, the greater the demand between its connecting points.

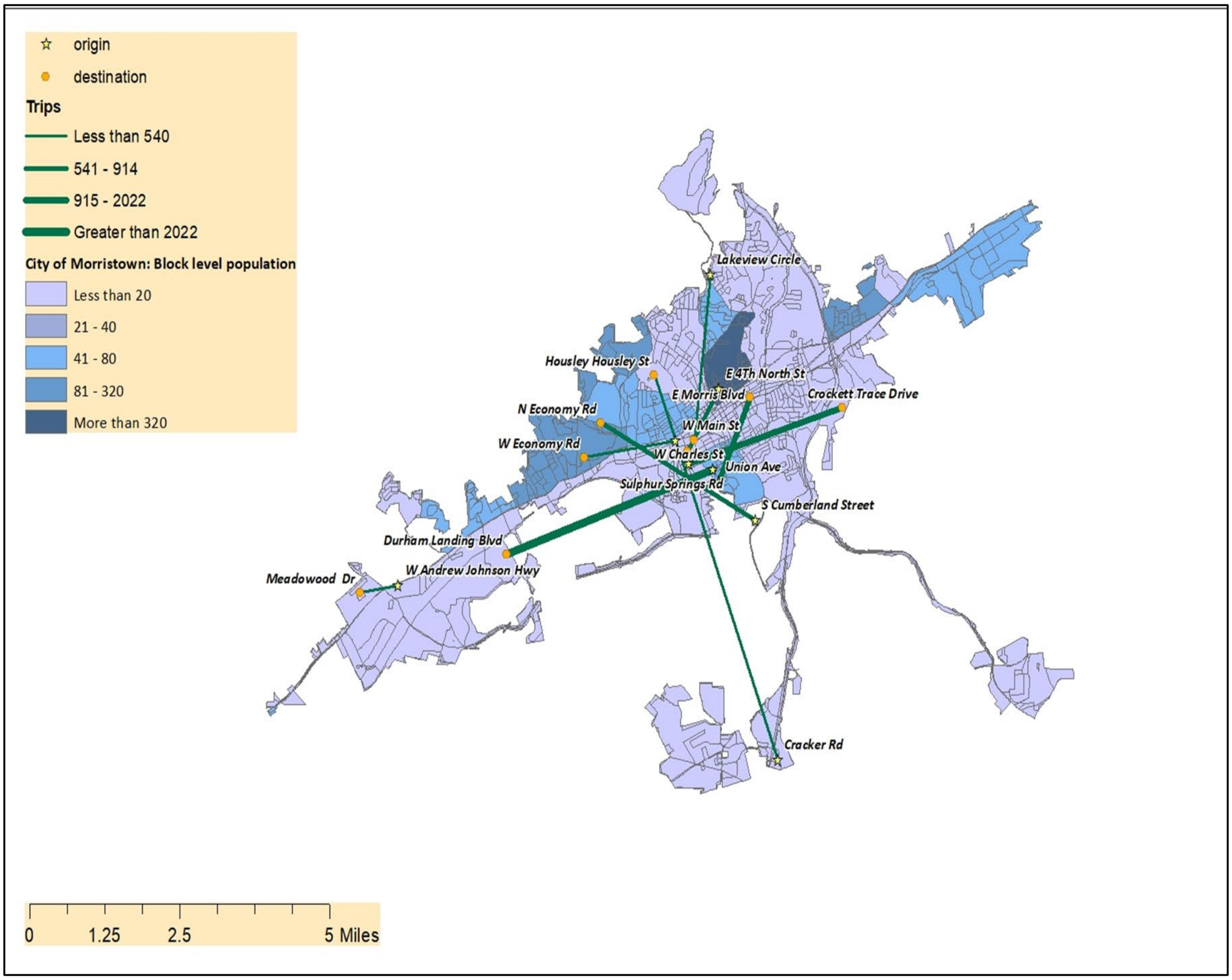

Figure 4-13 Frequent trips, O-D pairs with more than 200 trips

Chapter 5 Results and Discussion

The complete routable local road network of the area under study, Morristown, and its neighboring zip codes are used to create the graphs for the model. The generalized user cost and agency cost were calculated using US Census block-level data (2010), data on FRT and DRT features of fare, schedule, routes, and fleet acquired from ETHRA, and data from previous work. While it is expected that agencies do not have to operate TNCs directly, certain costs should be borne by those companies, as TNC rates are subsidized relative to their normal charges when integrated.

5.1 Possible Integration Scenarios

Using the origin and destination information extracted from DRT ticket data, a total of 27,906 journeys were filtered and included in the studies. The proposed scenarios are created for each O-D pair in the DRT ticket data. Seven integration options are studied, as well as a Hypothetical FRT scenario in which each origin is presumed to have an FRT network connecting it to its destination. Additionally, a complete FRT-FRT scenario is addressed for those O-Ds that have access to an FRT network from start to end. Due to the fact that the data was extracted from DRT ticket data, the base case taken in the study is DRT-DRT.

When the integration scenarios were simulated, it was discovered that 100% of the trips could be converted to TNC-TNC and current DRT-DRT scenarios; 92% of trips can be converted to TNC-FRT or DRT-FRT; 87.8% of trips can be transformed to DRT-TNC. In the DRT coordinated with the TNC scenario, it is believed that riders will take DRT to the next FRT stop and then a TNC to their destination, as FRT may be unavailable at that time. However, if the user's nearest FRT stop is the furthest from the targeted destination, this scenario is neither preferable nor rational. Three-mode scenarios involving DRT-FRT-TNC, and TNC-FRT-DRT have the potential to convert 71.4 percent of the original trips. Additionally, just 0.4 percent of existing trips have FRT stops at the origin and destination, implying that only 0.4 percent of existing trips include the FRT-FRT scenario (Figure 5-1).

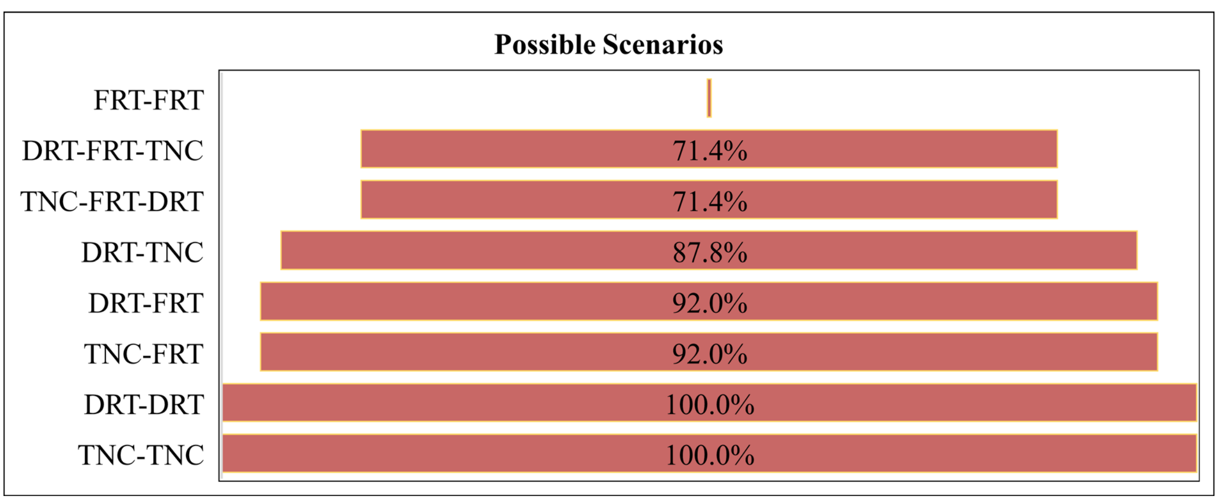

Figure 5-1 Percentage of Possible Integration Scenarios

5.2 Cost elements

5.2.1 Average User Cost and Average Agency Cost

For each O-D pair, the generalized user cost, the agency cost, and the total system cost were computed using the fare, the value of travel time, the agency's operating and maintenance costs, and surge pricing. The plot in Figure 5-2 depicts the estimated average costs for each scenario. The total system cost is computed as the sum of the agency's and the user's costs. The agencies offer a fixed fare for DRT and FRT in this study area, and the fare for TNCs is higher than these fares and similar values are adopted for simulation. Since it is assumed that the public transportation agency bears only a small portion of the operating and maintenance costs of TNCs, the agency's cost for TNCs will be minimal in the study. However, the case may be different if TNC fares are subsidized for users, where in that case the agencies must pay for the costs borne by these private companies.

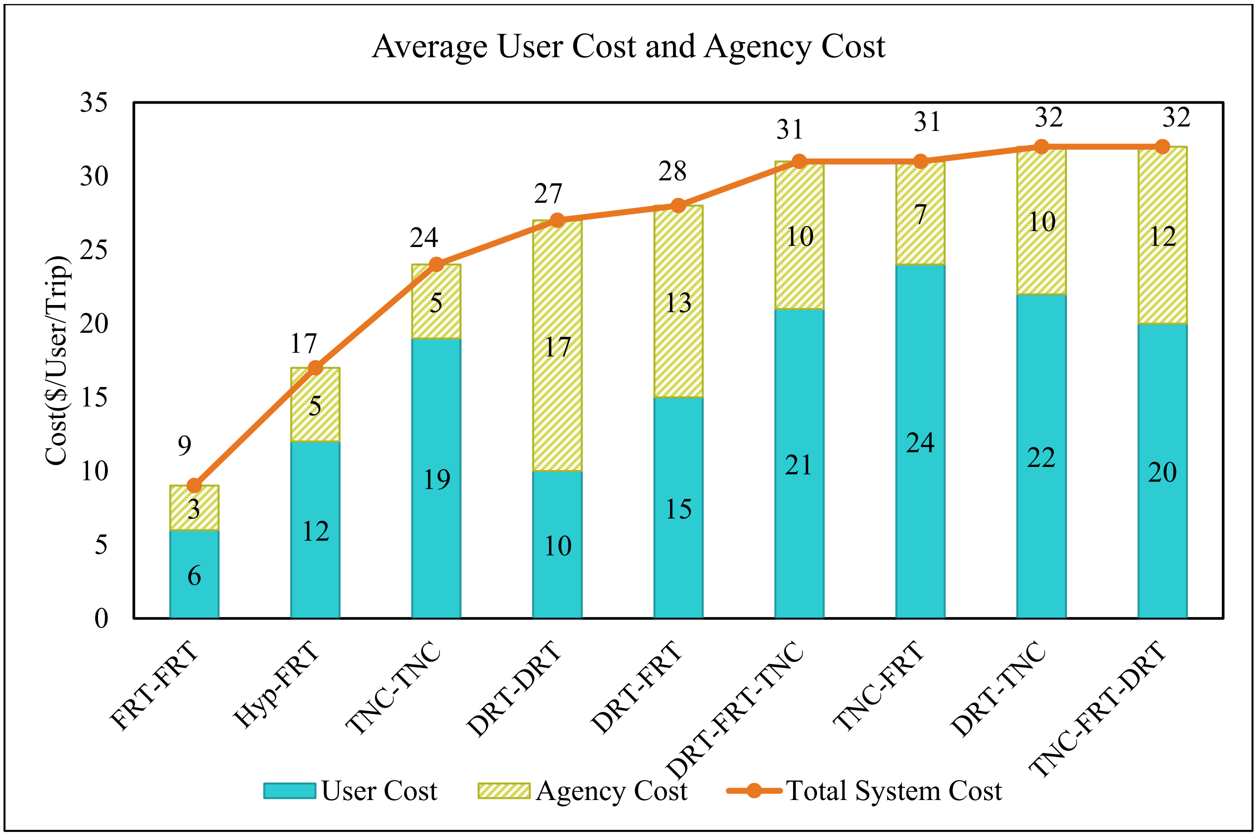

Figure 5-2 Average User Cost & Agency Cost

The FRT-FRT scenario has the lowest average user cost, average operating cost, and total system cost, but because this scenario was only possible for 0.4 percent of trips, it makes minimal contribution to the system and is not accessible to a majority of the people. The simulation makes use of the Hypothetical-FRT scenario to establish a baseline for comparison. While the Hypothetical FRT scenario on the imaginary FRT route is the most cost effective in terms of total system cost, providing a complete fixed route to every origin and destination is a laborious operation requiring significant capital expenditure. Apart from the Hypothetical FRT, the scenario DRT-DRT is the best alternative in terms of the lowest user costs. In the DRT-DRT scenario, the user prefers DRT service to complete the entire trip, and the average user cost per trip is $10, but the agency cost is the highest ($17/user/trip) due to DRTs' higher operating and maintenance costs per mile. The total cost of the system in a DRT-DRT scenario is $27 per user/trip. It can be observed that the FRT-DRT coordinated scenario has comparable user and agency costs that there is a balance between them with the users experiencing $15 per trip and the agency costing $13 per trip on an average and with an average total system cost of $28/user/trip. Different strategies must be employed to lower the user costs for efficient integration of FRTs and DRTs and must be further investigated.

the FRT-DRT coordinated scenario has comparable user and agency costs

The most expensive systems are DRT-TNC and TNC-FRT-DRT, both of which have an average system cost of $32/user/trip. In the scenario DRT-TNC, the user cost is $22/user/trip, while the agency cost is $10/user/trip. The reason for the high user cost in this scenario is likely due to the lengthy wait time, as the value of time is also a factor in the cost. Because it is assumed that the transfer occurs at an FRT stop and the user is supposed to take the TNC due to the lack of available FRT services, therefore two waiting times are added at one stop. As with TNC-FRT-DRT, the user cost is $20 per trip and the agency cost is $12 for each trip for a user. Utilizing multiple legs has a substantial impact on the total trip time because it automatically adds the time required for multiple transfers for the user, increasing the cost, and for the agency, they maintain two modes of public transport in this scenario.

Any scenario that incorporates TNCs generates a high user cost as a result of their high fares, particularly during peak periods due to surge pricing. However, the journey time with TNCs is shorter since they move at a considerably higher average speed, which contributes significantly to lowering in-vehicle travel time. Additionally, the shorter waiting time encourages consumers to choose TNC over just evaluating the fare values. TNCs create lower agency costs because of the assumption that there is no direct involvement of the transit agency in running the TNCs. The scenario TNC-FRT has the greatest user cost, which may be attributed to the higher fare for TNC and VOT increasing the cost of FRTs due to increased travel time, waiting time, and transfer time even though their fares are lower.

TNCs create lower agency costs because of the assumption that there is no direct involvement of the transit agency in running the TNCs

5.2.2 Cost and Time of the day

The variation of average agency costs and average user costs for different scenarios across different times of the day has been studied and the trips happen between 6 AM to 6 PM. Figure 5-3 illustrates the scenario-specific average user cost across different times of the day and Figure 5-4 shows the scenario-specific average agency cost at different times of the day.

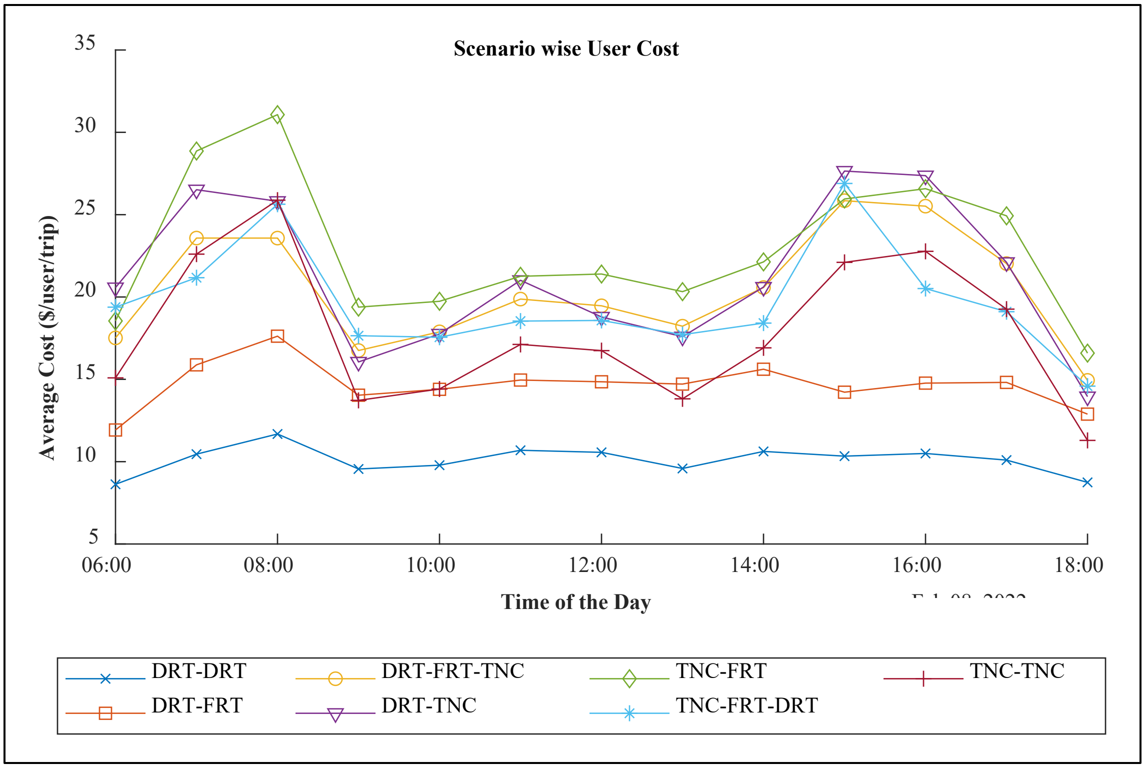

Figure 5-3 Average User Cost for each Scenario by Time of the day

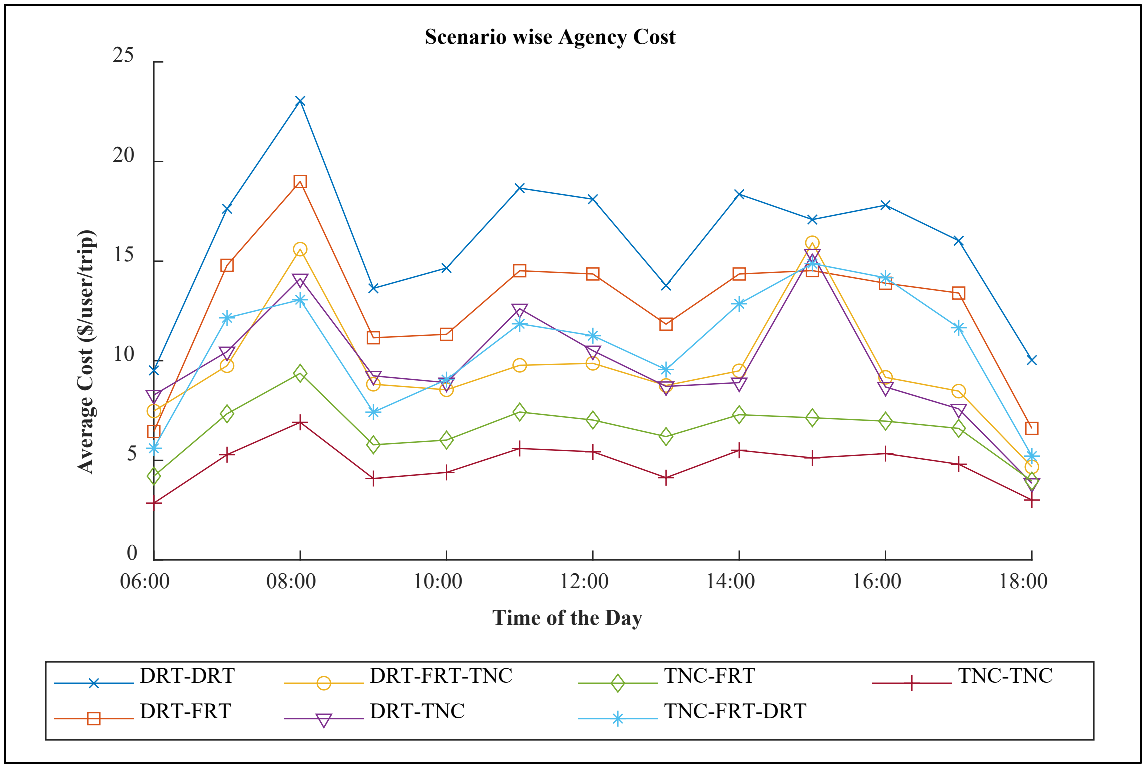

Figure 5-4 Average Agency Cost for each Scenario by Time of the day

It can be observed that the scenario DRT-DRT has the lowest average user cost and higher average agency cost throughout the day. DRT-FRT has the second-lowest user cost, and this can be an indication that the integration of DRT with FRT is viewed positively by the user considering the fare and the value of time. Any scenario involving a TNC has a significant user cost associated with it. The variance in costs throughout the day shows a clear trend toward higher pricing during peak periods, owing to TNC surge pricing and slower traverse speeds for all modes during peak periods due to increased demand and congestion. Figure 5-5 illustrates the scenario-specific total system cost at different times of the day. As for the average total system cost summing the average user cost and average agency cost TNC-TNC has the lowest system cost because of the smaller contribution from the agency cost.

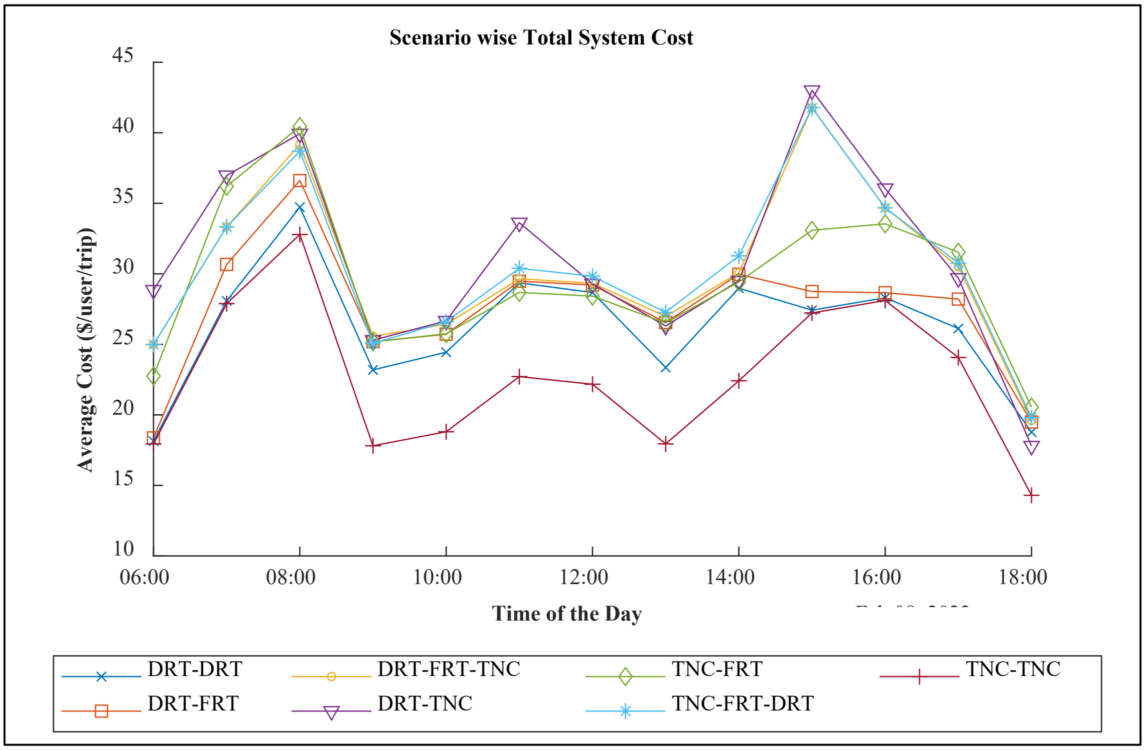

Figure 5-5 Average Total System Cost for each Scenario by Time of the day

5.2.3 Probability Distribution of Cost

For each origin-destination pair, the user cost and agency cost were calculated for each scenario, and the frequencies of each cost observation were noted, as well as their probability distributions. In accordance with the probability distributions of user cost and agency cost shown in Figures 5-6, the user cost is higher in the vast majority of cases because they are compelled to use the more expensive TNCs for a variety of reasons, such as a lack of availability of public transportation and considering the importance of travel time, as public transportation is slower. For an average travel length of 10 miles, the median user cost range obtained in the simulation is $14-$16, when all

the median user cost range obtained in the simulation is $14-$16 when all scenarios are taken into consideration scenarios are taken into consideration. Higher user costs were found when using TNCs, which were mainly due to the minimal access to public transit and preference for the fastest modes.

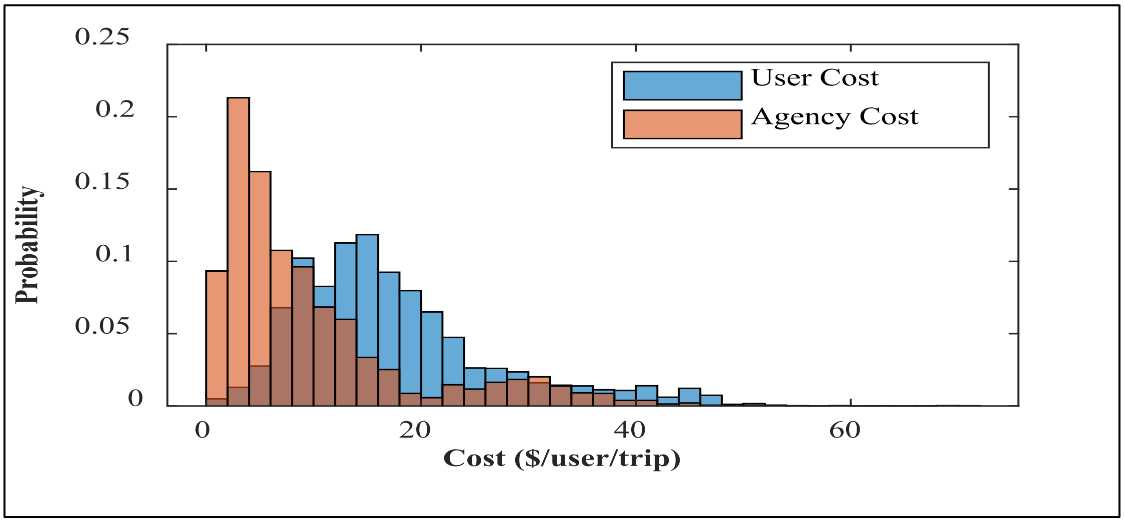

Figure 5-6 Probability Distribution of Cost

5.3 Travel time

The travel time for each scenario varies differently as TNC and DRT can take routes that are the fastest, unlike FRT where they must follow the predefined routes. The out-of-vehicle travel time includes the waiting time for the different modes depending on the time the trip was made and the transfer times. The speed of the FRTs is the lowest creating more in-vehicle travel time for the same distance and TNC is the fastest among the three. Figure 5-7 illustrate the average in-vehicle travel time (blue) and out-of-vehicle travel time (red) for a trip in different scenarios.

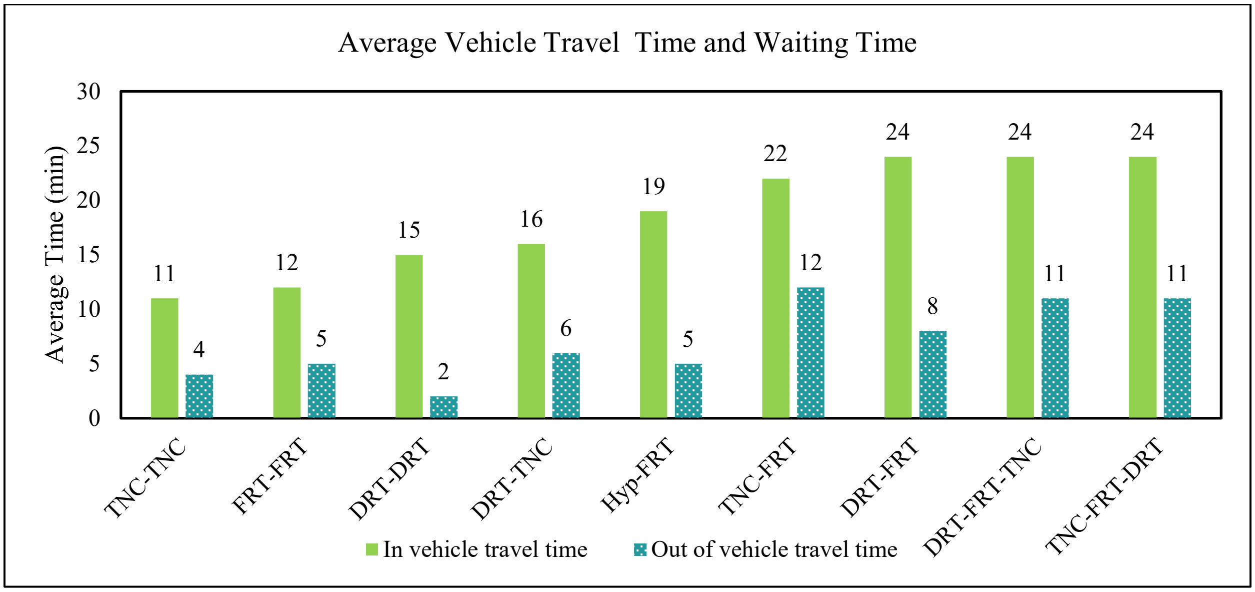

Figure 5-7 Travel Time for each Scenario

On average, the longest travel time is observed for the three-legged multimodal scenarios: DRT-FRT-TNC and TNC-FRT-DRT. They observe an average in-vehicle travel time of 24 minutes per trip and an average out vehicle travel time of 11 minutes per trip, summing a total trip time of 35 minutes on average. The numerous transfers are the most significant contributors to the increased out-vehicle travel time in multimodal scenarios. This out-vehicle travel time can be reduced by using a more centralized dispatching system. The shortest waiting times are observed for the scenarios DRT-DRT, followed by TNC-TNC. The waiting time for TNC increases on a considerably bigger scale during peak periods when compared to DRTs.

The numerous transfers are the most significant contributors to the increased out-vehicle travel time in multimodal scenarios. This out-vehicle travel time can be reduced by using a more centralized dispatching system

5.3.1 Travel Time and Time of the Day

Figure 5-8 depicts the scenario-specific variations in overall travel time (which includes in-vehicle travel time and out-vehicle travel time) at various times of the day. The morning and evening commutes are the busiest hours, with the highest commute times. Towards the middle of the day, a smaller peak can also be spotted. The integration is substantially influenced by the travel speeds of the modes. Due to the fact that FRT has the lowest speed among all the modes, FRT integrated scenarios tend to have a longer overall trip duration.

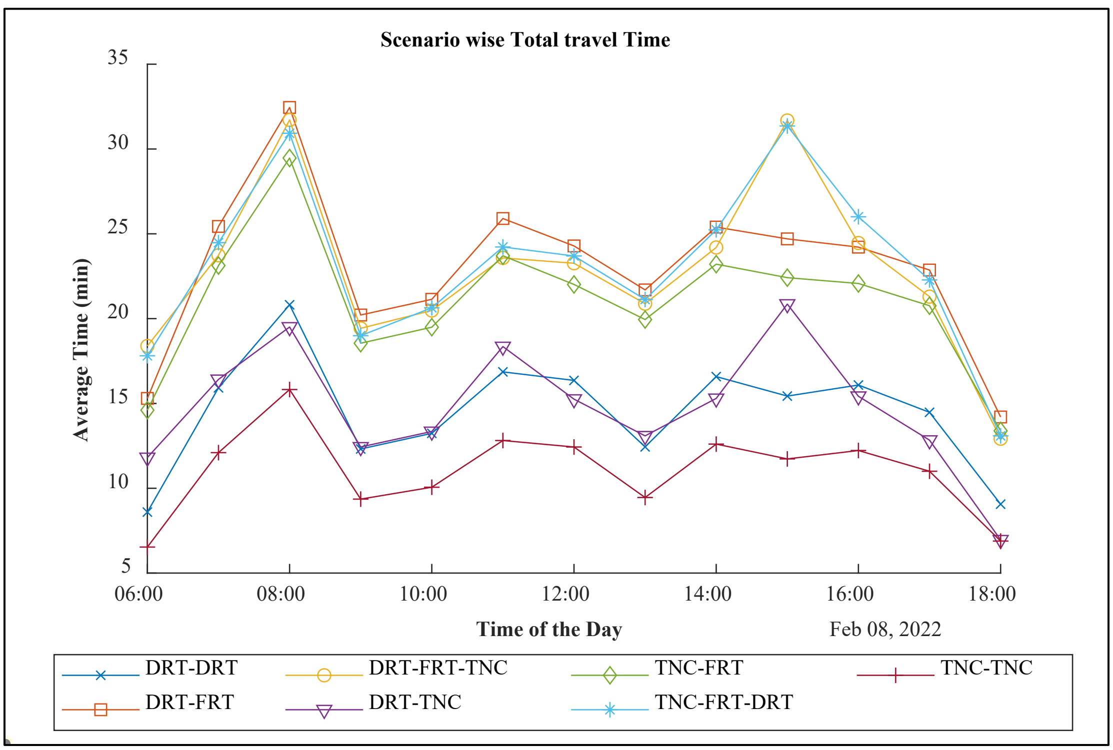

Figure 5-8 Average Total Travel Time for each Scenario by Time of the day

5.4 Preferred Scenario

When it comes to integrated systems, the preferred one is the one with the lowest system cost, which is calculated as the sum of agency and user costs. For each OD, several scenarios and their associated costs were calculated. Table 5-1 shows the aggregated O-D matrix of trips between zip codes following the simulation. The highest number of trips happens within the zip code 37814 (Morristown) with a total of 52407 simulated trips. The color coding indicates the number of trips made in each cell, with red representing the most and green representing the fewest. Most of the trips happen between the zip codes 37813 and 37814.

Table 5-1 Zip code Simulated O-D matrix

O/D	Bulls Gap 37711	Jefferson City 37760	Lowland 37813	Morristown 37814	New Market 37820	Talbot 37877	Baneberry 37890	Whitesburg 37891
Jefferson City 37760	0	1352	1764	2570	1104	60	344	0
Lowland 37813	56	2135	25067	37961	263	2959	3876	1846
Morristown 37814	4	3764	46497	52407	1219	2501	1495	1643
Russellville 37860	0	16	2126	1100	8	0	0	4
Talbot 37877	0	108	2534	2192	420	44	16	0
Whitesburg 37891	0	0	52	56	0	0	0	0

Corresponding to the zip code OD matrix, the matrix shown in Figure 5-10 gives the results of the simulation that which scenario performed best in all these zip codes ODs.

Table 5-2 Min system cost integrated Scenarios for zip code OD

O/D	Bulls Gap 37711	Jefferson City 37760	Lowland 37813	Morristown 37814	New Market 37820	Talbot 37877	Baneberry 37890	Whitesburg 37891
Jefferson City 37760	–	DRT-DRT	TNC-FRT	TNC-FRT-DRT	DRT-DRT	DRT-DRT	TNC-FRT	–
Lowland 37813	DRT-FRT-TNC	DRT-FRT-TNC	DRT-DRT	DRT-DRT	DRT-FRT	DRT-FRT-TNC	DRT-DRT	DRT-DRT
Morristown 37814	DRT-DRT	DRT-TNC	DRT-DRT	DRT-DRT	DRT-TNC	DRT-TNC	DRT-TNC	DRT-FRT-TNC
Russellville 37860	–	TNC-FRT	TNC-FRT	TNC-FRT-DRT	DRT-FRT	–	–	DRT-DRT
Talbot 37877	–	DRT-DRT	TNC-FRT-DRT	TNC-FRT-DRT	DRT-DRT	DRT-DRT	DRT-DRT	–
Whitesburg 37891	–	–	TNC-FRT-DRT	TNC-FRT-DRT	–	–	–	–

For example, the second-highest number of trips occurs between Morristown (37814) and Lowland-Morristown (37813), totaling 46,497, and the optimal scenario for ODs from these zip codes is DRT-DRT, i.e., the base scenario. This suggests that people prefer to stay on the existing DRT-DRT due to the system's overall cost, trip duration, and convenience. However, for a route between Morristown (37814) and Talbot (37877), DRT-TNC is favored above the base case scenario. The cells are color-coded differentiating the preferred scenario after multiple options are provided for every origin-destination pair and the aggregated modal results pertaining to ODs of these zip codes are shown in the table.

5.4.1 Preferred integrated System

The integration possibilities reveal that a significant amount of the DRT and TNC functions as a feeder to the FRT service in a fully integrated system.

Table 5-9 shows how each of the scenarios with multiple modes are perceived by the user as the best scenario in the study area. With DRT-DRT being the base case, 40% of the time they remained as the best option. But 60% of DRT-DRT trips preferred the integrated system in the agent-based simulation and that percentage is distributed across other mode combinations. Every trip can have up to three legs and use three modes. The DRT-FRT and TNC-FRT scenarios are further classified based on the order of the mode choice and the legs they use to serve each OD. For example, 8.6% of DRT-DRT trips preferred the scenario DRT-FRT where a dynamic response transit is integrated with a fixed transit. Out of the DRT-FRT scenario, 56% use the DRT-FRT-DRT three-legged option and the FRT-DRT two-legged option with FRT being in the first leg of the trip for 12% of the time and DRT serving the first leg for a percentage of 33. The integration possibilities reveal that a significant amount of the DRT and TNC functions as a feeder to the FRT service in a fully integrated system.

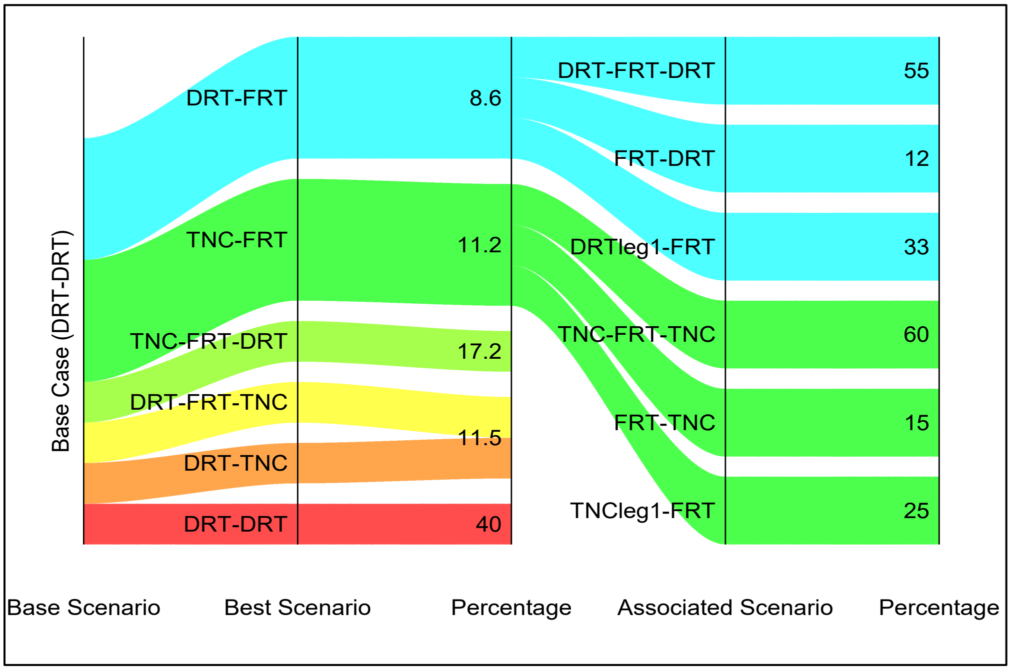

Figure 5-9 Percentage Distribution of each Scenario

5.4.2 Performance Evaluation-FRT Trip Length

Different measures can be used to find how the chosen best scenarios can be evaluated; the FRT trip length matrix gives an idea of how much of the trip distance is covered by FRT for ODs from every zip code. Equation 2 shows the percentage of trip length covered by FRT in the integrated system (*$\%TL_{FRT}$*) where the denominator is the total trip length, and the numerator is the trip length that is covered by Fixed Route Transit.

The value of GTC_{Total} less than one indicates that the integrated system is more attractive to the users than the base scenario of DRT-DRT

Equation 2

$$\%TL_{FRT} = \frac{TL_{FRT}}{TTL} \times 100$$

Where TL_{FRT} = Trip length by FRT and TTL = Total Trip Length.

Table 5-3 shows the FRT trip length percentages of ODs of each zip code. If $\%TL_{FRT}$ = 0, it indicates that 0% of trip length is covered by FRT in the entire trip or the absence of FRT. If the percentage is 50, it can be said that at least 50% of the trip length is covered by FRT and the integrated system can act as a good feeder system to the existing fixed route system. The color coding in the cell is set up in such a way that the longer the trip length covered by the fixed route service is, the greener the cell is. Almost 60% (55.99%) of the trip length from the zip code Morristown (37814) to Whitesburg (37891) is covered by the FRT using the DRT-FRT-TNC integrated scenario (table 5-2) and this has the maximum percentage of FRT trip length contribution in the study area.

Table 5-3 FRT Trip Length Matrix

$\%TL_{FRT}$	Bulls Gap 37711	Jefferson City 37760	Lowland 37813	Morristown 37814	New Market 37820	Talbot 37877	Baneberry 37890	Whitesburg 37891
Jefferson City 37760	–	0	28.12	30.97	0	0	29.7	–
Lowland 37813	53.54	30.79	0	0	33.2	41.01	0	0
Morristown 37814	0	0	0	0	0	0	0	55.99
Russellville 37860	–	35	49.07	49.42	35.38	–	–	0
Talbot 37877	–	0	38.19	34	0	0	32.26	–
Whitesburg 37891	–	–	51.11	48.37	–	–	–	–

5.4.3 Performance Evaluation- Generalized Travel Cost Ratio

The Generalized Travel Cost Ratio gives an idea of how the best-performing scenario worked better than the existing base case scenario of DRT-DRT. The Generalized Travel Cost Ratio (GTC_{Total}) is calculated using Equation-3, where the numerator is the total system cost of the best performing scenario after running the possible integration scenarios and the denominator is the total system cost of the base case scenario where the complete trip is traversed by DRT. Since the total system cost is compared, the lower the integrated system cost (numerator) better is the system. The value of GTC_{Total} less than one indicates that the integrated system is more attractive to the users than the base scenario of DRT-DRT and the matrix showing the GTC ratio of ODs from and to different zip codes are given in table 5-4. GTC ratio of 1 means the preferred mode is DRT itself all throughout the trip. The trip from Jefferson (37760) to Lowland (37813) has the lowest GTC_{Total} with a value of 0.76 and the preferred scenario for this OD is TNC-FRT (Table 5-2).

Equation 3

$$GTC_{Total} = \frac{C_{INT,Total}}{C_{DRT,Total}} \times 100$$

$C_{INT,Total}$ = Total System Cost of integrated trips

$C_{DRT,Total}$ = Total Cost of base case scenario DRT-DRT trips

Table 5-4 Generalized Travel Cost Ratio Matrix

GTC	Bulls Gap 37711	Jefferson City 37760	Lowland 37813	Morristown 37814	New Market 37820	Talbot 37877	Baneberry 37890	Whitesburg 37891
Jefferson City 37760	–	1	0.76	0.88	1	1	0.82	–
Lowland 37813	0.88	0.84	1	1	0.89	0.84	1	1
Morristown 37814	1	0.88	1	1	0.88	0.88	0.89	0.84
Russellville 37860	–	0.81	0.8	0.9	0.92	–	–	1
Talbot 37877	–	1	0.87	0.88	1	1	0.94	–
Whitesburg 37891	–	–	0.9	0.9	–	–	–	–

5.5 Environmental Cost of Integration

Mobility is certainly important for economic progress, but in our carbon-based environment, transporting people from one location to another comes at a high cost. Considering just the United States, in 2017, the transportation sector accounted for 29% of the nation's total emissions of 6.4 billion metric tons of carbon dioxide equivalent, or CO_2e which is the CO_2 equivalent of an individual greenhouse gas (*Sources of Greenhouse Gas Emissions | US EPA*, n.d.). This analysis is intended to evaluate the environmental performance by comparing the carbon dioxide (CO_2) emission per passenger mile for the various different scenarios proposed in the study as per the *ABA Foundation (« American Bus Association*, n.d.). Both energy consumption and emissions are stated in units per passenger mile operated for all modes. All exhaust emissions are measured in grams of emissions per passenger mile (g/pass-mi), and the average passenger miles traveled for each scenario are multiplied to obtain the study's emission matrix. It is evident from the analysis as observed from Figure 5-10 that the fixed route system is the one that produces the least carbon dioxide pollution, carrying multiple passengers in a single trip and three modal scenarios are the ones with maximum CO_2 emissions.

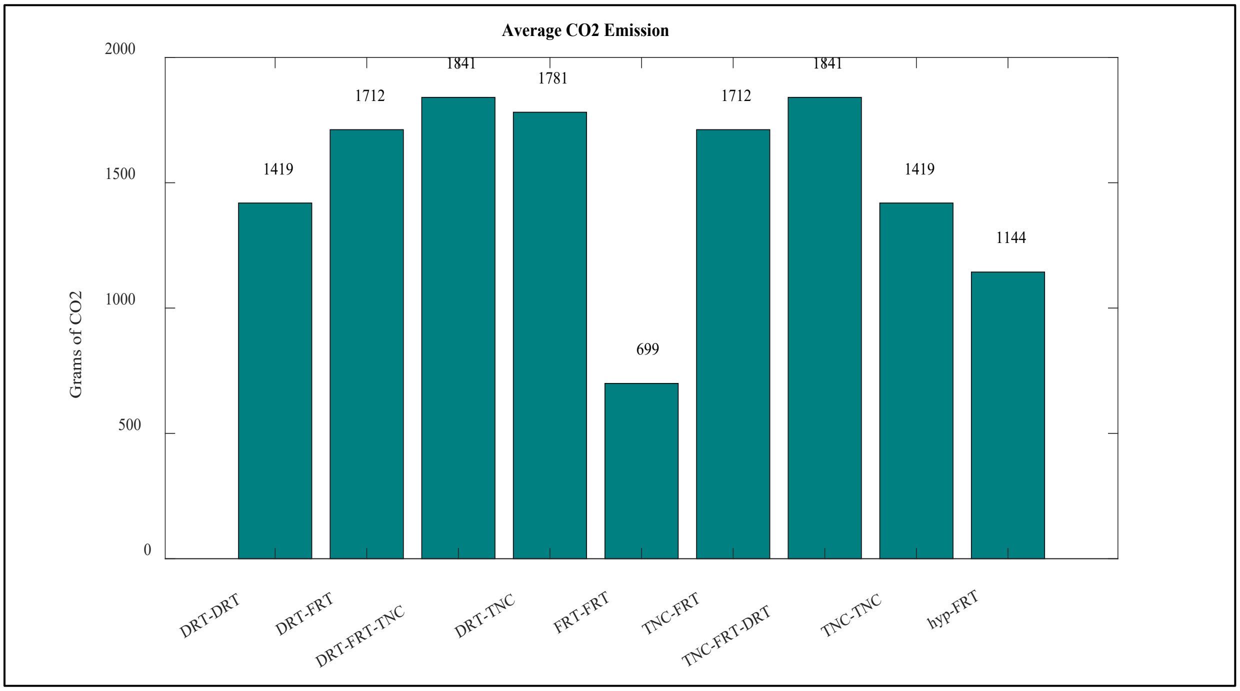

Figure 5-10 Average carbon dioxide emission for different scenarios

5.6 Equity Analysis

A transit network is made up of intricate interactions between stops and routes that serve multiple origins and destinations. A systematic depiction of network features and operational characteristics is required for the evaluation of transit supply and demand. There are a variety of connectivity measurements available in the literature. Even when used interchangeably, the terms "equality" and "equity" have distinct implications, particularly in the context of public transit. The concept of equality is comparable to "equality" or "sameness," which says that individuals and groups should be treated equally if they have equal opportunities and benefits.

This entails offering the same level of service to the entire population, which is not always the case with public transit. However, equity suggests that because not all individuals and groups have equal opportunity, they should not be treated differently to compensate for these disparities. As a result, equity implies "justice" or "fairness," implying that not everyone uses public transit and that those who do should be favored. (Sharma et al., 2020).

5.6.1 Lorenz Curves and Gini Index

Different measures have been discussed in previous literature and a common non modeling approach to the measurement of equity is the Lorenz curves coupled with the Gini index (Delbosc & Currie, 2011; Kaplan et al., 2014; Welch & Mishra, 2013). Lorenz curves are a graphical representation of the cumulative wealth distribution function throughout the population in economics (Lorenz, 1905) and they can be applied to any quantity that can be cumulated across a population. While the Lorenz Curve is a visual representation, the Gini coefficient is a single simple mathematical metric to represent the overall degree of inequality and it is a ratio of the area between the line of equity and the Lorenz curve upon the total area under the line of equity (Delbosc & Currie, 2011).

In terms of the accessibility for all OD, Figure 5-11 shows the measured inequity associated with proposed scenarios and exiting transit services (DRT-DRT, FRT-FRT) in terms of the total system cost each scenario is producing. The further a Lorenz curve deviates from the line of equity, the less equitable is the scenario. The scenario FRT-FRT deviates the most from the line of equity and this is because only 0.4% of the original trips used for analysis are covered by the existing FRT and therefore this scenario is the least accessible.

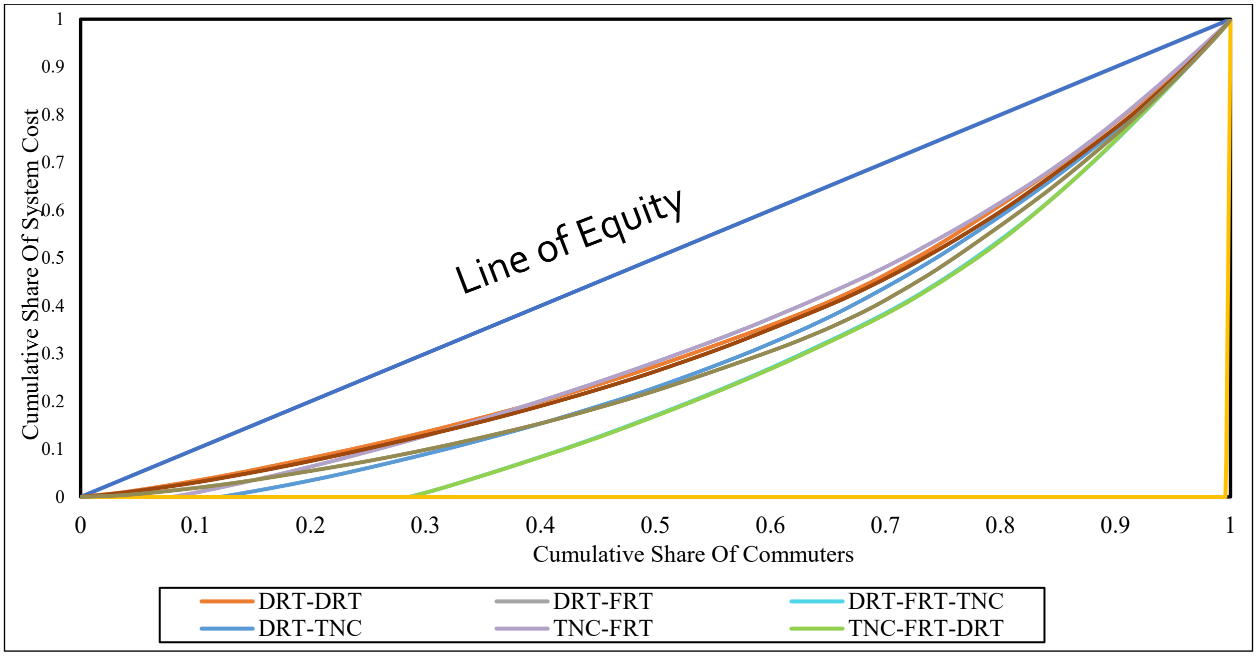

Figure 5-11 Lorenz Curve for Different integration Scenarios

While the Lorenz curve is a graphic depiction, the Gini coefficient is a single simple mathematical metric used to quantify the overall degree of inequality. It is calculated as the ratio of the area between the line of equity and the Lorenz curve to the total area under the line of equity (Delbosc

& Currie, 2011). Gini coefficient is a measure of deviation from perfect equity. A Gini index value of zero represents perfect equity and the coefficient of value one means perfect inequity (*Census.Gov*, n.d.). The Gini Indices of different scenarios of the study are shown in Figure 5-12. Incorporating the value of time in the calculation of cost elements, the Gini Index of the existing DRT-DRT is 0.315 and the lower Gini index can be explained by its accessibility to the majority of the OD pairs and all the integrated scenarios are more equitable than the existing FRT network and are highly advisable to implement.

all the integrated scenarios are more equitable than the existing FRT network

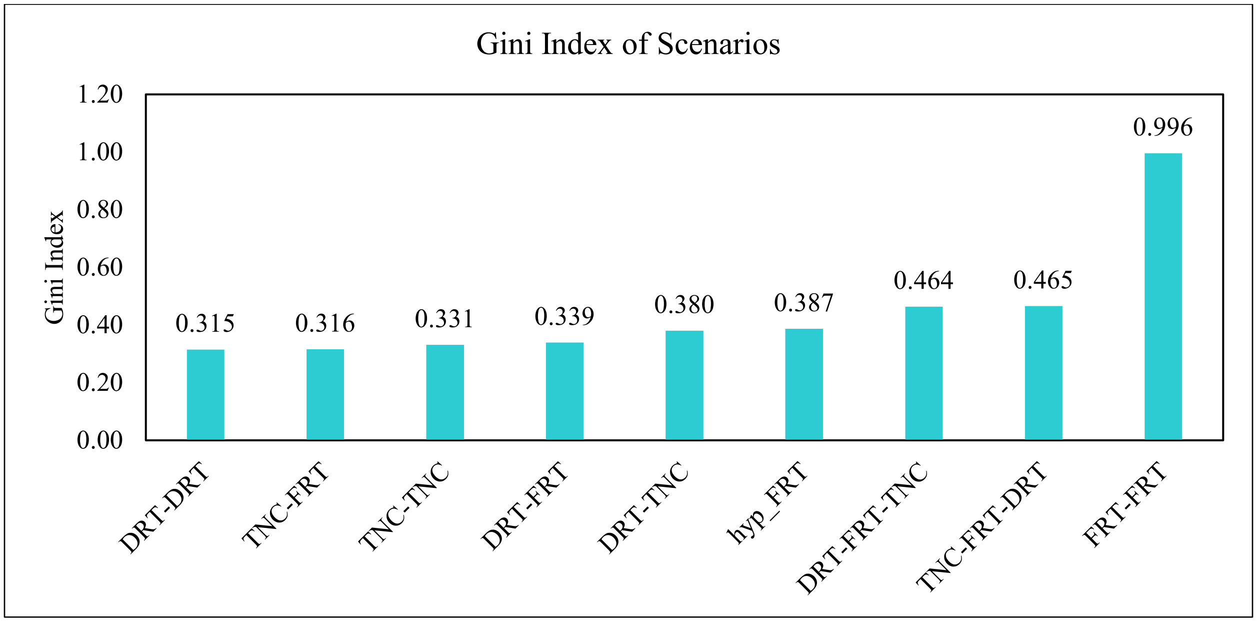

Figure 5-12 Gini Index of different integrated scenarios

Chapter 6 Conclusion

6.1 General

Integration of the fixed-route transit system with the dynamic responsive transit system and creating a hybrid public transit system is the necessity of the future as more people should be attracted to public transit for creating a sustainable environment. In this study, the existing DRT service data of the city of Morristown was used to create multiple scenarios of integrating the DRT with FRT along with TNCs for the completion of a trip. The scenarios thus consist of Fixed Route Transit service, Demand Response Transit service, and service by Transportation Network Companies, either individually or with multiple combinations of them. The attitudes of users and agencies about the prospects for FRT, DRT, and TNC integration were investigated in this study from the perspectives of both users and agencies. Table 6-1 is a Multicriteria Analysis Results table that summarizes how each scenario performed against the study's various criteria. Each cell represents the value of the measure, and the color coding of "green-yellow-red" indicates the scenario preference in the sequence "high-medium-low." Which means that a cell with a green background indicates a high preference for that scenario, based on that criterion. The most desired scenario results from a better tradeoff between these different criteria, and it must be researched further.

Table 6-1 Multicriteria analysis results

Scenario	User Cost ($/User/Trip)	Agency Cost ($/User/Trip)	Total System Cost ($/User/Trip)	Average CO_2 Emission (Grams of CO_2)	Equity: Gini Index
FRT-FRT	6	3	9	699	0.996
DRT-DRT	10	17	27	1419	0.315
Hyp-FRT	12	5	17	1144	0.387
DRT-DRT	15	13	28	1712	0.339
TNC-TNC	19	5	24	1419	0.331
TNC-FRT-DRT	20	12	32	1841	0.465
DRT-FRT-TNC	21	10	31	1841	0.465
DRT-TNC	22	10	32	1781	0.38
TNC-FRT	24	7	31	1712	0.316

According to the analysis, a significant portion of trips (40 percent) continued to prefer using DRT-DRT (base case scenario) to complete the entire trip, most likely because it is more accessible and does not require adherence to a fixed schedule, but the implementation cost for the agency is too high in this scenario. While the integrated scenario offers many alternatives, 60% of travelers preferred the Integrated scenario over the base case when it came to connecting demand responsive transportation to fixed transit. This superiority of these integrated scenarios over the base case can be attributed to the integration strategy's economic viability. From the standpoint of “Total System Cost,” it is viable to use DRTs and TNCs as a feeder system for FRTs. And as a result of equity considerations, integration scenarios are more equitable than FRT networks when it comes to meeting consumer demand while minimizing the system cost. Finally, it can be concluded that the integration of public transportation systems was deemed beneficial for both passengers and transportation providers to create a more equitable public transportation system and it is recommended to have additional research to develop largescale optimal implementation policies.

6.2 Limitations of the Present Study

The present study has some limitations as it is assumed that services are always available at all times, all trips are completed without failure and the availability of fleet or drivers is assumed to be present at the time of considering a trip. Surge pricing happens when demand for the service spikes, which typically occurs during morning and evening rush hours, special events, or inclement weather. According to Uber's website, the cost of requesting a vehicle climbs by 1.8 to 2.5 times the first anticipated cost. Surge pricing frequently varies by location within a city. The surge factor for the city of Morristown is assumed in the study. Finally, our analysis only examines the economic benefits of the proposed mobility system when transit authorities, DRT operators, and TNC service providers coordinate and work towards that shared goal, which may not always be the case in fact. Therefore, it's critical to look into possible incentive mechanisms and policy tools for non-cooperative situations.

6.3 Recommendations for Future Work

This project used an agent-based simulation model to develop a model for integrating existing fixed transit services with demand responsive services in the city of Morristown, Tennessee. While the study area was limited to a single city, the model is capable of expanding to multiple cities with a defined road network system. The results demonstrate the viability of possible integration and illustrate how the methodology might be broadened for large-scale implementation. Phase 1 was completed with the review of best practices and case studies relating to DRT and FRT integration, as well as the creation of a sketch planning tool that connects DRT to FRT and TNC. A major contribution of this research was to define the operational components of coordination and ultimately to quantify the benefits and significance of integration and this can help agencies in preparing such an integration and finding its spatial and economic viability.

6.3.1 Proposed Future Work: Phase 2 and Phase 3

While the current model is a fully functional, planning tool, there are several ways in which it might be enhanced and expanded to cover wider areas in the future. The initial path for future initiatives should be to improve the model by gathering additional transit data from new cities and greatly generalizing the model.

The primary objectives of Phase 2 could be to include Knoxville in the study area and to develop an algorithm for dynamically selecting the ideal scenario given an OD pair while minimizing user and agency costs. A centralized dispatching system model is to be developed for minimizing the waiting time. Investigating collaboration opportunities with TNCs and subsidizing TNC fares to develop a more effective integration policy that benefits individuals with disabilities.

Phase 3 could be focused on the widespread implementation of the plan throughout various cities in Tennessee to increase general public transit usage and acceptance. It is critical for the future that public transit become more appealing to customers for them to rely less on private vehicles, hence minimizing the carbon footprint of the transportation system.

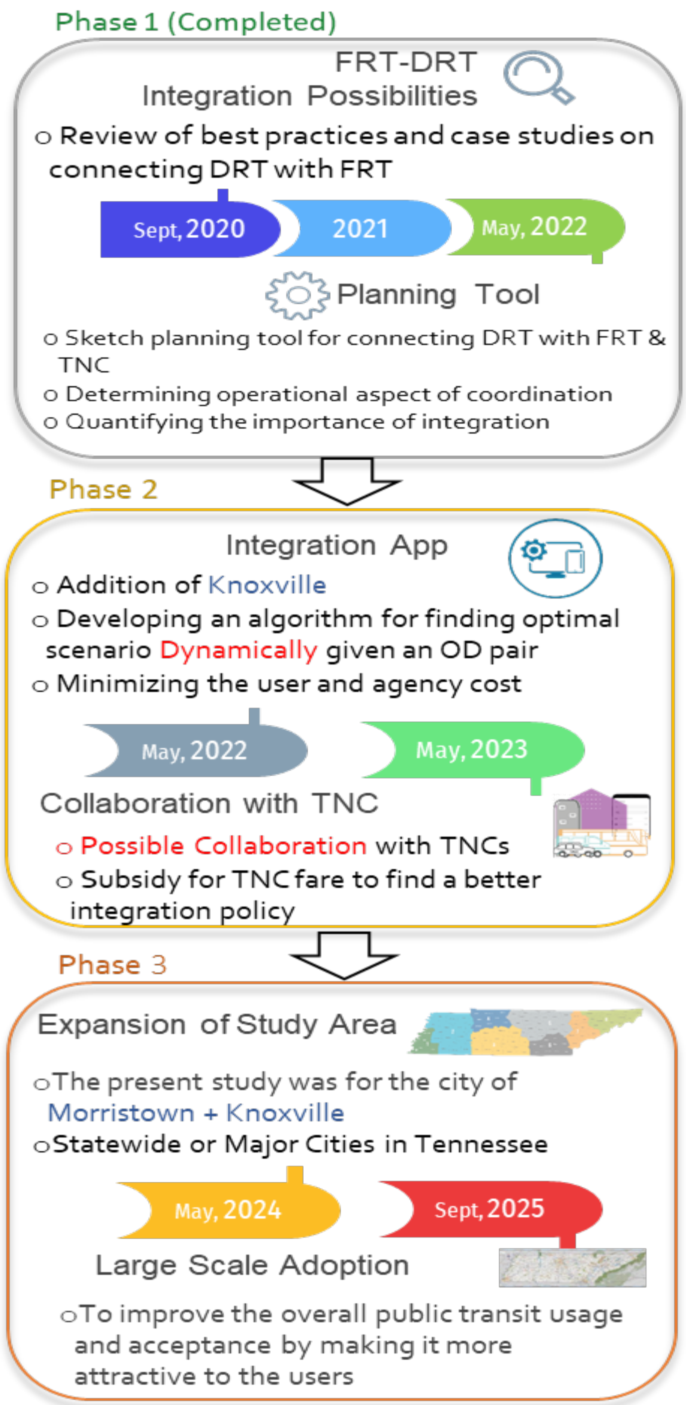

Figure 6-1 Research Road Map and Future Work

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Chapter 8 Appendices

Morristown Local Road Network

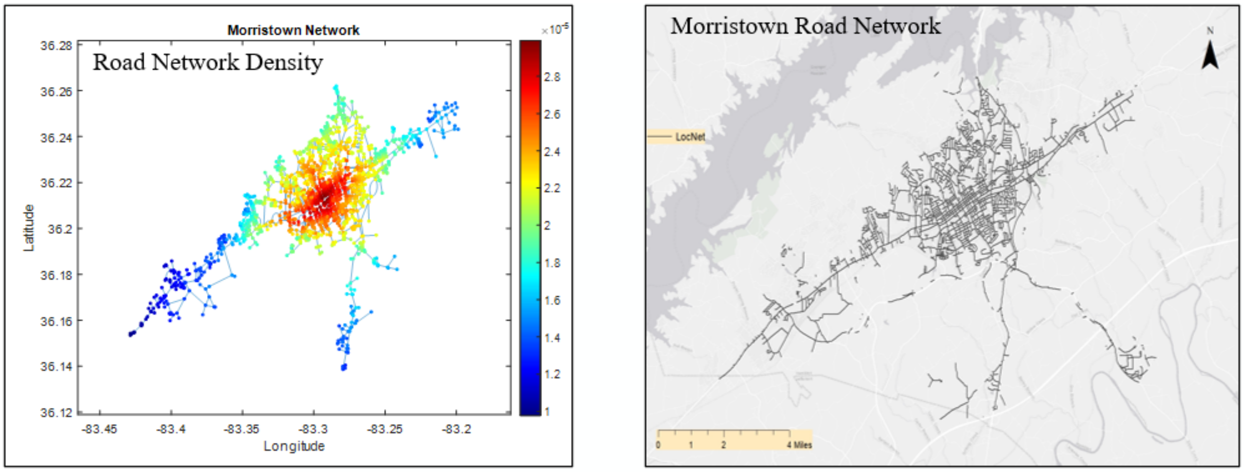

Figure 8-1 Routable Road Network of Morristown

Sensitivity Analysis

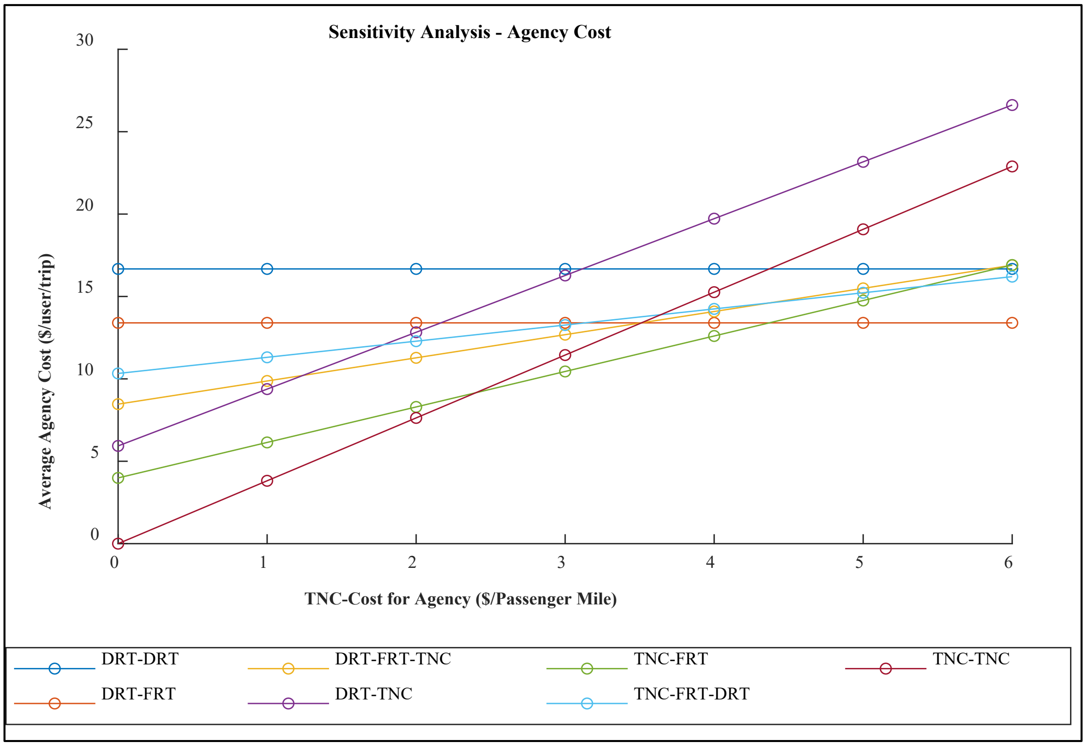

Figure 8-2 Sensitivity Analysis of Average Agency Cost Variation on Increasing the Cost Paid to TNCs by Public Transportation Agencies

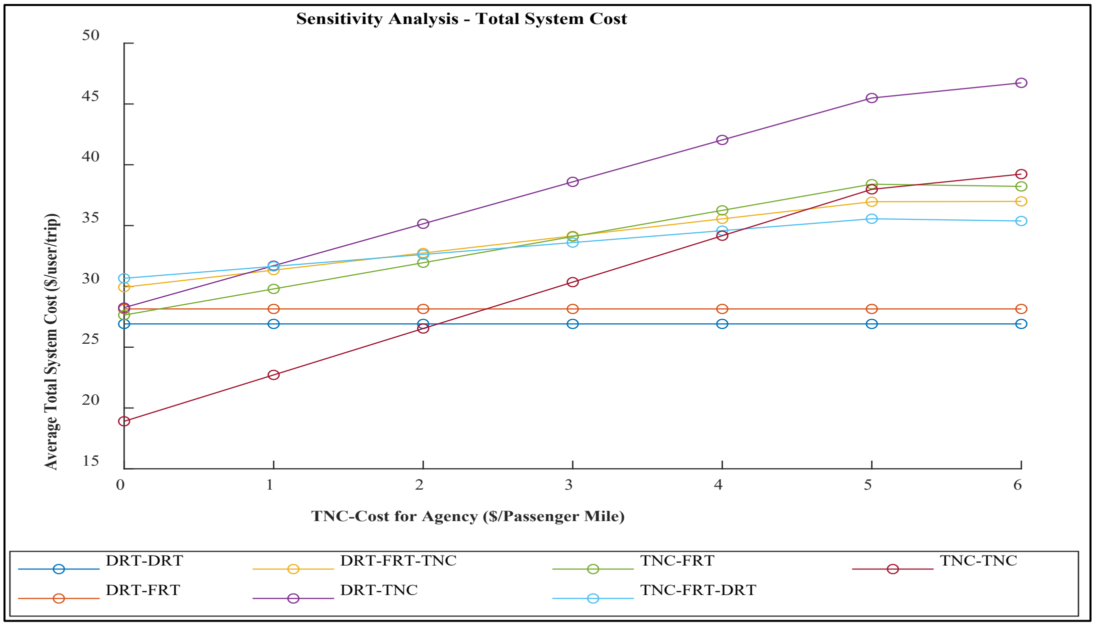

Figure 8-1 Sensitivity Analysis of Average Total System Cost Variation on Increasing the Cost Paid to TNCs by Public Transportation Agencies

Origin- Destination Density

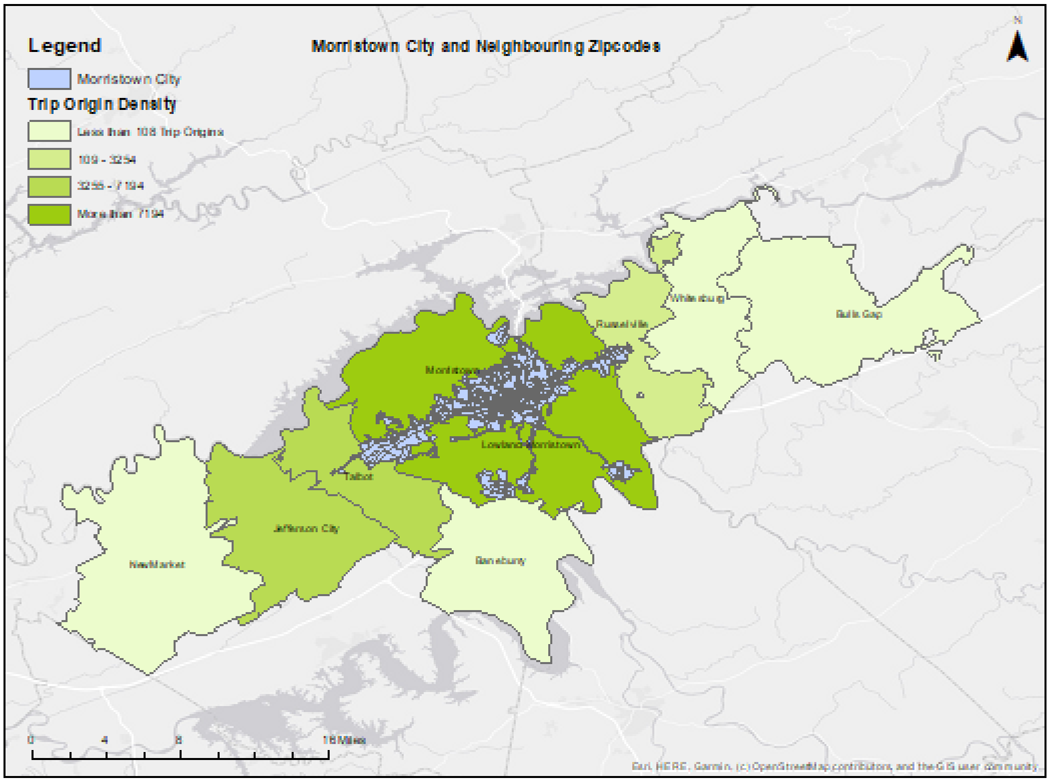

Figure 8-2 Trip Origin Points-Density

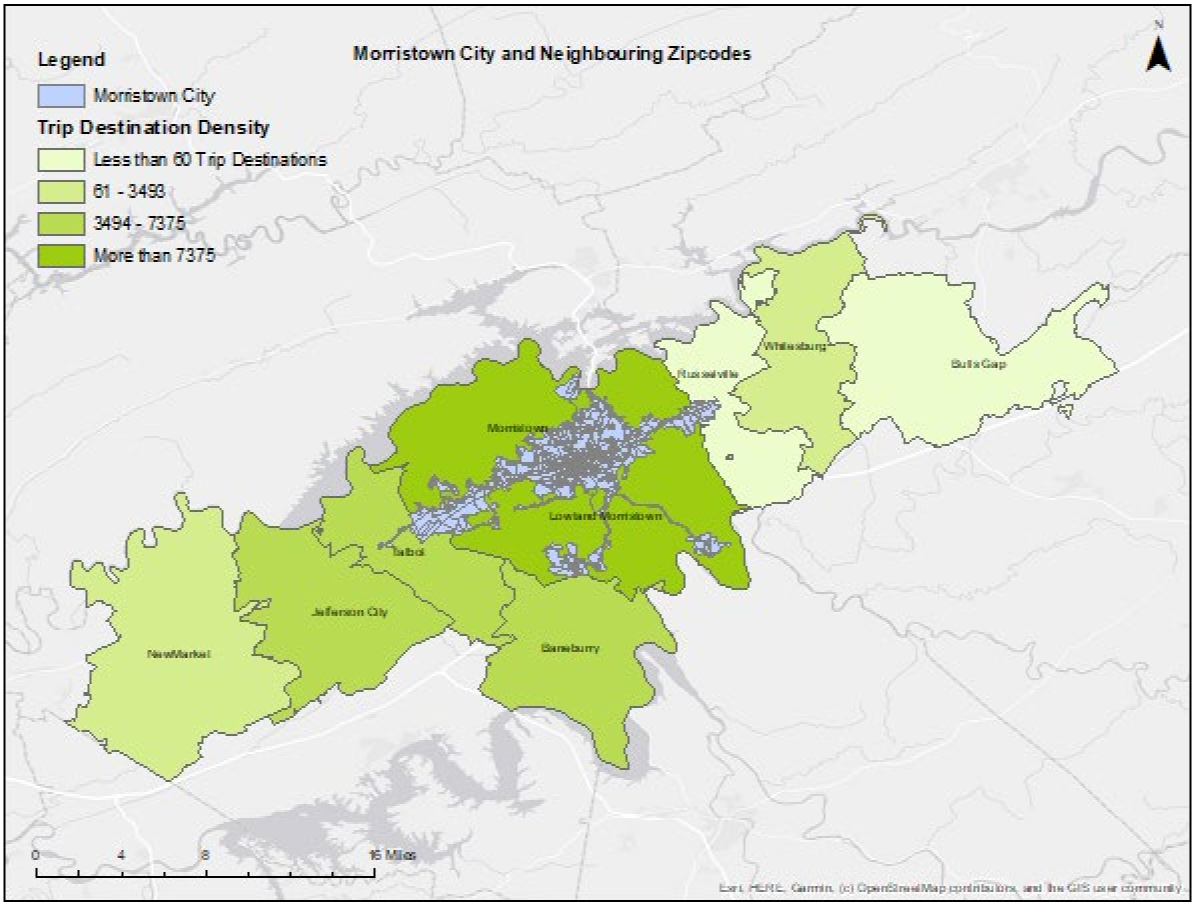

Figure 8-3 Trip Destination Points-Density

Table 8-1 Literature Review Table

S. No.	Source	Data & Location	Region applicability	Objective	Method	Mobility modes	Key findings
1	Kyte et al. (1982)	Transit ridership in Portland, OR	Local transit agency	Planning, implementation, and evaluation of a timed-transfer transit system	Scheduling: timed transfer concept	Transit buses (trunk lines and local lines)	The timed transfer concept increased the ridership, improved schedule efficiency, route performance, optimized capacity, and service level at the expense of increased economic performance. Concept was proved to be more cost-effective than radial transit system.
2	Daganzo (1984)	Hypothetical transit network	Regional Transit Agency	Feasibility of flexible route transit system	Optimization framework	FRT, DRT and flexible route transit	Flexible route service underperformed DRT in case of small demands and 5% less costly than FRT and was befitting for intermediate demand levels, mixed service under variable demand and reducing travel /dwell times with one-way transit trips (cul-de-sac).
3	Bakker et al. (1988)	Hypothetical transit network, Austin (TX)	Local Transit Agency	To transform radial bus route system into a multi-centered time transferred bus network	Timed Transfer System	DRT-FRT	Feeder routes can become Demand Responsive during low ridership periods and can be combined with paratransit. Route length can be increased if travel time decreases.
4	Chang & Schonfeld (1991)	Hypothetical transit network	Local transit agency	Integrating FRT with flexible route transit	Analytical model and threshold analysis	FRT and flexible route transit	Integration of both FRT and flexible route transit, resulted in lower system costs, optimal capacity of 37 seats/vehicles (48 and 17 in FRT and flexible route transit) and provide increased benefits for the lower demand durations.
5	Shyue Koong Chang & Yu, (1996)	Hypothetical transit network	Local transit agency	Comparison of subsidized FRT and flexible route transit.	Analytical model	FRT and flexible route transit	Flexible route service has lower user costs, but higher operator cost as compared to FRT and befitting for small and low-density areas with high travel speeds.
6	Pratelli & Schoen (2001)	Bus lines in Bologna, Italy	Local transit agency	Optimal location of flexible transit on-demand stops	Mixed-integer programming	Flexible route transit	Optimal location of on-demand stops depend on the weights assigned to the time spent in walking, waiting and travelling in the bus.
7	Fu (2002)	Hypothetical transit network	Local transit agency	To identify factors involved in flexible transit design	Optimization framework	Flexible route transit	Flexible route transit is befitting to the minimal number of fixed stops as due to additional slack time; idle time increases which negatively affects the passengers already on board.
8	Ting & Schonfeld (2005)	Hypothetical transit network	Local transit agency	Optimizing headway and slack times for a coordinated transit network	Heuristic algorithm	Transit bus network	Coordinated operation are worthwhile for a significant amount of transfer demand. Coordination is not preferred in case of low demand- high headway cases accompanied with excessive random arrivals.
9	Quadrifoglio & Li (2009)	Hypothetical transit network	Local Transit Agency	To derive critical demand densities	Insertion Heuristic Algorithm	DRT-FRT	Authors concluded with a critical demand density threshold for a particular transit service with cases of one and two vehicles to switch from FRT to DRC or vice versa.

S. No.	Source	Data & Location	Region applicability	Objective	Method	Mobility modes	Key findings
				where DRT and FRT are equivalent			
10	Gupta et al. (2010)	Metro Mobility (Twin Cities of Minneapolis and Saint Paul)	Regional transit agency	Improve operational efficiency of existing paratransit services	Route re-optimization	Paratransit and taxis	Re-optimizing existing routes of paratransit services and replacing them with taxis both result in significant cost savings. Re-optimizing saves about 5% of operating expenses whereas taxis will save about at least $100/per day to the agency.
11	Li & Quadrifoglio (2010)	Hypothetical transit network	Local Transit Agency	Assist decision-makers in choosing between DRT and FRT	Analytical derivation, and simulation	DRT-FRT	DRC is preferred in low demand, afternoon peak hours, high proportion of drop-off passengers, and higher weightage of waiting time (unsafe area & bad weather).
12	Alshalalfah & Shalaby (2012)	Three routes in Oakville city, Canada	Local transit agency	To investigate the feasibility of flexible transit	Optimization framework	Flexible route transit	High ridership FRT services outperform flexible route transit. The performance of both services depends on demand, accepted requests and slack time. Flexible services outperform FRT in terms of fare revenue due to demand responsive trips.
13	Broome et al. (2012)	Ticket sales and satisfactory survey (Queensland, Australia)	Local transit agency	Improvement in the use of FRT with flexible route service	Mann-Whitney U test	Transit bus service	Replacing FRT with Flexible route service increased the ticket sales by 90% and increase in both younger and older passengers.
14	Chevrier et al. (2012)	Hypothetical transit network	Regional Transit System	To develop an evolutionary approach to improve the quality of service of DRTs	Multiple algorithms including Genetic algorithm	DRT	IBEA Hybrid algorithm was proved to be more efficient than two other algorithms. The results favored converting existing DRT to flexible transit system.
15	M. Kim & Schonfeld (2012)	Hypothetical transit network	Local transit agency	Integration of FRT and flexible route transit	Optimization frameworks	FRT, flexible route transit	Integration can reduce the total cost when compared to FRT and flexible route transit and are befitting to variable demand and maintain a perfect balance between both FRT and flexible transit.
16	Nourbakhsh & Ouyang (2012)	Hypothetical transit network	Local transit agency	Design of a new structured flexible route transit system	Simple constrained non-linear optimization	FRT, Flexible bus transit service, taxis	The proposed flexible route transit service was advantageous under low to moderate passenger demand (4 to 40 passengers) as compared to taxi (low demand of <4 passenger) and FRT(high demand of >40 passengers). In addition, proposed service eliminates walking time from and to transit stations and easy to implement.

S. No.	Source	Data & Location	Region applicability	Objective	Method	Mobility modes	Key findings
17	Chandra & Quadrifoglio, (2013)	Hypothetical transit network	Local transit agency	Optimal cycle length for a demand responsive connector service	Analytical queueing model	Demand responsive connector	In a four-hour period and demand of 50 to 100 passengers, For service area dimension, in miles, of (L=W=1), (L=2, W = 0.5) and (L= 3, W=0.33), optimal cycle length were 11-15, 16-20 and 22-27 miles respectively.
18	Errico et al. (2013)	Literature synthesis	Regional Transit System	To develop a unifying modeling framework for semi-flexible systems.	Literature Review	Semi-flexible systems	Classification of the semi flexible systems are: route deviation, point deviation, demand responsive connector, request stops, flexible route segments and zone routes. Demand Adaptive Systems (DAS) is a generalized semi-flexible system that serves several lines interconnected to FRT and customers at some optional locations.
19	M. (Edward) Kim & Schonfeld (2013)	Hypothetical transit network	Regional transit agency	Optimized operation of Mixed Fleet Variable type bus operation (MFV)	Genetic algorithm and analytic optimization	Transit bus service	MFV is preferred when demand varies considerably across temporal and spatial dimensions. MFV will yield lower costs among other alternatives like single fleet and multiple fleet versions of FRT and flexible route transit services.
20	M. (Edward) Kim & Schonfeld (2014)	Hypothetical transit network	Regional Transit System	Integration of conventional and flexible bus services with timed transfers	Genetic Algorithm	DRT-FRT	The demand threshold between DRT and FRT was 0.4-0.5 trips/minute. Integration of DRT and FRT was desirable when demand densities varied considerably among served regions.
21	Qiu et al. (2014)	Hypothetical transit service	Local transit agency	Explore the feasibility of dynamic station strategy for a flexible route transit service	Insertion heuristic algorithm	Transit bus service	The proposed dynamic station strategy has a potential to decrease user costs under high demand scenarios. The strategy diminishes waiting times by at least 50% and expands the applicability of flexible route transit at 47 passenger per hour to 70 passenger per hour as compared to FRT.
22	Ryley et al. (2014)	SP survey: 409 UK residents	Regional Transit System	To investigate the sustainability of six types of DRT services	Mixed Logit Model	DRT, private car, FRT	DRTs serving airports, bus stations and employments generated more economic benefits. DRTs serving rural areas, shopping centers and hospitals met social needs.
23	Uehara et al. (2014)	Simulations in road network of Okinawa, Japan	Regional transit agency	Connecting demand responsive buses with mass transit	Insertion heuristic algorithm	Transit bus service and mass transit	The coordination system for demand responsive buses and mass transit shortened the overall trip time due to reduction in access and trip times.
24	Atasoy et al. (2015)	Hino City, Tokyo, Japan	Local Transit Agency	To introduce Flexible Mobility on Demand (FMOD) concept using an	Assortment Optimization and logit Model	Taxi, Shared Taxi, Mini-Bus	Dynamic allocation of vehicles yielded more benefit compared to static allocation. Lowest consumer surplus was generated when all vehicles served as taxi and lowest profit was generated when all vehicles served as mini bus.

S. No.	Source	Data & Location	Region applicability	Objective	Method	Mobility modes	Key findings
				optimization framework.			
25	Marković et al. (2015)	Regency Taxi (Maryland),	Regional transit agency	An optimal solution for managing Dial a ride operation: Mobile resource management system (MRMS)	Insertion heuristic algorithm	Taxis	Concept introduced locked blocks as passenger demand fixed location on same daily routine. Proposed MRMS can reduce the annual costs by 18% of operational expenses for a mid-size DAR operator. The system also provides a tactical platform for the operator to keep track of level of service, driver utility and fleet composition.
26	M. E. Kim & Schonfeld (2015)	Hypothetical transit network	Regional Transit System	To calculate maximum welfare for both FRT and DRT service with elastic demand	Genetic Algorithm	DRT-FRT	Total welfare difference between conventional and flexible service was about 5.45% in financially unconstrained cases. Flexible services are preferred over conventional services when potential demand density is low.
27	Qiu, Li, et al. (2015)	Hypothetical transit network	Local Transit Agency	To help planners to choose between fixed-route and flex routes for MTA Line 646 in LA county	Insertion Heuristic Algorithm	DRT-FRT	Flex route policy by Criterion RP performed worse during peak hours of weekdays but performed better with a lower L/W ratio of the service area. Slack time increases with smaller L/W ratio of the service area.
28	Qiu, Shen, et al. (2015)	Route 289, Zhengzhou City, China	Local transit agency	Evaluation of four types, demi-flexible, fixed, flex route, and flex-route with dynamic station-based services	Temporal Poisson distribution	Transit bus service	Demi-flexible or flag-stop services and flex route services are preferred by slow walking passengers under low to moderate demand conditions. Dynamic station policy bolsters flex route transit in adjusting under low demand conditions.
29	Yu et al. (2015)	Hypothetical transit network	Local Transit Agency	To determine an optimal set of routing and stopping decisions for a circulator bus	Bi-level non-linear mixed-integer programming model	DRT	Integrative search with exhaustive neighborhood (IS-SN) outperformed other algorithms for MLK stations, Austin's Case for its outstanding computational efficiency. Selecting bus stops adjacent to the high demand destinations reduced out of vehicle travel cost and total system cost.
30	Chen & Nie (2017)	Hypothetical service area	Local transit agency	Hybrid transit system integrating FRT with demand adaptive system	Metaheuristic algorithm	Transit bus service	Proposed hybrid service outperforms FRT under low demand levels in small areas. FRT outperform DAPL-HT when users prefer walking. The total system cost is least in DAPL-HT under all demand levels. Higher agency costs in DAPL-HT are offset by less user costs as compared to FRT.

S. No.	Source	Data & Location	Region applicability	Objective	Method	Mobility modes	Key findings
31	Qiu et al. (2014)	SP survey: 121 American respondents (Chicago)	Regional Transit System	To assess demand for flexible transit in Chicago region	Multiple choice models	Car, Traditional Transit and Hypothetical Flexible Transit	Waiting time for flexible transit vehicle was valued less than in-vehicle travel time. Suggested target market of flexible transit users were the employees not receiving commute cost reimbursement and car drivers who disliked driving.
32	J. Shen et al. (2017)	Service area and on-demand stations in Nanjing city, China	Local transit agency	Connecting demand responsive system with on-demand station through vehicle routing	Two-stage routing model	Transit bus service	The proposed service is suitable for specific conditions near transfer points like medium sized areas with low trip densities. The two-stage model are befitting for implementing demand response connector in a specific service area.
33	Papanikolaou et al. (2017)	Literature synthesis	Regional Transit System	Clarify the role of DRT system within the public transportation market	Literature Review	DRT	At urban/interurban level developing a network of DRT lines was suggested if the demand was low and scale was small. At urban level a new DRT service was suggested for people of special needs if the network was corridor level type.
34	Alonso-González et al. (2018)	Breng flex DRT pilot in Netherlands	Regional transit agency	Evaluating the potential of DRT services in complementing or substituting FRT services	Performance benchmark framework	Transit bus service	About half the times, passengers perceived FRT as twice longer as DRT services. DRT service improved accessibility of served trips as compared to FRT services. Introduction of DRT service could deter the performance of FRT, and authors suggest DRT-FRT coordination to maximize coverage and minimize associated risks.
35	Guo et al. (2018)	Hypothetical service area	Local transit agency	Development of a dynamic policy to enable a switch between fixed-route and flexible route service	Analytical decision model	Transit bus service	The proposed policy to switch between fixed and flexible service based on demand and operational thresholds can reduce about 72% operating costs. The cost of switching and thresholds are not symmetric and constant and change as per transportation system conditions and demand.
36	Navidi et al. (2018)	Hypothetical transit network	Regional Transit System	To investigate whether replacing FRT with DRT improves mobility or not	Ad-hoc Dynamic Routing algorithm	DRT-FRT	Additional travel time (VIVT) was independent of the demand in FRT as VIVT was between 15-19 minutes for DRT but 29 minutes for FRT with 7.5 minutes headway in grid network. Replacing FRTs with DRT was found advantageous when headways were long.
37	Perera et al. (2018)	Simulation experiments (N=30)	Local transit agency	Minimizing total passenger travel time through electric fleet-based DRT service	Hybrid genetic algorithm	Transit bus service	Under moderate electric vehicle DRT fleet utilization scenarios, proposed DRT system outperformed FRT services by 19% as compared to marginal benefit under high vehicle utilization case.

S. No.	Source	Data & Location	Region applicability	Objective	Method	Mobility modes	Key findings
				to the nearest transit stop			
38	Rahimi et al. (2018)	Service area of Paratransit service in New Jersey	Regional Transit System	To develop a continuum approximation model for the operating cost of DRT system	Ordinary Least Square	DRT	Total cost increased with increase in service area, level of demand and travel factor. Marginal cost of Access link exceeded average cost of taxis when annual demand was $5x10^5$ trips/year.
39	Shaheen & Cohen (2018)	Literature synthesis	NA	To identify the trends that can lead to fundamental changes in public transportation.	Literature Review	All public transportations: DRT, FRT, Ride sharing, ride-hailing	Increasing number of DRT options is identified as one of the five trends that is expected to change the fundamentals of public transportation. DRT services can become both opportunity and challenge for public transit.
40	Y. Shen et al. (2018)	Transit network in Nanjing city, China	Local transit agency	Scheduling demand responsive connector with on-demand stations	Two-stage Vehicle routing algorithm	Demand responsive connector	The demand responsive connector developed based on two-stage routing algorithm was proved to be befitting for areas with low trip density.
41	Weckström et al. (2018)	SP survey: 1,440 Finland respondents	Regional transit agency	To identify perspectives of users and non-users of flexible micro-transit service.	Qualitative and Geospatial analysis	DRT	Reasons for service discontinuation were vehicle unavailability and long response time. Reason for using the service were lack of good public transport connection, lower cost, and faster travel choice than taxi.
42	Zhang et al. (2018)	Hypothetical transit network	Local Transit agency	To develop an analytical model to make choices between Park-and-ride (PNR) and on-demand public bus (ODPB).	Heuristic Algorithm	DRT and PNR	ODPB surpassed PNR if the population density was more than 3240 person/km^2 and less than 10400 person/km^2. For a residential area of 2x1 km^2 that had an expansion rate of 0.1km/year, introduction of ODPB service would be favorable for operators' net profit perspective after eight years.
43	Zheng et al. (2018)	Line 646 in Los Angeles, CA	Local transit agency	To test slack arrival strategy for a flexible transit service	Simulation	Flexible transit	The slack arrival strategy, enabling curb to curb pickup between two transfer stations, decreased the passenger rejection rate, system cost, and idle time at transfer points at no additional cost or change in service cycle.
44	Herminghaus (2019)	New York City, Hamburg,	Regional Transit System	To examine the Demand Responsive Ride	Vehicle Routing Problem	DRRP	The price demand curve was inelastic for higher prices. The demand increased when the price dropped below the cost of private cars.

S. No.	Source	Data & Location	Region applicability	Objective	Method	Mobility modes	Key findings
		Gottingen, Eichsfeld		Pooling (DRRP) systems on a mean field framework.	(VRP), Route Assignment algorithm		
45	Inturri et al. (2019)	Ragusa, Italy	Regional transit agency	To explore the feasibility of flexible transit based on demand and supply	Agent based simulation	Flexible route transit	A large number of vehicles with low-capacity decrease travel time at the expense of increased operating costs whereas a smaller number of vehicles with high-capacity favored operator costs. Choosing particular routes over all eliminated empty vehicle miles and increased system performance.
46	Nannapaneni & Dubey (2019)	Nashville MTA	Regional transit agency	To explore the change in travel demand due to flexible transit service	Clustering and genetic algorithm	Flexible route transit	High demand areas were categorized as flex stops and transfer stops and the slack time available from departure time from a transfer point was utilized to reroute the bus to flex stop to pick up additional passenger. The service increased travel demand by 33%.
47	Currie & Fournier (2020)	Literature synthesis	Regional Transit agency	To review the performance of DRT/Micro Transit (MT) systems with particular focus on failure rates.	Literature, Media and industry search	DRT/MT	Indicators of successful DRTs were service in areas where conventional transit service level was low, use of smaller buses/taxis to reduce cost, operation in low demand times and niche markets.
48	Z. Wang, Yu, Hao, Chen, et al., (2020)	Changsha Metro Line 1, China	Local transit agency	To design a multitype demand responsive connector for transit system	Mixed integer programming	Demand responsive connector	The mixed running mode (picking and dropping passengers) could reduce seat utilization rate, total system cost, fleets requirement and mileage per passenger.
49	Z. Wang, Yu, Hao, Tang, et al. (2020)	Hypothetical transit network	Local transit agency	TO optimize multivehicle scheduling operation under mixed demand conditions	Two-stage Coordinated optimization model	Demand responsive connector	The proposed framework optimized the fleet requirements, departure time, total system utility and running time under mixed demands