Abstract: This research presents a method of comparing fixed-route transportation systems and demand-responsive feeder transit systems using passenger survey data, published transit schedules, and optimal routing techniques. Demand-responsive transportation can be utilized to improve transit service levels in low demand areas. Since cities can vary significantly in demand across the region and time of day, it is imperative that an effective means of determining when demand-responsive services can outperform fixed-route services and vice versa. This research builds upon existing comparison techniques, that are focused on gridded street systems, and expands the techniques to include all types of street networks, transit schedules, and passenger demand levels. The generic techniques are presented and a case study is given for the city of Atlanta to determine where demand-responsive feeder systems might be implemented to improve customer satisfaction and reduce operating costs.
INTRODUCTION
Extending public transit outside of dense urban areas is a major challenge for transportation operators. In medium and low density areas, it may not be economically viable for transit to run frequent service within easy walking distance to every location (1). As a result, ridership in these areas remains low (2). One method of effectively reaching areas of low density is to use demand-responsive transportation. In a demand-responsive transportation system, buses do not run on a fixed schedule or a fixed route. Instead, the buses or vans respond to real-time passenger demand and create dynamic schedules and routes.

Since cities can vary significantly in density from one area to another, determining which parts of the city that are better suited to demand-responsive transit than fixed-route transit is key to building an efficient system. To this end, this paper proposes a method of utilizing open source data and software to compare the performance of demand-responsive transportation (DRT) and traditional fixed-route transportation (FRT) in a variety of street and transit layouts.

This paper will briefly review the state of the art of demand-responsive transportation and current methods for comparing DRT and FRT. Existing comparison techniques are best suited for homogeneous city layouts i.e., gridded street systems with a uniform dispersion of passenger locations. Those comparison methods will then be extended to compare heterogeneous layouts with random passenger locations and complex street patterns. Two case studies are presented for comparing DRT and FRT. Both of these case studies operate as feeder systems where demand-responsive transportation is used in conjunction with existing static transit infrastructure to better solve the last mile problem. The first method is applied to a simple city with uniform street layouts and passenger locations. The second method is applied to the city of Atlanta as a case study for comparing DRT and FRT in a broad range of street layouts.

BACKGROUND AND LITERATURE REVIEW
While the idea of using dynamic vehicles to meet real-time passenger ride requests is not new, interest in demand-responsive transportation has increased in recent years (3). The increase in demand-responsive transportation research is due to the proliferation of mobile phone and mobile internet devices that make the process of requesting and organizing trips faster and simpler. Mobile internet-enabled devices allow passengers to instantly submit trip requests to a transit dispatcher. The transit dispatcher collects these trip requests and dispatches one or more vehicles to transport the passengers to their destinations along an optimal route.

Review of the Dial-a-Ride Problem
The mathematical problem of optimizing a route to visit a set of passenger locations is known as the dial-a-ride problem (4). The objective of the dial-a-ride problem is to create optimal dynamic bus routes to service a set of passengers, curb-to-curbs, with a priori information of the passengers' origins and destinations. A thorough mathematical model of the dial-a-ride problem is presented by Cordeau and Laport in (4)(5).

In addition to purely demand-responsive or purely fixed-route systems, a set of hybrid systems exist known as integrated demand-response systems (6). In an integrated demand-response system, a fixed-route transit network is leveraged to decrease operating costs for the demand-responsive vehicles (7)(8). Often the role of the demand-responsive vehicles in such a system is to provide first-mile transportation to a high-speed rail or bus line (9)(10). This type
of system is known as a transit feeder system. These integrated transit and feeder systems have shown promising results for balancing the high cost and flexibility of demand-responsive systems with the highly efficient but more rigid fixed-route transit systems \((11)\)\((12)\). For this reason, the systems studied in this research operate as feeder transit systems.

**Review of Demand-Responsive Transportation Comparison Techniques**

Since this research seeks to appropriately apply fixed-route and demand-responsive transportation systems where they will be most effective, an objective method of comparing these two systems is required. Current methods of comparing DRT and FRT transportation have focused on homogeneous street layouts. Methods by Diana et. al \((13)\), compare FRT and DRT in gridded street systems as well as ring-radial systems, common in European cities. Li and Quadrifoglio perform similar analysis of feeder systems \((3)\) \((14)\). The feeder systems analyzed by Quadrifoglio and Li divide a city into multiple feeder pools where each pool is rectangular in shape with a transit station at one end of the pool \((15)\). A feeder bus then traverses the length of the feeder pool, collecting passengers and dropping them at the transit station.

The techniques developed by Li, Quadrifoglio and Diana provide an excellent foundation for comparing DRT and FRT systems and determining when a DRT will outperform an FRT system. A key contribution of their research is identifying the costs of travel for the passenger and the transit operator \((16)\). The passenger costs are broken down into walking time for the passenger, time spent waiting for a vehicle, and the riding time for the passenger. These costs do not represent all the costs levied on the passenger, notably the fare is missing from this equation. These costs are intended to represent the variable costs to the customer. Theoretically, a transit fare is a flat rate, but the time it takes to complete a trip can be controlled by the operator in real time. The transit operator’s cost is expressed as vehicle miles traveled (VMT). Once again this is not intended to represent all the costs of operating a vehicle. It is merely an approximation of the costs that can be controlled by the driver, specifically how many miles the vehicle drives. These “costs” are what the dial-a-ride algorithms attempt to minimize when selecting optimal routes.

The main drawback of the existing techniques is that the cities and service areas studied are homogeneous, meaning that there is no randomness in their layout. Each system assumes a perfect grid or circular city layout. These techniques also work best for transit systems that arrive at unchanging intervals and with passenger arrival rates that are uniform. The next logical extension of this research is to apply these comparison techniques to heterogeneous systems that include random passenger arrival rates, non-uniform street layouts, and irregular transit schedules.

**ANALYSIS OF GRIDDED STREET SYSTEM**

In the first of two case studies, a decision must be made to expand the existing transit infrastructure or adopt a demand-responsive transportation policy in a homogenous city using a feeder system. This work is a direct extension of the work by Li and Quadrifoglio where instead of analyzing individual feeder areas, the system as a whole is analyzed.

**Layout and Behavior of the System**

The bus layout of the city under examination is a grid consisting of \(N\times N\) bus stops evenly separated by a distance \(H\), as seen in Figure 1. The grid of bus stops are serviced by a set of \(N\) north/south bus lines and a set of \(N\) east/west bus lines traveling at a speed of \(v_f\) with headway \(\tau\).
In the fixed-route system, passengers walk to the nearest bus stop, wait on the bus, possibly transfer between buses, ride a second bus, and then walk to their final destinations. In the demand-responsive system, a dynamic-route vehicle carries the passenger from his/her origin to the nearest fixed-route bus stop and dynamic-route vehicle also handles transporting the passenger between the passenger’s final bus stop and his/her final destination. The set of dynamic vehicles act as a feeder system for the fixed-route bus network.

The purpose of this examination is to determine whether a dynamic, feedersystem with sparse fixed-bus stops is preferable to a purely fixed-route system with frequent stops. These two systems will be compared for various densities of bus stops as well as varying levels of passenger demand. As with Li and Quadrifoglio, a combined cost of passenger walk time, wait time, and ride time will be considered as the passenger costs, and vehicles miles traveled will represent operator costs.

Passenger Costs
To create an efficient transit system, passenger costs and operator costs must be minimized. In this example, passenger costs consists of walking time $T_{wk}$, waiting time $T_{wt}$, and riding time $T_{rd}$. The combined passenger costs, $J_p$, is represented as a weighted combination of these individual costs.

$$J_p = w_{wk} \times T_{wk} + w_{wt} \times T_{wt} + w_{rd} \times T_{rd}$$  \hspace{1cm} (1)

The cost incurred by the operator, $J_o$, is represented as the total vehicle miles traveled (VMT) of the fleet, which is a combination of the fixed-route VMT and dynamic-route VMT.

$$J_o = VMT_f + VMT_d$$  \hspace{1cm} (2)

Passenger Walking Time
For the fixed-route system, passenger locations are spread uniformly across the city, and will always walk to the bus station closest to their origin location. Therefore, the expected distance that a passenger will walk, $E(D_{wk})$, is a combination of that passenger's north/south walking distance, $E(D_{wk,n})$, and his or her east/west walking distance, $E(D_{wk,e})$.

$$E(D_{wk}) = E(D_{wk,h}) + E(D_{wk,v})$$  \hspace{1cm} (3)
With square coverage areas, $E(D_{wk,h}) = E(D_{wk,v})$, which means that $E(D_{wk}) = 2E(D_{wk,h})$.

The range of distances that passengers can walk is $[0, H/2]$, and since the passengers are uniformly spaced along this interval, $E(D_{wk,h}) = H/4$. Therefore combining the expected vertical and horizontal waking distances for the passenger yields,

$$E(D_{wk}) = 2E(D_{wk,h}) = H/2. \quad (4)$$

This represents the total expected walking distance between the passenger's origin and the nearest static bus stop. To find the total expected walking distance for the trip, this number must be doubled since a passenger must also walk between his/her final bus stop and his/her destination.

To find the total expected passenger walking time, divide the expected distance by the average passenger walking velocity.

$$E(T_{wk}) = E(D_{wk}) \frac{1}{v_w} \quad (5)$$

**Passenger Waiting Time**

Since passengers desire trips at a uniform rate, the range of wait times that a passenger must endure is $[0, \tau]$. With a uniform arrival time, the expected wait time for any bus is, $E(T_{wt}) = \tau / 2$. In the grid system, most trips will result in a rail transfer causing the passenger to experience two waiting periods. In a system with $N$ vertical and $N$ horizontal bus lines, the probability that a passenger will require a transfer is $(N-1)/N$. Therefore the total expected wait time for a trip is,

$$E(T_{wt}) = \frac{\tau}{2} + \frac{(N-1)\tau}{2N} = \frac{(2N-1)\tau}{2N}. \quad (6)$$

**Passenger Ride Time**

Similar to passenger walking time, passenger ride time is composed of a vertical and horizontal component,

$$E(D_{rd}) = E(D_{rd,h}) + E(D_{rd,v}). \quad (7)$$

For a symetric, $N \times N$, system the expected ride time is simplified to $E(D_{rd}) = 2E(D_{rd,h})$. To find $E(D_{rd,h})$, consider a single horizontal bus line with $N$ stops. Along this horizontal bus line, there are $N$ possible starting locations and $N$ possible destination locations. For each possible starting location $i$, there is an expected ride time $E(D_{rd,h,i})$. Assuming that the destination bus stop for every passenger is uniformly dispersed, there is an equal chance that a passenger's destination will be any of the other stops along the line, and the expected distance is found by,

$$E(D_{rd,h,i}) = \frac{1}{N} \sum_{j=1}^{N} |i - j|H, \quad (8)$$

for,

$$i \in 1, N.$$
\[ E(D_{rd,h}) = \frac{1}{N} \sum_{i=1}^{N} E(D_{rd,h,i}) = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} |i - j|H. \quad (9) \]

The single line ride time is then found by dividing the expected distance by the average bus speed.

\[ E(T_{rd,h}) = E(D_{rd,h}) \frac{1}{v_f} \quad (10) \]

The total ride time, vertical and horizontal, is found by doubling the expected single line ride time.

\[ E(T_{rd}) = 2E(T_{rd,h}) \quad (11) \]

**Operator Costs**

The operator’s cost is defined as the total vehicle miles traveled of the fleet. Vehicle miles traveled (VMT) of the fleet is the sum of demand responsive VMT, \( VMT_d \), and fixed-route VMT, \( VMT_f \). Fixed route VMT is found by summing the travel distance of each bus, on every line across the entire simulation time.

\[ VMT_f = 2(N + N) \frac{T}{\tau} (NH) \quad (12) \]

Where, \((N+N)\) is the total number of bus lines, \( \frac{T}{\tau} \) is the length of the simulation divided by the average headway, and \( NH \) is the length of the bus line. The product of these values is then doubled to account for buses traveling in both directions, (i.e., the north/south lines has buses traveling in both the northbound and southbound directions and the east/west lines have buses traveling in both the eastbound and westbound directions). Equation 11 can then be reduced to,

\[ VMT_f = 4N^2 \frac{T}{\tau} H. \quad (13) \]

**Simulation Results**

In this simulation, a decision must be made between implementing a demand responsive system or expanding the fixed-route system to improve customer satisfaction. The characteristics of the original system are:

- \( N \) = number of horizontal and vertical transit lines = 6,
- \( H \) = block length = 4400 ft (1342 m),
- \( v_w \) = walking velocity = 3 mph (4.83 kph) = 4.4 ft/s (1.342 m/s),
- \( v_f \) = average train velocity = 15 mph (24.15 kph) = 22 ft/s (6.71 m/s),
- \( v_d \) = average dynamic-route vehicle velocity = 10 mph (16.10 kph) = 14.7 ft/s (4.48 m/s), and
- \( \tau \) = average headway = 600s.

Four possible scenarios are considered:

1. Utilizing a DRT system where a single demand-responsive vehicle is utilized at each bus station to act as a feeder for the station
2. decreasing the distance between each bus station to 2200 ft \((H = 2200)\) to make the distance more walkable
3. decreasing the distance between each bus station to 3300 ft \((H=3300)\)
4. making no change to the system, leaving the distance between each station at 4400 ft

In these simulations, the passenger cost is defined as the average door-to-door travel time, and the cost to the system operator is defined as the total vehicles miles traveled (VMT) of the fleet. The total cost of the system is a scaled average of the passenger cost and the operator cost. A comparison of the costs in these scenarios is shown in Figures 2-5. In Figure 2, the total average door-to-door trip time of the passengers is shown for five different levels of passenger demand. The passenger demand ranges from 1.5 passengers per minute to 15 passengers per minute. The only scenario in which passenger demand affects performance is in the DRT scenario. From this image, it can be seen that for very low levels of passenger demand, a DRT system outperforms all the fixed-route only systems. However, as passenger demand increases, fixed route service with frequent stops becomes more effective. The point at which the average door-to-door travel time of Scenario 2 exceeds that of Scenario 1 is at approximately 2 passengers per minute entering the system. The point at which travel time in Scenario 3 exceeds that of the DRT system is at approximately 9 passengers per minute. For these simulations, Scenario 4 failed to improve travel time over the DRT system for any level of passenger demand. The majority of the disparity in the total trip times comes from replacing walking with a demand responsive vehicle. Situations where a DRT vehicle can improve on walking time are the ones in which the feeder system suggested in Scenario 1 will be most effective.

![Figure 2: Total Door-to-Door Travel Time](image)

Decreasing door-to-door travel time comes at a cost to the system operator. Since operator costs cannot be ignored, Figure 3 shows the travel time costs for the passenger combined with the operation cost (VMT). Notice Scenario 3 ($H=3300$). While this scenario was not the best choice for travel time, when the cost of VMT is factored in, it becomes the most effective of the three FRT scenarios. Figure 3 shows the total cost of all four scenarios as passenger request rates vary.
The break-even point between a DRT service and a fixed route service is approximately 6 passengers per minute. At rates above six passengers per minute, the best policy is Scenario 3. This example shows how demand-responsive and fixed-route transportation can be objectively compared across a city-wide feeder system with a homogenous layout.

**NETWORK-INSPIRED TRANSPORTATION SYSTEM**

In a real-world application, the street layout will be much more complex than that of the previous section. Large cities will have many types of road networks and less regular distribution of transit stations. One method of implementing a demand-responsive feeder system in a real-world setting is by following the pattern of the network-inspired transportation system (NITS) (17). The NITS is a framework in which passengers are transported through a complex metropolitan transportation system in the same manner that data packets are routed through a telecommunications network. In the NITS framework, the entirety of the transit infrastructure is treated as a packet-switched network where passengers are analogous to data packets, high-speed rail and bus rapid transit are analogous to high-speed data trunk lines, and areas of on-demand service are analogous to subnetworks or subnets.

An on-demand subnet is defined as an area in which a passenger can be routed via an on-demand vehicle without the use of a static transit route. Typically, these subnets are centered around transit stations and the purpose of the subnet is to handle transportation along the passenger’s first and last miles of travel, feeding the passengers in and out of the nearest transit station. In most trip requests, a passenger will request a ride between two points in a city separated by many miles. The first leg of the passenger’s journey will take the passenger from his or her origin location to the transit station located in his subnet. The second leg of his journey will be handled by rail or bus rapid transit. The final leg of the passenger’s trip will once again be handled with demand-responsive transportation between the transit station in his or her destination subnet and his final destination. In the event that a passenger’s origin and destination lie within the same subnet, a single demand-responsive vehicle with handle the entire request. This last scenario separates this framework from being a pure feeder system because not all passengers must be fed into the rail network.

Dividing a city into many subnets in this manner has two advantages. The first advantage is that the distance that demand-responsive vehicles are required to travel is significantly reduced. Instead of vehicles being required to transport passengers across an entire metropolitan area, they
are limited to operating within a relatively small subnet area. The second advantage deals with computational complexity (18). The dial-a-ride problem is an extension of the traveling salesman problem. Like the traveling salesman problem, the dial-a-ride problem is known to be NP-hard, which means that a solution is not guaranteed to be found in polynomial time (19). Instead, heuristic or approximate optimization techniques are required to find near-optimal solutions. By limiting the area in which a vehicle can operate and limiting the number of potential passengers that vehicle can service, the solution search space is exponentially decreased, leading to much faster search times (20), a necessary requirement for real-time accommodation of passenger travel requests.

ANALYSIS OF DEMAND-RESPONSIVE TRANSIT IN COMPLEX STREET AND TRANSIT LAYOUTS

This section focuses on extending the current FRT and DRT comparison techniques to a more heterogeneous environment, such as that of the NITS. The methods and examples provided by Quadrifglio and Li (14) deal with perfect characteristics, i.e., the passenger locations and destinations are uniformly spread throughout a region, the arrival rates of the passengers are uniform, and the street layouts are grids. In order to better compare demand-responsive and fixed-route transportation in a wider array of settings, the methods must be adapted to handle comparisons from non-uniform environments.

The problem with applying these methods to a more generic street network and set of passengers is that closed-form solutions to represent the expected walk times, wait times, ride times, and vehicle miles traveled (VMT) are not easily found. Instead, those values must be estimated from large sets of passenger data. These sets of data can be estimated through travel demand modeling, or they can be collected directly through passenger surveys. Given a large set of passenger origins, destinations, and departure times, the expected travel times and vehicle miles traveled for the fleet can be estimated for both the demand-responsive and fixed-route transportation systems.

Fixed Route Transit Costs

Passenger Costs

Given a large set of passenger origins and destinations, the expected walk, wait, and ride times can be found by identifying the optimal route between each passenger’s origin and destination, given a specific departure time. Fortunately, methods of finding the optimal travel itineraries have been developed and made available for researchers. This research uses route optimization software known as Open Trip Planner (21). Open Trip Planner is an open-source multi-modal trip planning tool capable of finding optimal transit routes given a desired starting and ending location as well as a desired start time. For each passenger origin, destination, and start time, an optimal itinerary is calculated. This itinerary returns the most efficient buses and trains for the passenger to reach his/her destination as well as the associated walking time, waiting time, and riding time for the journey. The average of these times across a sufficiently large set of passenger data will give an estimate of the expected walk, wait, and ride times for the transit system.

Operators Costs

An estimate for the total vehicle miles traveled in the system is found by analyzing published General Transit Feed Specification (GTFS) schedules (22). The GTFS schedule identifies the total number of trips that occur in a transit system as well as the length of the route for each of these...
trips. By summing the total length of each trip’s route during a given time period, a total VMT for that time period is found.

**Demand Responsive Transit Costs**
Just as was the case with the gridded street simulation in the previous section, for demand-responsive transit, the average walk, wait, and ride times of the passengers as well as the fleet VMT are calculated through simulation. Given the same set of passenger locations collected from modeling or survey data, optimal demand-responsive vehicle paths are calculated in real time. Individual passenger routes are recorded during the simulation to find average walking, waiting, and riding times.

**ANALYSIS OF DEMAND-RESPONSIVE AND FIXED-ROUTE TRANSIT IN ATLANTA**
For this exercise, the city of Atlanta is divided into 38 feeder areas or subnets. Each subnet is circular, one mile in radius, and is centered around one of Atlanta’s 38 rail stations operated by the Metropolitan Atlanta Rapid Transit Authority (MARTA). These circular feeder areas are reminiscent of the ring-radial structures discussed by Diana in (13), except that the street layout within these feeder areas follow no strict pattern. The large set of passenger data was collected through passenger surveys conducted by the Atlanta Regional Commission. The survey represents 10% of MARTA passengers between October 2009 and January 2010 (23). This survey data provides the exact origin and destination of MARTA travelers as well as the time of day they used the system. During the morning peak hours, between 6AM and 9AM, approximately 4,000 riders responded whose destinations and origins lay within one mile of a MARTA station. The goal of this simulation is to determine, for this set of passengers, whether a fixed-route or dynamic route system will best meet the passengers’ needs. The dynamic system performance will be analyzed on a city-wide basis as well as on a subnet by subnet basis. The 38 subnets studied cover a wide array of street layouts. Subnets in the city center are located in gridded street layouts. Subnets that are farther from the city center become increasingly suburban in design. This wide array of subnet layout allows for suburban and city layouts to be individually studied.

In addition to comparing the performance of dynamic and fixed-route transit for the passengers, the passenger demand rate at which a fixed-route system begins to outperform the dynamic route system will be calculated.

**Create a Set of Passengers for Study**
The first task that must be accomplished is upsampling the set of passenger data. The data collected during the survey represents approximately 10% of the MARTA riders. In order to have a set that represents 100% of the riders, the data set must be upsampled. The method of upsampling is as follows.

1. For each passenger origin location, define a circle that is ¼ mile in radius around that location.
2. Within this circle, uniformly create N new origin locations representing N new passengers, where N represents the upsample rate.
3. For each of these new passengers, assign a random departure time weighted to the match the survey departure time statistics. (e.g., if 10% of all departures from the survey occur between 7:30 AM and 8:00 AM, then 10% of all upsampled departures should also occur between
4. Repeat steps 1 and 2 for each passenger’s destination location. After this step a set of origin locations and associated departure times will have been created as well as separate list of destination locations.

5. Randomly assign each location from the origin list to a location from the destination list until all locations have been assigned.

**Fixed Route Costs in Atlanta**

Once the set of passenger origins and destinations is created, calculating travel times and VMT can begin. An Open Trip Planner instance was created for the city of Atlanta where the street layout was provided by Open Street Maps and the GTFS schedule was provided by MARTA. The optimal itineraries for all passengers within one mile of a rail station were calculated. For these itineraries, optimal refers to minimum passenger travel time. For this set of passengers, the average time to complete a trip was 54 minutes. This 54 minute time is broken down into 11 minutes walking, 16 minutes waiting for transit, and 27 minutes spent riding transit. The total VMT for the MARTA bus fleet operating within the 1 mile service area around each rail station during this time period is 7,153 miles (11,516 km).

**Demand Responsive Costs in Atlanta**

To determine the performance of a demand-responsive feeder system, a simulation was run drawing passengers from the same survey set. However, instead of using a constant arrival rate, the arrival rate was varied from 8 passengers per minute to 200 passengers per minute. The results are shown in Figures 4 and 5.

The algorithm for the demand-responsive simulation is as follows.

1. Create a set of passengers from the sample data as described by the process above.
2. As each new passenger from this set requests a trip, identify the rail station nearest the passenger. An area one mile in radius around that station, will be the passenger’s subnet.
3. For each bus in that subnet, identify the additional cost for that bus to service the passenger. The cost referred to here is a weighted average between the passenger cost and operation cost. In this particular simulation, passenger cost is defined as the time between requesting the trip and arriving at the nearest rail station. Operation cost is defined as the total vehicle miles traveled.
4. Identify the bus with the least additional cost, and assign that bus to handle the first leg of the passenger’s trip i.e., transporting the passenger from his/her origin to the nearest rail station. If no bus can handle the transporting the passenger within 30 minutes, dispatch a new vehicle to the subnet.
5. When the passenger reaches his/her destination rail station, repeat steps 3 and 4, for the passenger’s destination subnet.

Figure 4 shows the vehicle miles traveled of the fixed-route and demand-responsive feeder systems. The NITS feeder layout for Atlanta was able to meet the customer demand with fewer vehicle miles traveled for all demand levels below 67 passengers per minute. Figure 5 shows the average trip times for FRT and the feeder system. The feeder system, on average, was only able to shorten the passengers’ trip times for very small demand levels across the city. This shows that this particular DRT setup in Atlanta may have some cost savings for the transit operator, but those
savings come at the cost of increased travel times for the passengers. Combining the passenger and operator costs indicates that the NITS is the lower cost option for passenger demand levels below 48 passengers per minute. Considering that these very low passenger demand levels only occur during a small portion of the service day, late in the evening and very early in the morning, this particular demand-responsive setup should not be applied, as is, to the city as a whole. Instead further analysis must be conducted to determine which areas of the city, if any, this DRT setup will be most effective.

![Figure 4: Vehicles Miles Traveled by the Fleet in Atlanta Simulation.](image)

![Figure 5: Average Passenger Travel Time in Atlanta Simulation.](image)

One area where the feeder system outperforms the FRT system is the subnet centered on the Chamblee MARTA station. The Chamblee Station subnet is far from the city center and has a suburban street layout. Figures 6, 7, and 8 show the DRT and FRT comparisons for vehicles operating in this subnet and for passenger travel times whose trips either ended or began within this subnet. Figure 6 shows that the DRT setup in this region has significant VMT savings for all passenger demand levels tested. Unlike the city-wide travel times shown in Figure 5, the DRT system decreased travel times for passengers for all demand levels below 44 passengers per minute.
After normalizing the VMT and passenger travel time costs, shown in Figure 8, the point at which FRT begins outperforming DRT is shown to be 165 passengers per minute. This is significantly higher than the FRT break even point for the city-wide scenario.

Figure 6: Vehicles Miles Traveled of the Fleet in Chamblee Station Subnet.

Figure 7: Average Passenger Travel Time in Chamblee Station Subnet.
These results show that DRT could provide a less expensive alternative for handling trip requests for stations with relatively low demand at off-peak hours. Other stations such as North Springs Station, Doraville Station, and Brookhaven Station also showed similar improvements in costs by using DRT. All of these stations have suburban street layouts. What is interesting to note here is that demand-responsive transit in these suburban areas was less efficient, in terms of operation cost and travel times, than demand-responsive transit in the more urban areas. However, fixed-route transit is also less efficient in these suburban areas. For instance, in the Chamblee subnet, the average fixed-route door-to-door time was 72 minutes, the system average was 54 minutes. The fact that DRT was more efficient than FRT in these areas does not necessarily mean that the DRT feeder system is best-suited for suburban areas. Instead it suggests that DRT is more adept at handling the difficulties of servicing a low-density, suburban area than a FRT system.

This method of comparison also brings to light areas that need improvement in the DRT algorithms. For instance in this simulation, the demand-responsive algorithm consistently reduced vehicle miles traveled compared to the fixed-route system. Unfortunately, this savings to the operator came a large expense to the passengers in terms of convenience. Adjusting the algorithm to give more passenger-friendly route selection could improve the overall performance of the system.

CONCLUSION
The purpose of this paper is to describe a technique to compare the effectiveness of fixed-route transit and demand-responsive transit in a wide variety of street and transit layouts.

The comparison techniques were successfully used to show where a demand-responsive feeder system may outperform a purely fixed-route system in the city of Atlanta as well as how the DRT routing algorithm can be adjusted to improve performance. Since the passenger demand across a metropolitan area can vary widely due to changes in population density and time of day, it is imperative that an effective comparison technique be utilized to optimally choose when and where DRT can best meet customer demands while minimizing operator costs. It is hoped that these methods will be utilized by transit planners to determine where DRT can be used instead of FRT to save transit costs and improve customer satisfaction.

This work is intended to give planners insight into where dynamic transit can improve
customer satisfaction while also saving cost to the operator. However, the precise details of operating dynamic transit for each city or community will have to be determined on a case by case basis. Future research will focus on handling the transition between dynamic and fixed route transit throughout the day, handling the interaction between fixed-route and dynamic route transit modes, efficiently delivering passenger between these two modes, and optimally designing the size and operation of each dynamic transit coverage area.

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