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Improving Bus Transit Services for Disabled Individuals: Demand Clustering, Bus Assignment, and Route Optimization

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ABSTRACT Bus transit provides shorter-distance public transportation services, which are subject to various disability discrimination acts with various dedicated features. The Americans with Disabilities Act (ADA) requires that disabled individuals shall have equal rights to receive fare bus transit services, including fixed-route and door-to-door bus services. Most previous studies were mainly focused on policy aspects as part of the efforts of disability rights. The proper planning of demand requests from disabled individuals has been a critical issue but has gained insufficient attention. The existing methodologies in planning route for special transit buses for disabled individuals normally do not consider passengers' waiting time, lack sufficient flexibility, and have strict restrictions on the total number of served destinations. This paper proposes a four-module based methodology for the planning of bus transit, including demand information collection, demand clustering, transit bus assignment, and a linear programming-based route planning with different objective functions. Houston MetroLift bus transit service was employed as an example to illustrate the proposed method. Three scenarios during the route planning module were designed in this case study: (1) planning for pre-timed shortest distance, (2) planning for the pre-timed shortest waiting time of passengers, and (3) flexible planning. Results showed that scenario 1 obtained the shortest total travel time and the highest benefit for bus providers, scenario 2 is with the shortest average waiting time, while scenario 3 is real-time based with longer total travel time and longer waiting time. Scenarios 2 and 3 consider the special needs of disabled passengers.

INDEX TERMS Paratransit planning, clustering, transportation assignment, route planning.

I. INTRODUCTION

Bus transit is one of the typical public transportation systems that also include airline, rail train, ferry, etc. [1]. The planning of the bus transit system is a process involving the analysis, forecasting, and development for moving people and goods [2], which yields a variety of requirements and practices to increase the accessibility, coverage, and ridership of fixed-route bus and rail transportation systems [3].

The disabled individuals are, however, special groups of the population that have strong needs of bus transit services but are with difficulties to access the stops of fixed-route bus transit. The World Health Organization (WHO) estimated that, 650 million among total 6.5 billion people in the whole world were moderate or severely disabled, which takes 10% of the population. This ratio is even higher in developing countries [4]. The United States government conducted a survey aiming at people with disabilities in 1990. Among the population who attended the survey, 90% of them do not have the same opportunities as those who do not have a disability. In 1990, the U.S. federal government published The Americans with Disabilities Act (ADA), which ensures that disabled people are with equal opportunity for jobs and access to private and government-funded facilities [5].

Title II Transportation of ADA requires that public transportation should be customized so that people with disabilities may have easy access to the public transit system, which means dedicated services shall be designed for people with disabilities who cannot use the fixed-route transit services [6], [7]. This includes the specially designed transit system for people who are unable to get from one destination

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to another due to mental or physical disabilities of potential passengers [8].

In this case, public transportation planning for people with disabilities should consider the design of flexible routes where fixed bus transit routes are not directly accessible. Several studies indicated that disabled people have not been treated as equally and friendly especially on bus transit systems [9]. Kennedy and Hesla (2008) indicated that public transportation for disabled people could be improved [10]. Existing research is mainly focused on the policy aspects on how to make the bus transit more elderly and disability friendly. The bus transit system for elderly and disabled people, which usually needs to be designed at the level of door-to-door or curb-to-curb services, is, however, still not receiving sufficient attention and lack of well-performed practical implementations [11], [12].

On the other hand, most of the existing bus route planning solutions have a limitation on the number of destinations. For example, Google Maps can only support ten destinations for bus planning. This paper devotes to develop a method to plan the bus transit for the elders and disabled individuals with a large number of origins and destinations. A case study based on the Houston MetroLift program, which is serving the disabled people as a supplement of Houston fix route transit, is conducted to illustrate the proposed methodology for better solutions.

II. LITERATURE REVIEW

Disability can be defined as an impairment of cognitive, developmental, intellectual, mental, physical, or combination of these [4]. According to the U.S. Census Bureau, there were 56.7 million disabled people, which count for 19% of all population as of 2010 [13]. As of 2008, 18.5% of the population in Australia was reported disabled [14]. The number of disabled veterans in the US were 2.9 million until 2008 [15]. This number is significantly higher in developing countries and areas with war. Lots of regions and countries have proposed policies to ensure disabilities have equal opportunities and equal rights including independent living, employment, education, housing, transportation, and free from abuse, neglect, and violations [16]. The US Architectural and Transportation Barriers Compliance Board created the Rehabilitation Act to provide the guidelines for transportation and accessibility for the disabled people in the year 1973 [17], [18]. Further, the ADA in 1990 includes detailed requirements on the accessibility of disabled individuals for both fixed route and Mobility-on-Demand (MOD) bus transit system [19].

Fixed route public transit services including bus, rail, and light rail systems, are normally operated along prescribed routes by a settled schedule. While ADA requires fixed-route public transportation systems to provide services with non-discrimination, provision of service, route identification, and stop announcements [8], some types of disabled individuals are still unable to conveniently ride those fixed-route bus transit.

This calls for the Mobility-on-Demand (MOD) bus transit or paratransit services for specially required disabled individuals. It is worth noting that not all people with disabilities are eligible for ADA complementary paratransit services. Only those who are unable to access their fixed-route system are eligible [19]. In addition, ADA requires paratransit services only for areas which have fixed-route services [20]. After the ADA being executed, the paratransit services have grown rapidly and will continue to grow in the future in the U.S. [21].

The planning of the MOD bus transit system is quite different from the traditional fixed-route bus transit system, which normally includes the planning of bus lines and stops and the scheduling of bus operations. Instead, the MOD bus transit is with no fixed routes, nor stops, nor pre-determined schedule, as they offer door-to-door or curb-to-curb services, and the demand varies with time and day. As the MOD services are designed to serve disabled individuals with a relatively smaller population, the capacity of MOD bus transit vehicles would be a constraint in the service planning process [6].

A research conducted by Fu at el. (2004) discussed the methodology on types of vehicles and the number of vehicles optimization for paratransit services [22], which addressed the fleet size and mixed problem, and developed a practical procedure. Cremers *et al.* (2009) proposed a two-stage model for paratransit route planning [23], each consists of two consecutive optimization problems for the paratransit planning model. The two optimization problems are: (1) the clustering of requests into routes, and (2) the assignment of these routes to service buses. It generated random data for simulation and solved by a genetic algorithm approach [23]. However, this research only considered the day-ahead MOD bus transit planning by making a decision one day ahead, which is not so convenient in practice.

Demand clustering involves collecting the passenger demand and then assigning them into respective service buses. In the existing literature, the objective function for demand clustering is the minimization of the number of vehicles. The constraints are the capacity of buses and the guarantee of the service to demands [23]. Vehicle route planning includes the shortest path problem, which involves the optimization of the route for minimized total travel time. The current methods focus more on the maximization of the benefit of bus companies by considering the trip travel time per route and the minimized number of buses in operation, but there is less consideration on the needs of passengers. For example, passengers' waiting time is normally not fully included in the route planning process.

III. METHODOLOGY

The proposed method in this paper includes four main modules: (1) collection of service candidates; (2) demand clustering; (3) bus assignment, and (4) route selection. Figure 1 shows the inputs, modules, processes, and outputs of this methodology.

As Figure 1 shows, the block Input includes demand location and time request information, transportation provides

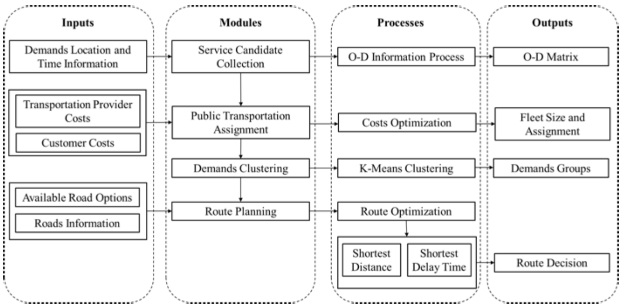


FIGURE 1. Inputs, modules, processes, and outputs of the methodolog.

costs, customer costs, available road options, and road information. The block Modules is the main body of this methodology and will be introduced in the next paragraphs. The block processes include the O-D information process, the cost optimization, and K-Mean clustering, and route optimization, with the shortest distance and shortest delay time as the objectives. The block outputs include the O-D matrix, the fleet size and assignment, the demands groups, and the route decision.

Within the block Modules, the "Service Candidate Selection" module classifies all demand information and assigns each demand into a vector. The demand information includes where and when to pick-up a passenger, and where to drop off. The output of this module is the formed O-D matrix.

The main objective of the "Public Transportation Assignment" or called "Transit Bus Assignment" module, is to decide the minimum fleet size to satisfy all demands. The inputs are the operational costs of buses. The process is an optimization model to minimize the fleet size, and the outputs are the number of vehicles in the fleet and the assignment of demands to each bus [24].

The inputs of the "Demand Clustering" module are the O-D matrix collected from the "Service Candidate Collection" module. The processes of this module are mainly the clustering of demands. The clustering procedures include clustering by passenger picking-up time and by the O-D matrix. The outputs are the groups of demands with clustered pick-up time and/or originations and destinations [25].

The purpose of the "Route Selection" module is to plan the driving routes for bus fleets. The routes should be either waiting time saving oriented or driving distance and time saving oriented. Thus, the inputs provide the available road options and road information as constants. This process is a route optimization model with the shortest travel time or lowest waiting time as objective functions. The outputs are the assigned route of each bus.

When passengers request bus transit services, they shall provide the locations of their origins with related latitude and longitude coordination, the locations of their destinations also with latitude and longitude coordination, and time ranges to be picked-up. The O-D information can be formed as a vector as: $D_{i,O} = (latitude_i, longitude_i)$, $D_{i,D} = (latitude'_i, longitude'_1)$, where $D_{i,O}$ means the origins of demand i, $D_{i,D}$ means the destination of demand i. O-D matrix could be generated by the demands vectors accordingly as are expressed in "(1) – (3)":

$$\text{origin } matrix : \begin{bmatrix} D_{1,O} \\ D_{2,O} \\ \vdots \\ D_{n,O} \end{bmatrix} \rightarrow \begin{bmatrix} latitude_1 & longitude_1 \\ latitude_2 & longitude_2 \\ \vdots & \vdots \\ latitude_n & longitude_n \end{bmatrix} \tag{1}$$

$$\text{destination matrix} : \begin{bmatrix} D_{1,D} \\ D_{2,D} \\ \vdots \\ D_{n,D} \end{bmatrix} \rightarrow \begin{bmatrix} latitude'_1 & longitude'_1 \\ latitude'_2 & longitude'_2 \\ \vdots & \vdots \\ latitude'_n & latitude'_n \end{bmatrix} \tag{2}$$

$$O - D\ matrax : \begin{array}{c} \begin{bmatrix} latitude_1 & latitude_1 & 0 & 0 \\ latitude_2 & latitude_2 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ latitude_n & latitude_n & 0 & 0 \\ 0 & 0 & longitude_{1'} & longitude_{1'} \\ 0 & 0 & longitude_{2'} & longitude_{2'} \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & longitude_{n'} & longitude_{n'} \end{bmatrix} \end{array} \begin{array}{l} row1 \\ row2 \\ \vdots \\ row\ n \\ row\ n{+}1 \\ row\ n{+}2 \\ \vdots \\ row\ n{+}n \end{array} \tag{3}$$

where n is the total number of demands. In the O-D matrix, rows $1 \ldots n$ are locations of origins, while rows $(n{+}1) \ldots (n+n)$ are locations of destinations.

The transit bus assignment can be expressed as to determine the number of buses that will be used to serve the demands. The idea is to minimize the total costs including bus operational costs, the number of buses in-service fleet, and passengers' waiting time. The optimization models can be expressed as follows.

Objective :
min F
Subject to :
$\mathrm{F} \times \mathrm{C} \geq \mathrm{R}$
$\mathrm{F} = \{0, 1, 2, \ldots, \mathrm{R}\}$

$$\mathrm{F} = \begin{cases} 1, & R\ pickup\ options\ per\ vehicle \\ 2, & (R-1)\ pickup\ options\ per\ vehicle \\ \vdots & \\ R, & 1\ pick-up\ option\ per\ vehicle \end{cases}$$

$\mathrm{R} \geq 0.$

where:

R: total O-D demands for public transportation
F: bus fleet size to serve demands
C: the capacity of one vehicle

The demand clustering module involves two parts. The first part is to cluster the demands by their picking-up time information. The second part is to cluster the demands by their O-D locations based on picking-up time. The clustering is implemented by using the K-Means Algorithm, with the objective stated in "(4)".

$$\arg_S \min \sum_{i=1}^{k} \sum_{x \in S_i} ||x - \mu_i||^2 \tag{4}$$

where, observations $(x_1, x_2, \ldots, x_n)$ are clustered into k sets: $S = (s_1, s_2, \ldots, s_k)$ with $k \leq n$.

For the clustering of picking-up time, the requested picking-up time is listed in set $T = (t_1, t_2, \ldots, t_n)$, which will be clustered into a set of groups so as to allow the maximum waiting time within a range, say, 10 minutes in this paper. This means for each passenger, the transit bus shall arrive at his/her trip origin within 10 minutes of his/her requested pick up time.

For the O-D clustering, each row of the original matrix in Equation (1) and destination matrix in Equation (2) are used as a vector. As the buses shall always arrive at the origin before reaching its corresponding destination for each demand, the location of row i should always be placed before the location of row $(i + n)$ for each O-D pair in Equation (3).

The proposed route planning model not only minimizes the costs of transit buses themselves including bus operational costs, and but also maximizes the welfare meaning of picking up by carrying as many passengers along one route as possible.

Figure 2 shows the diagram of bus transit operation for disabled individuals. Once a demand is received, the first step for the system to do is to prepare the most suitable bus, and arrive at the picking-up location timely. The time difference between the requested time and actual vehicle arriving time is the demand waiting time. Once a passenger is on board, the bus shall go to the next location, either a destination of one of the boarded passengers, or a new picking-up origin. The time difference between bus departure time and the time arriving at the next location is the driving time. Both waiting time and driving time should be analyzed and minimized.

Therefore, there are two main courses to save time cost. The first course is to save the demand waiting time, while the second course is to save the driving time. The first course needs to be analyzed based on the demand location and picking-up time to ensure that, passengers' waiting time is minimized. The second course is generally the shortest path problem, which could be expressed as:

Objective :
$\min \sum_{i=1}^{m} X_i$
Subject to :
$\sum_{i=1}^{m} D_i \leq C$,

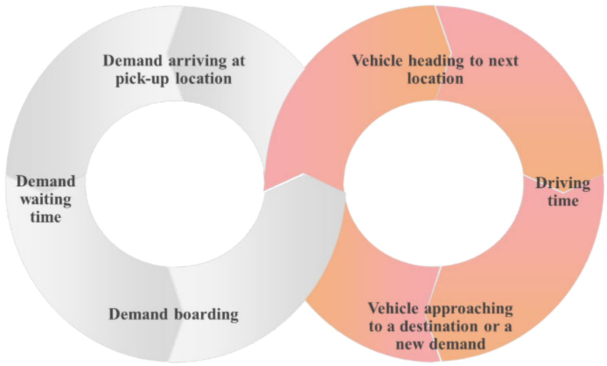


FIGURE 2. Diagram of bus transit operation.

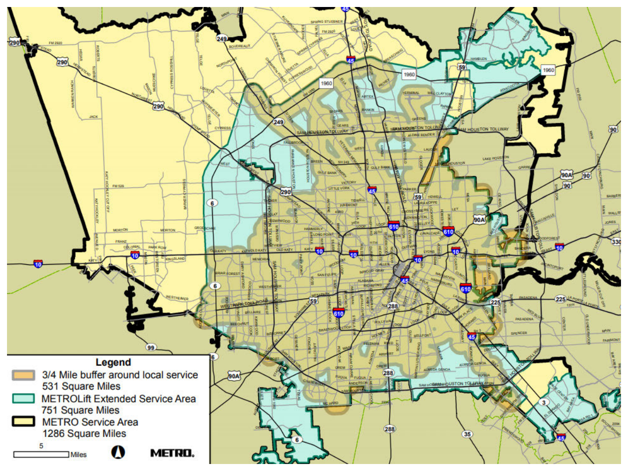


FIGURE 3. The service area of Houston MetroLift including both ADA required and non-required areas.

$$L_i = \begin{cases} 1, & \textit{Road i is chosen in route} \\ 0, & \textit{Other} \end{cases}$$
$\sum_{i=1}^{m} L_i \geq 1$,
$D_i \geq 0$

where:

C: capacity of vehicle, constant
L_i : road i
X_i : length of road L_i
D_i : demands along the road L_i
m: total number of available roads

IV. CASE STUDY

As a case study, the Houston MetroLift bus transit service is used as an example to illustrate the proposed methodology.

The Houston MetroLift, which is wheelchair accessible, is currently running in Houston area providing curb-to-curb and door-by-door services to disabled individuals. The total service area is 557 square miles as is required by ADA, and another 215 square miles that are not required by ADA (Figure 3).

In Figure 3, the ADA required service area is filled in orange color, while the area in blue color is the non-required

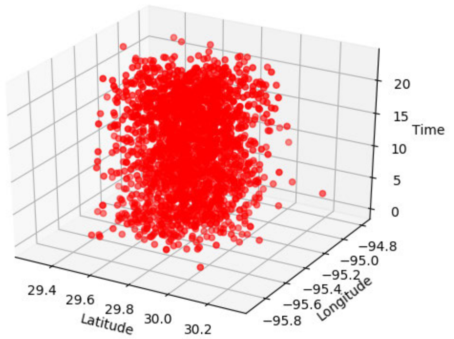


FIGURE 4. Total demand' origin information including time and locations.

of ADA. Both are Houston MetroLift service areas. The first picking up time is 3:25 a.m., while the last drop off time is 3:35 a.m. for the ADA required area. The total number of available vehicles is 118 Houston Metro bus transit vans with 200 yellow cab taxies as backups. Based on the historical statistics, the average demands on weekdays is 5,285, 39% of which used bus transit services. This means, there was an average of 2,061 demands for Houston MetroLift service in a weekday.

A. SERVICE DEMAND INFORMATION

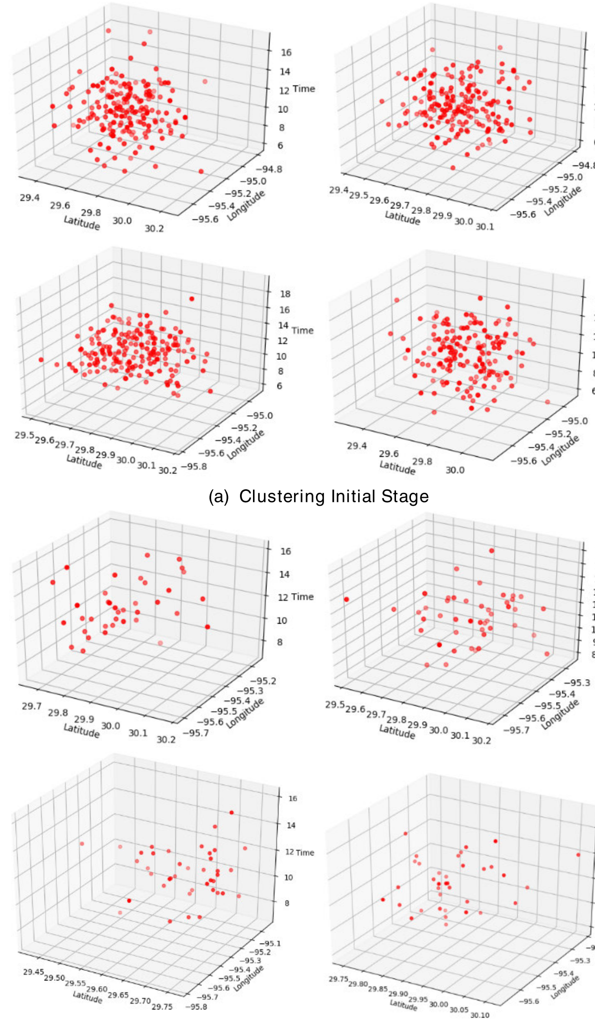
During the simulation test, the service demands were randomly generated based on the historical distribution of the demands with a total number of 2,061. The 3-D view of requested picking-up time and locations of the demands are shown in Figure 4.

In Figure 4, the x-axis shows the origin's latitudes, the y-axis shows the origin's longitude, and the z-axis shows the requested picking-up time of demands. The peak hours of picking-up demand are concentrated in the range of 10:00 a.m. to 6:00 p.m. which matches the busiest office hour period of a day. The picking-up location is focused within ($Latitude = 29.4$ to 30.0, $Longitude = -95.4$ to -94.8), which is the downtown area of Houston. The demands were then clustered by the origin information.

B. DEMAND CLUSTERING AND TRANSIT BUS ASSIGNMENT

There are several hierarchies when clustering demands. An initial state is set as 10 clusters (Figure 5(a)) for all demands to test the functioning of constraints, followed by the modification of the number of clusters for optimal solutions (Figure 5(b)).

As shown in Figure 5, the hierarchy of clustering in this research is classified into two stages. Figure 5(a) demonstrates four examples out of the 10 initial stage clusters. This stage uses K-Mean clustering with $K = 10$. The demands are then clustered by the picking-up time and locations. Each cluster in this stage contains 156-239 demands. The results of this clustering stage are then imported into the transit bus



(a) Clustering Initial Stage

(b) Clustering Final Stage

FIGURE 5. Examples of clustered demand.

assignment process. In this case study, the 10 clusters trigger the constraints that total travel time for one bus should be less than the service time. Then one cluster is added to the number of clusters and processed through the next clustering and optimization iteration.

Figure 5(b) demonstrated the four examples out of the total 53 final stage clusters. Each cluster contains 25 - 49 demands. The number of final stage clusters is derived from the optimization process of the transit bus assignment. Thus for this case study, there are 53 buses scheduled to serve the demands. Each bus is assigned one cluster of demands. Once the demands are assigned to transit buses, the next step is to plan routes for buses.

C. ROUTE PLANNING

The objective of the route planning process is to plan a suitable route for transit buses that serve a total of 53 clusters in a weekday. In this case study, we randomly selected a cluster, which contains 27 O-D demands as an illustration. The origins of these 27 O-D pairs are listed in Table 1.

TABLE 1. Demand picking-up location information for a sample cluster.

Demand	Latitude	Longitude	Picking-up Time
1	29.88274	-95.2353	7:00
2	29.79106	-95.6061	9:00
3	29.76092	-95.541	10:00
4	29.79608	-95.4636	10:00
5	29.81244	-95.4436	10:30
6	29.79928	-95.5825	10:30
7	29.8203	-95.4191	11:00
8	29.99246	-95.3265	11:00
9	29.77564	-95.521	11:00
10	29.8257	-95.3934	11:30
11	29.83001	-95.3167	11:30
12	29.74921	-95.3794	12:00
13	30.17799	-95.4741	12:00
14	29.79948	-95.4475	12:30
15	29.76793	-95.6849	12:30
16	29.92631	-95.5741	12:30
17	29.98791	-95.4568	13:00
18	30.09888	-95.353	13:30
19	29.86749	-95.3187	13:30
20	29.8957	-95.5731	13:30
21	29.92897	-95.1572	13:30
22	30.01836	-95.4372	14:00
23	29.66225	-95.5703	14:00
24	29.96226	-95.2576	15:00
25	29.85432	-95.2779	15:00
26	29.8557	-95.5014	15:30
27	29.74588	-95.6171	16:00

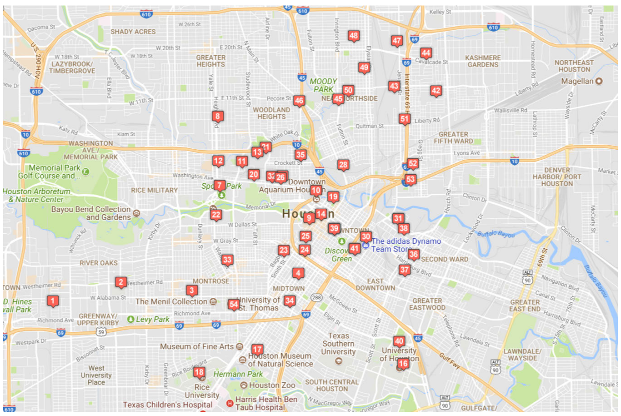


FIGURE 6. O-D locations of demands around the Houston Downtown are.

Table 1 sorts the demands by their pick-up time from the earliest to the latest. The picking-up time for this cluster is from 7:00 to 16:00. In Table 1, the O-D locations are mainly gathered in the Houston downtown area with a relatively higher degree of aggregation during the clustering process.

Figure 6 shows the O-D locations of the 27 demands marked with numbers. Numbers 1-27 are origins of demands, while numbers 28-54 are their relevant destinations. Among them, the number pair (n, $n+27$) for $n \in (1, 27)$ forms one O-D pair of a demand.

There are three scenarios during the route planning process: (1) pre-timed route planning for shortest distance; (2) pre-timed route planning for shortest waiting time; and (3) flexible route planning.

TABLE 2. Route planning result summary.

Sce nari o	Total Driving Time	Total Driving Distance	Shortest Waiting Time	Longest Waiting Time	Average Waiting Time
1	3 Hours 30 min	44.9 miles	0	45 min	22 min
2	6 Hours 46 min	109.4 miles	0	31 min	12 min
3	7 Hours 38 min	137.4 miles	0	34 min	25 min

The pre-timed route planning scenario for the shortest distance requires that all demands shall submit their serving requests in the previous day. The objective of this scenario is to plan the shortest driving route for buses. This scenario has three assumptions in this case study.

- The demand information is collected before the bus deploys;
- The demands do not change during the bus driving period; and
- There is no significant change in traffic situations on roads between route planning and actual bus driving.

The pre-timed route planning for the shortest waiting time shares the same assumption as the pre-timed route planning for the shortest distance. The objective of this scenario is to plan the route with minimized waiting and driving time.

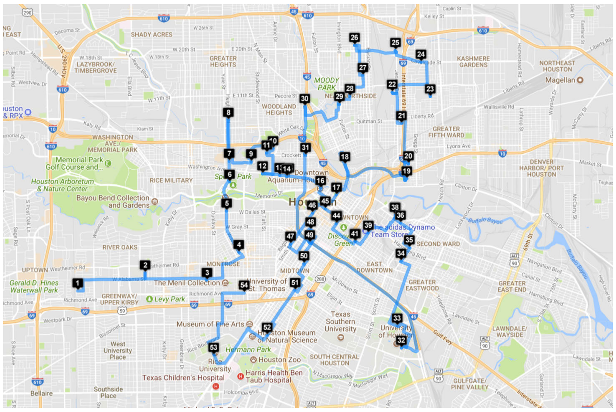
The flexible route planning does not require all demands to submit the service request one day before service. The objective of this scenario is to pick up the passengers per their real-time requests. In this case study, there are several assumptions for this scenario.

- Demand information does not change after the service requests have been submitted, and
- There is no significant change in traffic situations on roads since.

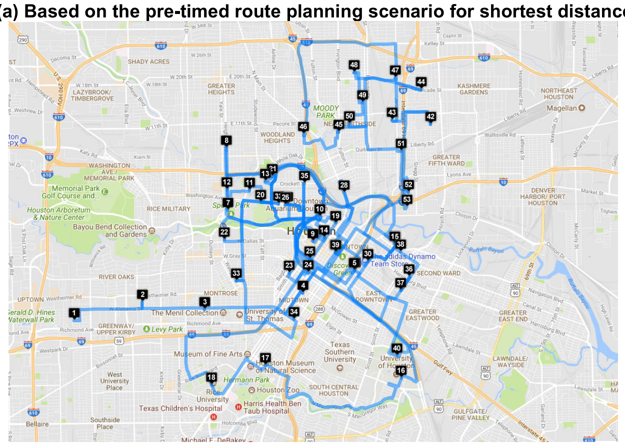
Figure 7 shows the route planning results of the three scenarios. The numbers with black tags are the picking-up sequence for all requested services. Figure 7(a) shows the planned routes for the pre-timed shortest distance scenario, Figure 7(b) shows the planned routes under the scenario of pre-timed planning for shortest waiting time, and Figure 7(c) shows the planned routes under the flexible route planning scenario. Table 2 summarizes the planning results under these three scenarios.

In Table 2, the total driving distance for scenario 1 is 44.9 miles, which costs 3 hours 30 min driving with an average of 22 min waiting time and the longest waiting time as 45 min. The total driving distance for scenario 2 is 109.4 miles, which costs 6 hours 46 min driving with an average waiting time of 12 min and the longest waiting time as 31 min. The total driving distance for scenario 3 is 137.4 miles, which costs 7 hours 38 min driving with an average waiting time of 25 min and the longest waiting time as 34 min.

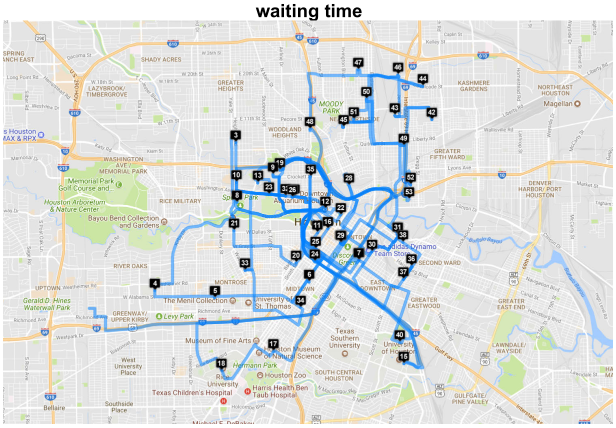
Based on the optimization results for scenario 1 with all demand information collected one day ago and the shortest



(a) Based on the pre-timed route planning scenario for shortest distance



(b) Based on the pre-timed route planning scenario for the shortest waiting time



(c) Based on the flexible route planning scenario

FIGURE 7. Driving route planning under three scenarios.

distance is considered in route planning, the transit bus company will be with the lowest operational costs and passengers also receive the shortest time on the route. The only shortcoming of this scenario is that the passengers' waiting time is relatively long. For passengers who are not so sensitive to their waiting time, especially for those who are waiting at home for bus services, scenario 1 is the best choice. However, this scenario does not accept the same day request of services. The passengers need to submit their requests one day ahead.

For scenario 2, while bus operational time is more than doubled than scenario 1, the average and longest waiting time of passengers is the shortest. This scenario is more suitable for passengers who need the fast picking up services like from the hospital or an ambient uncomfortable location. They may not care much if the driving time is longer or not. This scenario also needs the submission of requests one day ahead.

For scenario 3, the driving time and the longest waiting time are both the longest among the three scenarios. This means the operational cost and passengers' time costs are the highest. However, this scenario accepts instant service requests and is a feasible scenario for real-time services.

V. CONCLUSIONS

In this paper, a four-module methodology is proposed to better schedule the bus transit service for disabled individuals. The four modules include *Service Candidate Selection*, *Public Transportation Assignment,* or called *Transit Bus Assignment*, *Demand Clustering, and Route Selection*. The received demand requests are clustered into groups for bus assignment with one bus assigned for all demands within each cluster. and three scenarios are prepared for bus route planning. A set of linear programming algorithms is proposed to solve the planning problem. Each scenario carries out a different planning result with different advantages and disadvantages.

From the perspective of service providers, the pre-timed shortest distance scenario could yield more fuel and driver savings with a much shorter total driving distance and driving time. In the case study, this scenario may save more than half of the driving distance. However, this may result in reduced welfare of the disabled population because they need to wait for a longer time for a bus to come. Furthermore, this scenario does not allow flexible trip planning, thus disabled people need to schedule their trips early, which might be inconvenient for people in emergent needs. The non-scheduled travel demands of passengers will be delayed for a longer time.

From the passenger's perspective, the pre-timed shortest waiting time scenario could be more favorable as they could save their waiting time. In this case, however, the bus transit providers need to cost more on fuel consumption and drivers' manpower because of longer driving distance and driving time. This scenario still needs the disabled population to submit their trip request early and is thus not convenient for those who need an emergency service. The advantage of flexible route planning is that it supports non-scheduled requests for disabled individuals. In this case, the bus transit providers shall cost the highest with the longest driving distance and driving time. Passengers need to spend a longer time to wait for a bus to serve as the waiting time in this scenario is relatively longer. In a real implementation, the benefits from both bus transit providers and disabled passengers shall be systematically considered.

In future research, realistic transportation data will be analyzed with various scenarios. A numerical comparison between each scenario and planning method will be performed. A practical case study will be conducted to show how to find the optimal solution for the bus transit route planning.

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