デマンドバスを用いた階層型協調交通システムに関する研究

Doctoral Dissertation of Engineering

Study on a Hierarchical Cooperative Transport System Using Demand Responsive Buses

March 2016

Kazuki Uehara

Interdisciplinary Intelligent Systems Engineering Course
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Supervisor: Prof. Satoshi Endo

本論文は, 博士 (工学) の学位論文として適切であると認める.

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Abstract

This dissertation describes a hierarchical cooperative transport system using demand responsive buses to improve efficiency of public transport systems. In suburbs of local cities, many people rather use their car than a public transport system because it is inconvenient. The reason for the inconvenience can be considered as the distance from origin/destination to bus stop, reliability for punctuality, and a fewer number of available buses. To deal with the issues, we focused on a demand responsive bus system. The demand responsive bus system can provide flexible routes and schedules to meet customers ’ requests (origin, destination, and time). However, computational time of planning their routes and schedules extremely increases with the number of requests increases. The problem called dial-a-ride problem is known to be an NP-hard problem.

We have proposed the hierarchical cooperative transport system that can solve within the shorter computational time than conventional methods by dividing the problem into clusters of smaller problems. The system can be composed of various transportations such as trains and buses, depending on the structure of a target city. Thus, we have introduced two types of the systems consisting of different transportation. The first system is combined with urban transport system such as monorail and/or train. The system can effectively utilize existing resources. Another system consists of terminal demand responsive buses and backbone rapid buses. It can be introduced to a provincial city where insufficient transportation is provided. We have evaluated the effectiveness of the systems on both static and dynamic traffic simulations with realistic geographical data and trip data. The systems have been compared with common fixed route buses and a traditional demand responsive bus system. Finally, the feasibility of the system has been discussed.

Author's Publication List

1. Kazuki Uehara, Yuhei Akamine, Naruaki Toma, Moeko Nerome, and Satoshi Endo "Evaluation of a Hierarchical Cooperative Transport System Using Demand Responsive Bus on a Dynamic Simulation", IEICE TRANSACTIONS on Fundamentals of Electronics, Communications and Computer Sciences, Vol.E99-A, No.1, pp.310-318 (2016). Copyright ©2016 The Institute of Electronics, Information and Communication Engineers

2. 上原和樹，赤嶺有平，當間愛晃，根路銘もえ子，遠藤聡志：中規模都市圏を対象としたデマンドバスを用いる階層型協調交通システムの提案，情報処理学会論文誌, Vol.57, No.1, pp.89-99 (2016).

3. 上原和樹，赤嶺有平，當間愛晃，根路銘もえ子，遠藤聡志：デマンドバスと大型車両による協調型交通システムの提案，情報処理学会論文誌, Vol.56, No.1, pp.46-56 (2015).

4. 赤嶺有平，遠藤聡志，上原和樹，根路銘もえ子：時間的交通分散を目指した旅行計画提示手法の提案，情報処理学会論文誌, Vol55, No.1, pp.438-447 (2014).

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1 Introduction

1.1 Background

Many local cities and its suburbs suffer from traffic congestion. It causes many problems such as loss of time, fuel wastage, and gas emission. In Japan, Ministry of Land, Infrastructure, Transport and Tourism (MLIT) reports that the amount of annual time losses reaches about 30 hours per person.

Traffic demand management (TDM), which is an application of strategies and policies, has been conducted in many cities to reduce traffic volume or to redistribute traffic demands for solving the problem. TDM is generally achieved by improvement of road utilization efficiency such as enhancement of car usage efficiency, shifting commuting time, promoting use of public transport systems and so on. Especially, promoting replacement of traffic mode from a private car to public transportations is effective in terms of reduction of traffic volume.

Route buses are popularly used as public transport systems. However, people living in an underpopulated area rather use a private car than route buses because of inconvenience of the bus system. The inconvenience is caused by too long distance to get a bus and fewer number of available buses. As many people choose private car, operation of the buses becomes more unprofitable for operation in the area.

In recent years, a demand responsive buses (DRBs) have been introduced in many cities. The system is referred to as a form of public transport system characterized by flexible route and schedule in shared ride mode. The system can reduce an access distance[1] because it picks-up/drops-off customers at their desired place. Moreover, the schedule of the bus is flexibly planned for request of its customers. However, the DRB system is unsuitable for operation with large amount of requests even in a local city such as the center city of a prefecture because the computational time of planning routes and schedules sharply increases with the increasing of the number of customers. Planning routes and schedules is a problem to find optimal visiting order and vehicle assignment like Traveling Salesman Problem [1] or Vehicle Routing Problem [2]. The problem is called dial-a-ride problem (DARP), and it is known as a non-deterministic polynomial hard (NP-hard) problem [3]. Consequently, the DRB system is generally operated in underpopulated areas. The detail of the DRB system is mentioned in chapter 2.

[1] Here we define an access distance as the distance between a user's origin/destination and a bus stop.

1.2 Research Objective

The main objective of this study is to propose a method which can plan routes and schedules of DRB system in a mid-sized area such as local city. In this study, local city is defined as a city whose population is approximately 300,000. The goal of this work is to operate DRB system that can provide higher level of service. As mentioned in section 1.1, planning routes and schedules of the DRB system for many customers' requests is hard to solve in practical time. To deal with the problem, we focused on grouping of customers' requests to divide the solution space. In this study, we propose a hierarchical cooperative transport system (HCTS) consisting of a terminal DRB service and a backbone rapid bus service. In the terminal part as the lower layer, small-sized vehicles such as micro-buses transport customers with the DRB system between a depot and customer's desired place. In the system, the depots are also used for customers' transit like bus stations. In the backbone part as the higher layer, cooperative rapid buses (CRBs) transport customers cooperate with the DRBs, and transport them along the transit depots to make passengers' connection with other mode including the DRBs. The system users are assigned to a depot depending on their origin and destination. The assigned customers are treated as a small group for solving the scheduling problem. By grouping customers, the schedules and routes of the DRBs can be planned in each depot respectively. Therefore, the scale of the problem can be reduced because the problem is divided into smaller DARPs concerning with the depot, then the computing time can be reduced. Providing DRB system can improve level of service because of picking-up/dropping-off its customers at their desired place and time. The system is effective especially in the area that provides insufficient transport system.

1.3 Organization of the Dissertation

The organization of this dissertation is as follows. Chapter 1 describes background and motivation of this study, and objectives. Chapter 2 introduces demand responsive transport system and summarizes the concerning researches which for case studies and planning algorithms. Chapter 3 describes our proposed system that is a Hierarchical Cooperative Transport System. In the chapter, two types of HCTS are introduced. One is the system with urban transport system such monorails. The other is provided without urban transport system for a city which has insufficient urban transport systems. Chapter 4 describes evaluation of the HCTS on the dynamic microscopic simulator developed by the authors and specification of the simulator. Chapter 5 concludes this study and leads to further improvement of the proposed system.

2 Demand Responsive Transport

This chapter introduces an overview of demand responsive buses (DRBs), and researches concerning DRBs are reviewed.

2.1 Demand Responsive Bus

Demand Responsive Bus (DRB) system provides flexible routes and schedules when the operator receives customers' requests (origin, destination, desired time). The system is referred to as a form of public transport systems between bus and taxi service characterized by flexible routes and schedules of vehicles in shared ride mode.

2.1.1 Classification of Demand Responsive Bus

The type of DRB operation is classified from the view point of routes, schedules, transit method, and reservation procedure [4]. The classification for routing method is as follows:

- Fixed-route
- Fixed-route with detour
- Flexible route (on bus stop)
- Flexible route (door-to-door)

Fixed route typed DRBs are operated on fixed routes same as fixed route bus (Fig. 2.1). However, the buses are operated when it receives requests. Fixed-route with detour typed DRBs are operated on fixed routes but they are allowed to make detour for customers who want get a bus at the bus stop apart from the fixed routes (Fig. 2.2). Flexible route (on bus stop) typed DRBs pick-up (or drop-off) customers at a bus stop which is preselected by operators (Fig. 2.3). The buses transport their customers between bus stops. Flexible route (door-to-door) typed DRBs are the most flexible in the whole DRB types mentioned above. The buses pick-up (or drop-off) customers at customer's desired place (Fig. 2.4).

The classification for scheduling method is as follows:

- Fixed-schedule

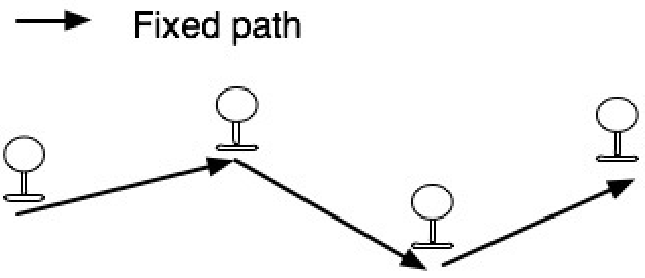

Figure 2.1: Path of fixed route bus.

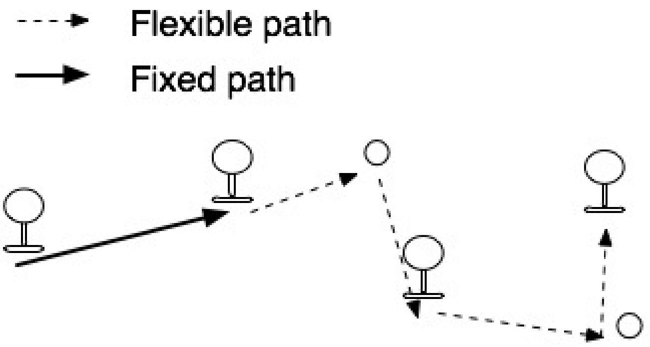

Figure 2.2: Path of fixed route bus that can change its route when demands arise.

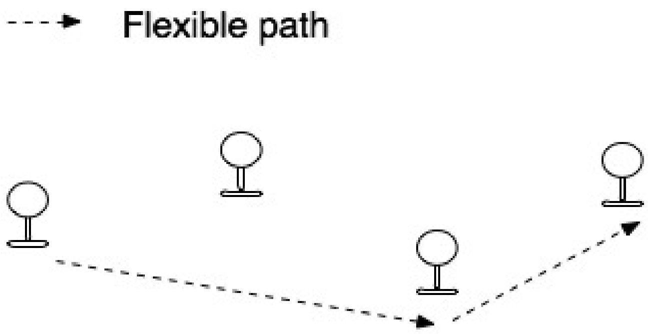

Figure 2.3: Path of demand responsive bus that can stop only at bus stop. (Semi-demand responsive bus)

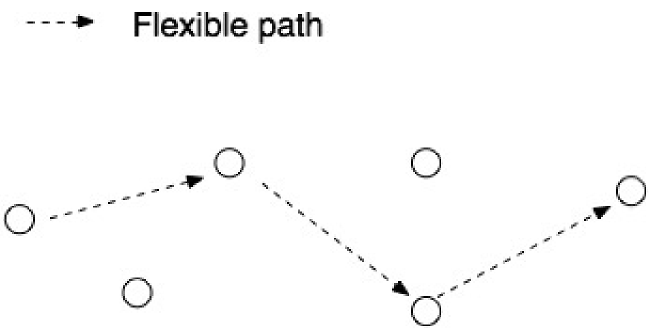

Figure 2.4: Path of demand responsive bus whose route is flexible. (door-to-door)

- Fixed-schedule (demand response)
- Flexible schedule

The fixed-schedule typed DRB is operated according to fixed schedule. The fixed-schedule (demand response) typed DRB follows fixed schedule, but it is operated when operators receives customer's request. The flexible schedule typed DRB can run anytime when the operator receives customer's request.

The classification for transit method is as follows:

- Direct line type
- Main line and branch line type

Transit method is classified into two types: direct line type and main line and branch line type. Direct line typed DRB transports customers from their origin to destination by one vehicle. On the other hand, transit typed DRBs transport customers by multiple vehicles.

The classification of reservation method is as follows:

- Batch processing
- Real time processing

In batch processing method, operators receives customer's requests until previous day or a few hours before. Routes and schedules are planned at the same time. In real time processing method, operators receives customer's requests anytime and changes the existing routes and schedules to fit the request if it is possible.

In addition, DRB system is classified by size of vehicles and whether applying membership or not.

2.1.2 Operated Demand Responsive Bus Services by Country

This section provides some case studies about DRT service operated in some contries.

United States

In the U.S., there are 1500 rural and 400 urban DRB systems. For example, RTD (Regional Transport District) provides Call-n-Ride service to Denver metro area, Golden city Colorado. The Call-n-Ride has two types of service. One is a reservation based service that requires passengers to call in advance (two or more hours before). It is generally door-to-door service. The other is a flexible route with bus stops to provide regular service during peak hours to popular destinations. The total length of flexible route is approximately 10 km.

Switzerland

In Switzerland, fully flexible (nearly door to door) DRB service called PubliCar is operated by PostAuto. PubliCar can be booked via call centers or via the Internet. The service is used as complement or as alternative to the public transport system, and it is provided in lower density area. The service is available in 32 area. On the average, approximately 50 to 90 customers use the system per a day.

United Kingdom

SPT (Strathclyde Partnership for Transport) located in Glasgow city, Scotland provides two types of DRB services to 33 areas. One is MyBus (formerly Dial-a-Bus) service provided for person having a difficulty using pulic transport due to disability or to age. The other is MyBus Rural (formerly Ring 'n' Ride) service provided for residence living in area having limited or no public transport system. SPT recieves approximately 1350 requests per a day. The customers for SPT services is mainly elderly and or disabled people.

Japan

Junpuzi provides DRB service called Convenicle (Convenient and Smart Vehicle). The service is collaboratively developed with The University of Tokyo. Their buses stop at predetermined place (flexible route on bus stop) and runs when the time period that fixed buses are not operated. Convenicle is operated in 32 area having approximately 30 km^2.

2.2 Study of Demand Responsive Bus

Study for the DRB system is mainly classified into two types. One is developing scheduling algorithms for the DRB operation called dial-a-ride problem and the other is evaluating the service quality of the DRB services.

2.2.1 Algorithms for the Dial-a-Ride Problem

The Dial-A-Ride Problem (DARP) is the problem to make routes and schedules for n customers requesting pickup point and delivery point. In the standard version of the DARP, k fleet of vehicles based at the same depot provides transport service. The objective is to create a set of minimum cost of routes for vehicles satisfying as many requests as possible with a set of constraints.

The DARP is derived version of a number of vehicle routing problems such as the Pickup and Delivery Vehicle Routing Problem(PDVRP), which is known to be NP-hard Problem. What makes the DARP different from such the problem is considering human perspective. From this reason, constraints concerning with time is narrower than common PDVRP.

The DARP has two types of variation with respect to processing request method: static DARP and dynamic DARP. For the first case, all of requests are known in advance, while for the second case, requests gradually arise throughout operational time. The routes and schedules are adjusted to the revealed requests in real-time. Moreover, there are some variation of the DARP. For example, several depots and heterogenous vehicles are considered.

The nature of the DARP can be categorized [5] as follows:

- The pattern of origins to destinations (one-to-many, many-to-many, many-to-one).
- The type of reservation (advance, real-time).
- The number of depots (single or multiple).
- The number of vehicles (single or multiple).
- The type of request (pick-up, drop-off or both).
- The treatment of trip time (static or dynamic).

The objectives can be categorized as follows:

- Objectives related to operators:
  - minimizing the total vehicle travel time.

- minimizing the number of vehicles used.
- minimizing vehicle waiting time.
- maximizing the total number of trips per vehicle.

- Objectives relative to customers:
  - minimizing customers' excess ride time.
  - minimizing customers' waiting time.
  - minimizing customers' actual ride time.

Most DARPs optimize above objectives under the several constraints. The constraints are as follows:

- Every route starts and ends at the depot.
- For every request i, the origin i^+ and destination i^- pair must be in the same route.
- The origin i^+ must be visited before the destination i^-.
- Vehicles have capacity.
- Customers specify either desired pick-up or drop-off times and must be scheduled to be picked up or dropped off at specific time periods.
- The total duration of each route must not exceed a specified time.
- The ride time of any user must not exceed a specified time.

Formulation of the Dial-a-Ride Problem

The static DARP is formulated [6] as follows: Let $G = (V, A)$ be a directional graph. The vertex set $V = \{\{0, 2n+1\}, P, D\}$ where 0 and $2n+1$ are the depots. In the elements of V, $P = \{1, \cdots, n\}$ is the set of pickup vertices and $D = \{n+1, \cdots, 2n\}$ is the set of delivery vertices. A request consists of $(i, n+i)$, where $i \in P$ and $n+i \in D$. A load q_i concerning with vertex v_i is defined as $q_0 = q_{2n+1} = 0$ and $q_i \geq 0$ $(i = 1, \cdots, n)$, and $q_i = -q_{i-n}$ $(i = n+1, \cdots, 2n)$. The arc set is defined as A $= \{(i, j) : i = 0, j \in P$, or $i, j \in P \cup D, i \neq j$ and $i \neq n+j$, or $i \in D, j = 2n+1\}$. The capacity of vehicle k is presented as Q_k, and maximal duration of route $k \in K$ is denoted by T_k. The traveling cost of arc (i, j) with vehicle k is presented as c_{ij}^k, and the travel time of arc (i, j) is denoted by t_{ij}. The maximum ride time is defined as L, and the time window of vertex i is $[e_i,\ l_i]$.

The model uses binary three-index variables x_{ij}^k is 1 when the vehicle k traverse arc (i, j). Let u_i^k be the time at which vehicle k starts servicing vertex i, w_i^k the load of vehicle k upon leaving vertex i, and r_i^k the ride time of user i. The model is as follows.

$$Minimize \sum_{k \in K} \sum_{i \in V} \sum_{j \in V} c_{ij}^k x_{ij}^k \tag{2.1}$$

subject to

$$\sum_{k \in K} \sum_{j \in V} x_{ij}^k = 1 \qquad (i \in P), \tag{2.2}$$
$$\sum_{i \in V} x_{0i}^k = \sum_{i \in V} x_{i,2n+1}^k = 1 \qquad (k \in K), \tag{2.3}$$
$$\sum_{j \in V} x_{ij}^k - \sum_{j \in V} x_{ij}^k = 0 \qquad (i \in P, k \in K), \tag{2.4}$$
$$\sum_{j \in V} x_{ji}^k - \sum_{j \in V} x_{ij}^k = 0 \qquad (i \in P \cup D, k \in K), \tag{2.5}$$
$$u_j^k \geq (u_i^k + d_i + t_{ij}) x_{ij}^k \qquad (i, j \in V, k \in K), \tag{2.6}$$
$$w_j^k \geq (w - k_i + q_j) x_{ij}^k \qquad (i, j \in V, k \in K), \tag{2.7}$$
$$r_i^k \geq u_{n+i}^k - (u_i^k + d_i) \qquad (i \in P, k \in K), \tag{2.8}$$
$$u_{2n+1}^k - u_0^k \leq T_k \qquad (k \in K), \tag{2.9}$$
$$e_i \leq u1_i \leq l_i \qquad (i \in V, k \in K), \tag{2.10}$$
$$t_{i,n+i} \leq r_i^k \leq L \qquad (i \in P, k \in K), \tag{2.11}$$
$$max\{0, q_i\} \leq w_i^k \leq min\{Q_k, Q_k + q_i\} \qquad (i \in V, k \in K), \tag{2.12}$$
$$x_{ij}^k = 0 \text{ or } 1 \qquad (i, j \in V, k \in K). \tag{2.13}$$

In this formulation, (2.2) and (2.4) mean each request is served once by the same vehicle. The equations (2.3) and (2.5) ensure that each vehicle starts and ends its operation at the depot. Constraints (2.9) and (2.12) ensure that the each equation means feasible.

Algorithms for the DARP can be categorized into exact algorithm, heuristic algorithm and meta-heuristic algorithm. Because of the NP-hard nature of the DARP, almost of its solutions are heuristic method except for fewer number of customers and vehicles. The literature review for the algorithms is provided in below.

Exact Algorithm

Psaraftis [7] has formulated and solved the DARP as a dynamic programming. The algorithm was applied to 9 requests. Their formulation did not considered time window constraint but special priority constraints was imposed. The algorithm was updated to handle time windows of both pickup time and delivery time [8].

Desrosiers et al. [9] have formulated the DARP as a forward dynamic programming. They tested the algorithm with 93 problems including up to 40 customers. Problems with over 25 requests were constructed by combining smaller problem based on time period.

Cordeau [10] has formulated mixed integer programming and introduced branch-and-cut algorithm as an exact method of the DARP. Their approach identifies violation of inequality by separation heuristic, and obtains upper bound by tabu search heuristic. Their algorithm was applied to randomly generated instances comprising up to 32 users. Their algorithm was faster than CPLEX, and some optimal solutions were identified from the instances.

Heuristic Algorithms

There are many heuristics approaches for solving the DARP within acceptable time. Psaraftis [11] has proposed two heuristic approach: route construction method based on the Minimum Spanning Tree (MST) and route improvement method based on 2- and 3-interchange procedures similar to k-opt method for the DARP. They tested the heuristic on random problem instances and their test case included up to 50 requests. Borndőrfer et al. [12] have proposed a clustering and chaining approach to schedule vehicles for the DARP. The approach consists of two steps. The first step called clustering finds segments of possible bus tours such that more than one person is transported at a time. In chaining phase as the second step, feasible routes are ordered by combining clusters. They solved their approach by branch-and-cut algorithm. They tested their approach on TeleBus test set including between 859 and 1771 requests per a day in Berlin.

Jaw et al. [13] have proposed a parallel insertion heuristic called ADARTW. The method is one of the first heuristics for the multi-vehicle DARP [6]. The algorithm processes requests sequentially, inserting one customer at a time into the schedule of some vehicle. The insertion heuristic can solve the DARP fast, can provide fair solutions, and can implement easily. They have applied the heuristic to randomly generated 250 requests and real world instance with 2617 requests. There are some improvement of the procedure and applications as the insertion heuristics perform fast and are easy to implement.

Diana and Dessouky [14] have developed a parallel regret insertion heuristic. Its route initialization procedure considers both spatial and temporal aspects of the problem, and regret insertion is executed to serve the remaining requests. The algorithm was developed for high volume problem including between 250 and 2000 requests depending on the region within Los Angeles County. The basic idea of the method is to find for each unrouted request its best insertion in each route. The metric of the regret has been employed for the study of the basic vehicle routing problem with time windows [15]. It is useful in finding feasible solutions for highly constrained problem. They tested their algorithm on dial-a-ride system data provided by Access Services, Inc. The request was generated randomly, and its each service area was 15 bins of 10×10 miles. Their algorithm has shown reduction of the number of vehicles, total trip miles, empty traveling, and operated hours relative to basic insertion heuristic on 500 and 1000 requests. And also, they have shown their improved algorithm had no significant differences with 100 requests (fewer number of requests) between their algorithm and classical insertion heuristic.

Luo and Schonfeld [16] have proposed a rejected-reinsertion heuristic that keeps the fast computational advantage of an insertion heuristic. Thier algorithm tries to exchange rejected customer and already inserted customer having similar demand in terms of time and location. In addition, they have introduced improvement procedure after the algorithm constructs solutions. Because of high computational cost, the improvement is performed only on the restricted neighborhoods. They examined their approach on randomly generated hourly instance including up to 200 requests per hour and the test cases provided by Diana and Dessouky [14].

Meta-heuristic Algorithms

Tabu search: Tabu search (TS) proposed by Glover [17] has been applied to various combinatorial problems in the operations research. The basic idea of TS is to continue local search whenever it falls into a local optimum by allowing non-improving moves; back to previously visited solutions called cycling is prevented by the use of tabu lists that record the recent history of the search.

Cordeau and Laporte have developed a tabu search algorithm [18] for the static multi-vehicle DARP and they have proposed a procedure for neighborhood evaluation. The procedure facilitates the identification of feasible solutions and improvement of the overall quality of the solutions. Their algorithm is allowed to violate time window and vehicle capacity constraints during searching procedure. They tested their method by applying to randomly generated 20 instances according to realistic assumptions. The instances contain between 24 and 144 requests. Moreover, they tested the approach on six real-life datasets provided by a Danish transporter. The real-life datasets include 200 or 295 requests. Their methodology facilitates the searching of feasible solutions, and is flexible to handle multiple depots or vehicles types, by following their previous presented framework [19].

Melachrinoudis et al. [20] have proposed a double request dial-a-ride model with soft time windows. They used TS after branch and bound method failed to solve the problem in a reasonable amount of time. The problem included 20 days was solved in each day separately. They have shown that two methods provided the optimal solution in 14 problems. In addition, TS has provided a better solution in one problem with 4 requests.

Simulated annealing: Simulated annealing (SA) proposed by Kirkpatrick et al. [21] is search algorithm that mimics tha annealing of solids. The annealing is a technique gradually cooling after heating to increase size of crystal and to reduce defects. The algorithm explores solution by making small changes to initial solution frequently at a high temperature. The solution will converge as the temperature decrease. As the change is large when the temperature is high, the algorithm can exit from a local optimum.

Baugh et al. [22] used simulated annealing method to solve a multiple objective DARP for the Winston Salem Transit Authority. Their work is based on classical cluster-first route-second approach. The clustering is performed with simulated annealing. Their approach was applied to real-life data set with 300 customers. The algorithm showed near to global optimal solution.

Mauri et al. [23] have proposed general mathematical and multiobjective model to represent the DARP and applied SA with other heuristics to treat the model. In their SA, initial solution is constructed by distribution heuristic that makes vehicle routes, and programming heuristic presented by Cordeau and Laporte [18] reduces the violations of time window in the routes. For making changes to initial solutions, they employed Re-order route, Re-allocate points and Change points as neighborhood structure. These changes are presented in other works ([18], [2]). They tested their approach with instances containing between 24 to 144 requests. The results have shown that their SA method improved service time of customers relative to the other heuristics.

Genetic Algorithm: Genetic Algorithm (GA) is a search heuristic that mimics some of the processes of natural evolution [24]. It simulates the survival of individuals over continuous generations. The evolution starts from a population that is set of randomly generated solutions presented as individuals. In each generation, fitness of individuals are evaluated. The fitness is usually the value of objective function in the problem. Adaptive individuals are selected to form a next generation by using genetic operators. The genetic operators usually consist of crossover and mutation. Crossover is used to make offsprings deriving characteristic of their parents, that means exploring near to the parents solutions. Mutation procedure is used to maintain diversity of the population, it prevents convergence of solutions to a local optimum.

Uchimura et al. [25] have proposed routing method for the DARP using GA. Their proposed algorithm can easily select the routing and scheduling assented from the view point of customers or operators by adjusting the parameter k. They solved the DARP with 10 customers' requests by GA, and have shown sensitivity analysis for the parameter k.

Jorgensen et al. [26] have proposed implementation of heuristic approach using cluster-first route-second framework for the DARP. GA is used for clustering phase, and routing is solved using the space-time nearest neighbor heuristc developed by Baugh et al. [22]. They tested their approach with test set provided by Cordeau and Laporte [18]. The test set includes 20 instances containing between 24 and 144 requests. Their result has shown better service quality than that of Cordeau and Laporte [18].

Cubillos et al. [27] have applied GA to the DARP, and they have proposed specific encoding of GA for the problem. They have shown their proposed encoding for gene: bus-passenger representation, a tournament selection, the partially matched crossover, and the 2-opt operator for mutation are better for configuration of GA solutions. Their result has shown the solutions obtained by GA were comparable to the ones solved by insertion heuristic proposed by Jaw et al. [13] with respect to the number of vehicles for 25 requests.

2.2.2 Evaluation of Demand Responsive Transport System

Evaluating DRB system is important to realize the DRB service because availability (e.g. service quality, effect on traffic environment, and operating cost) of such the system is not clear well. Usually, such an availability is evaluated by traffic simulator or demonstration experiment. Traffic simulation is more popular to evaluate the dial-a-ride system.

Noda et al. [28, 29] have evaluated service quality of DRBs system. To evaluate the service quality, they have defined travel time as *usability*. Their simulation result has shown *usability* of the DRBs service is higher than that of the fixed route bus system when the scale of the system increases according to the number of users with keeping its profitability. Furthermore, their result indicated the improvement of *usability* of DRBs service was better than that of the fixed route service when many demands raised from/to a certain point. Koshiba et al. [30] have evaluated DRB system on dynamic simulation for realizing the DRB operation in Hakodate city Hokkaido, Japan. They constructed the simulator with open source software, and they implemented physical aspect for the DRB simulation. As a result, *usability* defined by Noda et al. [28, 29] was decreased when the service scale increased according to the number of customers with keeping its profitability. Reason for the *usability* reduction is traffic congestion due to oversupplying of DRBs. The result is different from that of Noda et al. [29], and it indicates importance of considering physical aspect of traffic simulation.

Yamato et al. [31, 32] have developed routing and scheduling algorithms for real-time DRB system. The algorithm consists of vehicle selecting algorithm and insertion algorithm. In the vehicle selecting algorithm, it selects some buses that has similar direction to customers' OD (from origin to destination) direction in time period near customers' desired time. In insertion algorithm, it tries inserting a customer's request to schedule sequence of the bus selected by the bus selection algorithm. Tsubouchi et al. [33] have developed reservation system for the DRB services that can inform its users of estimated arrival time when they make a reservation. As demonstration test, Tsubouchi et al. [34] have compared the result of simulation and that of demonstration test in Moriyama city Shiga, Japan. The simulation have been achieved by computer-supported cooperative work (CSCW) that is frame work for supporting cooperation between municipality and the system users. The result has shown their simulator has had few difference between the simulation and demonstration test.

2.3 Summary

This chapter has shown introduction of demand responsive bus (DRB) and its case study and literature review concerning with DRB.

In section 2.1, the classification of the operational method of DRB and introduction of the bus system operated in some countries has been provided. Many countries operate DRB service for elderly and/or disabled people to provide transport service.

In section 2.2, studies for DRB system that are planning routes and schedule algorithms and simulations for operation of DRB, have been provided. There have been many studies for routing and scheduling of DRB called dial-a-ride problem (DARP). Algorithm for the DARP known to be an NP-hard problem are almost heuristic approach except for very small problem size. The algorithms are classified into 3 categories: exact method, heuristic method and meta-heuristic method. Especially, insertion heuristics are popular because thye are fast, easy to implement, and can be handled easily with various constraints. While meta heuristics aproach such as tabu search can provide better solution, they require a lot of computing time, complex parameter tuning, and appropriate design of the problem. For the DARP algorithms, Cordeau and Laporte have given a comprehensive review [6].

3 Hierarchical Cooperative Transport System

3.1 Introduction

This chapter introduces a new transport system that is a Hierarchical Cooperative Transport System (HCTS) consisting of demand responsive buses (DRBs) and trunk transport system. The system can be composed of various transportations such as trains and buses, depending on the structure of a target city. Then, we have proposed two types of HCTS consisting of different transportation. The first system is combined with urban transport systems such as monorails and/or trains [35]. The system can effectively utilize existing resources. The other system consists of terminal demand responsive buses and backbone rapid buses [36]. It can be introduced to a provincial city where insufficient transportation is provided.

3.2 Related Works

As similar study to our system, Uchimura et al. [25] proposed a hierarchical transportation system to simplify the bus network that causes traffic congestion due to frequent bus stops in major streets. Their system consists of three levels of service: Level 1 serves city-to-city transportation, Level 2 provides a community-to-community service in each city, and Level 3 offers a dial-a-ride service that connects door-to-door as much as possible within each community. To realize the system, the DRB operation should be planned in acceptable time. They have introduced genetic algorithm to solve the DARP for dial-a-ride services in Level 3. As a result, they have shown effectiveness of their proposed algorithm to realize the hierarchical system by solving the problem for 10 customers' requests. It is considered that the system is designed for larger amount of customers. However, evaluation of the system has been insufficient. In addition, efficiency of the whole of the system should be discussed.

3.3 Hierarchical Cooperative Transport System with Urban Transport

In this section, HCTS with urban transport systems such as monorails and/or trains are described. Many local cities suffer from traffic congestion especially within commuting hours. One of the reason for the traffic congestion is that many people drives their private car for any purpose with decision based on trip time relative to the other transit modes. Users must cost their extra time (access time) to get the mode. Especially, such the time tends to be long in underpopulated area such as a provincial city. As a result, people rather use their private car than other traffic modes such as public transport system. Then, a number of vehicles get to concentrate at the road connecting between downtown and its suburbs in the time when the traffic demands increase. In addition, the congestion spreads gradually to other areas. Thus, reducing access time is important for promoting use of mass transit to ease traffic congestion.

We focused on DRBs that can reduce access time to get the bus because it picks-up/drops-off its customers at their desired place and time.

We have proposed HCTS that connects DRBs with existing public transport systems or cooperative rapid buses (CRBs) which is higher DRBs. DRBs collect their customers who depart from a suburban city, and transport them to a *depot* for making the customers' connection with a CRB. Then, the CRB transports customers from the *depot* to downtown. In the system, the term *depot* expresses the place where buses wait customers. In addition, *depot* is also used for transit like bus station.

Advantages of connecting customers with CRBs are as follows:

1. Increase of utilization efficiency of DRBs.

2. Reduction of the number of vehicles accessing to downtown.

3. Fast transportation with less detour and fewer number of bus stops.

Note that we have considered in morning case [1] to simplify explanation and discussion.

3.3.1 Method

The proposed concept is an attempt for reducing the access time of a person who commutes from a suburban area to downtown by a trunk transit (CRB) in combination with the special DRB designed for access to a *depot* of the CRB. Every customers of the proposed system get access to the *depot* located at the edge of a suburban area toward a central urban area by DRBs and transfers to a CRB. The CRB is also scheduled by the system to minimize the waiting time of the transit by synchronizing the departure time

[1] Time periods that many people towards downtown to go work or school.

with arrival time of the DRBs. We assumed a downtown provides sufficient transport system that can serve its customers from central station to anywhere in the city. The CRB terminates the central station of the downtown. The customers arrived at the central station can get to various place using existing public transportation such as monorail or route buses.

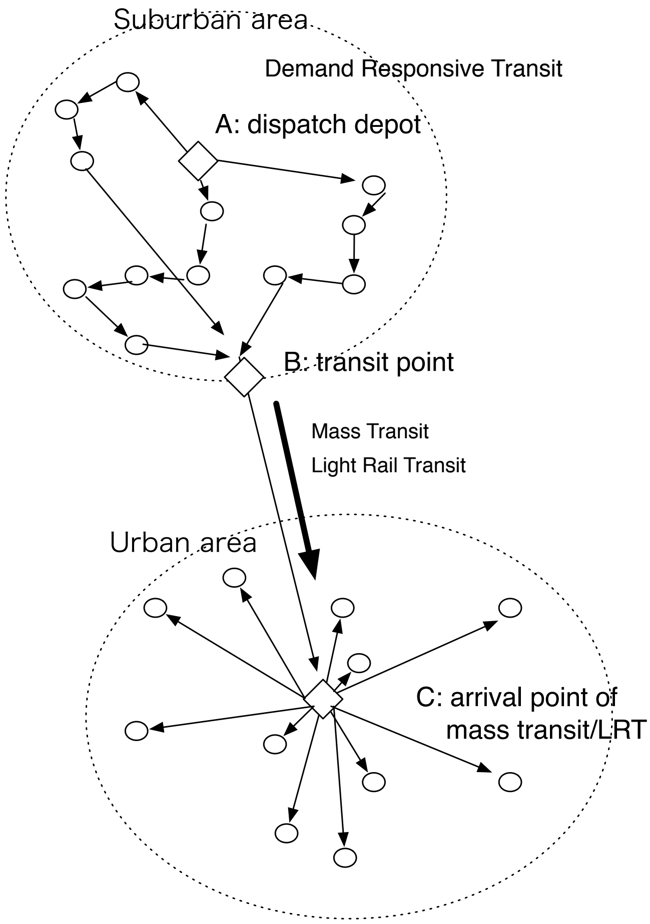

Figure 3.1: Illustration of the Hierarchical and Cooperative Transport System

Procedures for Routing and Scheduling

Using DRBs in suburban cities requires routing and scheduling of the bus by solving the DARP. In this study, the DARP is simplified by collecting customers at a transit *depot* because customers' delivery points are gathered at one point. It allows no consideration of delivery for the scheduling procedures. This section describes a new routing and scheduling method using clustering for the DRBs. Since the clustering considers only spatial aspect, the customers are sorted in ascending order of the latest pick up time (LPT) [13] to support the temporal aspect.

Routing and scheduling procedure is as follows:

1. Sort the demands in ascending order of LPT.
2. Classify the demands radially by their pickup points around the *depot*. The classified demands are assigned to DRBs respectively.
3. For each DRB i $(i = 1, 2, ..., m)$
   (a) Make routes by tracing the pickup point of the demand in the decreasing order of distance from the transit *depot* (see Fig. 3.2).
   (b) Calculate the deadline time of DRB i. The deadline time is time limit that the DRB i must arrive to the transit *depot*.
   (c) For each passenger j $(j = 1, 2, ..., n)$ of DRB i:
      i. Calculate the pickup time of passenger j and check whether he/she can board or not by his/her time window WS. If the determined pickup time is earlier than the passenger j's acceptable time, he/she is not assigned to DRB i.

Clustering of Demands

Demands in suburban area are classified by customized k-means algorithm whose distance is replaced by direction. The direction is determined from customers' pickup point and location of the *depot*. Procedures for the clustering is described in Fig. 3.3.

In the initialization procedure, place of the *depot* O, the number of clusters N, the number of maximum fleet size V_{max},and the maximum angle of the area θmax are configured. All demands are randomly assigned to any clusters to determine the standard direction as the center of each cluster. After calculating the standard direction, the direction is checked whether changed or not. If all of the direction have changed, each demand is reassigned to any cluster which has similar direction to the demand. Otherwise, the exit condition is checked. When the condition is not fulfilled, the clustering procedure is continued.

We have defined the exit condition was as follows:

$$\theta_{max} \geq \Phi_i(i = 1, 2, \cdots, N) \quad (3.1)$$

$$N \geq V_{max} \quad (3.2)$$

The Φ is the angle described by directions between two demands that are farthest each other in the cluster (see Fig. 3.4). The angle is smaller, then the route has less detour. Therefor, the trip time of each customer is short when the value θ_{max} is set to be small. However, the number of required vehicles tend to increase because operational area of each vehicle is narrow.

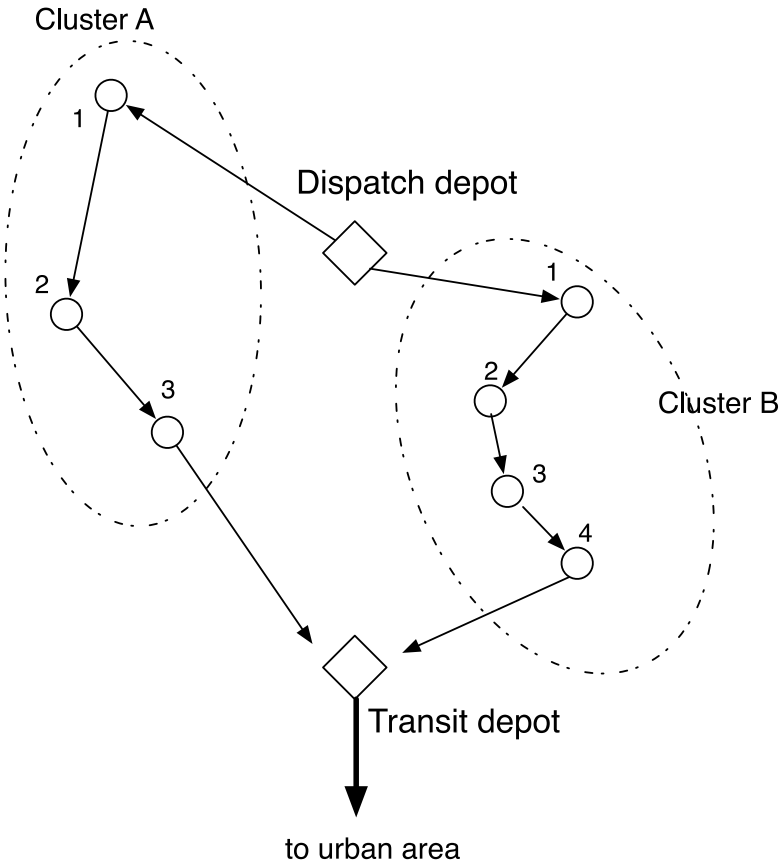

Figure 3.2: Procedure of the route designing. The routes are designed by connecting the demands decreasing order of distance from the transit *depot*.

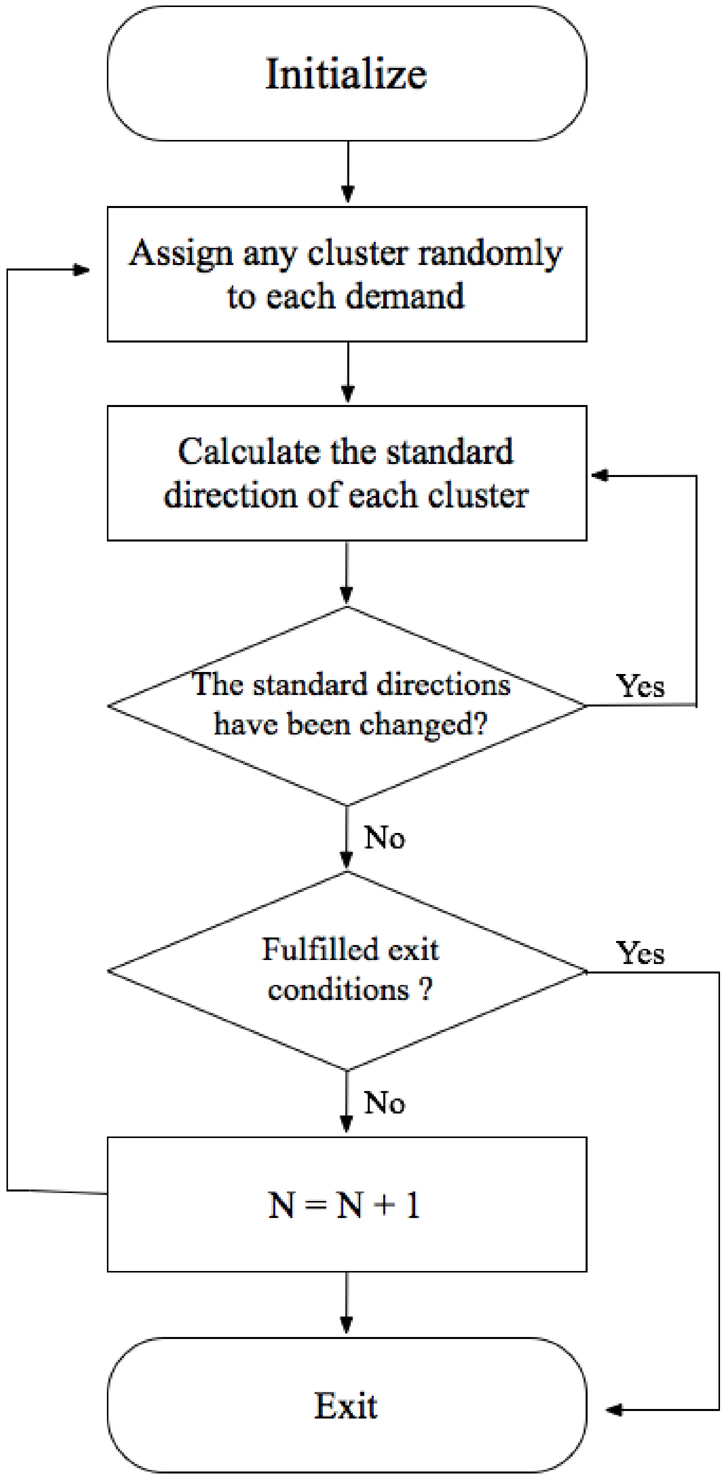

Figure 3.3: The procedure of classifying demands.

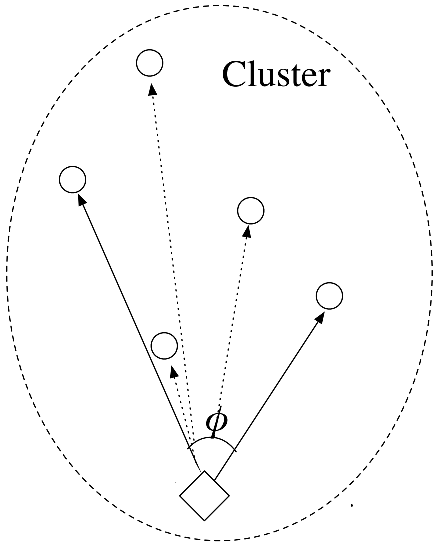

Figure 3.4: Angle Φ in the cluster which are determined by two demands.

Routing and Scheduling for DRBs

After classifying the demands, determining the route and temporal departure time is planned. It is possible that the time is changed when the demands are assigned to a CRB. The procedure for schedule of departure time is as follows:

- For each cluster i $(i = 1, 2, \cdots, N)$,
    1. Schedule deadline time DL_j of each DRB j $(j = 1, 2, \cdots, M_i)$
    2. Calculate boarding time for each customers. The time is defined by deadline of its DRB.

DL_j describes deadline for DRB_j which must arrive at arrival *depot*. The deadline is the earliest time of customers who belong to the DRB.

$$DL_j = min\ dl_k(k = 1, 2, \cdots, L) \quad (3.3)$$

$$dl_k = DAT_k - DTT(depot_C, D_k) - DTT(depot_B, depot_C) \quad (3.4)$$

where, DAT_k is desired arrival time of $customer_k$, $DTT(\alpha, \beta)$ is direct travel time from α to β by vehicle, D_k is destination of $customer_k$, $depot_B$ and $depot_C$ describe transit *depot*s those are departure point and arrival point of trunk buses respectively.

Scheduling for CRB

Customers arriving at a *depot* have to transfer to a CRB. Departure time of CRB is determined by arrival time of DRBs assigned to the CRB. It is possible that arrival time of the DRBs are different. Therefore, the difference of the arrival time of DRBs should be minimized to reduce wait time for departure of CRBs. The arrival time of DRBs assigned to the CRB is arranged by following procedures:

1. Sort the DRBs in the ascending order of their deadline time.
2. For each DRB$_i$ ($i = 1, 2, \cdots, N$):
   (a) For each CRB$_k$ ($k = 1, 2, \cdots, N$):
      i. If DRB$_i$ is the first bus for CRB$_k$, deadline of CRB$_k$ is set to the same time of the deadline of DRB$_i$
      ii. Calculate the difference Dif between the deadlines of DRB$_i$ and CRB$_k$.
      iii. For each passenger$j (j = 1, 2, \cdots, n)$ assigned to DRB$_i$:
         A. Put the pickup time of passenger$_j$ ahead by Dif. If the pickup times of all passengers are later than their earliest pick up time, DRB$_i$ and its passengers are assigned to CRB$_k$ ($i = i + 1$). Otherwise, add a new CRB ($k = k + 1$).

3.3.2 Experiments and Results

To evaluate the HCTS, we compared the system with fixed route bus and conventional full typed DRB planned with the insertion heuristic developed by Jaw et al [13]. The target area of the simulation is South Central of Okinawa, Japan. Trips were generated from Person Trip (PT) Survey Report [37] carried out in 2006.

Road Network Model

The road network model used in the simulation is constructed from digital road map 25,000 of south central of Okinawa, Japan, issued by Geospatial Information Authority of Japan. The road network was manually modified by removing pathway whose trip is very low. In this study, the cities located in the south of Uruma city are described as south central of Okinawa.

Table 3.1: Specifications of the road model used by the traffic simulation.

The num. of nodes	639
The num. of edges	2006
The total length of edges (km)	376

Figure 3.5: The road network model used in the traffic simulation.

Correction of Trip Time between Origin and Destination

In this simulation, users depart/arrive from/at any node of the network. However, users' origin and destination are actually located at any point in a traffic analysis zone that is unit of origin and destination. Thus, an estimated distance is shorter than the actual distance. The zone in the simulation is same as "C zone" in the PT survey report (see, Fig. 3.6). To correct the error, we estimated the distance d from actual origin (destination) to simulation's origin (destination) by the following equation:

$$d = k\sqrt{S} \tag{3.5}$$

where, S is area of a zone, k is adjustment coefficient of the trip distance in the zone. In this simulation, k was set as $2/\pi$. We decided the value from preliminary experiment giving higher correlation coefficient of the trip time between observed data and estimated data.

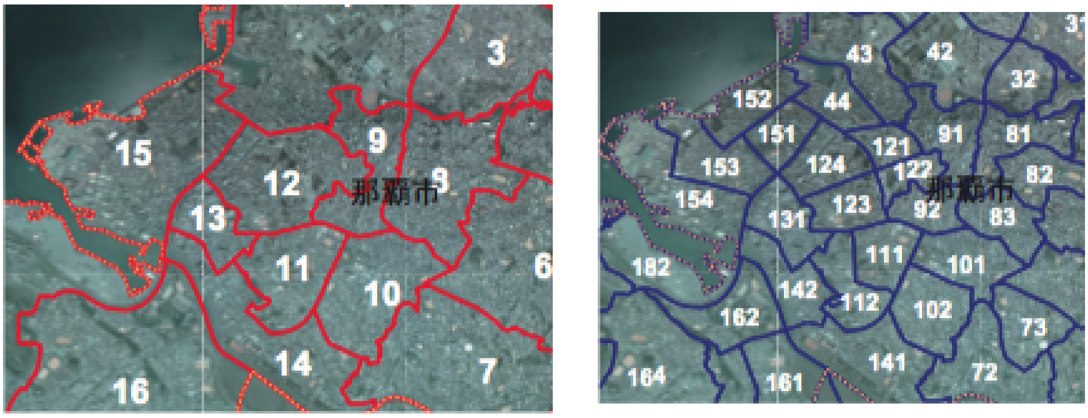

Figure 3.6: Setting of range of each zone used in PT survey report. The left image shows "B zone" and the right image shows "C zone".

Fixed Route Bus Model

The routes of the fixed route bus model was constructed from "Bus route map" used in Okinawa, Japan, in 2006. Behavior of the bus users was as follows.

- Transit between origin/destination and bus stop by walk.
- Transit between bus stops by bus.

Since we assumed that bus users choose the nearest bus arriving on desired time of the users, the wait time for boarding was not considered. In addition, the users can change their bus freely if they need. The overhead for picking up and delivering customers at each bus stop was set to 12 seconds [38].

Configuration of Simulation

The operating scenario was the following:

- The simulations for each city were independent.
- Background traffic such as traffic signals, other modes and traffic congestion was not considered.
- The number of vehicles is unlimited.
- The time for boarding and getting off took 3 seconds [39].
- Travel time for buses were constant.
- The trips whose destination was within 500m of any monorail station were used for simulation.
- Simulated time period was from 7:30 AM to 8:30 AM. The time period is peak time of traffic volume in south central of Okinawa.
- Travel speed of buses was set as 31 km/h. The speed was estimated from some time schedules and the distance between bus stops.
- Walk speed was set as 4.3 km/h [40].
- Travel speed of monorail was set as 30 km/h. The speed was estimated from time schedules and the distance between monorail stations.

Settings for the Proposed System

In the proposed system, vehicle capacity of DRBs was set to 20, and capacity of CRBs was set to 60. These capacity were assumed that DRBs were micro bus and CRBs were large sized bus. The destination of CRB was any station of monorail. The users go their destination by monorail and walk after they arrive at a monorail station. Wait time for monorail was set as 2.5 minutes estimated from the time interval of schedules. Desired arrival time of each user was determined from the PT survey report. Parameters for the proposed system were as follows:

WS = 20(min)

The maximum area angle $\theta_{max} = 60°$

The number of initial clusters = (the number of customers)/(the capacity of DRB)

We defined *AREA* that were consisting of one or more cities (or towns, villages). The placement of the *AREA* is shown in Fig. 3.7. Departure *depot* was set in each *AREA*, and located at the place that was the closest to arrival *AREA*. Arrival station of trunk bus was determined by the number of destination of the customers who depart from their *AREA*. The details of the *AREA* is as follows:

- Okinawa area: Okinawa city and Chatan town (A of Fig.3.7)
- Ginowan area: Ginowan city, Kitanakagusuku village, and Nakagusuku village (B of Fig. 3.7)
- Urasoe area: Urasoe city (C of Fig. 3.7)
- Nishihara area: Nishihara city, Yonabaru town, and Haebaru town (D of Fig. 3.7)
- Naha area: Naha city (E of Fig. 3.7)
- Nanjo area: Nanjo city (F of Fig. 3.7)
- Tomigusuku area: Tomigusuku city (G of Fig. 3.7)
- Yaese area: Yaese town and Itoman city (H of Fig. 3.7)

Naha area was set as arrival area and the others were set as departure area.

Settings for the Full DRBs

Capacity of the DRB was set as 20. Parameters for insertion heuristic were set as follows:

$$C_1 = C_2 = C_3 = C_4 = 1 \tag{3.6}$$

$$C_5 = C_6 = C_7 = C_8 = 0 \tag{3.7}$$

The parameters C1, C2, C3, C4 were determined by preliminary experiments. The others are concerning operational cost. In this study, the number of vehicles were set to unlimited. Consequently, the values were set to 0. The arrival time of customers were set from the PT survey report.

Parameters concerning time window were as follows:

$\alpha = 10$(min)

$\beta = 1.5$

WS = 20(min)

In this study, we assumed all customers have the same time window. However, the values may be different among customers. Thus, further discussion for the parameters is required.

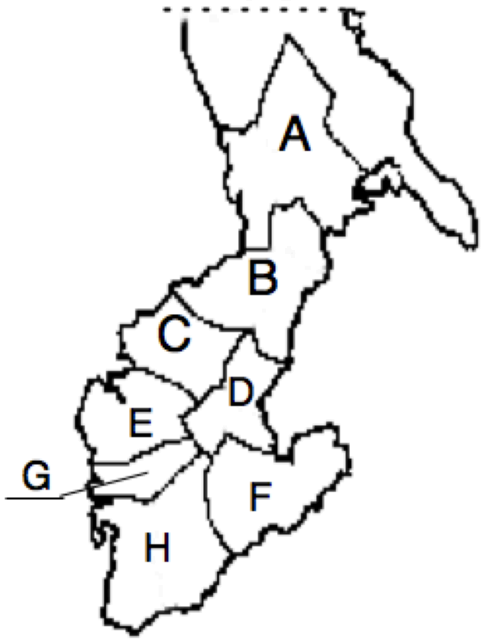

Figure 3.7: The placement of the *AREA* used in simulation.

Experiment for Fixed Route Bus Users

This section describes experiments carried out by assuming that the bus customers use the proposed system or conventional full typed DRB system.

Average Travel Time

Figure 3.8 shows average of travel time of customers transported by each transport system. Travel time means duration that from a person's pickup time until his/her desired arrival time.

In explanatory note of the Fig. 3.8, description of Demand Bus means ride time of DRB, description of Trunk Bus means ride time of CRB used in the proposed system, description of Monorail shows ride time of monorail. There must be wait time when a person arrives at their destination before his/her desired arrival time. The wait time is depicted by description of Extra time of the Fig. 3.8. In addition, the proposed system users and conventional DRB system users walk after they drop off the bus or the monorail. Figure 3.8 shows full typed DRB transported customers 5 minutes earlier than the others. The mean trip time of the proposed system customers is similar to that of fixed route bus customers. However, about 10 minutes of walk time of the fixed route users was changed

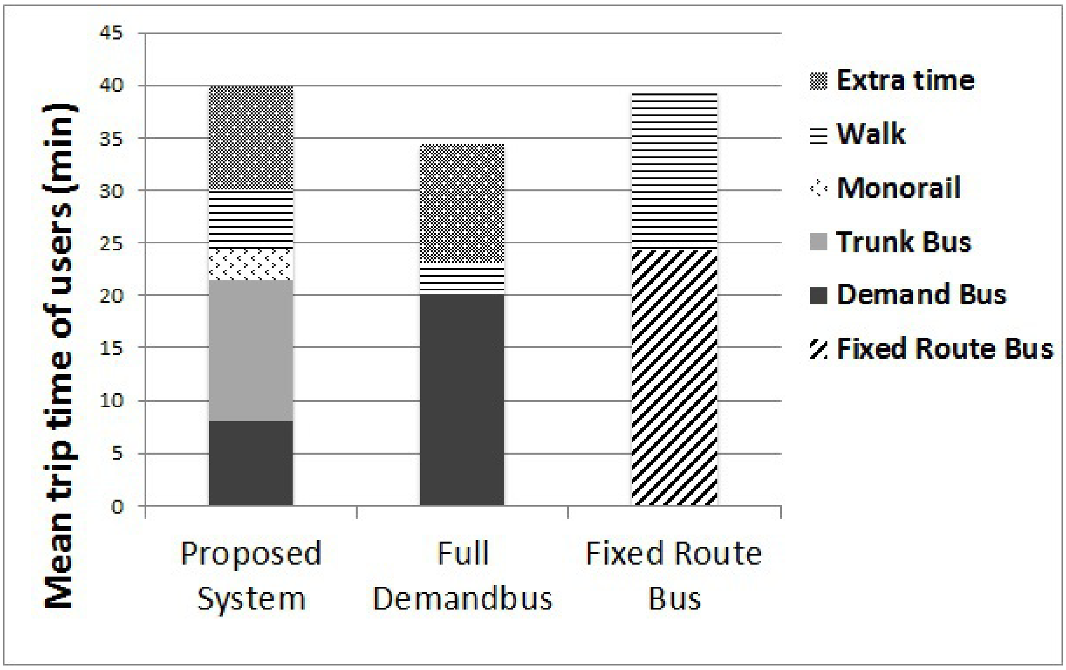

Figure 3.8: The mean trip time (minute) of users transported by each transport system.

to extra time of the proposed system users.

The Number of Required Vehicles and Vehicle Usage Efficiency

Typical *AREA*s those are not next to Naha area were extracted for evaluating the number of required vehicles and utilization efficiency of vehicles. Figure 3.9 shows usage frequency per an hour of each transport system. The usage frequency means the number of times of vehicles that they back to their *depot* after they transport all of their customers.

In the fixed route system, showing usage frequency of the system is difficult because the system across some areas. Therefore, the usage frequency of fixed route bus was calculated from the duration between bus stop located at terminal of an area and another one as reference. In the figure, the result of proposed system shows higher usage efficiency. The result of full DRB system shows similar efficiency to that of fixed route bus system.

Tables 3.2, 3.3, and 3.4 show the number of required vehicles in each area. All of results show full typed DRB required less the number of vehicles.

Change by Transition of the Number of Customers

In this section, Ginowan area was focused to experiment that the proposed system widespread situation because the area has one of the largest number of trips in the areas. The experiment was carried out with trips whose transport mode were not limited and

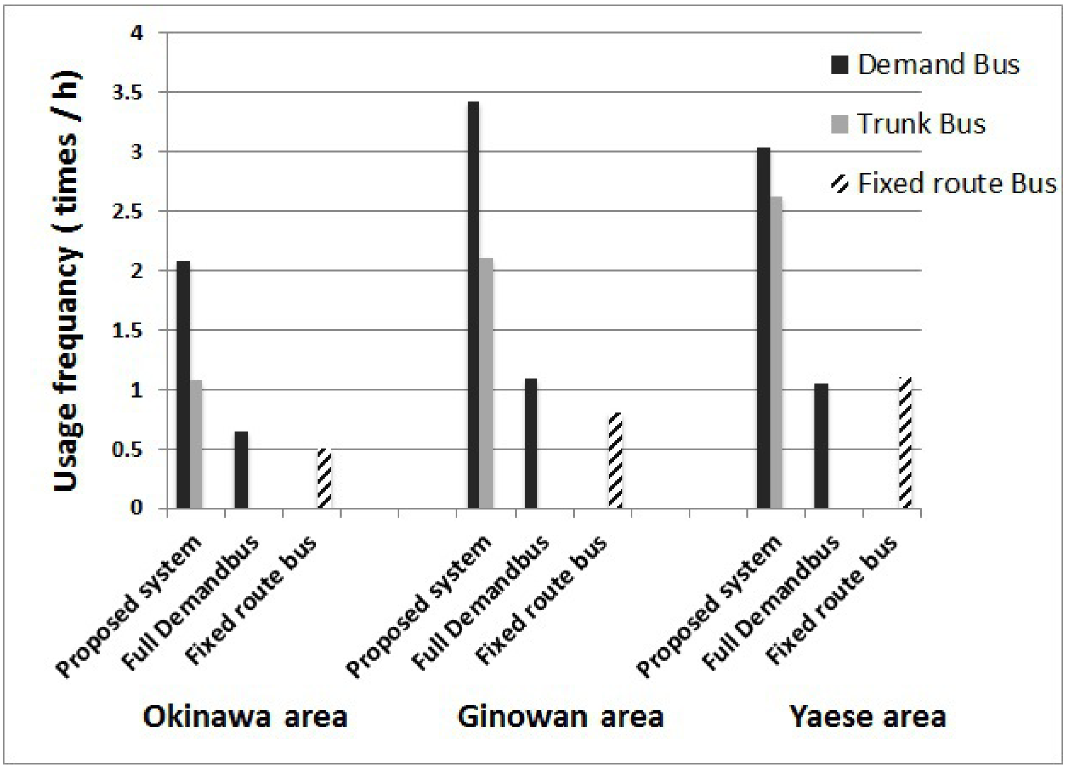

Figure 3.9: The mean usage frequency (times/hour) of vehicles.

Table 3.2: The number of required vehicles for Okinawa area

	Okinawa area (139 customers)	
	Proposed system	Full DRB
The num. of micro buses	13	8
The num. of mass transits	3	0
Total	16	8

they were extracted at a rate of 10%, 30%, 50%, and 70 %. The number of customers at each rate is shown in Table 3.5

Figures 3.10 and 3.11 describe travel time and the number of used vehicle at each rate. In Fig. 3.10, travel time of the proposed system customers decreased as the number of customers increase. On the other hand, trip time of the full DRB users were shortened but it was a little relative to the proposed system users.

In Fig. 3.11, the proposed system required much vehicles than full DRB system at the rate of 10% and 30%. However, the proposed system used less vehicles when the customers over 50%.

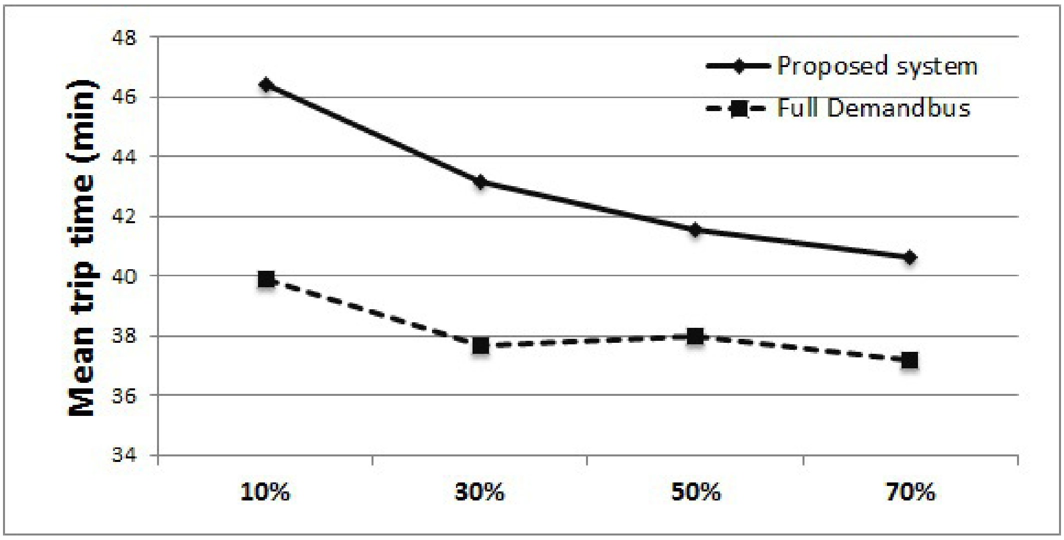

Figure 3.10: Transition of the mean trip time (minute).

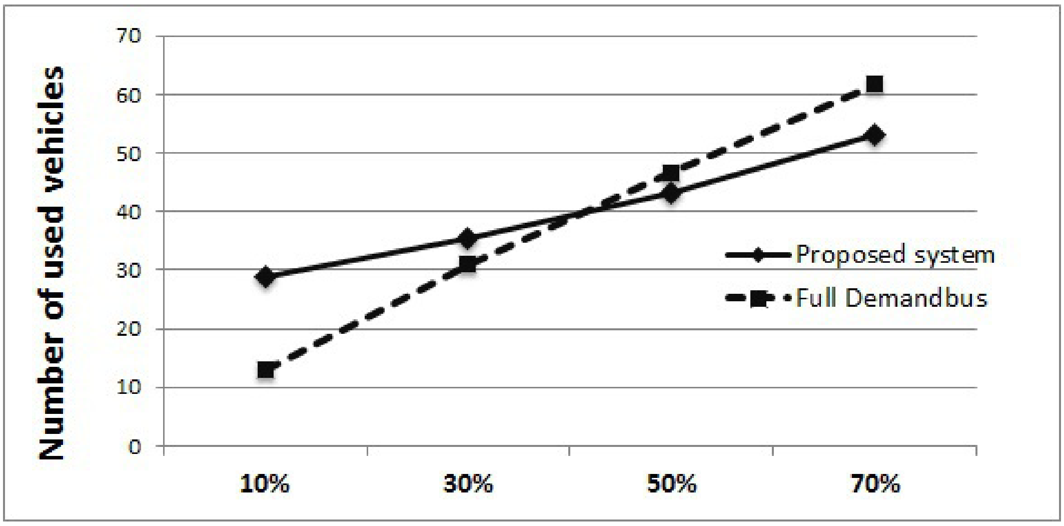

Figure 3.11: Transition of the number of used vehicles.

Table 3.3: The number of required vehicles for Ginowan area

	Ginowan area (418 customers)	
	Proposed system	Full DRB
The num. of micro buses	19	19
The num. of mass transits	5	0
Total	24	19

Table 3.4: The number of required vehicles for Yaese area

	Yaese area (253 customers)	
	Proposed system	Full DRB
The num. of micro buses	16	11
The num. of mass transits	2	0
Total	18	11

3.3.3 Discussion

Substitution with Existing Bus Services

In Fig. 3.8, trip time of full DRB users was the shortest than others. Trip time of the proposed system was same to that of the fixed route bus. However, about 10 minutes of walk time was replaced by extra time. In perspective from flexibility, extra time is generally more valuable than walk time. Furthermore, walk time of the proposed system and full DRB system was shorter than that of the fixed route bus system. It can reduce customers' load. Therefore, the proposed system and full DRB system improved accessibility relative to the fixed bus system. In addition, proposed system gathers its customers into specific places (*depot*s) and transport them by a fewer number of mass transits at a same time. It facilitates traffic management and forecast. Thus, it is expect that the proposed system is improved by trip time reduction due to combining with sharing traffic information system [41] and estimation system [42].

Table 3.5: The number of trips at each rate.

Rate of users	10%	30%	50%	70%
The num. of customers	211	609	1014	1426

Placement of depots

This section discusses placement of *depot*s. In this study, *depot*s are assumed to be placed to minimize travel time of customers, but sometimes it is difficult because of land use condition. Thus, area planning is required for optimizing the utilization efficiency of the system in such the case.

Figure 3.9 shows usage frequency of the vehicles within one hour, and the proposed system has higher efficiency relative to the others. The reason for the higher efficiency is taking partial responsibility of transportation by DRBs (transporting some customers and shorter distance but high frequent) and CRB (transporting many customers at a same time and longer distance but without stop). The usage frequency of the full DRB system and the fixed route system were the same. Usage frequency of these transport system are influenced by size of $AREA$ and transport distance. The proposed system is especially affected the size of $AREA$ and travel distance because DRBs for the system are operated in the $AREA$. Consequently, usage efficiency reduces when the DRBs are operated in larger $AREA$. In addition, usage efficiency of CRB is affected by distance between $AREA$s. Size of $AREA$ and distance of the cities are as shown in Table 3.6.

Table 3.6: The size and distance of $AREA$s.

	Okinawa area	Ginowan area	Yaese area
Size of area (km^2)	63	47	74
Distance of area (km)	21.5	11.2	12.1

Ginowan area is smaller than other cities, and the utilization efficiency in the area was higher. Comparing Okinawa area with Yaese area, Okinawa area is smaller than Yaese area. However, utilization efficiency of Okinawa area is lower than that of Yaese. In the proposed system, bus routes are close to linear due to its algorithm, and Okinawa area has longer distance than Yaese. Therefore, longer transportation distance of Okinawa area decreased utilization efficiency. From these results, placement of *depot* and composition of area should be carefully considered for operating the proposed system.

Discussion for Dstribution

Figures 3.10 and 3.11 show comparison between the proposed system and the full DRB system at a rate of users. Travel time of the proposed system was longer than that of full DRB system. However, the difference was shortened as the number of customers increased. To examine the reason of trip time reduction, the experimental result focused on the relation between trip time and the number of customers is shown in Fig. 3.12. The walk time and ride time of monorail were omitted to simply explain.

Figure 3.12 describes that ride times were constant at each rate, and extra time reduced as the number of trips increased. The reason for the extra time reduction is considered

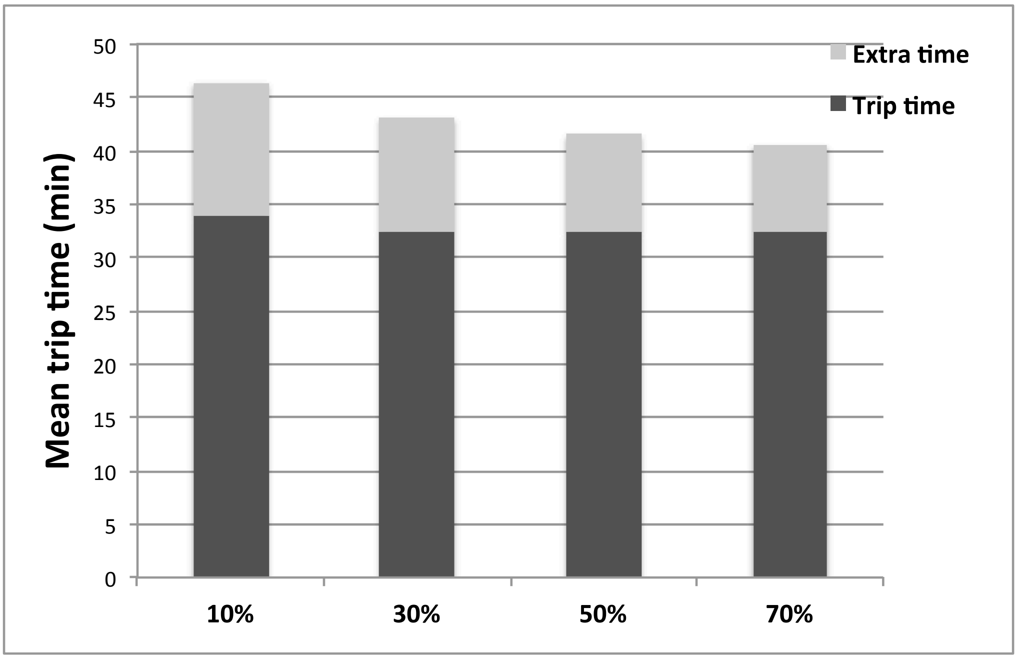

Figure 3.12: Transition of mean trip time (minute) at a rate of customers.

as follows. The routing algorithm of the proposed system classifies the demands without considering time differences. As a result, customers classified into a cluster have varied desired time. Increasing of customers raise the probability of classification whose class has customers having similar desired time. The result indicates proposed system can reduce its travel time improving by routing algorithm. Routing and scheduling algorithm for the proposed system can apply algorithm for vehicle routing problem because its delivery points are gathered into one *depot*. Many researchers study for algorithms for the VRP, so that the proposed system can be improved by applying more sophisticated algorithm for routing and scheduling.

Figure 3.11 shows that the number of required vehicles was less than that of the full DRB system under the many trips situation. This is caused by the difference of the utilization efficiency described in Fig. 3.9. The vehicles of the proposed system can be reused after they transport their passengers in higher frequency because DRBs and CRBs used in the proposed system are operated with taking partial responsibility of limited area. This higher efficiency may be effective for other cities because we obtained the similar results carried out in virtual road network constructed as model of down town and its suburbs. From these results, the proposed system has higher utilization efficiency of vehicles relative to the full DRB system. The higher efficiency facilitates reducing operational cost and improving level of service.

Operational Cost

This section discusses operational cost of the proposed system, full DRB system, and fixed route bus system. Profitability is important for operating transport system. As indices of profitability, running distance per one person and the number of passengers per vehicle are considered. The profitability of the proposed system and that of full DRBs were estimated from simulation results. The profitability of the fixed route bus system was estimated from routes map and time schedules depicted in bus route map of Okinawa. All of the bus trips using inbound line within time period between 7:30AM and 8:30AM were used for the estimation. Table 3.7 shows operational cost of each transport system and the number of customers.

Table 3.8 describes profitability of each transport system. The fixed route bus showed higher profitability than the others. In the proposed system, the total operational distance was 30% less than that of full DRB system. However, full DRB system can transport more customers per vehicle than the proposed system. From these results, the proposed system can plan routes better than ADARTW, but assign customers to vehicles is not well. In addition, the proposed system and full DRB required more number of vehicles than the fixed route bus system. In terms of the proposed system, it transports customers without considering cooperation between other areas. This behavior may require much number of vehicles. The results shows that operation of the system requires more cost than traditional bus system. However, it is considered that the level of service was improved by reducing walking time with keeping travel time. New demands acquisition is possible because improvement of service quality offsets higher cost relative to the existing system.

Table 3.7: Operating cost and the number of customers.

	Proposed system	Full DRB	Fixed route bus
The total operated distance (km)	1,937.4	2837.8	3,370.4
The num. of vehicles	124	99	160
The num. of customers	2300	2300	5303

Table 3.8: The operational cost-benefit.

	Proposed system	Full DRB	Fixed route bus
Total distance/the num. of customers	0.84	1.23	0.65
The num. of customers per vehicle	18.54	23.23	31.38

Consideration for Realization

This section describes consideration for realizing the proposed system. The number of vehicles were assumed to be unlimited, but it is not realistic situation. Actually, the number of vehicles and bus drivers is constraints. To deal with the issue, for example, the system denies customers if the demands exceeds capacity, and provides alternative transport mode for the customers. In addition, this system covers only the trips who depart suburb and arrive at downtown. Operating DRB service in suburban area and providing cooperative operation between cities can solve the problem.

The proposed system gathers its customers into one *depot* to make their connection with CRBs. Consequently, the concentration of traffic volume around *depot*s should be considered. Figure 3.13 depicts the number of vehicles arriving at the transit *depot* calculated at 5 minutes in Ginowan area.

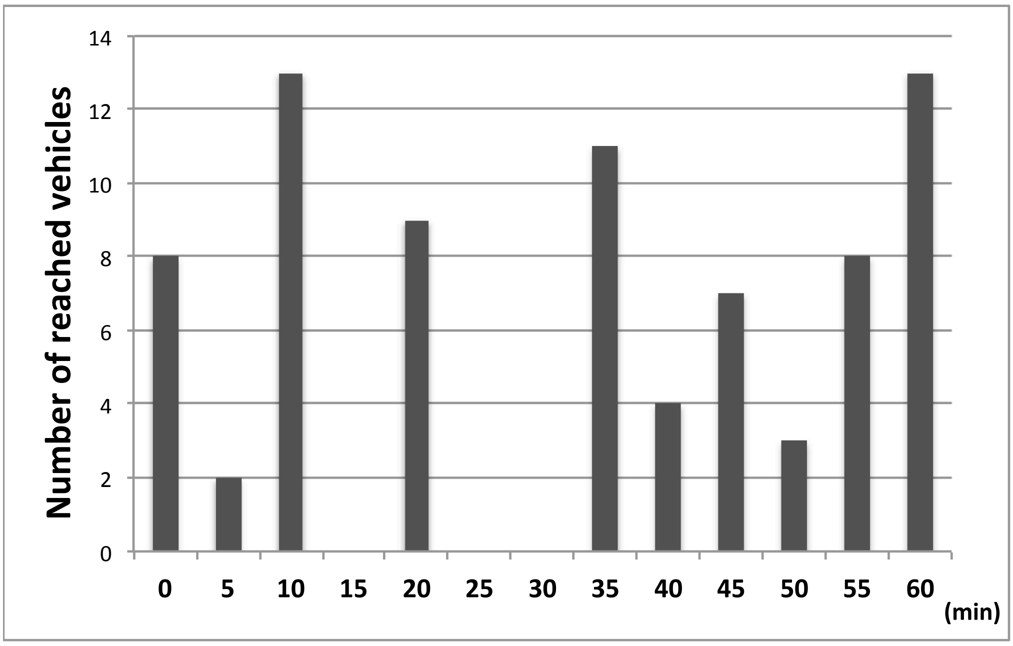

Figure 3.13: The number of arrival vehicles arriving at transit *depot*.

The average of the number of vehicles was 6, the maximum number of vehicles was 13, and the minimum number of vehicles was 0. This shows the number of vehicles arriving at the *depot*s varies in time because the schedules of DRBs are adjusted for that of CRBs. Therefore, optimization of schedules of DRBs and that of CRBs is required to enhance convenience for all users.

3.3.4 Brief Summary of the Section

This section introduces one of the form of the Hierarchical Cooperative Transport system using demand responsive buses. The system is designed for the city that sufficiently provides transport system. In the system, demand responsive buses collect their customers to make customers' connection with a trunk bus. The trunk bus terminates the center station of a downtown, and the customers can go to their desired place by using urban transport system. The system can improve accessibility using demand responsive buses, and trunk buses can provide rapid transportation and reduce traffic volume caused by the trip from suburb to downtown. To evaluate the efficiency of the system, it has been compared with traditional demand responsive buses and existing route buses. The results have shown that proposed system can improve level of service by keeping with the same travel time relative to the fixed route bus system. In addition, the proposed system has higher utilization efficiency in the city that is small and close to a downtown.

3.4 Hierarchical Cooperative Transport System without Urban Transport

This section describes hierarchical cooperative transport system (HCTS) without urban transportation such as monorail or train. The system is more generalized version of HCTS described in the chapter 3, and applicable to areas having insufficient transport system. HCTS consists of a terminal demand responsive bus (DRB) service and a backbone rapid bus service. In the terminal part (lower layer), small sized vehicles such as micro-bus transport customers as the DRB system between the *depot* and customers' desired place. In the backbone part (higher layer), the cooperative rapid buses (CRBs) transport customers in concert with schedules of the DRBs, and run between the *depot*s to make customers connecting with their transit *depot*. The customers' origin and destination places are associated with the *depot*s respectively, and they are grouped into the *depot*s. By grouping customers, the scale of the problem can be reduced because the problem scale will be distributed, and the computing time reduction therefore can be prospective. This chapter describes evaluation of the HCTS on a static traffic simulation.

3.4.1 Method

System Overview

To operate DRBs service in the large scale area with a large number of requests, the proposed system hierarchically consists of DRBs and CRBs, and it groups customers into transit *depot*s to divide problem scale for reducing the computing time. The system has two layers. In the lower layer, the DRBs pickup/drop-off customers at their desired place located around the *depot*s and transport them to the *depot* for making their connection with the CRB. Origin and destination of the customers are associated with the *depot*, and the *depot*s are defined as $depot_o$ and $depot_D$, respectively. The DRB system increases service quality of the transportation since they pickup or drop-off their customers at their desired place on desired time. In the higher layer, the CRBs that are large vehicles transport the grouped customers from one *depot* to the other *depot* together. The CRBs are cooperatively scheduled for the DRBs in order to increase the utilization efficiency. In addition, CRBs can reduce traffic volume of arterial roads because it transports many customers at a time.

Problem Definition

In the general DARP, there are n requests from customers and m fleet of vehicles. The request consists of origin (ORG), destination (DST), and desired pickup or delivery time[2]. The vehicles are capable of c customers transportation simultaneously. From a perspective of customers, traveling cost (travel time, fare, waiting time) TC should be minimized under a set of constraints. On the other hand, the operating cost (e.g. the number of used vehicles and travel distance of vehicles) OC should be minimized from the view point of operators. However, these costs sometimes cannot be minimized at the same time. The DARP is the problem, finding optimal routes and vehicle assignment to minimize both of the costs.

In the proposed system, ORG and DST of the requests are respectively associated with *depot*s chosen to minimize the travel cost TC' via the *depot*s. A customer is transported by a DRB from ORG to the *depot* near the ORG ($depot_O$), then the customer transfers to the CRB. The CRB transports them from the $depot_O$ to the *depot* near the DST ($depot_D$). After that the group including the customer is transported from the $depot_D$ to DST by another DRB. Hence. the problem is to minimize the traveling cost when customers travel via the *depot*s.

Procedure of the Proposed System

Procedure of route planning and scheduling of the proposed system is as follows:

1. Assigning every customer to $depot_O$ and $depot_D$ according to their ORG and DST.
2. Planning route and schedule of DRBs based on customers' $depot_D$. Then, the departure time of the DRBs, customers' arrival time at $depot_D$, are determined as $DL1$.
3. Grouping every customer according to their $depot_O$, $depot_D$, and $DL1$.
4. Planning route and schedule of CRBs based on grouped customers. The departure time of the CRBs, customers' arrival time at $depot_O$, are determined as $DL2$.
5. Planning route and schedule of DRBs based on customers' $depot_O$. Then, the customers' pick-up time at ORG pick-up time at ORG are determined.

To explain the proposed system, a specific example of operating the proposed system is described in Fig. 3.14.

There are 5 customers (A, B, C, D, E) and 3 *depot*s (*depot*1, *depot*2, *depot*3). The symbol "+" means pick-up of a customer, and "-" means drop-off of the customer. The solid arrow describes path of DRBs that are operated around the *depot*s, and the dashed arrow shows path of the CRBs. This explanation is assumed as the customers desired time are near. The customers A and B are transported from their origin to *depot* 2 as $depot_O$ by DRBs separately. Then, they are transported by the CRB from *depot* 2 to

[2]In this study, the desired delivery time is considered.

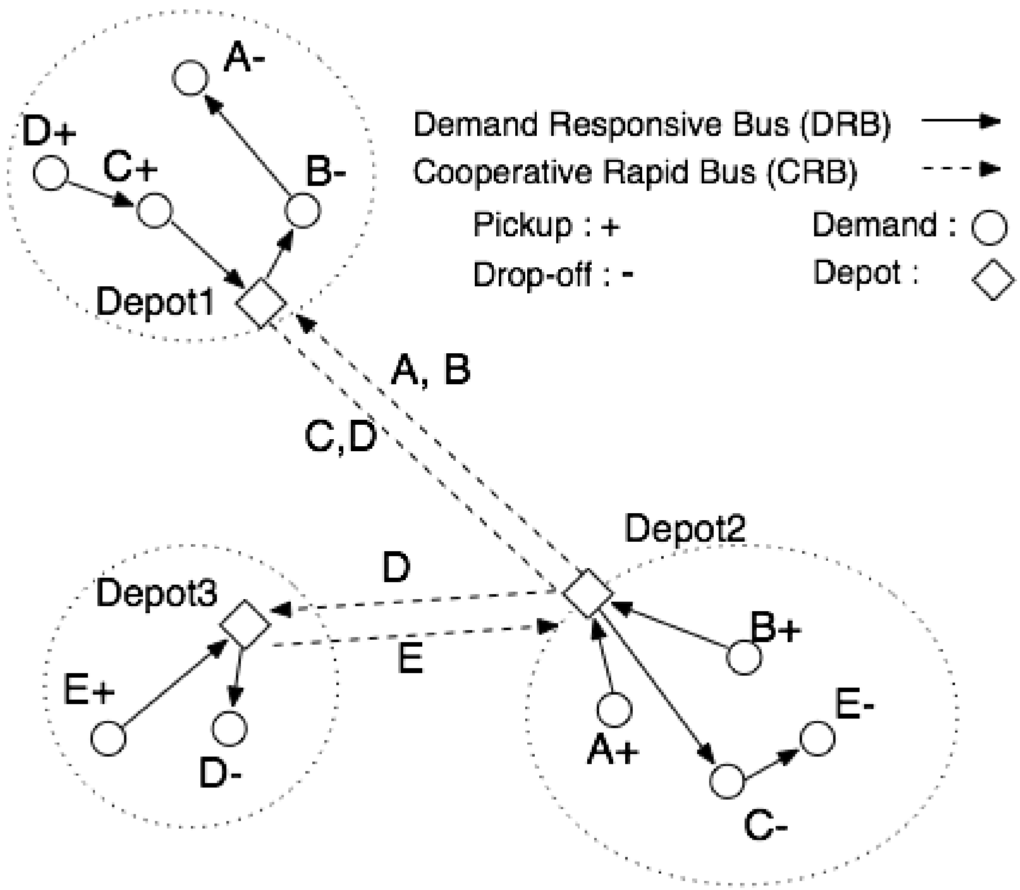

Figure 3.14: Illustration of the overview of Hierarchical and Cooperative Transport System with 5 customers.

depot 1, and the *depot* 1 is considered as $depot_D$ for the customers. After that, they are transported by another DRB from *depot* 1 to their destination. In the same manner as the case of customers A and B, customers C and D are transported by DRBs and they transit to the CRB. The CRB transport then from *depot* 1 to *depot* 2. The customer C drop-off at *depot* 2 and customer D is transported to *depot* 3. At the same time, customer E is transported by the CRB from *depot* 3 to *depot* 2. Customer C and E are transported by the CRB from *depot* 3 to *depot* 2 to their destination respectively.

Grouping Customers

From the view point of hierarchical structure, the scheduling process is a two-part process that its scheduling on higher layer and lower layer. At the higher layer, the problem is converted by integrating many nodes to one node (*depot*) to shrink its size. In other words, the higher layer deals with grouped customers as smaller DARP. In the lower layer, the customers' requests are gathered into *depot*s and the requests are solved as a cluster of small DARPs. Thus computational time at each *depot* is adequately shorter than the DARP for the whole requests. This section describes grouping customers at the higher layer.

The customers are grouped based on their request to increase transportation efficiency of the CRB. The group is made from similar requests having same *depot*s ($depot_O$, and $depot_D$) and the desired time whose difference is within τ. Moreover, the routes of CRBs are optimized among groups by solving the DARP in terms of the groups.

3.4.2 Experiments and Results

This chapter describes evaluation of the HCTS compared with conventional full DRB system and the fixed route bus model. The target area of the simulation is south central of Okinawa, Japan. The trips were extracted from PT survey report.

Road Network Model

The road network model used in the simulation is constructed from digital road map 25,000 of south central of Okinawa, Japan, issued by Geospatial Information Authority of Japan. The detail of the road network model is described in section 3.3.2.

Estimation of Link Traffic Speed

Traffic speed of each link was estimated by BPR function [43]. The function requires traffic volume of link to estimate traffic speed. The traffic volume was assigned by user equilibrium (UE) assignment. The assignment is based on an assumption that the users have perfect knowledge about cost of all routes, and that the all users choose their optimum route for each from the knowledge. As a result, the generalized cost of all used routes are equal, and less than those of unused routes (Wardrop's first principle [44]). Traffic speed of vehicles was same to the link traffic speed.

General Settings for Experiments

The simulation settings are listed in below:

- The number of vehicles was assumed to be unlimited.
- All requests were known in advance (batch processing).
- Every customer was assumed to accept their schedule notified by the system.
- All customers were generated from the fixed route bus users reported in PT survey report [37].

Settings for the Proposed System

The time difference τ for grouping was set as 5 to minimize the waiting time for transferring to the CRB. The reason for the value is time (departure time and arrival time) of the trip data from PT survey report is discrete (almost of time is reported every 5 minutes) because of questionnaire survey. The capacity of the DRB was set as 25 customers and the CRB was set as 70 customers. The proposed system was developed for substitution with existing transport system (fixed route bus system). To use the existing resources, the capacity of the CRB was same to the fixed route bus. The capacity of DRB was set considering mobility.

Wait time for pick-up/drop-off customers were estimated by following equation.

$$WT_i = 3 + 1.53 \cdot n_i \tag{3.8}$$

where n is the number of customers who boarded/dropped-off at node i. These values influence simulation result. Therefore, the values should be determined carefully. In this study, we applied the value described in the paper [45]

Settings for the Full DRB system

Algorithm applied for routing and scheduling of the full DRB system was ADARTW [13]. The capacity of bus was 70. Since difference of service providing method with the proposed system, parameters for ADARTW were set in order to achieve the similar service quality that is travel time for customers to compare efficiency of both the systems.

Settings for the Fixed Route Bus

The route of the fixed route bus was constructed from "Bus route map" actually used in Okinawa, Japan in 2006. Bus waiting time BWT (min) was estimated by following equation described in PT survey report.

$$BWT = \begin{cases} 0.418g & (0 \leq g < 6.6) \\ 0.197g + 1.459 & (6.6 \leq g < 15.6) \\ 0.057g + 3.643 & (15.6 \leq g) \end{cases} \tag{3.9}$$

where g is time interval (min) of operation. The ratio of average of estimated trip time to observed trip time was 1.05. The result indicates the estimated time was close to the observed time.

Comparison with Full DRB System

This section describes comparison between the proposed system and full DRB system.

Computational Time

Figure 3.15 shows computational time for making routes and schedules of each system. The demands for scheduling were generated from PT survey report at a rate of 10% (8660 customers), 20% (17210 customers), 30% (25782 customers) of bus customers. The calculation time for the conventional algorithm took 40 minutes at a rate of 10%, about 3 hours at a rate of 20%, and about 6 hours at a rate of 30%. On the other hand, the proposed system completed its calculation about 20 minutes.

Comparison of Customers' Mean Travel Time

This section describes comparison of customer's mean travel time between both of the systems. Travel time means duration from the customer depart his/her origin until his/her desired arrival time. Travel time of the proposed system was 42.4 minutes, and that of the full DRB system was 41.5 minutes.

Comparison of Operational Efficiency

Figures 3.16 and 3.17 show total travel distance and required vehicle number respectively. The number of bus means estimated vehicle num when the vehicles required at a same time.

In the proposed system, the total travel distance was 4400km longer than the full DRB system, and the number of required vehicle was more 230 vehicles than another one. The

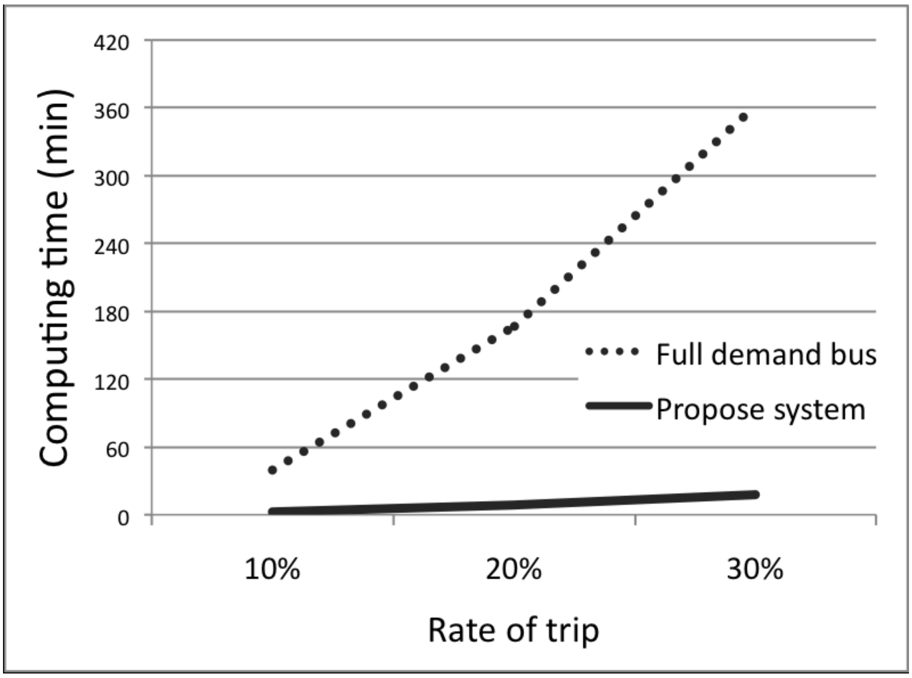

Figure 3.15: Comparison of computational time (min).

proposed system requires small vehicles (DRB) than large vehicle (CRB). The difference of the operational cost decreased as the number of customers increased.

Comparison with Fixed Route Bus System

This section describes comparison between the proposed system and the fixed route bus system. The simulated trip was extracted from PT survey and the number of trip was 85943. Because calculation of the full DRB was not finished within a whole day, the calculation was stopped.

Comparison of Travel Time

Figure 3.18 shows comparison of customers' mean trip time between the proposed system and the fixed route system. In explanatory notes, the description of "Demand bus" means ride time of DRB, "Fixed bus" indicates ride time of the fixed route bus, "Cooperative bus" means ride time of CRB, "Wait time" and "Walk time" show wait time and walk time of customers respectively.

The result showed that the average travel time of both system were 41.5 minutes. In the fixed route bus system, 16 minutes was walk time, and 7.8 minutes was wait time. On the other hand, the proposed system required 12.5 minutes walk time and 6.3 minutes for wait time. Both of the walk time and wait time of the proposed system were shorter than those of fixed route bus system.

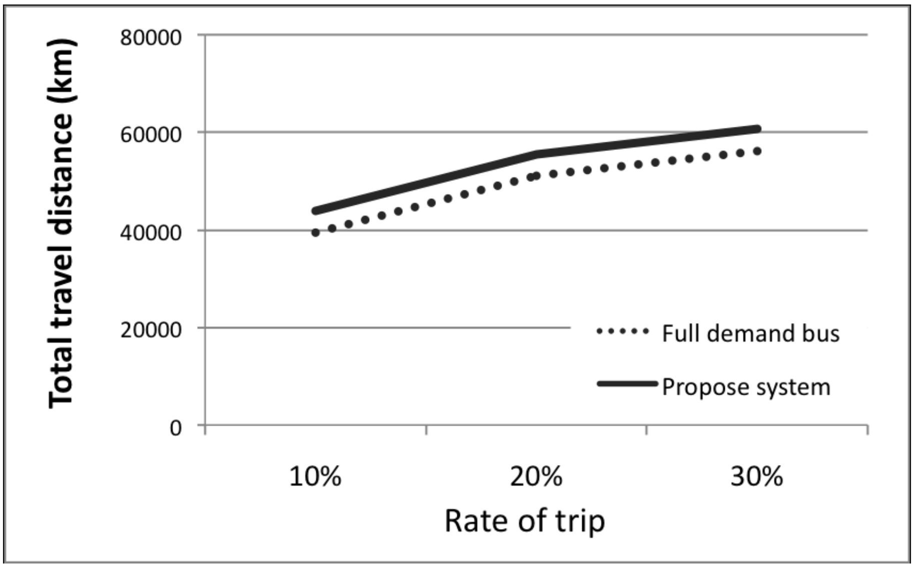

Figure 3.16: Comparison of the total travel distance (km) of vehicles.

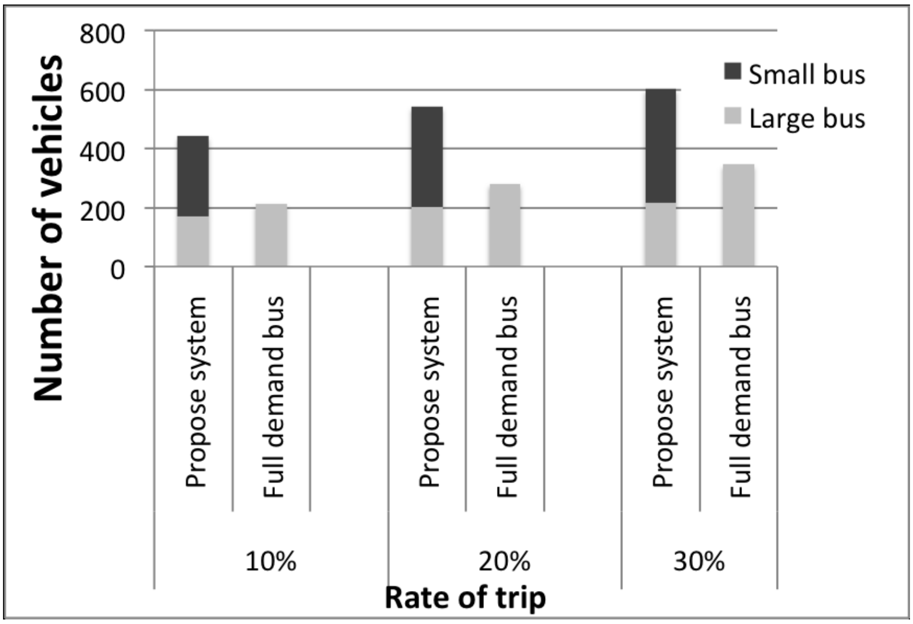

Figure 3.17: Comparison of the number of required vehicles.

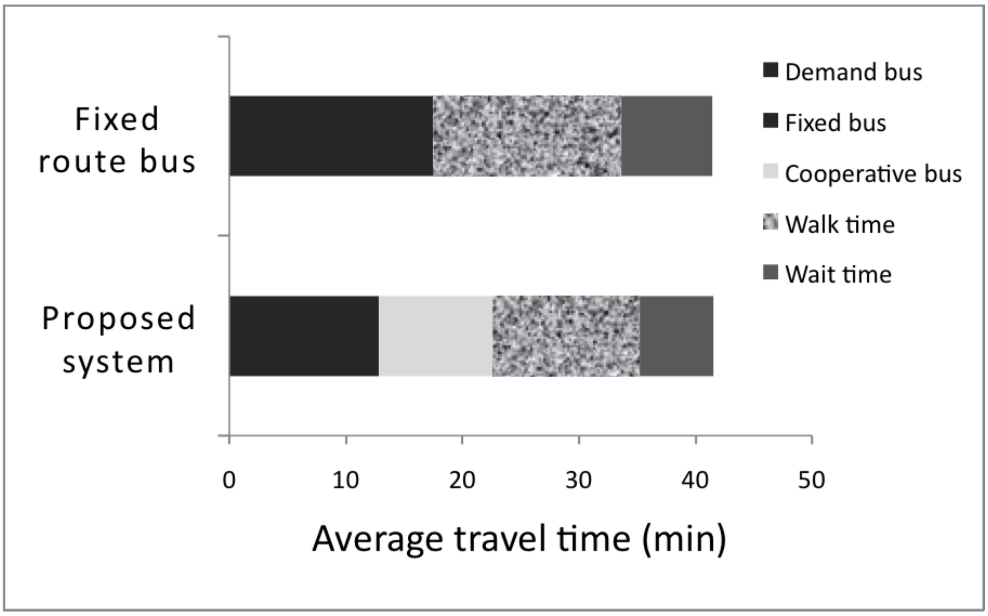

Figure 3.18: Comparison of the Travel time between the proposed system and the fixed route bus system.

Comparison of Operational Cost

This section describes comparison of operational cost between the proposed system and the fixed route bus system. The result is shown in Table 3.9.

Table 3.9: Comparison of the operational cost among the systems.

	Proposed system	Fixed bus	Full DRB
Total distance (km)	83241.2	82147.9	-
Total time (hours)	3668.3	3773.1	-
Required vehicle (large bus)	325	646	-
Required vehicle (small bus)	587	-	-

In this section, total travel distance, total travel time, and the number of required vehicles were measured as operational cost. These cost of fixed route bus were estimated from "bus route map". In terms of the proposed system, the total travel distance was about 83241km, the total travel time was about 3670 hours, and the number of required vehicles was 912. In, fixed route bus system, the total travel distance was about 82150km, the total travel time was 3770 hours, and the number of vehicles was 646 [3].

The proposed system operated vehicles about 100 hours less than the fixed bus system. However, the total travel distance was 1091km larger and the number vehicle was 266 more vehicles than those of the fixed route system.

[3]This number is the total number of possessed bus of 4 bus companies.

3.4.3 Discussion

Comparison between Proposed System and Full DRB System

Customers' Average Travel Time

In terms of the proposed system, the average travel time was 42.4 minutes when the number of customers were lower. The time was shortened when the number of customers increased. To clarify the reason of the difference, average travel time and average boarding rate at each rate of customers are shown in Figure 3.19.

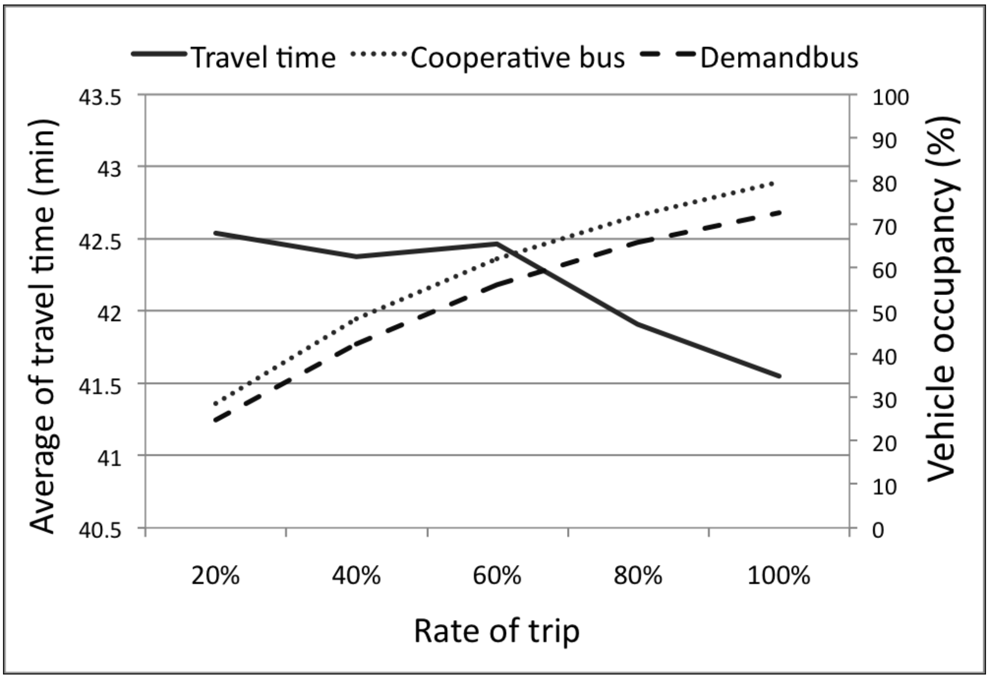

Figure 3.19: Average travel time and board rate of each vehicle of the proposed system.

In Fig. 3.19, solid line shows average travel time of customers, dotted line and dashed line show boarding rate of the CRB and DRB respectively. As the number of customer increased, the average travel time decreased, and the boarding rate increased. The reason for the result is that the probability of simultaneous transportation of customers whose origin, destination, and time are really near was increased. Consequently, distance of detour was decreased. However, trip time of some customers might increase due to stop at bus stop for picking-up/dropping-off other passengers. Trip time reduction due to increase of customers have reported by existing research [29], so that the full DRB system will reduce customers' travel time same as the proposed system. Both of the system: the proposed system and full DRB system show trip time reduction due to less detour when the number of customers and operational scale are large.

Computational Time and Transport Efficiency

In section 3.4.2, the proposed system was compared with Full DRB system. Full DRB took about 6 hours when the number of customer was over 25000. On the other hand, the proposed system completed its calculation about 20 minutes. Computational order of ADARTW used for scheduling was $O(n^2)$ [16], and its computational time will increase with the increasing of the number of requests. In terms of the proposed system, it applied the same algorithm for routing and scheduling for its customers. However, it can reduce computational load due to distribution of requests into its *depot*s. In this study, we supposed all demands were known before planning routes and schedules (batch processing). This assumption means the all users requests had been received the day before users' departure. Hence, we considered the calculation time is acceptable for the users as public transport service. What largely influence on calculation time is the number of requests solved in each *depot*. Therefore, location and number of *depot*s are important factors to reduce the time. Calculation time can be reduced by adjusting the number of *depot*s. Moreover, it can be shortened by parallel computing because scheduling process on *depot*s are independent.

With respect to operational cost, the proposed system showed that the efficiency was not good as the full DRB system because it disperse its request into *depot*s to reduce the problem scale. However, accepting the inefficiency is possible because operational cost of the proposed system was similar to that of the fixed route bus system except the number of used vehicles. Transport efficiency defined by number of passenger per vehicle is shown in Table 3.10.

Table 3.10: Comparison of the transport efficiency at each rate.

Rate of trip	10%	20%	30%
Proposed system	19.6	31.8	42.9
Full DRB system	40.9	61.2	74.6

From Table 3.10, both of the systems improved their efficiency with the increasing of the number of customers. The reason for the result is also less detour as mentioned above.

Effectiveness as Public Transport System

In section 3.4.2, effectiveness of the proposed system was compared with that of fixed route bus system to evaluate feasibility as public transport system. When both of the system achieves the same travel time, walk time and wait time of the proposed system were less than fixed bus system. Hence, the level of service quality is considered that the quality was improved.

The operational cost (total operated distance and time) of the proposed system was similar to those of the fixed route bus, while the number of required bus of the proposed system was more 260 than that of the fixed route system. Table 3.9 shows more number of small bus was required than that of large bus. Figure 3.20 shows the number of transported customers per schedule. The term schedule means that the vehicle operation from the departure from *depot* until it returns to the *depot*.

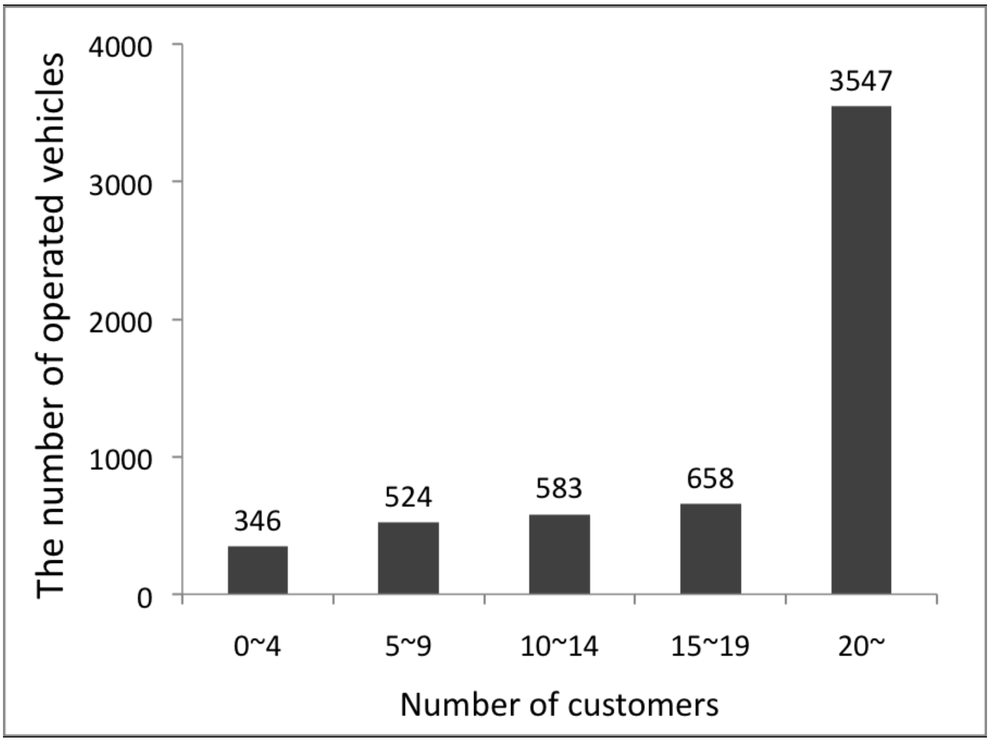

Figure 3.20: The number of transported customers per one schedule of small vehicle.

The figure shows that 3747 times of operation transported more 20 customers. In addition, the operation transporting the maximum capacity of customers was 1850 times. It is about 30 percent of the whole operations. In this study, a new vehicle is added when the schedule is filled to capacity. The reason for a number of vehicles is that vehicles were added by filled capacity. To deal with the issue, appropriate size of vehicle should be used according to the situation (e.g. the number of customers, area width, and time period). For example, there were operation with under 9 passengers. The operation can be achieved by smaller vehicles such as mini van or taxi. Therefore, algorithm for providing appropriate sized vehicles according to the situation and collaboration with existing main transport service will be effective for reducing operational cost.

Combining with Public Transport Priority System

Combining public transport system with public transport priority system (PTPS) is effective. As an example, a experiment assumed that bus priority lanes are introduced on lanes having more two lines. We supposed that the strategy is realizable when the system is distributed, and dependency of using car for people living in an area with a fewer public transport system reduces. The simulated result is shown in Table 3.11

Table 3.11: Travel time and operational cost using the proposed system with public transport priority system.

	Proposed system (with PTPS)	Compare with before
Travel time of users(min)	36.6	(-4.9min)
Total distance (km)	96621.6	(+16%)
Total time (hours)	2955.79	(-20%)
The num. of trunk buses	314	(-11)
The num. of demand buses	533	(-54)

Table 3.11 shows about 5 minutes of trip time reduction, about 710 hours of operated time reduction, and decrease of 65 number of vehicles. However, the operated distance increased about 13400 km. The reason for the increase of operated distance is that the buses used bus lanes to decrease their travel time with detour. The travel time reduction causes increase of vehicle utilization efficiency. Therefore, such a measure can facilitate efficient operation of the proposed system.

Remaining Issues

This section describes remaining issues to realize the proposed system. The issues are as follws:

- Employment of fast and efficient algorithm for making routes and schedules.
- Location of *depot*s and its numbers.
- Operational scale
- Cost for transit
- On-line response by solving the dynamic dial-a-ride problem

Employment of fast and efficient algorithm

The proposed system employed the insertion heuristic that can solve the DARP fast. However, the algorithm tends to generate myopic solutions (local optima) [16]. Some algorithms that can deal with the issue has been developed. These algorithm can make high efficient routes and schedules which cost fewer number of vehicles, shorter operational distance, shorter travel time, etc. However, these algorithms cost much time to solve the DARP compared with simple insertion heuristic.

Location of depots and The Number of depots

Location and the number of *depot*s largely influence on calculation time, level of service quality, and operational cost. We assumed that the number of *depot*s was 20, and the placement of the *depot*s was searched by genetic algorithm [46]. The objective function was designed for minimizing customers' travel time. The design was advantageous to customers, while more appropriate objective function can be exist.

In terms of the number of *depot*s, the number of customers dealt in each *depot* can be decreased when the number of *depot*s is large. In addition, operational area for one vehicle would decrease. However, operational efficiency would be decrease. In other words, more vehicles would be required because each *depot* should treat fewer number of requests. Thus, location and the number of *depot*s should be determined carefully.

Operational scale

In section 3.4.2, the proposed system was experimented in Naha commuting area. The Table 3.9 indicates that the proposed system required more vehicles than the fixed route bus system. To discuss operational cost concerning with operational scale, we simulated two case of experiments. This experiments assumed that the proposed system has been operated only in Naha city, and except for Naha city independently. Tables 3.12 and 3.13 show operational cost of the proposed system operated in Naha city, or except for Naha city.

Table 3.12: Operational cost of the proposed system operated in only Naha city. (with 25728 customers)

	Proposed system	Fixed route bus
Travel time of users(min)	29.09	29.08
Total distance (km)	16723	7858
Total time (hours)	772	387.7
The num. of trunk buses	61	-
The num. of demand buses	136	-

Table 3.13: Operational cost of the proposed system operated in except for Naha city. (with 60215 customers)

	Proposed system	Fixed route bus
Travel time of users(min)	46.16	46.79
Total distance (km)	66702	74289
Total time (hours)	2914.6	3385.3
The num. of trunk buses	273	-
The num. of demand buses	466	-

In Table 3.12, the proposed system cost about twice distance and time to achieve same travel time to the fixed route bus. On the other hand, Table 3.13 shows the proposed system cost 10% less distance and time relative to the fixed system.

The proposed system requires customers to transit to a trunk bus. The detour for the transit tends to be long especially in narrow area. Consequently, the proposed system is unsuited for high frequent and narrow area such as downtown.

In contrast, the proposed system showed less cost than the fixed route bus for operating in suburban cities. The demands arriving in such a city/town/village are temporary and spatially distributed. The fixed route system is inefficient for the demands, but the flexible route and schedule system can be operated efficiently in the area. Thus, the proposed system is more efficient than fixed route system in suburban area. Note that the number of required vehicles were more than the total number of buses possessed in Okinawa operated even in only suburban area. The number of required vehicles for operation is one of the most important cost to realize the system. To deal with the problem, employment of higher efficient algorithm and development of vehicle assignment system mentioned in sections 3.4.3 are needed. Moreover, appropriate the number of vehicles should be considered based on demands forecasting.

Cost for Transit

Customers of the proposed system may transit at most two times. The transit customers can board rapid operated trunk bus called CRB to shorten their travel time (to increase level of service quality). The level of service quality of the customers, however, decreases due to transit vehicles, and resistance (cost) for transit should be considered. The cost for transit of typically public transportation such as buses and train is caused by waiting time, moving to the next mode, and unease for whether they can get a seat or not. The proposed system can minimize waiting time by cooperative scheduling of CRBs and DRBs. In addition, transit from DRB (or CRB) to CRB(or DRB) can be done at same place. This means the distance for transit also be minimized. Concerning unease for the customer can get a seat or not, the proposed system can reserve in advance. Therefore, the customer can always get a seat. From these reasons, the cost for transit is lower than typical public transport system. To consider the cost, it is concluded as generalized cost when the system is evaluated.

On-line response for Instant Requests

In this study, all requests are assumed to be known in advance for making routes and schedules. However, On-line reservation must be implemented to deal with the instant request as public transportation system. For example, customers missing their reserved bus can be considered. To deal with such requests, suggesting a bus that will path through near the customer with respect to time and position. This is realizable because the proposed system is operated largely.

3.4.4 Brief Summary of the Section

This section describes one of a variation of the hierarchical cooperative transport system using demand responsive buses to operate in an area where insufficient transport is provided. The system consists of two layers for serving its customers. In the lower layer, demand responsive buses transport their customers to make customers' connection with the trunk bus which is responsible for higher layer. The demand responsive buses play an important roll for increase of accessibility of the system. In the higher layer, trunk buses can transport their passengers rapidly. The system can provide transportation even in an area where its population density and transport requests are lower. In addition, it can reduce computational time of planning routes and schedules by dividing problem scale into smaller problems. The experimental results have shown the system can improve level of service quality relative to the route buses due to walk time and wait time reduction. We have also discussed that the operational scale for the system. The system is effective for a suburban area where its traffic demands are distributed spatially and temporally.

3.5 Summary

This chapter has described Hierarchical Cooperative Transport System using demand responsive buses to improve efficiency of public transport systems. Two types of variations of the system which can apply to typical local cities has been proposed. The main difference between the two systems is that the trunk buses connect to either urban transport system or demand responsive buses.

The first system combined with urban transport system is applicable to the city providing sufficient transport system. The effectiveness of the system has been evaluated by comparing with common fixed route bus system and a traditional demand responsive bus on a static simulation constructed from the real geographical data and census trip data. The result has shown that the travel time of the system was the same to that of the fixed route bus system but customers' walk time of the system has decreased. In addition, the result has shown higher utilization efficiency of the system when the lower layer of the system is served in a small area and the higher layer of the system is served in the city that is closer to downtown.

The second system is applicable to the areas that provides insufficient transport system. The effectiveness of the system has been examined by the same way to the first system. The system has performed shorter calculation time than the traditional demand responsive bus system. Furthermore, the experimental result has shown the system is effective for an area where its traffic demands distribute spatially and temporally. Finally, the discussion about feasibility of the system has been described. We have discussed some remaining issues. First, operating the system requires high operational cost. To reduce the operational cost, employing more effective algorithm for planning routes and schedules of the system is required. Secondly, responding to instance requests should be provided for customers who missed their bus. Some algorithms for on-line DARP have been developed for dealing with instance requests. Such requests can be treated by applying the algorithm. Location and number of *depot*s are also adequately considered. These parameters influence on efficiency and usability of the system.

4 Evaluation of Feasibility

4.1 Introduction

This chapter describes evaluation of the hierarchical cooperative transport system (HCTS) on a dynamic microscopic simulator developed by the authors [47]. Evaluating profitability, traffic efficiency, and effects is important to introduce a new type of transport system. Usually, such the system is evaluated on a traffic simulation. Many traffic models and applications have been developed in recent years. We have applied dynamic microscopic simulator to evaluate feasibility of the HCTS because the dynamic model can observe car flow and interaction among vehicles minutely.

In this chapter, the specification of the simulator and experiment of the HCTS are introduced. Section 4.2.1 describes detailed specification of the traffic simulator developed by us. Then, the evaluation of the simulator is discussed. In section 4.3, simulation of the HCTS are demonstrated.

4.2 Dynamic Microscopic Traffic Simulation

4.2.1 Specification of the Simulator

This section shows detailed specification of the dynamic microscopic simulator.

Car Following Model

Traffic flow is presented by multi-agent system that consists of Driver-Vehicle Unit (DVU). The DVU is based on Gazis-Herman-Rothery model [48], and is added acceleration term and deceleration term. Commercial application called PARAMICS applied similar behavior model [49]. More sophisticated models have been formulated in recent years. However, we have applied the simple model because of a lower computational cost for large scale of dynamic microscopic simulation. The DVU model describes three behavior as follows:

- *acceleration state*: A car accelerates in the maximum acceleration rate A_1 when there is an enough space ahead.

- *deceleration state*: A car decelerates in the maximum deceleration rate A_2 when it close to another car ahead.
- *following state*: A car close its speed to the speed $\dot{x}_0(t)$ of car ahead to keep appropriate distance to the car ahead.

Introducing delay T for following to the car ahead to reproduce propagation of traffic congestion wave. Acceleration $\ddot{x}_1(t+T)$ is as follows:

$$\ddot{x}_1(t+T) = aA_1 + bA_2 + (1-a-b)f \tag{4.1}$$

$$f = \alpha\frac{\{\dot{x}_1(t)\}^m}{g^l}(\dot{x}_0(t) - \dot{x}_1(t)) \tag{4.2}$$

$$\alpha = R(\frac{g - D(\dot{x}_0(t), \dot{x}_1(t) + A_1)}{\beta}) \tag{4.3}$$

$$\beta = R(\{D(\dot{x}_0(t), \dot{x}_1(t)) - g\}\frac{\dot{x}_1(t)}{\gamma}) \tag{4.4}$$

$$g = x_0(t) - x_1(t) \tag{4.5}$$

$$R(z) = \begin{cases} 0 & (z < 0) \\ 1 & (z > 1) \\ z & (other) \end{cases} \tag{4.6}$$

where $x_1(t)$ and $x_0(t)$ describe position of a target car and a car ahead of the target car, respectively. A_1 and A_2 indicate the maximum acceleration and the maximum deceleration. $D(\dot{x}_0, \dot{x}_1)$ describes the distance between two cars that the behind car can stop safely when it running with its speed $\dot{x}_1$ and the car ahead decelerating its speed $\dot{x}_0$ by A_2. The variables m, l, α, β, and γ are parameters.

The variable g indicates gap between front of two cars. The variable a describes a coefficient of acceleration according to the gap g. It becomes 1 if the g is adequately large, otherwise it becomes 0. β describes driver's tendency for acceleration with respect to the gap to the car ahead. The variable b shows a coefficient of deceleration according to the gap g. It becomes 0 if the gap is adequately large, otherwise it becomes 1. In addition, the car is sensitive to the gap g when its speed is high. The sensitivity is adjusted by the parameter γ. f is Gazis-Herman-Rothery model and it adjust car's speed when the car is *following state*. R is function relative to the saturation. In this study, A_1 and A_2 are set as 2.4 (m/s^2).

Stop Model as Behavior of Intersection Model

Every vehicle in the simulation temporary stops at every intersections while signal delay time DT. We call this model TS model in this paper. Wait time at intersection IT_i is calculated by the following equation:

$$IT_i = TT_i + DT \tag{4.7}$$

where TT_i is transit time in free flow traffic on the link connected to the intersection i. We have not introduced traffic signal control system to dynamic simulation for intersection model because traffic signal model requires a large amount of parameters such as cycle length, offsets, and splits at every intersections. In addition, these parameters strongly affect accuracy of the simulation. TS model makes finding appropriate parameters easy.

Traffic Assignment

Traffic volume of all routes were assigned by user equilibrium (UE) assignment. The detail of this assignment is described in section 3.4.2

Path Finding

UE assignment determines traffic volume and trip time between origin and destination (OD). However, the route between OD is not determined uniquely. In this study, UE was solved by Frank-Wolfe algorithm. The process in the algorithm iterates calculating the shortest paths for all the traffic demands and adjusting the traffic volume of each link to minimize the objective function for the UE. The routes between each OD are computed from the shortest paths and the amount of the adjustment in the iteration.

4.2.2 Evaluation of the Simulator

Estimation of Traffic Demands

We evaluated traffic flow of each link by comparing simulated data with observed data. The result is shown in Figure 4.1.

The estimated data was obtained by a static simulation of UE assignment. The observed data was reported in traffic survey report (road traffic census) carried out in 2005. As the result shows the correlation coefficient is 0.95, these two data were strongly related. It means traffic flow of each link is appropriate. Note that Fig. 4.1 depicts reproducibility of some links were low. However, the purpose of this simulation is rather estimation of the trip time between origin and destination than reproduction of traffic volume in each link. Some links indicating lower reproducibility of traffic has a few influence on trip time because the traffic were assigned by UE assignment [44].

Reproducibility Evaluation

Traffic demands used in microscopic simulation was generated from PT survey report. In this section, trip data of the private cars were extracted for evaluating the reproducibility of the simulator.

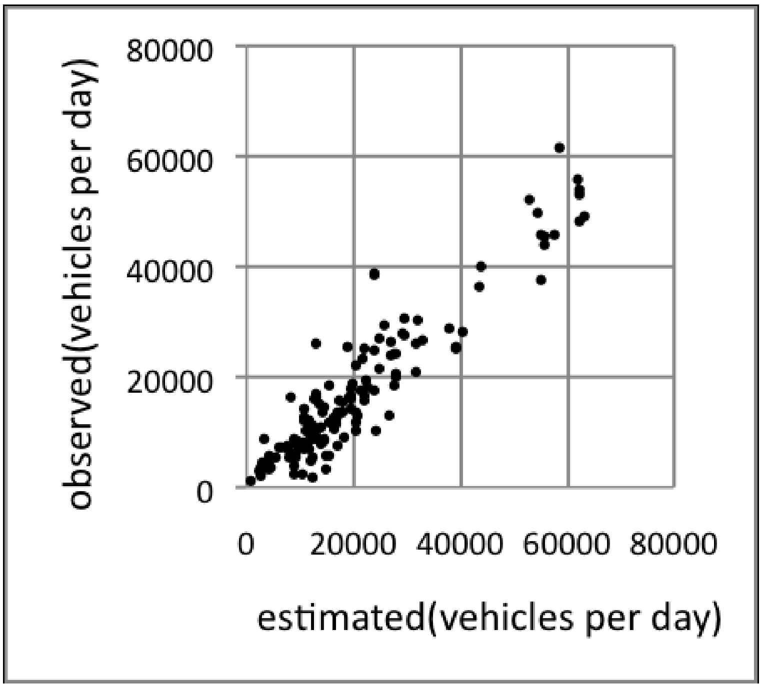

Figure 4.1: Scatter plot of estimated link traffic and observed link traffic.

Figure 4.2 shows hourly average trip time. The solid line shows simulated time, and the dashed line describes observed time.

Figure 4.3 shows hourly correlation coefficient and average error rate of trip time between simulated time and observed time.

Estimated time was an average trip time of vehicles arrived at destination between t o' clock to $(t + 1)$ o' clock in the simulation time. Those values have been measured independently. In this study, the error rate Err of each trip is described by following equation.

$$Err_i = \frac{|o_i - s_i|}{o_i} \tag{4.8}$$

where o is observed trip time described in PT report, s is simulated trip time estimated by the simulation. The correlation coefficient transits around 0.8 and the average error rate transits around 0.3.

Because the scale of the dynamic simulation is large, settings for signal parameters at the whole of intersections are difficult. To deal with the issue, we have applied a simplified intersection model (TS model) to the dynamic simulation. The values measured in high traffic time such as 8'o clock indicate appropriateness of the car-following model and the intersection model. In the other time period, the values indicate appropriateness of free flow traffic speed. The value at around 19 o' clock was not relatively good, but we have considered the reproducibility is enough to evaluate the proposed system because the evaluation was conducted with the simulations under the same background traffic.

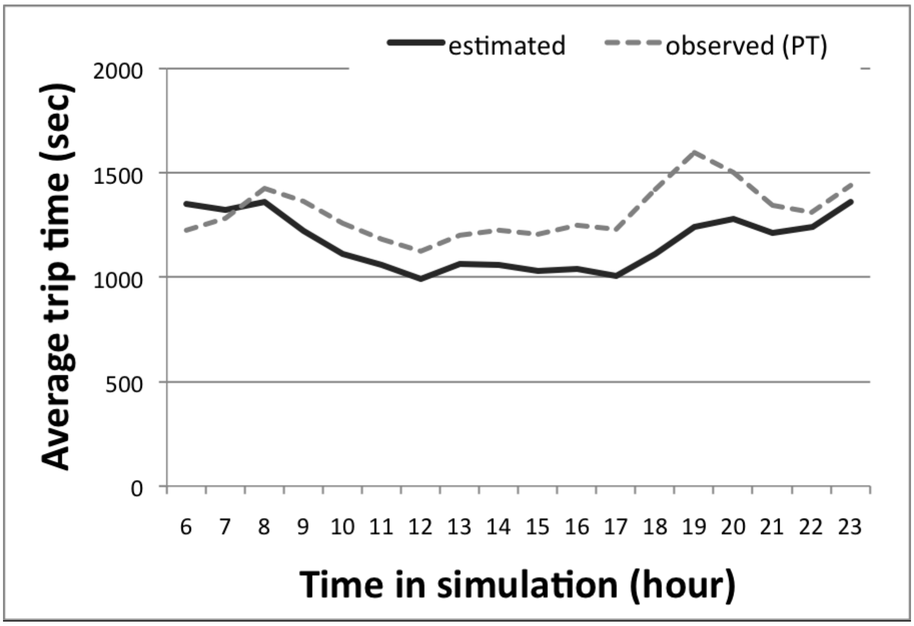

Figure 4.2: Time series average of trip time (sec).

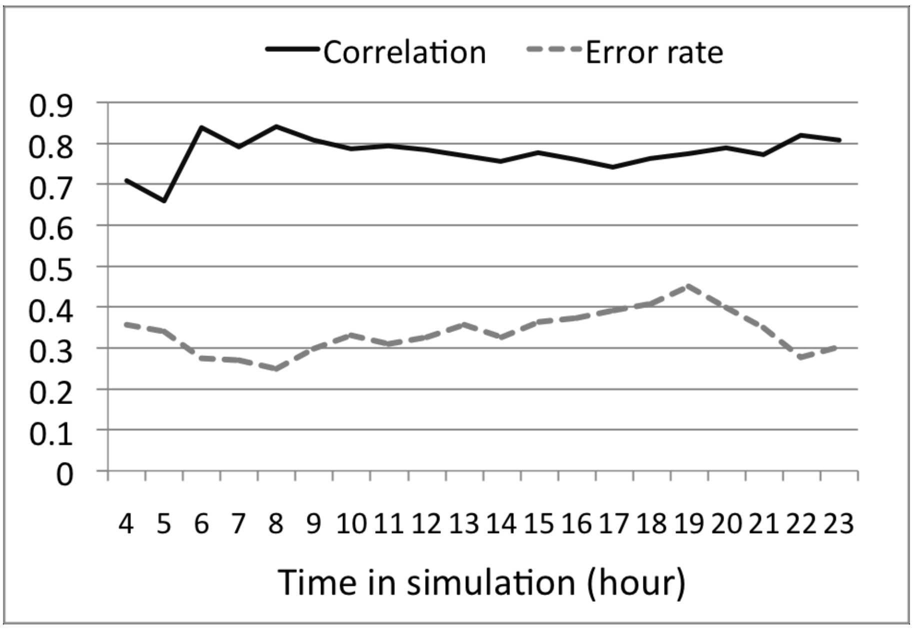

Figure 4.3: Time series correlation coefficient of OD trip time.

4.3 Experiments and Results

Figure 4.4 shows the average trip time of the static simulation (left bar) and of the dynamic simulation (center and right bars). These trip time include walk time because the walk time is constant at each simulation. The center bar shows the result of the dynamic simulation carried out without background traffic, and it is close to the result of the static simulation. The right bar shows the result of the dynamic simulation executed with background traffic. The wait time of the right bar notably increased relative to other two results.

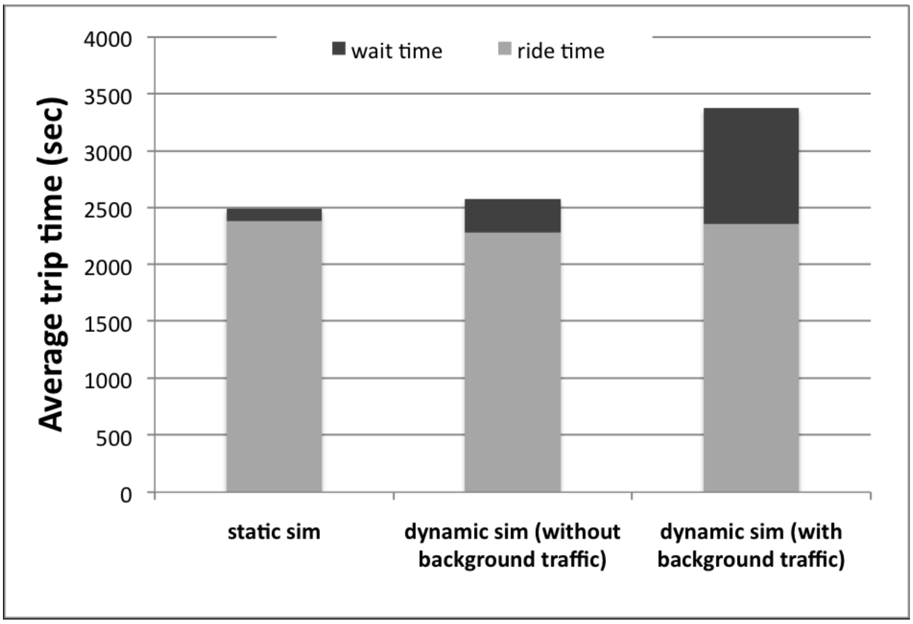

Figure 4.4: Comparison of average trip time between static simulation and dynamic simulation.

Table 4.1: Trip time of the private car users.

	Only car	With proposed system
Average trip time (sec)	1226	1228

Table 4.1 shows the average trip time of the private car drivers in the dynamic simulation. This experiment was carried out to evaluate the influence of the proposed system on private car drivers. There was slight difference between the two results.

4.3.1 Comparison with Different Vehicle Sizes

In this section, we have evaluated the HCTS with the dynamic microscopic simulator. The operated schedules was the same in each simulations. The schedules were planned for different sized DRBs that are for 25 customers, 10 customers, and 4 customers. These size were supposed that the vehicles were small bus, mini-van, and normal car such as taxi respectively.

The vehicle capacity for 25 passengers is the same to Fig. 4.4. In the static simulation, the ride time of vehicle was 2384 seconds, and the wait time was 107 seconds. In the dynamic simulation performed without background traffic, the ride time of vehicle was 2283 seconds, and the wait time was 290 seconds. In the dynamic simulation performed with background traffic, the ride time of vehicle was 2359 seconds, and the wait time was 1014 seconds.

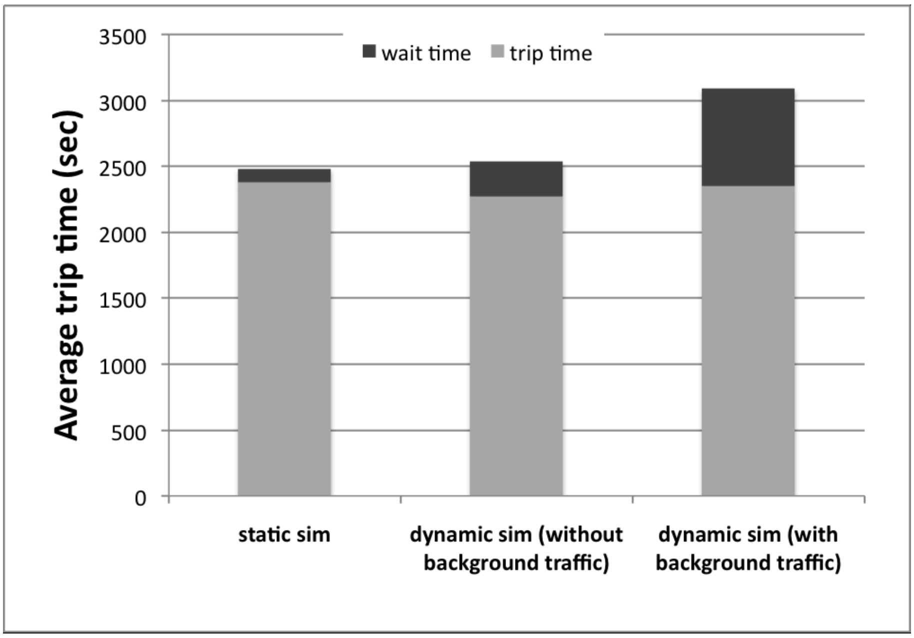

Figure 4.5: Comparison of average trip time between static simulation and dynamic simulation. The capacity of the DRB was 10 customers.

Figure 4.5 depicts comparison of each simulations. The vehicle capacity was 10. In the static simulation, the ride time was 2378 seconds, and the wait time was 105 seconds. In the dynamic simulation carried out without background traffic, the ride time was 2272 seconds, and the wait time was 262 seconds. In the dynamic simulation carried out with background traffic, the ride time was 2348 seconds, and wait time was 743 seconds.

Figure 4.6 describes comparison of each simulations. The vehicle capacity was 4. In the static simulation, the ride time was 2368 seconds, and the wait time was 106 seconds. In the dynamic simulation performed without background traffic, the ride time was 2262 seconds, and the wait time was 268 seconds. In the dynamic simulation performed with background traffic, the ride time was 2341 seconds, and the wait time was 1128 seconds.

Finally, Fig. 4.7 shows comparison of the trip time among different capacities. The figure indicates trip time of the capacity for 10 passengers was shorter than the others.

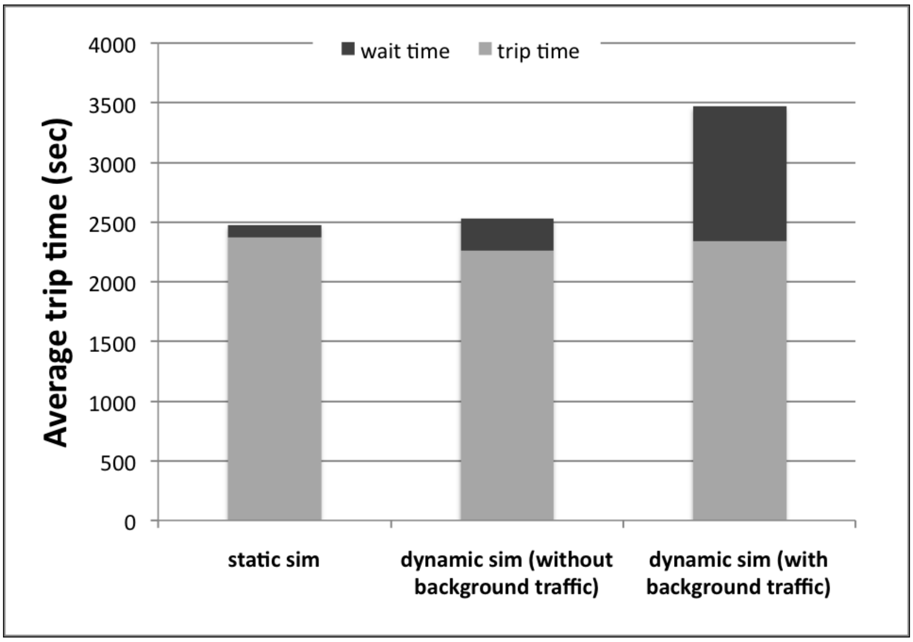

Figure 4.6: Comparison of average trip time between static simulation and dynamic simulation. The capacity of the DRB was 4 customers.

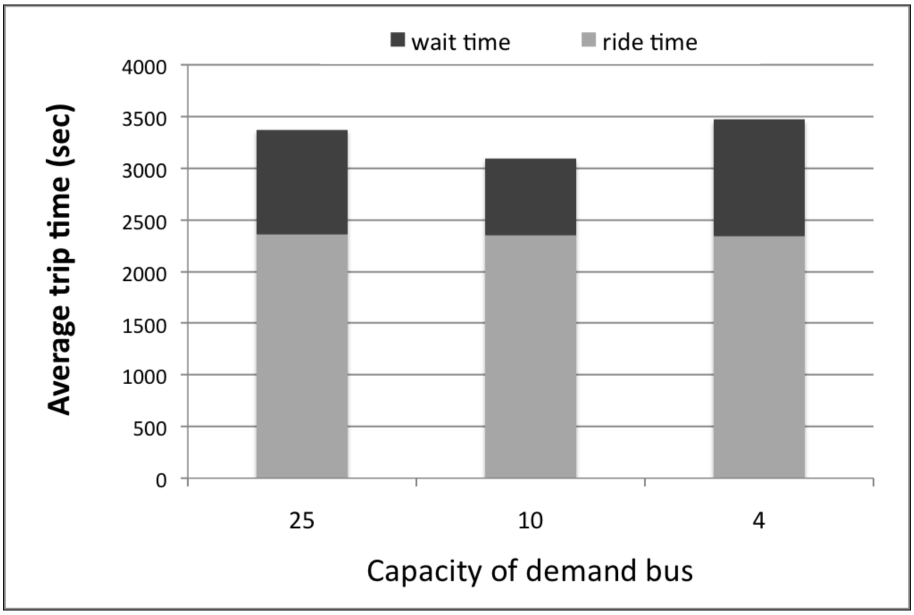

Figure 4.7: Comparison of the simulation result that was carried out with background traffic. (Summary)

The detour for picking up (dropping off) customers decrease as the vehicle capacity is less. In contrast, the number of vehicles increases when the capacity is less because the utilization efficiency of vehicle is less. The wait time for transit become shorter when the vehicle capacity is less but it causes local traffic congestion due to the number of the vehicles. In the experiment, traffic congestion has occurred when the vehicle capacity was 4.

4.4 Discussion

The trip time of the proposed system in three difference situations were compared. Both the trip times of the static simulation and of the dynamic simulation without background traffic, indicated similar result because trips of the static simulation are independent of each other (i.e. the system has no influence on other traffic and also other traffic has no influence on the system). In contrast, wait time of the dynamic simulation with background trip was approximately 50% longer than that of the dynamic case without car trips. The longer waiting time was caused from deviation of schedule due to stop at intersection and interaction between vehicles. Especially in CRB, wait time of CRB can be increased because CRB must wait all DRBs assigned to the DRB at each depot. The deviation must be avoided by improvement of procedure for schedule planning that can consider delay at intersection and interaction among vehicles. In addition, delay can be reduced by combining with bus lanes or PTPS discussed in section 3.4.3.

The influence of the proposed system on private cars are shown in Table 4.1. The table indicates the proposed system has small influence on other traffic. However, traffic congestion due to concentrating DRBs around a depot can occur. Thus, detailed experiment about traffic flow around depots are needed.

4.5 Summary

This chapter has described evaluation of the hierarchical cooperative transport system on the dynamic microscopic simulator developed by the authors. The results have shown that the system has less influence on other traffic, but trip time of the system users, especially wait time, was susceptible to external factors such as intersection and other traffics. To enhance feasibility, improvement of scheduling accuracy is required for further investigation.

5 Conclusion

5.1 Conclusion

This dissertation has proposed a new transport system that is hierarchical cooperative transport system (HCTS) using demand responsive bus (DRB).

Many researchers have tackled the problem for DRB system. Especially, the algorithms for planning routes and schedules of DRBs, called the dial-a-ride problem (DARP), have been developed for the last several decades. Some algorithms for the DARP and studies for introducing DRB system are reviewed in chapter 2.

In chapter 3, we have developed the system to use DRBs for larger number of requests than traditional DRB systems. HCTS provides flexible routes and schedules with DRBs and rapid transportation with trunk transport systems. Two versions of the system have been introduced to fit the system to different type of cities. The first version of HCTS is applicable to local cities whose downtown provides sufficient transportation system. The trunk transport of the system terminates the central station of downtown for making their customers' connection with urban transport system. In addition, a new algorithm of routing and scheduling for DRBs operated in suburban area has been proposed. From the experiments for the HCTS, it has improved level of service by reducing walk time, and some travel time have been replaced with extra time at customers' destination. Moreover, the HCTS has higher utilization efficiency relative to the fixed route bus system when the system is provided in the area where its size is small and location is close to downtown. The efficiency has increased when the number of customer increases.

The second HCTS is designed for local cities and its suburbs which provides insufficient transport system. The system provides DRB transportation for making customers' access (or egress) to trunk transportation. The system has shown effectiveness especially in an area where its traffic demands distribute spatially and temporally.

In chapter 4, the evaluation of the HCTS on a dynamic microscopic simulator developed by the authors has been described. The simulator which consists of multi-agent system can simulate behavior of each vehicle. Therefore, the influence of background traffic on the proposed system can be minutely examined by using the simulator. The result showed that trip time of the proposed system was similar to that of the static simulation when the simulation was performed without background traffic. In the experiment with background traffic, the result has shown that the wait time for transferring increased due to the influence of background traffic. To deal with the issue, a new scheduling algorithm considering background traffic should be developed.

Contribution of this work is to develop a new transport system that can improve level of service using demand responsive buses for a large number of requests. Actually, routes and schedules for over 80,000 requests has been planned within practical time by proposed method. Using this system, demand responsive bus can be provided for people living in a local city and its suburbs.

5.2 The Future Works

Future works for this study are as follows:

- Reduction of the number of required vehicles.
- Dealing with on-line response to requests.

HCTS requires much cost such as the number of vehicles relative to the existing route bus system. The reason for the cost can be considered that the system divides the problem for planning routes and schedules into smaller problems to reduce computational time. It is possible that similar requests assigned to different *depots* are not transported by single bus. However, the system can apply more efficient algorithm for planning routes and schedules to enhance vehicle utilization efficiency. The algorithm employed in this work [13] is one of the fastest heuristic but its result has been myopic [14, 16]. Therefore, it is possible that the system improves its operational cost to employ more sophisticated algorithms and optimization procedures.

On-line scheduling is also essential for public transport system in real situation. In this study, we have assumed that all requests were received until the day before of customers' trip. However, instant requests can occur in real situation. Suggesting a bus passing the closer stop to customers is often available because the system is largely operated. Searching the nearest bus is achieved by on-line DARP such as the references [50] and [51].

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