Is Dial-a-Ride Bus Reasonable in Large Scale Towns? Evaluation of Usability of Dial-a-Ride Systems by Simulation

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Abstract. Dial-a-ride systems are attracting attention as a new style of transportation systems for urban areas. While it has been reported that such systems improve the usability of bus systems when applied in a small town or area, it is not obvious how and under what conditions the systems are effective in comparison to traditional fixed-route bus systems. We conducted two computer simulations of dial-a-ride and fixed-route systems in order to compare the usability and profitability of both systems. Simulation results indicated that: (1) The usability of the dial-a-ride system with a fixed number of buses drops very quickly when the number of requests(demands) increases. (2) When we increase the number of buses proportionally to the number of demand, the usability of the dial-a-ride system is improved more significantly than that of the fixed-route system. (3) When frequency of demands is sufficiently, the dial-a-ride system is a reasonable solution from the both usability and profitability perspectives.

1 Introduction

Dial-a-ride is a door-to-door public transport service for individuals who, because of a disability, are prevented from using transports, the city's fixed-route bus service. It is a system in which a passenger calls a control center of buses and tells his/her destination; and the center re-plans route of an appropriate bus to service the request.

The dial-a-ride system is also attracting attention as a new public transportation system that provides convenient transportation for disabled persons while solving traffic-jams in urban areas. It is, however, applied to limited and small-scale cases for the following several reasons:

– It is difficult to handle a huge number of passengers with many buses. Generally, the problem of finding an optimal assignment of a passenger's request to a bus is a NP-hard problem.

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– Traditional fixed-route systems cannot obviously be replaced by the dial-a-ride system. Especially, it is not well-studied how the usability of the dial-a-ride system changes when the number of passenger increases compared with the fixed-route systems.

Many researchers have already attacked the first issue. Assignment of passengers' requests and planning bus routes is considered a variation of the *traveling-salesman problem*[1, 2] and the *vehicle routing problem*[3, 4, 5, 6, 7]. Various optimization techniques are used to solve the problem. [8] and [9] makes use of local search and tab search, respectively. Simulated annealing and GA has also been applied in [10, 11]. Complexity of calculation has been investigated by [12].

In addition to these studies, various studies have addressed the dial-a-ride problem from the following various perspectives:

– comparison of performance under various constraints on buses:
  Many studies [13, 3, 14, 15, 16] have investigated changes of performance when the dial-a-ride system is run with various numbers of buses.
– on-line and off-line algorithms:
  Various operation research techniques have been applied to solve assignment and re-routing problems under on-line and off-line conditions[17, 18, 13, 19, 20].
– relation to other traffic constraints:
  [21] investigated how the dial-a-ride system interacts with other long-distance transportation systems such as trains. [22] addressed the relation between efficiency of buses and town size. [18, 23] took traffic conditions into account to evaluate the performance of dial-a-ride systems.

On the other hand, however, few studies have examined the problem from the viewpoint of the second issue stated above. Currently, dial-a-ride systems serve mainly disabled persons. It is difficult for the system to garner sufficient revenue from passengers' fees because the number of disabled persons is limited. We should conceptualize a way for traditional fixed-route system users to use the dial-a-ride system to increase the number of passengers. For that purpose, a comparison of usabilities of fixed-route and dial-a-ride systems is necessary in order to determine the conditions in which the dial-a-ride system will provide a better solution for whole social systems. This article, shows the results of a comparison of the usability of both of fixed-route and dial-a-ride systems by simulations of transportation in a virtual town. In the rest of the article, we formalize the problem of dial-a-ride systems in Section 2 and in Section 3 describe a detailed setup of simulations. Finally, simulation results are shown and analyzed in Section 4.

2 Formalization

2.1 Dial-a-Ride System

There are several frameworks of dial-a-ride systems according to styles of accepting *demands*[1] and policies of bus routing. Two major style variations are:

– **Reservation Style**:
  A passenger calls and makes a request to the bus control center a certain period ahead of the requested departure time. For example, a passenger must make a reservation one hour before riding.
– **Real-Time Style**:
  A passenger can make a request when she wants to ride: that is, she simply calls the control center when she wants a ride.

This study presumes, we suppose the **real-time** service because it can be applied more generally to various conditions that include the usage of fixed-route systems.

Bus routing policy also has some variations. For example, here are two typical policies:

– **Basic-Route with Optional Detour Routes**:
  A bus mainly follows a basic route; it turns onto predefined optional detour routes according to passengers' requests. A passenger can embark or disembark at anywhere along these routes.
– **Free-Routing**:
  A bus can runs on any road in a certain area. A passenger can embark or disembark anywhere in the area.

We focus on **free-routing** In these policies,because it provides the most important service of the dial-a-ride system.

2.2 Usability and Profitability

As stated in Section 1, the purpose of the simulation is to compare usabilities and *profitabilities* of dial-a-ride and fixed-route systems. Generally, the evaluation of such criteria is difficult because usabilities depend on subjective factors and profitabilities may change according to social conditions. In order to avoid these difficulties and to enable such evaluation by simulation, we simplify usabilities and profitabilities in order to allow them to be handled quantitatively as follows.

For *usability*, we focus on the primary purpose of a bus system, that is, to provide a way for a passenger to get to his/her destination as quickly as possible. From this point of view, *usability* can be defined as follows:

Usability: average elapsed time from when a demand is told to the bus center until the demand is satisfied.

[1] We call the passenger's request to ride from somewhere to another place as a *demand*.

Note that we use the time when the request is made instead the time when the passenger departs, because we need to compare dial-a-ride and fixed-route systems under the same conditions. In the case of a fixed-route system, a passenger goes to a bus-stop when he/she needs a ride. This means that the elapsed time is measured from then. Thus, we use the same measure in the case of a dial-a-ride system.

In addition, we suppose that a passenger never transfers buses. The first reason is that it is difficult to measure physical and mental costs of the transfers. People may use a slower bus route instead of a faster one when the latter one requires many transfers. This implies that we need to interpret such costs in *usability*, which by definition is measured in term of time. To avoid such complexity, we do not consider cases in which a passenger transfers buses.

Profitability is formalized as follows. The profit (or deficit) of a bus company depends on maintenance, fuel and labor costs, and fare incomes, which vary in terms of social and economic conditions. In addition, fare-pricing causes secondary social effects by which the number of passengers changes. Therefore, it is difficult to directly quantify *profitability*. Instead, we simplify it as a balance between fare revenue and cost, where revenue and cost change in proportion to the number of passengers and buses, respectively. In other words, *profitability* is defined as follows:

> **Profitability**: the number of demands that occur in a unit period per one bus.

2.3 Virtual Town

In order to prepare field for the simulation, we compose a virtual town as follows:

- Streets in the town are arranged in a grid pattern as in Kyoto and New York City.
- The town shape is a square.
- All stops are at the crossings.
- There are no traffic jams.
- A bus goes through, turns left or right at a crossing with the same duration.
- There are no limitations in the passengers capacity per bus.
- Getting on and off buses requires no time.

In this virtual town, demands occurs under the following conditions:

- Demands occur at a constant frequency.
- Departure and destination points are decided randomly. (All positions of crossings in the town have the same probability of being departure or destination points.)
- If a passenger can reach his/her destination on foot faster than riding a bus, the passenger refuses to use a bus. In this case, the time to walk is treated as the elapsed time to satisfy the demand.
- A passenger does not transit buses.

3 Simulation Setup

3.1 Fixed-Route Systems

The usability of a fixed-route systems varies according to bus-routes. It is difficult to find the optimal set of routes to cover a town theoretically because it is affected by many factors such as number of buses, average bus speed, number of routes, the shape of the town, and so on. Therefore, we apply a genetic algorithm (GA) in order to determine a semi-optimal set of routes.

Individual of Fixed-Route Systems In this simulation, an individual of GA consists of a set of bus-routes. We suppose that the number of routes is fixed, and that just one bus runs on one route. Therefore, the number of buses is equal to the number of routes. There are two route types: *normal* routes and *loop* routes. On a *normal* route, a bus runs back and forth between two terminals. On a *loop* route, a bus circulates in a loop.

Evaluation of Usability As mentioned in Section 2.2, usability is measured by *average time needed to satisfy a demand* (ATCD). When a passenger decides which route to use, the ATCD (T_{demand}) can be calculated as.

$$\begin{aligned} T_{\mathrm{demand}} = & (L_{\mathrm{src}} + L_{\mathrm{dst}})/V_{\mathrm{walk}} \\ & + L_{\mathrm{route}}/(M_{\mathrm{bus}} \times V_{\mathrm{bus}}) \\ & + L_{\mathrm{bus}}/V_{\mathrm{bus}}, \end{aligned} \quad (1)$$

where L_{src}, L_{dst}, and L_{bus} are distances between a departure-point and an embarkation stop, between a disembarkation stop and a destination point, and between the two stops, respectively. L_{route} is the length of the whole route. V_{walk} and V_{bus} are walking speed and bus speed; M_{bus} is the number of buses per a route[2]. In the equation, the first, second, and third terms of the right-hand side indicate "walking time", "average waiting time at bus stop", and "riding time on bus", respectively.

Because we evaluate the best performance of an individual (a set of bus-routes), the individual searches for the best route from a set of routes and determines the best combination of stops to embark and disembark for a given demand. Note that evaluation includes ATCD of the case where a passenger chooses to walk the whole journey to the destination because walking is faster than using a bus. In this case, L_{route} and L_{bus} are assumed to be zero; $L_{\mathrm{src}}+L_{\mathrm{dst}}$ is equal to the distance between the departure-point and the destination-point.

[2] As mentioned above, M_{bus} is fixed to be 1 in this simulation.

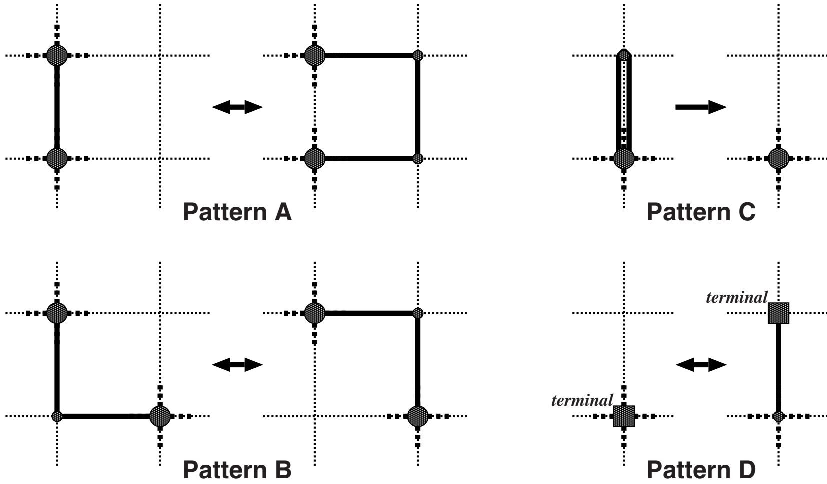


Fig. 1. Mutation pattern

Alternation of Generations A generation consists of 100 individuals. Each individual is evaluated by calculating average ATCD based on Eq. 1 using 50 randomly generated demands. Then, the top 10 individuals are selected and survive to the next generation. The next generation consists of 10 survivors, 70 descendants generated from the survivors (7 descendants per a survivors), and 20 new randomly-generated individuals.

Individuals in the last population (and in the initial generations) are generated as follows:

1. Two terminal points are chosen from all crossings in the town randomly.
2. A type of route is chosen from *normal* and *loop*.
3. When the route is the *normal* type, then the route connects the two terminals by 'L'- and 'Γ'-shape paths. When the route is the *loop* type, the route forms a rectangle whose two diagonal apexes are the two terminals.

Descendants are generated by mutation and cross-over described as follows;

Mutation We restrict mutation within the following four patterns to guarantee that a mutated bus route is a valid route.

Pattern A (Fig. 1-A) : If a route connects two adjoining crossings by a direct edge, replace the edge is replaced by a detour of three edges (and its inverse transformation).

Pattern B (Fig. 1-B) : If a route connects two diagonal crossings of a block by two edges, the two edges are replaced by other two edges of the block.

Pattern C (Fig. 1-C) : If a route has a branch that goes between two adjoining crossings directly, the branch is shortened.

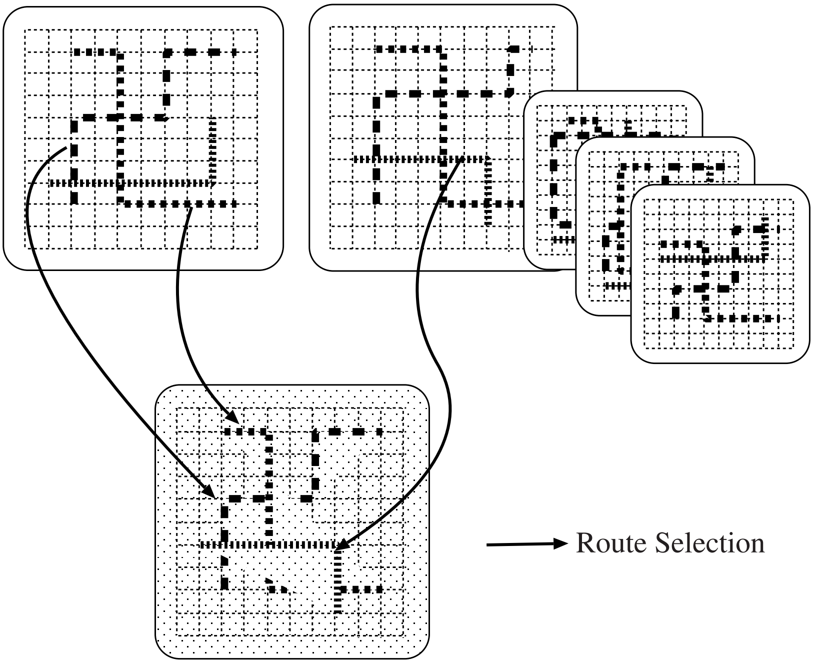


Fig. 2. Cross-over

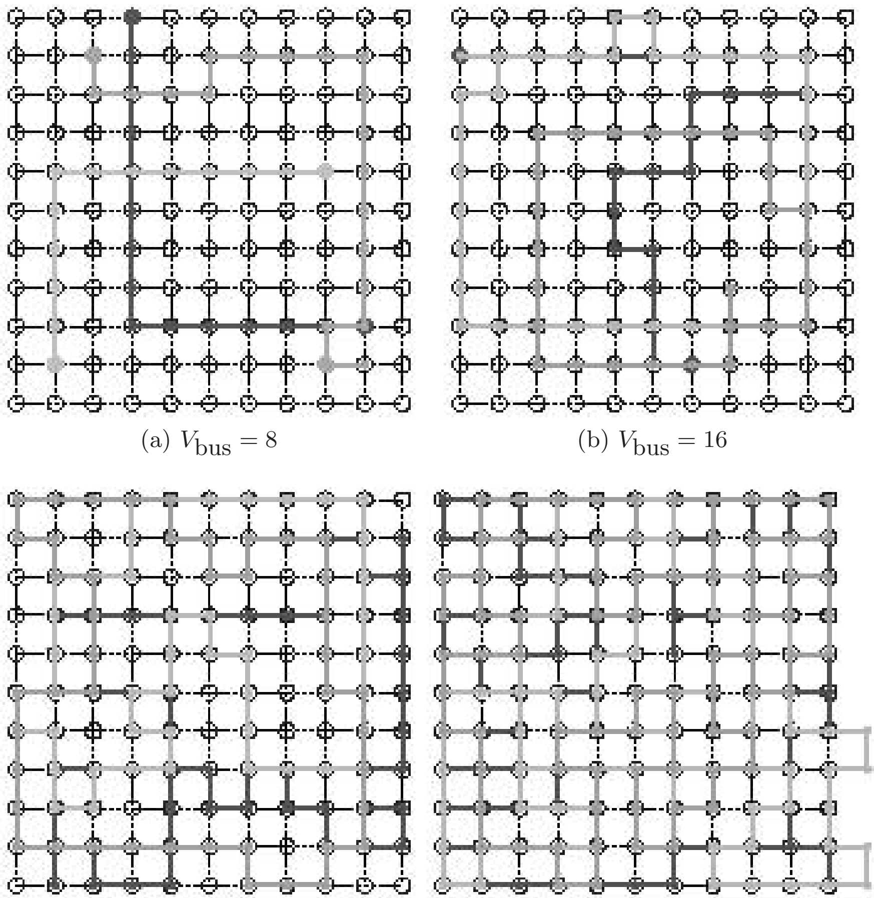
Pattern D (Fig. 1-D) : In the case of a *normal* route, a terminal is moved to on an adjoining crossing and extends/shortens the route.

When a descendant is generated from a parent individual, up to one mutation occurs per route[3].

Cross-Over Cross-over is realized by exchange routes between survivors' descendants as shown in Fig. 2. Note that the cross-over changes only the combination of routes, not routes themselves.

Acquired Routes Figure 3 shows examples of routes acquired by GA. These examples are the best individuals of the 10,000th generation, where the number of routes is 3 and the ratio of bus and walking speed varies from 8 to 256. Figure 3 shows that the town is roughly covered by three 'L'-shape routes when the bus speed is slow, while the routes come to cover almost all crossings when the speed increases. These results indicate that the proposed GA method can yield reasonable semi-optimal routes for a given condition.

[3] Because most mutations change the usability for the worse, the probability of improving usability becomes very low when we apply multiple mutations per route. Therefore, we restrict the number of mutations to one per route.



(a) $V_{\text{bus}} = 8$ (b) $V_{\text{bus}} = 16$

(c) $V_{\text{bus}} = 32$ (d) $V_{\text{bus}} = 256$

Fig. 3. Semi-optimal fixed-routes acquired by GA

3.2 Dial-a-Ride System

For simulation of a dial-a-ride system, we must solve the problem of how to assign a new demand to buses and to re-plan a path for each bus. This is a kind of dynamic traveling salesman problem. Moreover, the problem includes more complex constraint in which each demand is refused when the expected arrival time is overdue for its deadline[4]. Therefore, it is hard to find the optimal assignment in a reasonable time. Instead, we take a way to find a semi-optimal

[4] Deadline of a demand is defined as the latest time the demand should be completed. In our simulation, the deadline is the time when the demand will be completed if the passenger walks me entire distance to his/her destination.

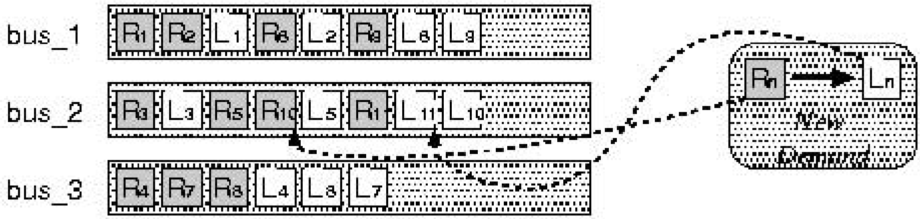


Fig. 4. Successive best insertion

assignment by using an approximation method called *successive best insertion* (Fig. 4) described as follows:

1. Each bus stores assigned demands in a via-point queue, in which an assigned demand is divided two way-points: the departure point and destination point, which are inserted at appropriate positions. The bus always runs toward a way-point at the top of the queue, and removes it from the queue upon arrival. We suppose that the order in the queue is not changed after the assignment.
2. Each bus also satisfies its expected time to complete each assigned demand. The expected time is calculated by supposing that the bus will run according to the *current* queue of via-points.
3. When a new demand occurs, each bus searches for the best positions to insert two via-points of the demand, which minimizes the cost, that is, the sum of the total delay of existing demands and expected time to complete the new demand. If the deadline of an existing or new demand expires by the insertion, the bus reports it has *no solution*.
4. The bus control center assigns the demand to a bus whose cost is the minimum of all buses. When all buses report *no solution*, then the demand is refused.

4 Simulation Result

We conducted various simulations of both bus systems using the following parameters: The size of the town is 11×11, and the ratio of walking and bus speeds is 1 : 8.

4.1 Case 1: Fixed Number of Buses

In the first simulation, we evaluate the case in which a fixed number of buses are used in both systems. Figure 5 shows changes of ATCD of both systems using three buses when the number of demands per unit time increases. In this figure, a strait horizontal line indicates the ATCD of the fixed-route system. The ATCD

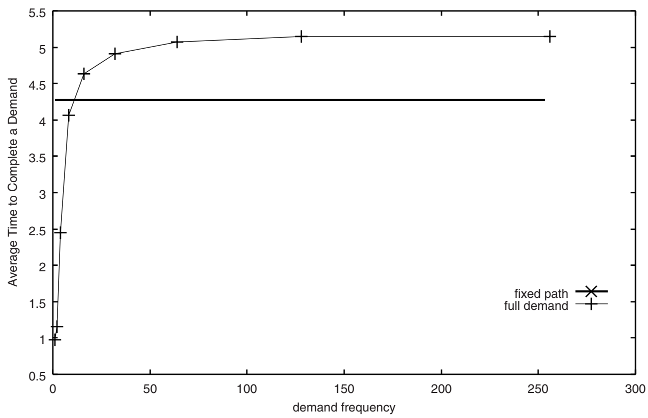


Fig. 5. Changes of average time needed to satisfy a demand in the case of three buses

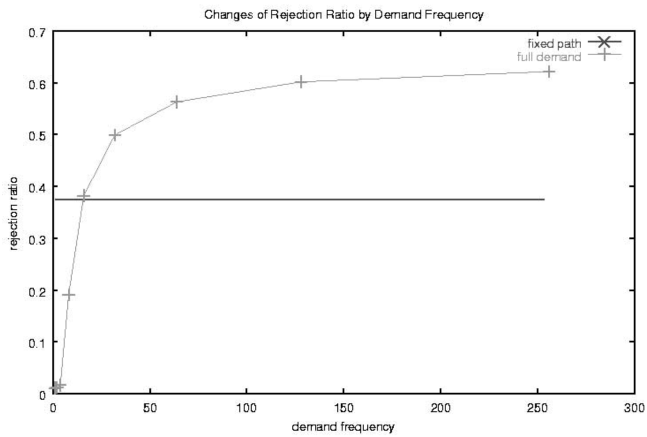


Fig. 6. Changes of ratio to refuse demands in the case of three buses

of the fixed-route system does not change according to the number of demands because we do not consider time to get on and off.

On the other hand, the ATCD of the dial-a-ride system starts with a small value in the case of few demands and increases immediately over the fixed-route system. This means that usability of the dial-a-ride system with the fixed number of buses quickly decreases when the number of demands increases. The reason for this change for the worse in the dial-a-ride system is that most of the demands are refused when many demands occur. Figure 6 shows changes in the ratio of refused demands. As indicated in this graph, the refusal ratio of the dial-a-ride system decreases more quickly than that of the fixed-route system.

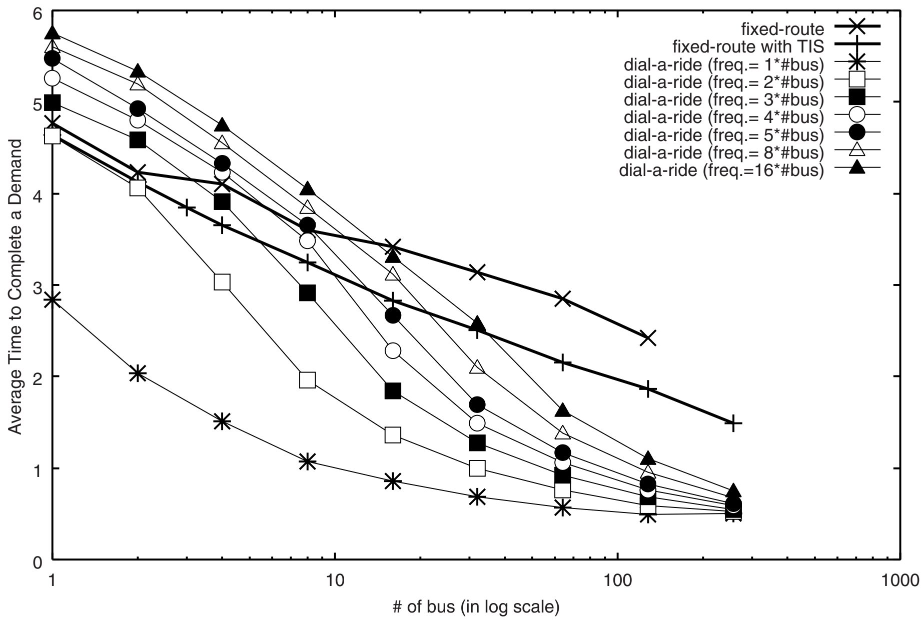


Fig. 7. Changes of average time to complete a demand when the profitability is fixed (the number of buses increases constantly according to the number of demands)

4.2 Case 2: Fixed Profitability

In the second simulation, we evaluate the case in which profitability of the systems is fixed. As defined in Section 2.2, profitability is the number of demands occurring in a unit period per bus. Therefore, in this simulation, we increase the number of buses according to the number of demands while maintaining a certain ratio of demands and buses.

Figure 7 shows the simulation results. In the figure, two thick lines indicate performance of the fixed-route systems. The upper thick line shows the case of a normal fixed-route system in which a passenger decides a route according to the expected ATCD of each route. The lower thick line is the case of a TIS(Traffic Information System)-supported fixed-route system. This case is discussed later. Other thin lines indicate performances of dial-a-ride systems with various profit-abilities. The profitability varies from $\langle$# of demands in unit period$\rangle$/$\langle$# of buses$\rangle$ = 1 to 16. The graph plots changes of ATCD in each case by the number of buses. This figure shows that the usabilities are improved in each case. In Addition, improvement of dial-a-ride systems comes more quickly than fixed-route systems. In both systems, the usabilities are improved because a passenger is provided many choices in reaching his/her destination. In addition, because the dial-a-ride system provides more flexibility to fit passenger's demands, the improvement is greater than that of the fixed-route system.

4.3 Case 3: Comparison with TIS-Supported Fixed-Route Systems

In the previous simulation, we assume that a passenger decides a route according only to the expected ATCD of routes in a fixed-route system. This is a reasonable assumption when a passenger does not know when the next bus of each route will come. However, the usability of this fixed-route system can be improved using recent TIS. Suppose that there are many possible routes that provide similar ATCDs for a demand and that a passenger can know the exact time for the next bus of each route at any stop by TIS. In this case, the passenger can calculate a more accurate time to satisfy his/her demand for each route instead of the average one. Using the accurate value, he/she can choose a more appropriate route.

The lower thick line in Fig. 7 indicates performance of this case. As shown in the graph, usability is improved by the TIS support. This improvement becomes obvious when the number of buses increases. Nevertheless, the usability of the dial-a-ride system offers an advantage when the number of buses is large.

4.4 Case 4: Fixed Profitability with Converged Demands

In the previous three cases, we assumed that demands occur uniformly in any place in the virtual town. This is, however, not realistic because a town generally has several centers such as a train station and a shopping center, where demands converge. We conducted a simulation using converged demand to reflect such a condition in the simulation.

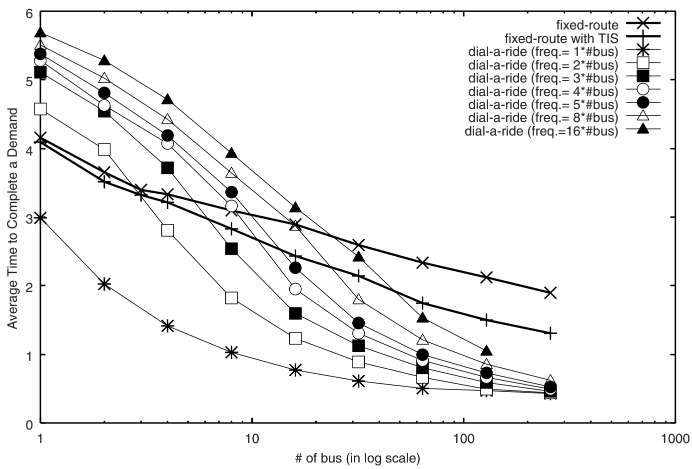
In the simulation, we assume that there is a center of convergence of demands in the middle of the town. When a demand is generated, one of departure point or destination is the center in a certain ratio, called *convergence ratio*.

Figure 8 shows results of the simulation when the convergence ratio is (a) 0.5 and (b) 0.9. Compared these graphs and Fig. 7, we can see that the advantage of dial-a-ride systems in the usability becomes more obvious when the convergence ratio is high. For example, when a dial-a-ride system supposes profitability ($\langle$# of demands in unit period$\rangle$/$\langle$# of buses$\rangle$) is 16, its usability becomes better than the fixed-route system with TIS at the number of buses is 64 in Fig. 8 and 16 in Fig. 7-(b).

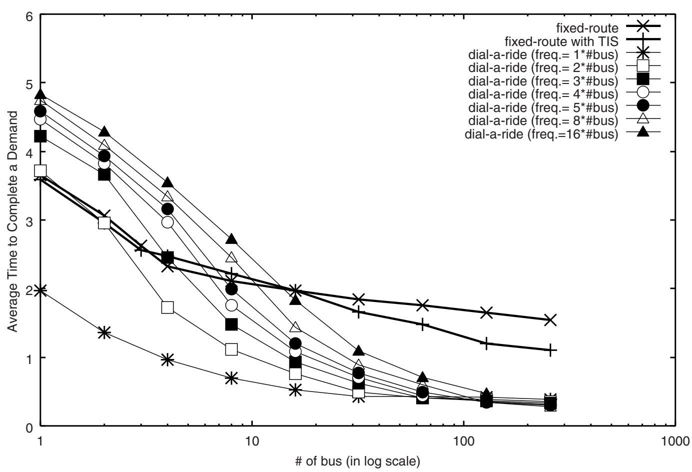
5 Discussion and Conclusion

In conclusion, we can summarize features of a dial-a-ride system compared with a fixed-route system from simulations in previous section, as follows:

- When the number of buses is fixed, the usability of the dial-a-ride system degrades quickly when the number of demands increases. On the other hand,



(a) convergence ratio = 0.5



(b) convergence ratio = 0.9

Fig. 8. Changes of average time to complete a demand when the profitability is fixed with converged demands

usability of the fixed-route system is stable against changes of the number of demands until buses become full. For usability, in other words, we can choose the dial-a-ride system with a fixed number of buses only when frequency of demands is very low. This is bad news for the dial-a-ride system because it is difficult to keep usability at a reasonable level by the dial-a-ride system, while more and more demands are required for profitability. It is, therefore, not true that "dial-a-ride systems will be profitable when we have sufficient demands".

– When the number of buses increases with the fixed profitability, usability of the dial-a-ride system is improved more quickly than the fixed-route system. Therefore, even if the case where usability of the dial-a-ride system is worse than the fixed-route system in the case of low frequent demands because of keeping the high-profitability, it gets better when the demand frequency increases.

The following open issues about the simulation remain:

– **Correspondence with Real Values**: Parameters in simulations shown in this article are abstracted so that it is difficult to make a correspondence with realistic values of actual phenomena. For example, we need to investigate the ratio of bus and walking speeds, and to use an actual town map in which is complicated compared with grid pattern town.
– **Collaboration with other Transportation**: In the actual transportation in urban areas, we use several transportations at the same time. Usability of a bus system should be evaluated in conjunction with other systems like trains.
– **Comparison between Transferable Bus System and Dial-a-Ride**: In this simulation, the assumption that passengers cannot transfer buses is applied. If passengers can transfer the buses, can the usability of fixed route systems become better than that of dial-a-ride systems? Furthermore, from the point of view of applying dial-a-ride systems to real world, the combinational systems of dial-a-ride and fixed route systems may be required actually.
– **Inconstant Demands**: The simulation described here evaluate systems only under the condition where demands occur constantly. Inconstant and intermittent occurrence of demands like 'rush-hours' are general phenomena for transportation systems. In such cases, a simulation must address a framework to switch bus systems.

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