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WORKING PAPER

# On-Demand Public Transportation

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# On-Demand Public Transportation

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**Abstract**

In this paper we assess an on-demand public transportation system through a simulation study. The on-demand system makes use of minibuses that have neither fixed itineraries nor fixed stops. The minibuses are rerouted online to dynamically accommodate the requests received by the users. To use the on-demand service users communicate, close to their desired departure time, the origin and destination of the trip. If the estimated arrival time at destination fulfills the user acceptance threshold, it will be chosen. In the simulation we allow the user to walk, to use the on-demand service, a bus or a private car. We will consider a large number of scenarios to evaluate the potential costs/benefits of the introduction of an on-demand service. We will also analyze the scalability and the responsiveness of the service. The results suggest that an on-demand public transportation system would be preferred by most users to the private car and to a bus service. This in turn would imply a more efficient and environmentally friendly transportation system.

# 1 Introduction

A recent analysis on modal split of inland passenger transportation has revealed that in Europe 15-20% of the passengers' moves are satisfied by public transportation (motor coaches, buses, trolley buses and trains), while 80-85% are made through cars (see statistics from Eurostat [2]). With a moving population of more than 80% of the total, this data implies that on a daily basis the number of cars on the roads exceeds half of the population.

Traffic congestion is a primary problem everywhere. As stated in [18], the automobile has had a dramatic impact on the society during the last century. A crucial issue has become the sustainability of such a growing number of cars on the roads which has led to a renewed interest in alternative forms of transportation, especially in urban areas. This is witnessed by the wide diffusion of bicycle and car sharing systems, as well as car pooling. However, the main issue concerning the scarce use of public transportation means has not yet been properly addressed.

Why is the public transportation system so unpopular? One of the main reasons that leads people to use their own private vehicle is the lack of flexibility of the public transportation system. Mass mobility systems typically work on fixed schedules which in many situations can not satisfy the dynamic demand of people. The frequency is too low and the average travel time is much higher than that required by moving privately. A further issue related to the public transportation system is its inherent inefficiency: buses are too crowded during peak hours while they are almost empty in other parts of the day. This clearly has a strong impact on the operational cost and the sustainability of the system. Thus, there is the need to redesign the public transportation system in order to make it more suited to the users' needs and, also, to increase its efficiency.

Demand Responsive Transit (DRT) systems (also called dial-a-ride systems) have emerged in the last decades as an attempt to satisfy the dynamic nature of users' demands. They rely on flexible services able to provide almost 'door-to-door' transportation in small vehicles, with the possibility of pre-booking (see [5], [15] and [20]). DRT systems are nowadays mainly implemented as services for small groups of persons (e.g. elderly or handicapped persons, see [11], [26] and [16]). However, massive and on-demand services are far from being considered as a possibility or an alternative to the conventional public transportation system. The literature is very limited too (see [30], [8], [7], [26] and [25] for studies on the topic and [17] for planning multi-leg journeys with fixed-route and demand-responsive passenger transportation services).

An excellent review of the literature dealing with DRT systems is presented in a recent paper [23] where a minibus service is studied to serve low and intermediate density areas (see also [13] and [12]). The authors propose a classification of DRT systems previously introduced in [5] as:

- with fixed itineraries and stops, where users must pre-book the service;
- with fixed itineraries and stops with possible detours;
- with unspecified itineraries and predefined stops;
- with unspecified itineraries and unspecified stops.

The first category is the most closely related to the traditional public transportation service. This category may also include systems with fixed timetables. The difference is that users have to pre-book the service which is performed on demand. As specified in [23], the last type of service, which is the most flexible one, can be considered as the closest to the concept of shared taxis. The shared taxi system is studied in [22] and is the system where taxis are used to serve more than one customer at a time. Customers are assigned to shared taxis on the basis of their origin and destination requests and their service time, while guaranteeing a predefined threshold of service level. The authors simulate, on the city of Lisbon, the behavior of a system combining traditional taxis, i.e., taxis serving one person at a time, with shared taxis. Users can hail for a taxi on the street, go to a taxi stand or phone to a dispatching company. Shared taxis can only serve customers that place their service request to a dispatch company. The simulator assigns users to taxis with the objective of minimizing waiting time for the users and balancing workload (and thus rewards) of taxi drivers. The indicators used to measure the performance of the system are: waiting time for users, cost for users and taxi drivers revenues. The results show that passengers may benefit from an average 9% fare reduction compared with the traditional system. Even if this value may seem low, it is expected that demand would increase thanks to the fare reduction.

More recently, DRT systems have been referred to as Flexible Transportation Services (FTS) (see [25]) when used as feeder systems for more traditional public transportation services such as buses or trains. From this point of view, DRT are seen as flexible, demand-responsive transportation services used to ease the user access to massive public transportation means. A recent paper [3] has introduced a new system called Flexible Mobility On Demand (FMOD) which provides different levels of service to each passenger request. The system utilizes three services, taxi, shared taxi and minibus, where the minibus service works as a regular bus service with fixed schedules. Passengers place their requests to the system provider and are presented with a menu of choices from which they make a selection based on their preference. The list of travel services is designed in real time. These services vary both in terms of flexibility and cost. The authors present a simulation of the system on the Hino city in Tokyo and compare different scenarios in terms of fleet configuration.

The purpose of this paper is to evaluate, through global performance measures, the impact of an innovative large-scale on-demand service for public transportation. The service we are proposing belongs to the last class of DRT systems presented above as it is based on the use of minibuses with unspecified itineraries and unspecified stops and, thus, is fully flexible. It is an on-line service in the sense that users place their transportation requests and receive an answer in a very short time, usually within a few seconds. The system differs from the shared-taxi system for the following reasons:

- There are no revenues for the drivers. This makes a big difference with respect to the shared-taxi system where one of the objectives when assigning service requests to taxis is to keep revenues balanced among drivers;
- Drivers are not traveling around looking for clients as it is typically done by taxi drivers while they are empty;
- The vehicles are minibuses with a higher capacity than taxis.
- Performance measures of shared-taxi systems are based on fares paid by clients and revenues gained by drivers. The goal of the proposed system is to attract to a public transportation service a large portion of the persons that travel with their own car in urban areas, to reduce congestion and pollution, on one side, and to improve the efficiency of the public system, on the other side.

The goal of this paper is to present a preliminary simulation study of an on-demand public transportation system. We will simulate the behavior of the system for different settings of the road network and of the users requests. The purpose is to study the performance of the system in terms of average travel time of the users, average distance traveled, fuel consumption and global system cost. The global system cost is measured as the sum of the cost for the drivers of the minibuses, cost for fuel and cost for the maintenance and insurance of vehicles (minibuses, buses and private cars). We do not include fares paid by the users in this preliminary study and suppose that, if the service level provided by the public transportation system satisfies the flexibility request of a user, then the user will use the public system, otherwise he/she will turn to a private car. We will simulate four different scenarios, where in addition to private cars the following means of public transportation are available: no public transportation service (i.e., all transportation requests are satisfied by private cars), traditional buses only, on-demand public transportation only, buses plus on-demand transportation. The simulation will allow us to compare the behavior of a system where no public transportation is available with systems where one or more public transportation means are available. In particular, we will evaluate the potential costs/benefits of the introduction of an on-demand service. An extensive computational study is made by simulating different road networks, number of available vehicles and number of requests. The results show that the on-demand service dominates the conventional public transportation by buses in the sense that it serves a much higher number of requests with a comparable cost and it remarkably decreases the average travel time. Moreover, the system performs better when the number of transportation requests increases, is highly competitive, in terms of cost, with respect to the transportation by private cars and is much more environmentally friendly.

The remaining part of the paper is organized as follows. In Section 2 we describe a flexible transportation system on which we base the simulation and present the main ideas behind the on-demand public transportation service. Section 3 deals with the simulation of the system. We first define the underlying structures, namely the road network and the transportation requests. Then, we discuss the simulation of direct trips, i.e. trips performed by walking or by private cars, of conventional public transportation by buses and of the proposed on-demand public transportation service. We also give an overview of the parameters and the performance indicators of the simulation. A comparison between the different modes of transportation is performed in Section 4. In Section 5 we examine some properties of the proposed on-demand public transportation service more in detail. Finally, Section 6 contains a discussion of the results, the conclusions and an outlook of promising research directions.

## 2 A flexible transportation system

We consider a system where users express transportation requests that can be satisfied by means of conventional buses, on-demand minibuses or private cars. Each request is characterized by the time at which it is expressed, by an origin and a destination, by a desired departure time and a flexibility value. The latter value indicates the excess travel time a user is willing to accept by using public transportation with respect to the usage of a private car. Note that the desired departure time is the earliest time at which a customer can be picked up. In our simulations, we fix no maximum waiting time. However, this can be easily calculated as the difference between the flexibility value and the shortest path to reach the destination. Moreover, our results show that, in all scenarios, the waiting time is always limited, never exceeding 4 minutes.

Conventional buses work on the basis of a predefined schedule and no deviation is allowed from their fixed itineraries, stops and timetables.

The on-demand service makes use of minibuses. Any user request is communicated to a central system together with the trip origin and destination and the desired departure time. The request will be tentatively assigned to the minibus that best fits the request, i.e., that minimizes the travel time, and the system will return to the user the information on the expected departure time from the origin and arrival time at the destination. If the user accepts the service, the request will be actually assigned to the minibus that will be rerouted to accommodate the new request.

Private cars are located at the user origin and take the user to the destination through the fastest path. We additionally take into account walking and parking time.

We model the user behavior as follows. If a public transportation mode, either a conventional bus or an on-demand minibus, is available to satisfy the request within its flexibility value, then the user will travel using one of these two modes. The underlying assumption is that the user prefers not to use a private car if a public transportation mode satisfies the flexibility value. The choice between the conventional bus and the on-demand minibus is made on the basis of the total traveling time, i.e., the user will choose the fastest mode. In case no public transportation mean satisfies the flexibility value, then the user will use the private car.

A user will tend to choose a conventional bus if there is a bus departing from a bus stop close to the trip origin at the time the user wants to leave (or shortly after) and arriving to a bus stop close to the trip destination. In such a situation, even when the flexibility value may be satisfied by a bus and an on-demand minibus, the bus may be faster and, thus, be chosen. If the bus stops are not conveniently located with respect to the trip origin or destination, or the bus timetable is not convenient, then the flexibility value may fail to be satisfied by a bus or, in case it is satisfied, the trip may take longer with a bus than with the on-demand minibus. In this case the user will choose the on-demand service. If neither a bus nor an on-demand minibus are available to guarantee the flexibility value, the user will resort to using a private car.

# 3 Simulation of the transportation system

In this section we will give an overview of the simulation of the transportation system. In Sections 3.1 and 3.2 we will describe the structure of the road network and of the transportation requests. The road network represents the topology of a city or a region together with the relevant transportation properties such as travel times and distances. The transportation requests represent the travel behavior of the people in the given city or region. In addition to the usual parameters such as origin, destination and departure time, it is crucial for our work to also model the willingness to travel by public transportation.

We then present the algorithms used for the simulation of the different modes of transportation. We begin with the simulation of direct trips by private cars in Section 3.3, followed by the simulation of conventional buses in Section 3.4 and the simulation of the on-demand transportation service in Section 3.5.

The simulation environment requires the setup of many different parameters. We discuss these parameters in Section 3.6, together with their standard values which are used in most of the simulations conducted in this work.

Finally, in Section 3.7 we present the performance indicators that are measured during the simulation.

## 3.1 The road network

The road network is represented as a strongly connected directed graph $G = (V,A)$ with vertex set $V$ and arc set $A$. The arcs are the roads and the vertices are crossroads or could be used to divide roads into parts with different properties (e.g. travel speed). A function $d : A \to \mathbb{R}^+$ assigns distances to the arcs and a function $t : A \to \mathbb{R}^+$ assigns travel times. To obtain a variety of road networks with different properties, a network generator has been implemented. The network generator is based on the grid structure depicted in Figure 1. The boundary of such a grid consists of roads with high travel speed. The grid is then divided into cells by roads of medium travel speed and the cells are further divided by roads of slow travel speed. Clusters of given sizes are then formed by attaching such grid structures next to each other. These clusters are again attached to other clusters to form the overall road network. In a last step this network is perturbed in different ways to obtain the final road network. An example of a network generated is given in Figure 2. Although the generated networks might differ

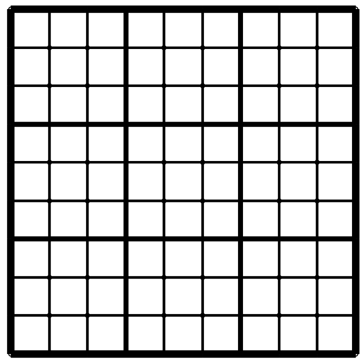


Figure 1: The grid structure used in the network generator. The thickness of the edges is proportional to the travel speed.

in some respects from real road networks, we believe that they share with them the properties which are relevant for our study.

## 3.2 The transportation requests

The requests are modeled on top of a given road network. Each request has an origin location and a destination location. Both are defined by a certain edge and the position on that edge. Additionally, a request has assigned a time at which this request is made and a desired departure time. For the conventional modes of transportation, bus and private car, the time at which a request is made is not relevant, but for the on-demand service it is important to distinguish between these two points of time. A request has also assigned a walking threshold. In case the distance between the origin and the destination is below the walking threshold, the person just walks instead of using any other mode of transportation. Otherwise, the walking threshold is used to determine the bus stops that are sufficiently close to the origin and destination. Finally, we assign a flexibility value to each request. This value is used to model the willingness of a person to travel by public transportation. Technically, it is the maximum ratio between the total travel time using public transportation and the total travel time using a direct trip by car. For example, a value of 1.5 indicates that the person would use public transportation even if it would take 50% longer to reach the destination.

The requests for a given road network and a given time horizon are generated in two different ways. The first approach just generates requests uniformly at random over time and space. The second, and more realistic, approach uses a time-dependent origin-destination matrix (OD-matrix). This method assumes that we can partition the whole time horizon into a set of continuous time windows

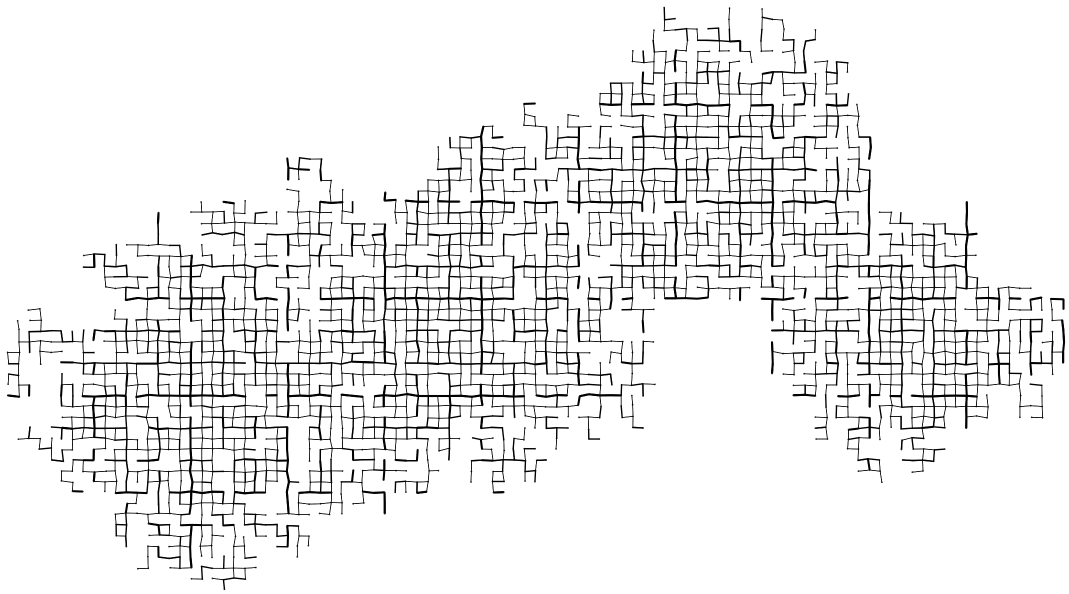


Figure 2: An example of a road network created by the network generator. The thickness of the edges is proportional to the travel speed.

$T = \{T_1, T_2, \ldots, T_n\}$, $n \in \mathbb{N}$, and the edges of the graph into a set of cells $C = \{C_1, C_2, \ldots, C_m\}$, $m \in \mathbb{N}$. The latter partition is possible, since the generated road networks belong to a two-dimensional Euclidean space. A function $p : T \times C \times C \to \mathbb{R}$ gives the probability of travel requests, where $p(t, c_1, c_2)$ denotes the probability for a travel request with departure time in time window $t$ from cell $c_1$ to cell $c_2$. In this way more realistic sets of requests can be generated, for example by simulating the typical peaks during rush hours and by having different distributions of requests. Further details about the request generation are discussed in Section 4.

### 3.3 Simulation of direct trips

The algorithm used for walking is quite simple. Each request is associated with a walking threshold and if the shortest distance between the origin and the destination is below the walking threshold, the person simply walks from the origin to the destination with a certain average speed. This approach is used in all the simulations and filters extremely short trips. As there may be persons whose walking threshold is very small or even 0, we think it is important to include such requests in the simulation.

Direct trips by car are the main point of reference for our comparison with the proposed on-demand public transportation service. The algorithm used for such trips is as follows. For each request we compute the fastest path between the origin and the destination. This might not be the shortest route, but since the main indicator for efficiency is time, we decided for such an approach. In fact, in many situations people prioritize time over distance while traveling. We then additionally consider the time required to walk from the origin to the car, the time required to find a parking spot close to the destination and the time required to walk to the destination. Several studies have shown that these amounts of time substantially contribute to the overall travel times. A nice overview about this issue is given in [27]. According to different studies that are cited in this paper, the average search times for a parking spot are several minutes for different major cities around the world: between 7.9 and 13.9 minutes in different areas of New York (according to a study from 1993), 6.5 minutes in San Francisco (according to a study from 1997) and 6.5 minutes in Sydney (according to a study from 2001). These values do not even include the time which is necessary to walk to the actual destination or back to the parking spot.

We consider the driving time from the origin to the destination, although the car might not be parked at the origin and although it might be impossible to park at the destination. Thus, the total travel time is given by the sum of the driving, walking and parking time.

### 3.4 Simulation of public transportation by buses

For the conventional public transportation by bus we consider a system of fixed routes which are periodically traveled. The generation of an efficient bus network and schedule is a difficult optimization problem. We refer to [28], [29], [21], [10], [9] and [4] as pioneering studies of the topic and to [6], [19], [32], [14], [24] and [31] for more recent references. For the study in this paper we use a grid like bus network consisting of horizontal and vertical bus routes. Given some reference points, the actual route is computed using the paths with the smallest travel time between the reference points. Along this route, bus stops are created at regular intervals and all the routes are traveled in both directions with a given frequency. We are aware that a more efficient bus network and bus schedule may exist. We will discuss this issue in Section 4. The simulation of the travel behavior for this system is based on the time-dependent fastest connections between any pair of bus stops. Those values are computed in a preprocessing step with a time-dependent variant of the shortest path algorithm. To obtain the travel time for a given request, we consider all bus stops which are within the walking threshold from the origin and all bus stops which are within the walking threshold from the destination. For each such pair of bus stops, we compute the total travel time, consisting of the time required to walk to the bus stop, the time for waiting and traveling (and changing buses) and the time to walk from the bus stop to the destination. The smallest of these travel times, which means the travel time corresponding to the fastest connection, is then used as the total travel time for the given request.

## 3.5 Simulation of the on-demand public transportation service

For the on-demand public transportation service, we consider a given fleet of vehicles, the minibuses, with a certain capacity which are distributed over the road network. The route of each vehicle is initially empty. Once a vehicle is traveling to a location, we do not allow a change of this part of the route anymore, whereas the remaining route can be altered. The requests arrive over time, usually slightly before the desired departure time. Whenever a request arrives, a visit to the origin and a visit to the destination are embedded into the routes of the vehicles, such that the total travel time of the requests given up to that point of time is minimized. For our preliminary simulation study, we have decided for this rather simple algorithm, which can be seen as a greedy algorithm for solving the underlying optimization problem.

## 3.6 Parameters

The parameters used in the simulations are the following. The average walking speed is set to 5 km/h. The travel speeds used during the network generation are 50 km/h, 30 km/h and 20 km/h for the edges with high, medium and slow speed, respectively. The fuel consumption is set to an average of 8 l / 100 km for private vehicles, 12 l / 100 km for vehicles used in the on-demand public transportation service and 50 l / 100 km for buses. The running costs, which are often underestimated by car owners, are set to 1 €/km for private vehicles, 1.5 €/km for vehicles used in the on-demand public transportation service and 5 €/km for buses. The salary for drivers is estimated in 15 €/h. The average time per stop, which also includes the time for braking and accelerating, is set to 20 seconds for the on-demand public transportation service and to 30 seconds for buses. For the on-demand service, the time difference between the request of a trip and the desired departure time is set to 5 minutes. We call this time the lead time. Finally, the walking times used for direct trips are sampled uniformly at random between 30 seconds and 180 seconds and the parking times used for direct trips are sampled uniformly at random between 60 seconds and 300 seconds. These values might seem large, but they are in fact quite moderate compared to values reported in investigations of parking times in urban

| parameter | value |
|---|---|
| walking speed | 5 km/h |
| high travel speed | 50 km/h |
| medium travel speed | 30 km/h |
| slow speed | 20 km/h |
| fuel consumption private | 8 l / 100 km |
| fuel consumption on-demand | 12 l / 100 km |
| fuel consumption buses | 50 l / 100 km |
| running costs private | 1 €/km |
| running costs on-demand | 1.5 €/km |
| running costs buses | 5 €/km |
| salary for drivers | 15 €/h |
| stopping time on-demand | 20 seconds |
| stopping time buses | 30 seconds |
| lead time for requests | 300 seconds |
| walking times | 30-180 seconds |
| parking times | 60-300 seconds |

Table 1: The standard parameters used for the simulations.

areas [27]. An overview of these parameters is given in Table 1.

### 3.7 Indicators of the system performance

During the simulation of the transportation system, we measure several different performance indicators. First of all, we measure how many of the requests are actually handled by the different modes of transportation. Here the flexibility value decides whether a request is handled by public transportation or by direct trips. In case of two different public transportation systems, the faster one is used to handle a request. We will see in Section 4 that this is a reasonable assumption, since the costs for the two public transportation systems are similar. For each mode of transportation we measure efficiency indicators, economic indicators and environmental indicators. The main indicators for the efficiency of a transportation system are the average distance and the average travel time. The economic indicators are basically the costs of the transportation system, partitioned into costs for drivers, costs for fuel and costs for the maintenance and insurance of vehicles. The environmental indicator is the fuel consumption which is strictly related to pollutant emission.

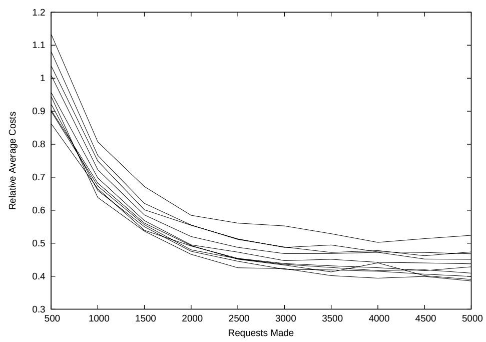
# 4 A comparison of transportation modes

In this section we will perform a comparison of the different transportation modes. For this purpose we first show that the relative performance of the different transportation systems is quite stable for different kinds of road networks. We then perform a more detailed analysis on a representative road network. Here we study the following three scenarios: (1) direct trips without any public transportation system, (2) direct trips and public transportation by bus, and (3) direct trips and the on-demand public transportation service. A request is served by public transportation, when considered, if the flexibility value for the request is fulfilled. The first scenario is used as a basis of comparison for the other two scenarios. Our goal is to evaluate the performance of a transportation system which includes a public transportation mode (either conventional buses or on-demand service) and to compare it with a system where no public transportation is available. Secondly, we will compare the performance of the two systems which include public transportation. The results indicate that the on-demand public transportation service operates in a very efficient way at competitive costs. To further understand the relationship between the on-demand public transportation service and public transportation by buses, we additionally analyze the scenario in which all three different modes of transportation are present. Note that throughout the article we will present the results for requests generated by time-dependent OD-matrices. The results for uniform demands are similar and can be found in the additional material in [1].

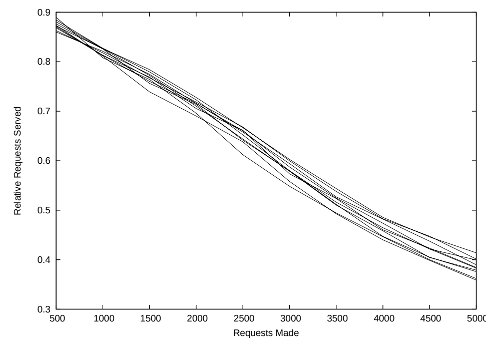
The goal of our first computational study is to analyze the influence of the road network on the results of the simulation. For this purpose we created 10 networks with different sizes and topologies. Additionally, we varied the number of transportation requests per hour and the size of the fleet of vehicles used in the public transportation scenarios. The simulations are performed for each of the three scenarios described above and for each combination of road network and number of requests. We measure the indicators described in the previous section. As mentioned above, we use the first scenario as the basis and we compute the ratio between the indicators related to the scenarios 2 and 3, respectively, and the indicators of scenario 1.

The results show that, while different road networks lead to substantially different results in terms of absolute values, the impact of different road networks on the relative values (i.e., the ratio with respect to scenario 1) turns out to be quite small. This means that the ratio of the costs of two different transportation modes, or the ratio of the average travel times of two different transportation modes does not significantly depend on the actual road network. Figure 3 illustrates these findings using the on-demand public transportation service with 300 vehicles and a capacity of 8 and public transportation by bus with a bus network of average density and a frequency of 3 trips per hour. Each line depicted in the graphics corresponds to a road network. The first three graphs report the relative average cost, the relative requests served and the relative average travel time between the on-demand public transportation service and direct trips with demands generated by an OD-matrix. The same indicators are reported in the last three graphs for the public transportation by bus with demands generated by an OD-matrix. We can see that these relative indicators do not change much for the on-demand public transportation service. The same holds for the relative average cost for public transportation by bus. The relative requests served and the relative average travel time for public transportation by bus is significantly influenced by the actual road network. However, although these relative values depend on the road network, the overall picture remains the same: only a small fraction of requests is served by buses and, moreover, the travel time by bus significantly exceeds the travel time of direct trips and the travel time obtained by the on-demand service. In fact, comparing Figure 3.b with Figure 3.e, we see that the average percentage of requests served by the on-demand service goes from almost 90%, when the number of requests is small, to almost 40% when this number is high. On the other side, for the conventional bus service this percentage is quite unstable and never goes above 8%. This percentage is consistent what is typically observed in many urban areas. Moreover, when comparing the relative average travel time in Figures 3.c and 3.f, we see that, for the on-demand service, it increases almost logarithmically with the number of requests and it does not exceed 1.4, which means that the on-demand service never requires more than 40% of the time spent by traveling with private cars. Furthermore, when the number of requests is small, the on-demand service is faster than private cars. The conventional bus service presents an relative average travel time with respect to private cars which is never lower than 1.6 and goes up to 2.3.

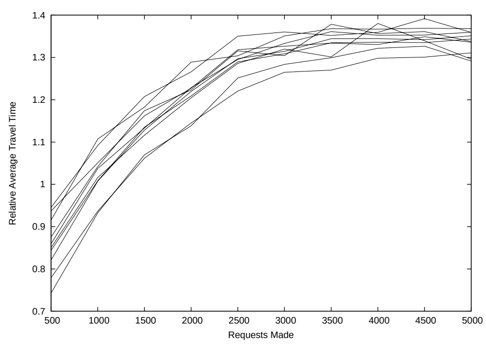
In this study we are interested in the overall picture, that is in general trends and in orders of magnitude rather than in actual numbers. The results about the impact of the road network on the relative indicators allow us to focus on a representative road network. To keep the comparison as fair as possible, we have selected for the following analysis a medium size network which represents the average behavior illustrated in Figure 3, that is a road network for which the corresponding statistics are always located in between the two extremes reported in those figures. Using this road network we now analyze more in detail the other scenarios related to different numbers of requests and different fleet sizes for conventional buses and minibuses.



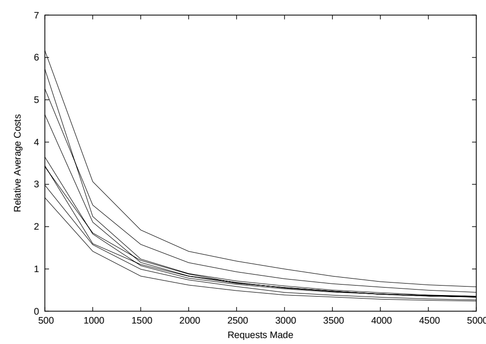

(a) on-demand: relative average cost



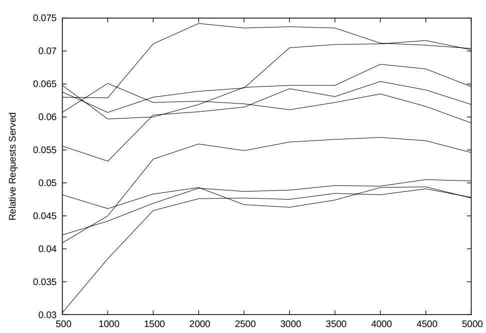

(b) on-demand: relative requests served



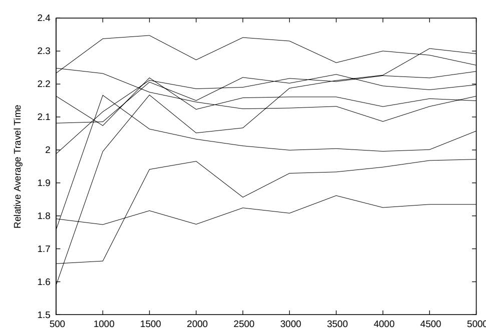

(c) on-demand: relative average travel time




(d) bus: relative average cost




(e) bus: relative requests served




(f) bus: relative average travel time

Figure 3: The relative average cost, the relative requests served and the relative average travel time for public transportation by bus and the on-demand public transportation service on different networks.

We first compare the same three scenarios mentioned above, i.e.: (1) direct trips without any public transportation system, (2) direct trips and public transportation by bus, and (3) direct trips and the on-demand public transportation service. For the conventional public transportation system we use an average density bus network with 2, 3, 4 and 6 trips per hour per bus line. For the on-demand public transportation service we use a fixed size fleet of 200, 300, 400 and 500 vehicles. For each of these 9 different settings (1 for scenario 1 and 4 for each of scenarios 2 and 3) we perform a simulation of one hour with uniform requests and requests generated by an OD-matrix. The number of requests varies from 500 to 5000 in steps of 500. For each simulation we measure the various indicators, in particular the number of requests that are served by public transportation, the average travel time per request, the average cost per request, the average distance per request and the average fuel consumption per request. In the scenarios in which a public transportation system is present, these indicators are measured only for the requests that are actually served by public transportation. The results of these experiments for the requests generated by an OD-matrix are depicted in Figures 4-8.

The average cost per request served by on-demand transportation system tends to become competitive with the cost for direct trips once a certain number of requests per hour is reached. At the same time, the average distance traveled per request and, to some extent, also the average fuel consumption per request for the public transportation systems is lower than those for the direct trips, except for the case where the requests are very few. On the other hand, the public transportation system using buses is not able to serve a reasonable number of requests and the average travel time for the requests that are actually served is much higher than for direct trips. This reflects the current situation with public transportation systems using buses in many cities around the world. In contrast to that, the on-demand public transportation service is able to serve the majority of requests while the average travel time remains competitive with that of direct trips. The results clearly show that the on-demand service dominates the conventional bus service both in terms of number of requests served and in terms of average costs and fuel consumption. Thus, a first important indication provided by these simulations is that an on-demand service can be provided at a cost which is comparable to the cost which is implied by the conventional bus service. Moreover, the on-demand service has the advantage of being able to capture a much higher number of users. Another aspect that is evident from Figures 4-8 is that the performance of the system strictly depends on the number of transportation requests. This indicates that, in order for the system to be sustainable, a large number of transportation requests is needed. This implies that such a system is beneficial when the service is deeply integrated in the population habits.

To further understand the relation between the two public transportation systems, we perform

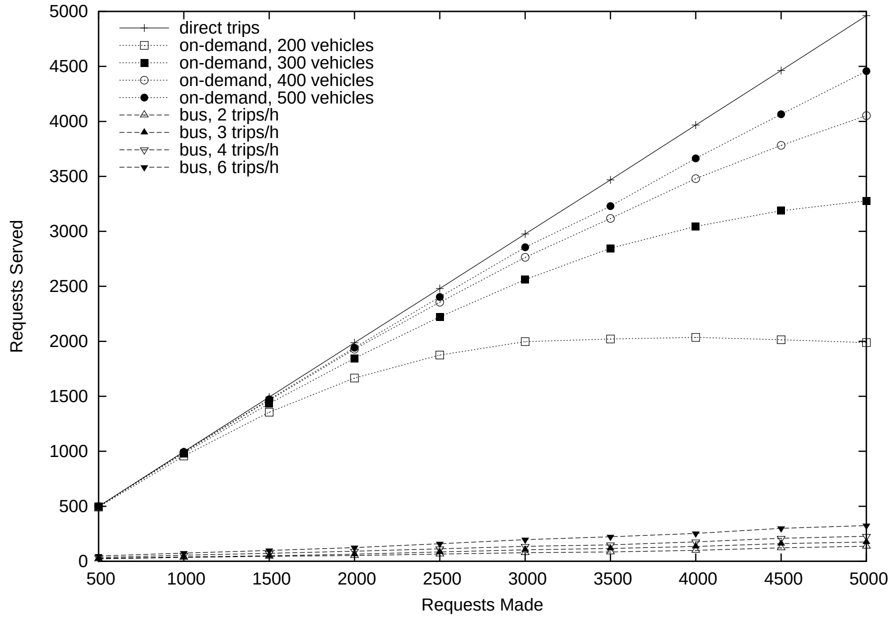



Figure 4: The number of requests served.

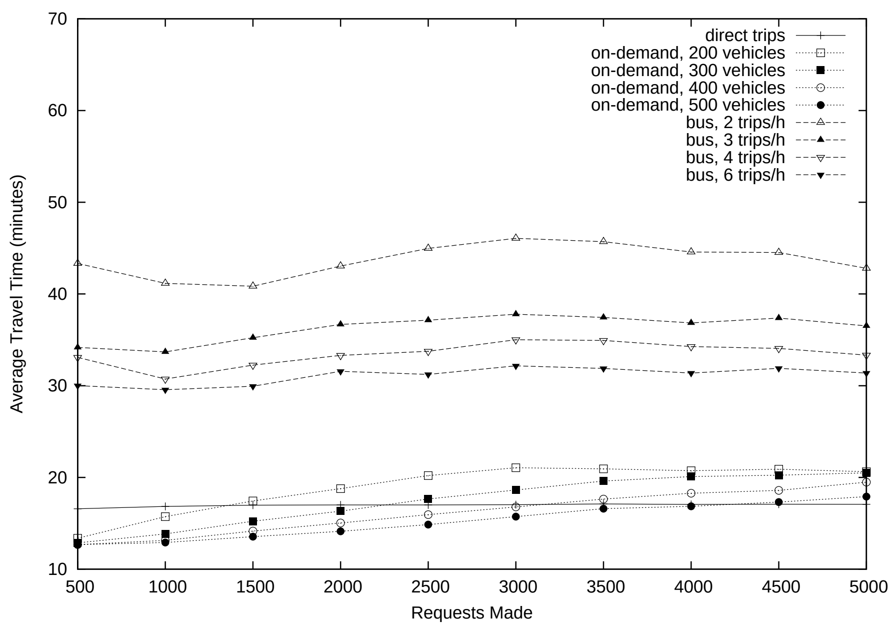



Figure 5: The average travel time per request.

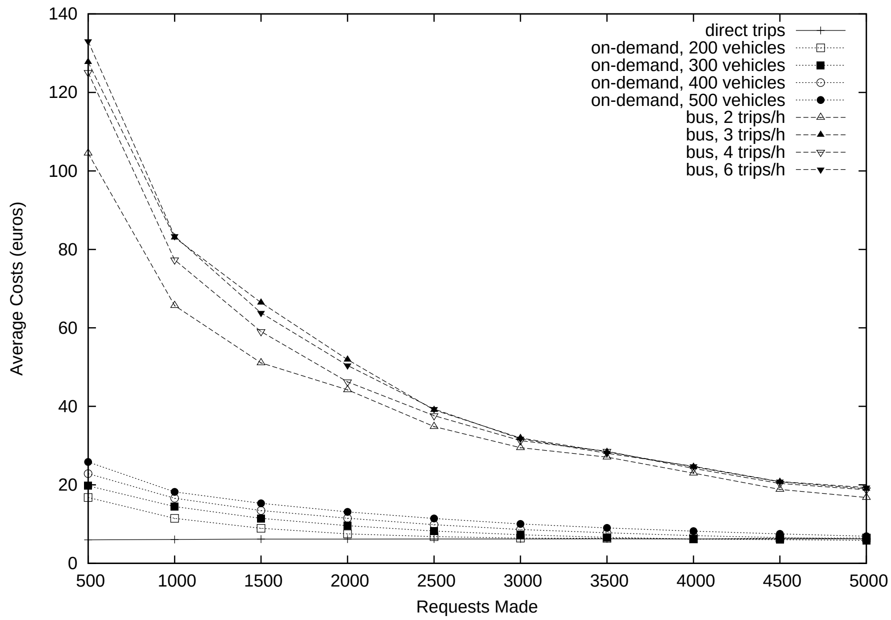



Figure 6: The average costs per request.

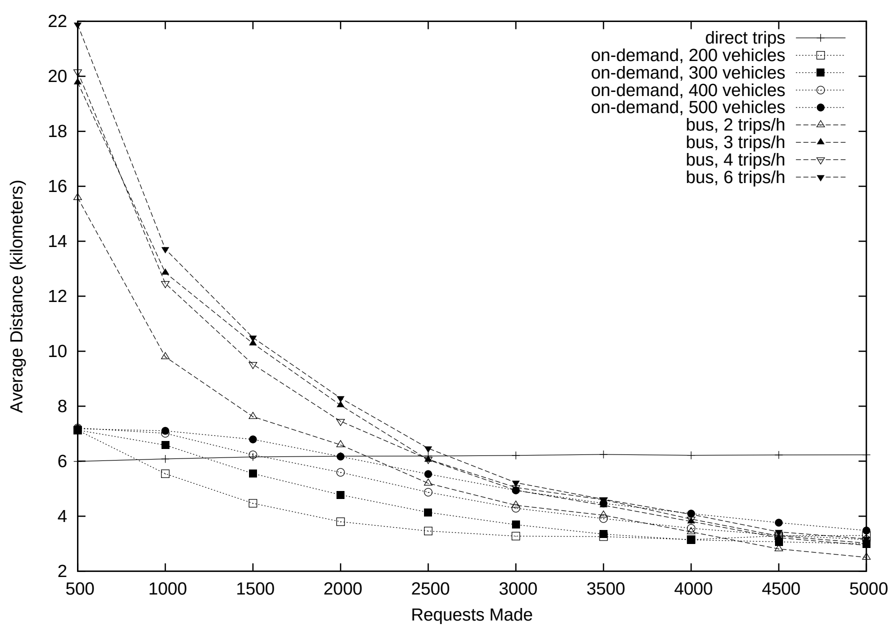



Figure 7: The average distance traveled per request.

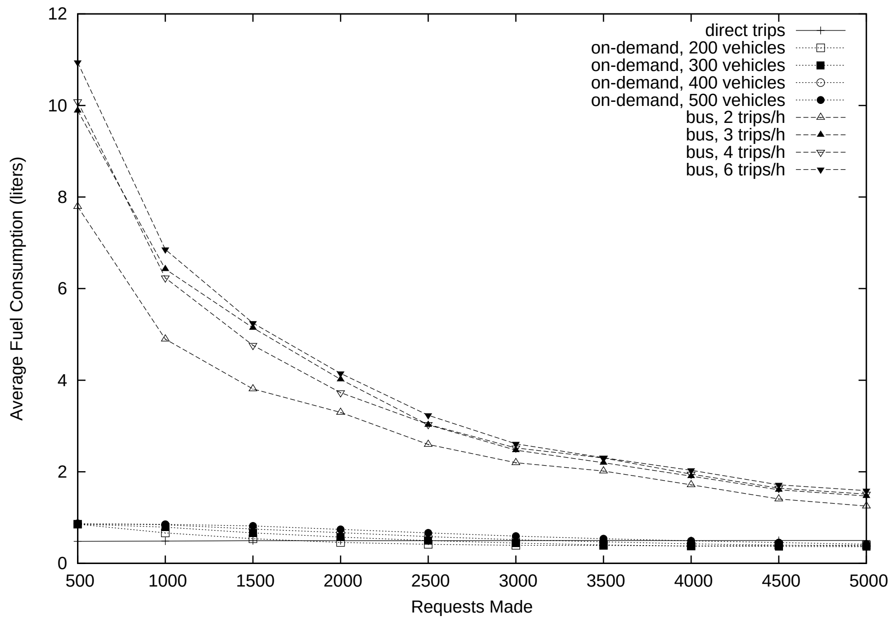



Figure 8: The average fuel consumption per request.

experiments using a scenario in which both of them are present. We recall that a request is served by public transportation if the flexibility value for that request is fulfilled. If it is fulfilled for both public transportation modes, the request is served by the system which provides a more efficient service in terms of travel time. Thus, we assume that the travel time is the only criterion for choosing between the two public transportation modes. We believe that this is a reasonable assumption, considering that our previous simulations showed that the costs of the systems are comparable. We use an average density bus network with 6 trips per hour per bus line. According to our previous experiments, this is the most efficient bus system in terms of average travel time per request and the number of requests that are served. We then add the on-demand public transportation service with a fixed size fleet of 300 and 500 vehicles. For both scenarios we perform a simulation of one hour with requests generated uniformly over time and space and with requests generated by an OD-matrix. The number of requests varies from 500 to 5000 in steps of 500. The results for the requests generated by an OD-matrix are shown in Figures 9 and 10. We observe that in all cases the largest number of requests is served by the on-demand public transportation service. This number increases almost linearly with the total number of requests, up to a point where the capacity limit of this transportation mode is approached, where the share of requests served by direct trips suddenly increases faster. In contrast to that, the number of requests served by the public transportation by bus is almost negligible and much lower than in the previous experiments. This shows that the public transportation system by bus is strictly dominated by the on-demand public transportation service.

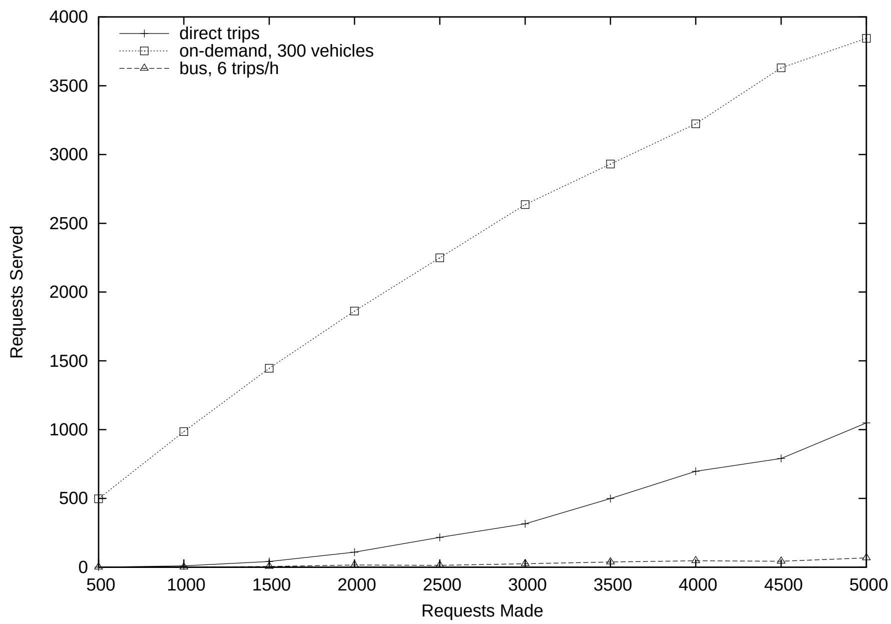



Figure 9: The number of requests served (300 vehicles for the on-demand service).

We have to be careful drawing conclusions from these experiments, since some uncertainties and inaccuracies are involved. However, as we have already pointed out, we are interested in the general picture, in trends and in orders of magnitude and not in absolute values. We have seen that both public transportation systems can operate at competitive costs once a sufficient number of requests per hour is made. The average distance traveled per request is also reduced for both public transportation systems, which means that they can be effectively used to reduce traffic. Additionally, the average fuel consumption per request is reduced by the on-demand public transportation service and, to some extent, also by the public transportation system using buses, which directly implies positive environmental effects. The main differences between the two public transportation systems can be observed with respect to the number of requests that can be actually served and the average travel time per request. The public transportation system based on buses is not able to serve a reasonable number of

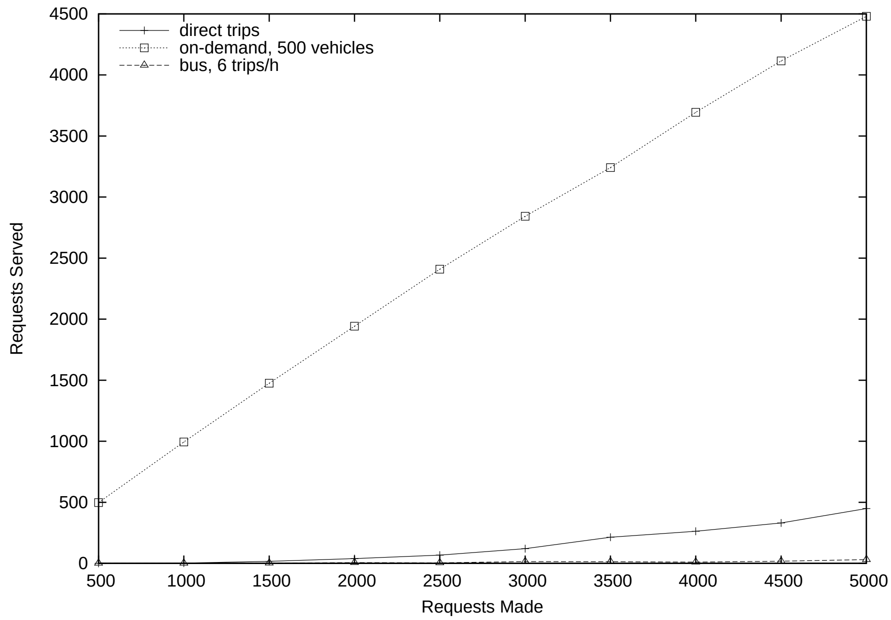



Figure 10: The number of requests served (500 vehicles for the on-demand service).

requests and the average travel times exceed those of the other systems by far. This result is consistent with the performance of public transportation systems based on buses in many cities around the world. In contrast to that, the on-demand public transportation service is able to serve a large number of requests and the average travel time is competitive with that obtained by direct trips. Finally, we have seen that in a scenario where both public transportation systems are present, the public transportation system using buses is clearly dominated by the on-demand public transportation service. This indicates that a system based on buses traveling regularly on fixed lines could be partially or completely replaced by an on-demand service. To summarize, the proposed on-demand service seems to be quite promising as an alternative to conventional public transportation systems.

# 5 Properties of the on-demand public transportation service

In this section we will further analyze the proposed on-demand public transportation service. For this purpose, we focus on two important properties of this system: the scalability and the responsiveness.

We have already investigated some aspects of the scalability of the on-demand service in the previous section, where we have seen that the performance of the system depends heavily on the number of requests that are made. For a fleet of vehicles with a fixed size, a certain critical mass has to be reached in order to allow the system to operate efficiently. Intuitively this is clear, since a certain number of requests is necessary to use the capacities of the fleet efficiently and, additionally, an increasing number of requests allows for more synergies in the route planning. In this section we look at this issue from a different point of view: we keep the ratio between number of vehicles and requests constant and investigate the performance of the on-demand service using this fixed ratio under increasing number of requests per hour. After that we focus on another property, which we call in this context responsiveness. With responsiveness we mean how the system reacts to travel requests which are made just before the desired departure time. To measure the responsiveness of the on-demand service, we investigate the performance under different values for the lead time.

## 5.1 Scalability

In the previous experiments we have seen that the on-demand public transportation service operates very efficiently as long as the ratio between the number of available vehicles and the requests made per hour is somewhere in the range between 0.05 and 0.15. We therefore conduct a series of experiments with the on-demand service, where this ratio is kept constant to a fixed value, while the total number of requests per hour (and therefore also the size of the fleet) is varied between 1000 and 10000 in steps of 1000. We simulate the transportation system for one hour using 6, 8, 10 and 12 vehicles per 100 requests. Again, we measure the performance indicators, in particular the number of requests that can be served by the public transportation system, the average travel time per request, the average cost per request and the average distance per request (which in this particular simulation is also an indicator for the average fuel consumption per request, because only one mode of transportation with identical vehicles is used). The results of these experiments are depicted in Figures 11-14.

First of all, we can see that the number of requests that can be served by the on-demand transportation system increases slightly faster than linear with the total number of requests per hour. Additionally, the average travel time per request decreases with an increasing number of total requests. This shows that the overall system scales very well. The situation for the average cost per request and the average distance per request is similar, although these indicators decrease more slowly than

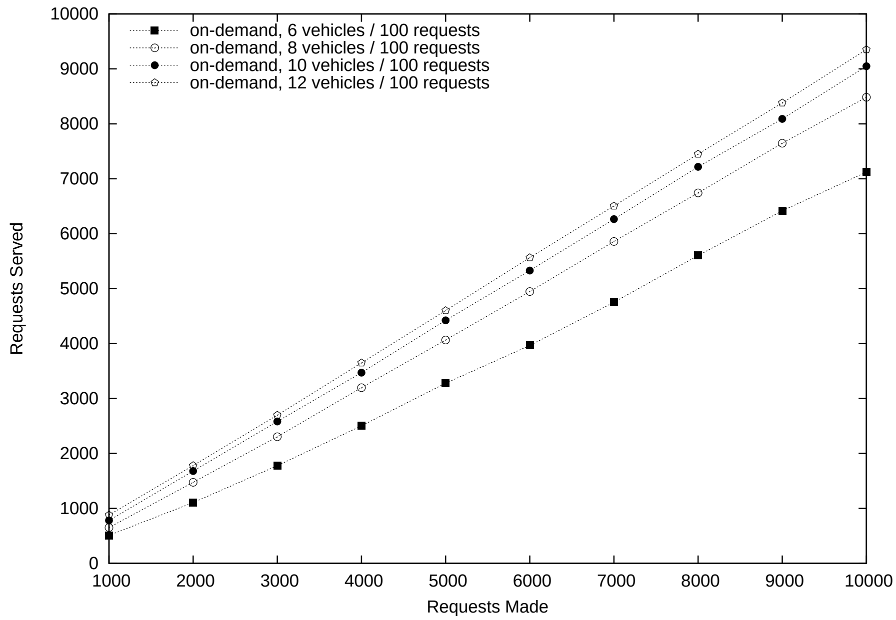



Figure 11: The number of requests served.

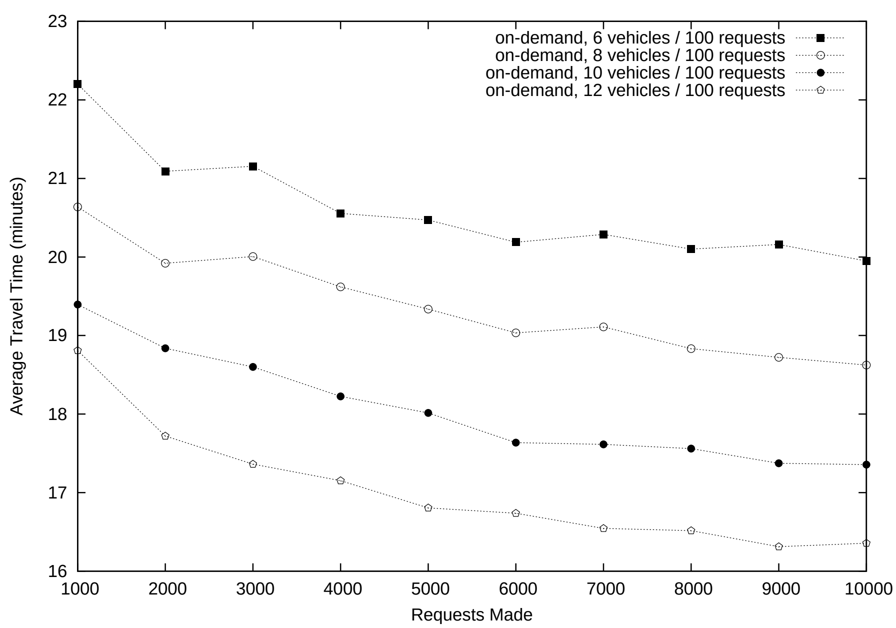



Figure 12: The average travel time per request.

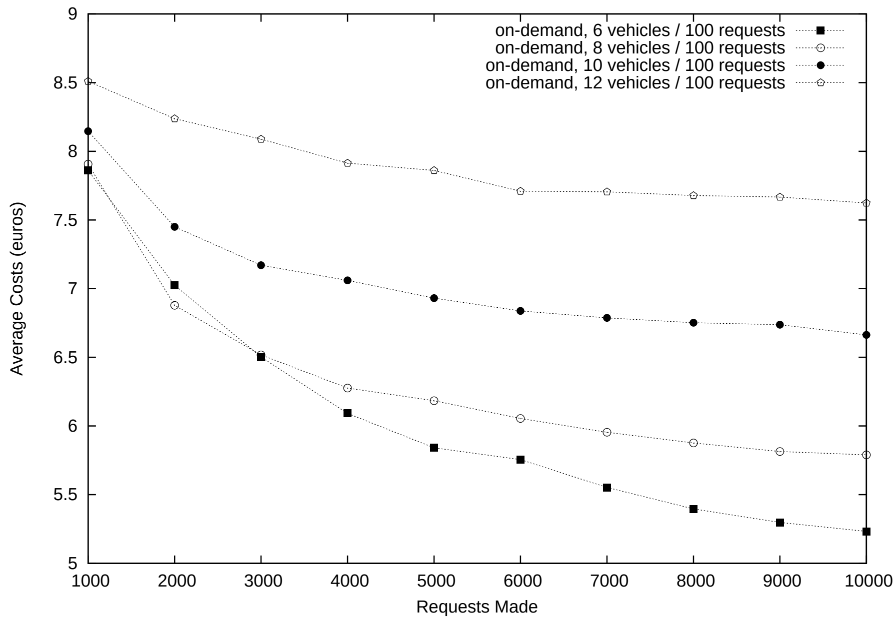



Figure 13: The average costs per request.

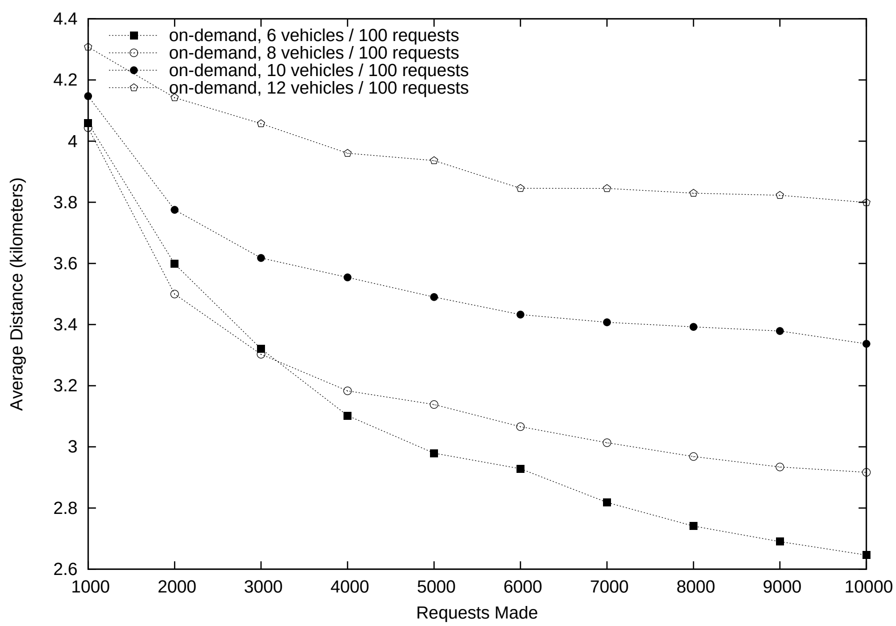



Figure 14: The average distance per request.

the average travel time per request. This clearly reflects the fact that our algorithm is optimizing for the average travel time per request and not for the other indicators. It seems that a reduction of the average travel time per request automatically leads to a reduction of the other two indicators, which is a quite desirable behavior of the overall system. On the other hand, there might be situations in which more emphasis has to be put on economical or ecological issues and this could be handled by explicitly using other indicators in the objective function. In any case, the on-demand public transportation service is capable of handling huge number of requests, and in fact, it achieves its best performance in such a mass transit scenario.

## 5.2 Responsiveness

Another important property for the on-demand public transportation system is the responsiveness, which describes how well the system can cope with requests that are made very close to the desired departure time. In the previous experiments, the lead time was fixed to 5 minutes. In this section we will perform a series of experiments where the lead time is fixed to values of 0, 2, 4, 6, 8 and 10 minutes. For each of these settings we perform a simulation where the total number of requests is varied from 500 to 5000 in steps of 500. We measure the same performance indicators used in the previous section with the addition of the average waiting time per request which is defined as the interval between the desired departure time and the actual pickup time. This is clearly an indicator that remarkably depends on the lead time. The results of this series of experiments are shown for requests generated by an OD-matrix in Figures 15-19.

We can see that the number of requests that are served by the on-demand service and the average cost per request are only slightly influenced by the lead time, whereas the average travel time per request and the average waiting time per request are significantly influenced by the lead time. The average distance per request depends quite strongly on the lead time for a small number of requests per hour, but the difference vanishes for a large number of requests per hour. A lead time of 0, which means that the requests are just made at the desired departure times, leads to a significantly worse average travel time per request and average waiting time per request, while the difference among the other lead times is not that large. This is due to the fact that a lead time of 0 does not allow an efficient reassignment of requests among drivers. In any case, the results show that the on-demand service is highly responsive and that already small lead times of 2 minutes lead to a very efficient

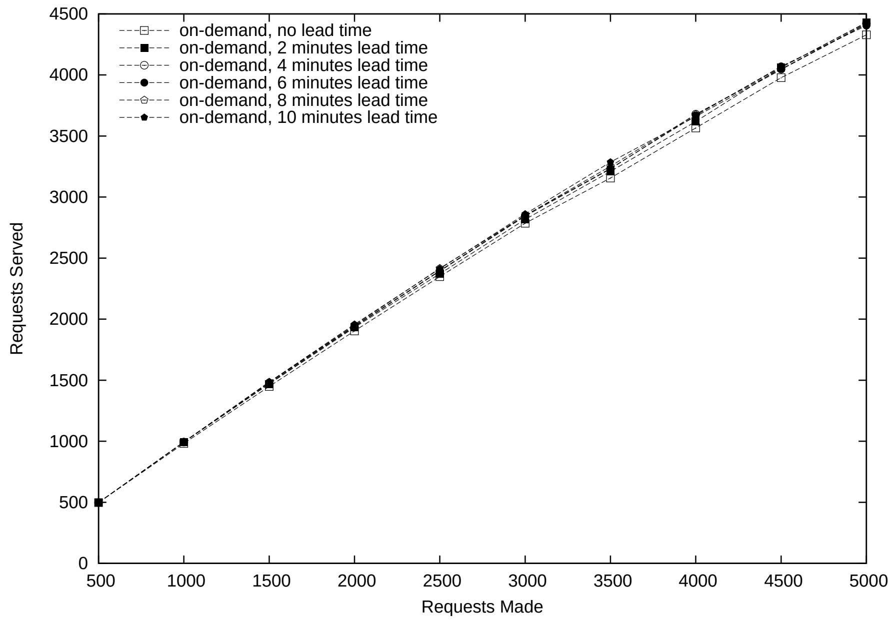



Figure 15: The number of requests served.

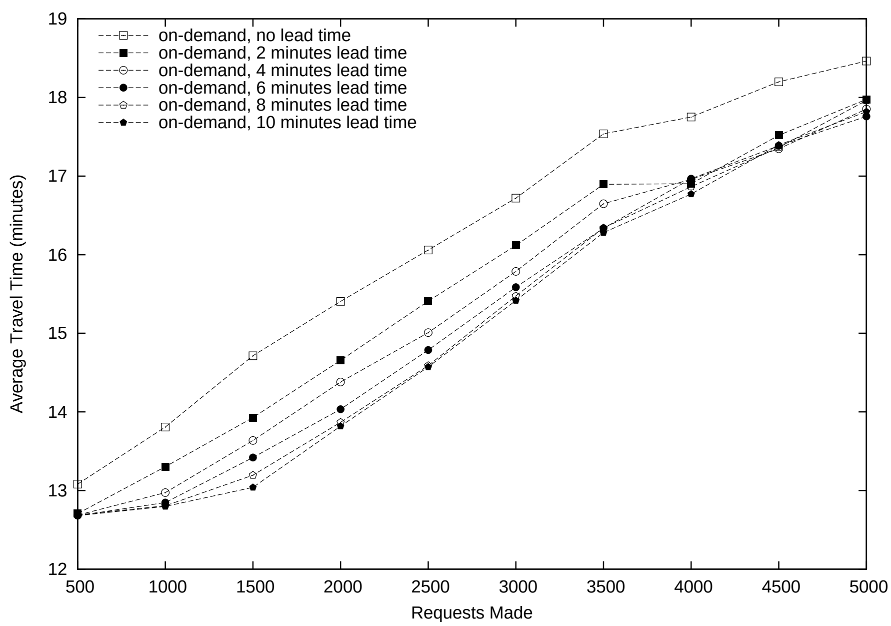



Figure 16: The average travel time per request.

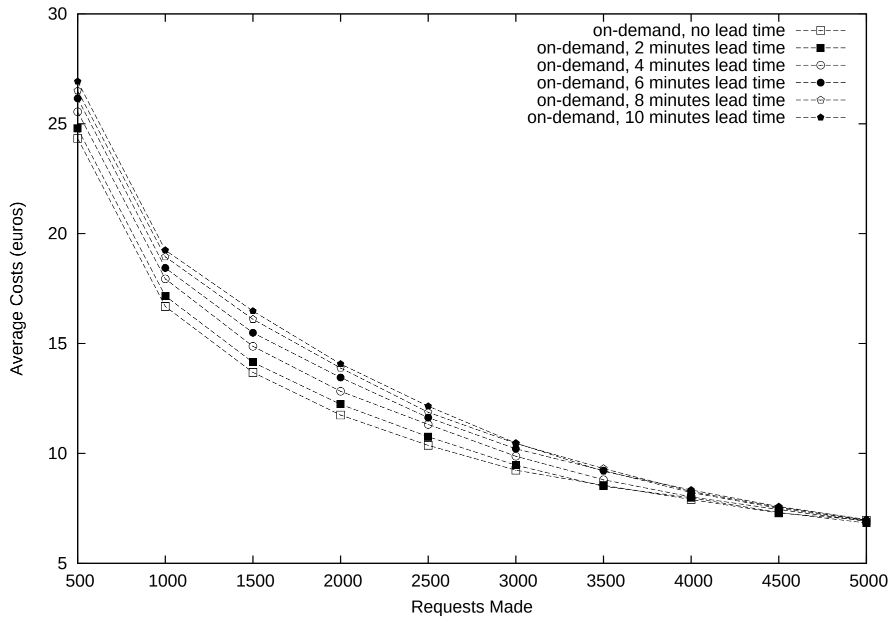



Figure 17: The average costs per request.

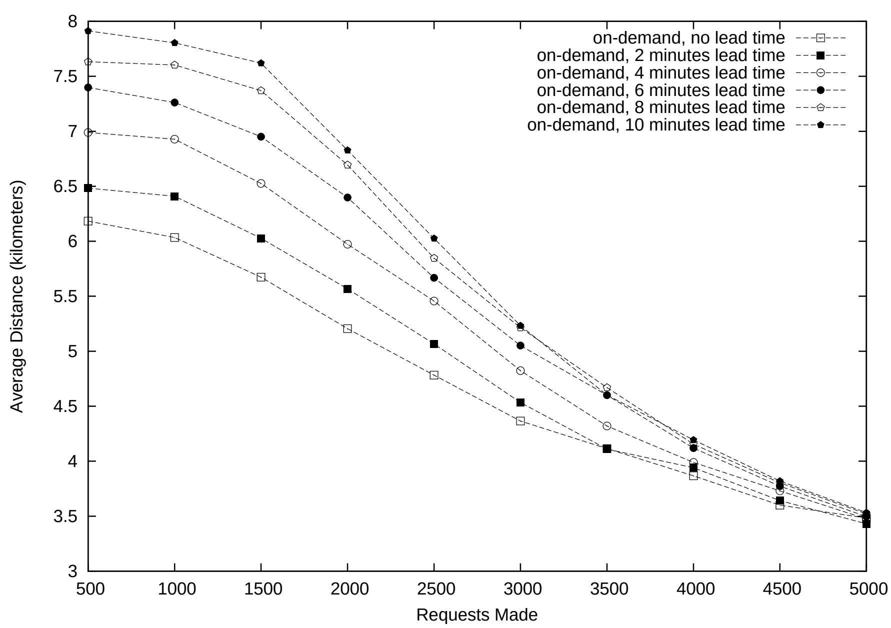



Figure 18: The average distance per request.

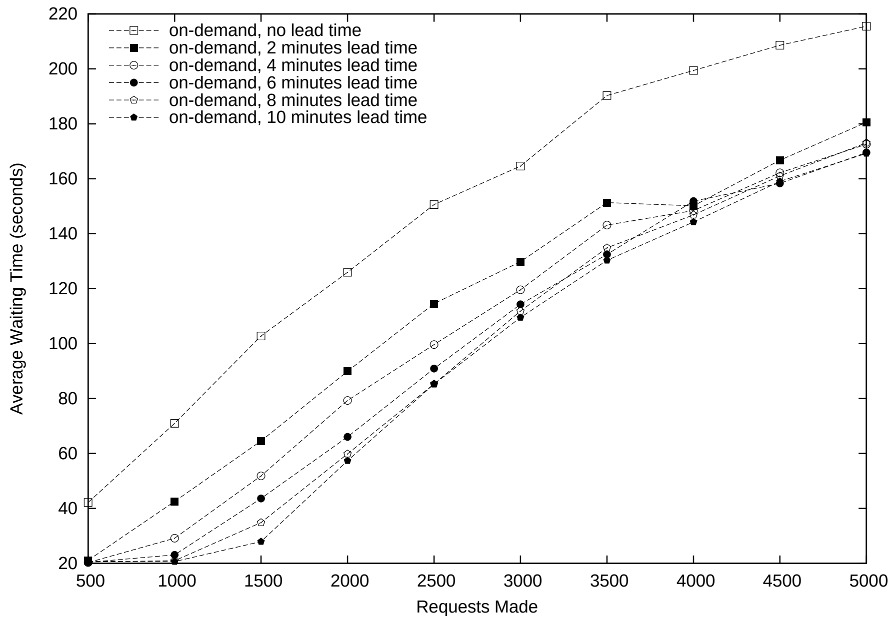



Figure 19: The average waiting time per request.

system with small waiting times for the users. On the other hand, it seems that the current algorithm is not able to properly exploit larger lead times. It would be very interesting to understand if a more sophisticated algorithm could make use of larger lead times and in this way further reduce the average travel time and the average waiting time per request. This is left to future research. All in all, the analysis suggests that the on-demand public transportation service offers a great flexibility for the users, which can barely be found in other public transportation systems that are currently used.

# 6 Conclusions and future research

Traffic congestion is a primary problem in most urban areas, also due to the constantly increasing size of cities. A crucial issue has become the sustainability of the ever growing number of cars on the roads which has led to a renewed interest in alternative forms of transportation. This is witnessed by the wide diffusion of bicycle and car sharing systems, as well as car pooling. However, the main issue concerning the scarce use of public transportation means has not yet been properly addressed.

In this paper we have assessed a public transportation system that includes, besides the conventional buses, an on-demand service with no fixed itineraries that allows users to communicate the desired departure time, origin and destination of the trip. A minibus, if acceptable in terms of arrival time to destination, will pick up the user at the origin and deliver him/her to the destination. In case the public system, conventional bus or on-demand minibus, does not satisfy the acceptance threshold set by the user, the user will resort to using a private car.

A large number of scenarios have been tested in the simulation study. The analysis performed suggest the following conclusions:

- the on-demand service is dominating conventional public transportation by buses, in terms of number of requests attracted, travel time and cost;
- the on-demand service is more environmentally friendly, can reduce traffic, pollution and congestion.

There are several directions that are worth of further research, such as the usage of more sophisticated algorithms for the routing and rerouting of minibuses, the usage of more complex objective functions and a detailed analysis of the ecological impacts of the proposed on-demand public transportation service.

### *Acknowledgements*

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## References

[1] Additional material. `http://www.dennisweyland.net` – The document is accessible from the publications page, it is listed in the corresponding entry for this article.

[2] Eurostat passenger transport statistics. `http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_transport_statistics`, oct 2014.

[3] B. Atasoy, T. Ikeda, and M.E. Ben-Akiva. The concept and impact analysis of a flexible mobility on demand system. *Intelligent Transporation Systems Lab - Working Papers*, 2014-11-03, 2014.

[4] M.H. Baaj and H.S. Mahmassani. Hybrid route generation heuristic algorithm for the design of transit networks. *Transportation Research C*, 3:31–50, 1995.

[5] C. Bellini, G. Dellepiane, and C. Quaglierini. The demand responsive transport services: Italian approach. In L.J. Sucharov and C.A. Brebbia, editors, *Urban Transport IX: Urban Transport and the Environment in the 21st Century, Vol. 14*, pages 63–71. WIT Press, Southampton, UK, 2003.

[6] M. Bielli, M. Caramia, and P. Carotenuto. Genetic algorithms in bus network optimization. *Transportation Research C*, 10:19–34, 2002.

[7] J. Brake, C. Mulley, J.D. Nelson, and S. Wright. Key lessons learned from recent experience with flexible transport services. *Transport Policy*, 14:458–466, 2007.

[8] J. Brake, J.D. Nelson, and S. Wright. Demand responsive transport: towards the emergence of a new market segment. *Journal of Transport Geography*, 12:323–337, 2004.

[9] A. Ceder and N.H.M. Wilson. Bus network design. *Transportation Research B*, 20:331–344, 1986.

[10] T.A. Chua. The planning of urban bus routes and frequencies: A survey. *Transportation*, 12:147–172, 1984.

[11] J.-F. Cordeau and G. Laporte. The dial-a-ride problem: Models and algorithms. *Annals of Operations Research*, 153:29–46, 2007.

[12] T. Eiró, L.M. Martínez, and J.M. Viegas. Configuration of innovative minibus service in the Lisbon, Portugal municipality. *Transportation Research Record: Journal of the Transportation Research Board*, 2217:127–135, 2011.

[13] T. Eiró, J.M. Viegas, and L.M. Martínez. A new optimisation procedure to design minibus services: An application for the Lisbon metropolitan area. *Procedia Social and Behavioral Sciences*, 20:856–865, 2007.

[14] W. Fan and R. Machemehl. Using a simulated annealing algorithm to solve the transit route network design problem. *Journal of Transportation Engineering*, 132:122–132, 2006.

[15] L. Ferreira, P. Charles, and C. Tether. Evaluating flexible transport solutions. *Transportation Planning and Technology*, 30:249–269, 2007.

[16] F. Grootenboers, M. de Weerdt, and M. Zargayouna. Impact of competition on quality of service in demand responsive transit. In L.J. Sucharov and C.A. Brebbia, editors, *Multiagent System Technologies, Lecture Notes in Computer Science, Vol. 6251*, pages 113–124. Springer, Berlin, 2010.

[17] M.E.T. Horn. Procedures for planning multi-leg journeys with fixed-route and demand-responsive passenger transport services. *Transportation Research C*, 12:33–55, 2004.

[18] C.A. Kennedy. A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area. *Transportation*, 29:459–493, 2002.

[19] K. Kliewer, T. Mellouli, and L. Suhl. A time-space network based exact optimization model for multi-depot bus scheduling. *European Journal of Operational Research*, 175:1616–1627, 2006.

[20] P. Logan. Best practice demand-responsive transport (DRT) policy. *Road and Transport Research*, 16:50–59, 2007.

[21] C.E. Mandl. Evaluation and optimization of urban public transportation networks. *European Journal of Operational Research*, 5:396–404, 1980.

[22] L.M. Martínez, G.H.A. Correia, and Viegas. An agent-based simulation model to assess the impacts of introducing a shared-taxi system: an application to Lisbon (Portugal). *Journal of Advanced Transportation*, to appear. doi:10.1002/atr.1283.

[23] L.M. Martínez, J.M. Viegas, and T. Eiró. Formulating a new express minibus service design problem as a clustering problem. *Transportation Science*, to appear. doi:10.1287/trsc.2013.0497.

[24] D. Meignan, O. Simonin, and A. Koukam. Simulation and evaluation of urban bus-networks using a multiagent approach. *Simulation Modelling Practice and Theory*, 15:659–671, 2007.

[25] C. Mulley and J.D. Nelson. Flexible transport services: A new market opportunity for public transport. *Research in Transportation Economics*, 25:39–45, 2009.

[26] K. Palmer, M. Dessouky, and T. Abdelmaguid. Impacts of management practices and advanced technologies on demand responsive transit systems. *Transportation Research A*, 38:495–509, 2004.

[27] D.C. Shoup. Cruising for parking. *Transport Policy*, 13:479–486, 2006.

[28] L.A. Silman, Z. Barzily, and U. Passy. Planning the route system for urban buses. *Computers and Operations Research*, 1:201–211, 1974.

[29] M.A. Turnquist and L.A. Bowman. The effects of network structure on reliability of transit service. *Transportation Research B*, 14:79–86, 1980.

[30] K. Uchimura, H. Takahashi, and T. Saitoh. Demand responsive services in hierarchical public transportation system. *IEEE Transactions on Vehicular Technology*, 51:760–766, 2002.

[31] Z. Yang, B. Yu, and C. Cheng. A parallel ant colony algorithm for bus network optimization. *Computer-Aided Civil and Infrastructure Engineering*, 22:44–55, 2007.

[32] F. Zhao and X. Zeng. Simulated annealing-genetic algorithm for transit network optimization. *Journal of Computing in Civil Engineering*, 20:57–68, 2006.