A paratransit-inspired evolutionary process for public transit network design

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Abstract

The success of a public transport system highly depends on its network design. When transport companies try to optimize a line with respect to running costs there is also the demand to be taken into consideration. The best cost structure will not be sustainable if potential customers leave the system and opt for alternatives like private cars. The basic problem to solve is to find sustainable transit lines which offer the best service possible for the customer.

More specifically

- The demand side of the customers asks for direct hassle-free connections.
- The supply side of the operators asks for profitable lines to operate.

Examples of a market-oriented and moreover self-organizing public transport system are informal public transit systems around the world. These services are often referred to as paratransit. Despite the great importance of this transport mode it is mainly unsubsidized and only relies on the collected fares. Thus, the knowledge on paratransit and its ability to identify and fill market niches with self-supporting transit services provides an interesting approach to solve the network design problem of a formal public transit company.

Accordingly, the following three objectives are treated in the thesis:

1. Provide an understanding of the underlying principles of paratransit services, namely minibus services, its stakeholders, fares, route functions, and patterns.

2. Develop a model to simulate paratransit, in particular minibus services as the most important type, that allows policymakers to assess the impact of actions before they are implemented.

3. Apply this model to the network planning of formal public transit. The underlying demand-responsive algorithm adopted from paratransit needs to respect the requirements of both the supply and demand side.

The minibus model is integrated in a multi-modal multi-agent simulation. In the model, competing minibus operators start exploring the public transport market offering their services. With more successful operators expanding and less successful operators going bankrupt, a sustainable network of minibus services evolves. The model is verified through multiple illustrative scenarios that analyze the model's sensitivity towards different demand patterns, transfers, and the interactions of minibuses and a formal operator's fixed train line.

The minibus model can be applied to two different fields of transport planning. First, there is the simulation of real paratransit that aims to help understand the implications that lie within the relationship of the different paratransit stakeholders. The model is able to create "close-to-reality" minibus networks in a South African context. Second, the same model provides a demand-driven approach to solve the network design problem of a formal transit authority. Thus, it can be used as a planning tool for the optimization of single lines or networks. In the thesis, the model is applied to two different planning problems of the public transit authority of Berlin, BVG. In the first scenario, the model constructs a transit system from scratch for the district of Steglitz-Zehlendorf. The second scenario analyzes the impact of the closure of Tegel airport on BVG's bus network. Apart from Tegel itself, the rest of the bus network is found to be unaffected by the closure of the airport. The resulting transit system of the minibus model resembles the changes BVG had scheduled for the closure of Tegel.

In conclusion, the minibus model developed in the thesis automatically adapts the supply to the demand. The model does not only grow networks

from scratch but can also test for an existing transit line's sustainability and can further optimize the line regarding its frequency, its time of operation, its length, and its route. Again, the optimization process is fully integrated into the behavior-rich environment of a multi-agent simulation reflecting the reactions from the passengers as well as from competing transit services and other road users. Thus, the minibus model can be used along with more complex scenarios like city-wide tolls or pollution analyses.

Zusammenfassung

Der Erfolg eines öffentlichen Verkehrssystems hängt entscheidend von dessen Netzstruktur ab. Dabei dürfen die Verkehrsunternehmen nicht nur hinsichtlich der damit verbundenden Kosten optimieren, sondern müssen gleichfalls die Belange der Nachfrage berücksichtigen. Eine gute Kostenstruktur allein ist langfristig nicht tragfähig, wenn die Nachfrage auf andere Verkehrsangebote wie den motorisierten Individualverkehr ausweicht. Das Netzwerk muss dahingehend geplant werden, dass sowohl kundenfreundliche wie auch tragfähige Verkehrsangebote gefunden werden.

Im Kern stehen sich dabei zwei gegensätzliche Ziele gegenüber

- Die Nachfrageseite sucht schnelle und möglichst direkte Verbindungen.
- Die Angebotsseite sucht nach profitabel zu betreibenden Linien.

Beispiele für marktorientierte und selbstorganisierende Verkehrssysteme finden sich weltweit in den sogenannten informellen Paratransitsystemen. Obwohl Paratransit z.B. in Südafrika den formalen öffentlichen Nahverkehr hinsichtlich Marktanteil und Verkehrsleistung übertrifft, wird Paratransit nicht subventioniert und ist daher gezwungen seine Kosten vollständig über die Fahrpreise zu decken. Die dem Paratransit inne liegende Fähigkeit Angebotslücken zu finden und kostendeckend auszufüllen liefert einen interessanten Ansatz für die Netzplanung eines formalen Nahverkehrsanbieters.

Die vorliegende Arbeit behandelt daher die folgenden drei Ziele:

1. Die dem Paratransit zu Grunde liegenden Gesetzmäßigkeiten zu identifizieren, insbesondere die der dabei beteiligten Akteure, der Preisstruktur, der Routengestaltung und -funktion.

2. Ein Modell zu entwickeln welches in der Lage ist Minibusse als dominante Form des Paratransits zu simulieren und damit in Zusammenhang stehende Maßnahmen vor deren Umsetzung in ihren Auswirkungen zu bewerten.

3. Das Modell auf ein Planungsproblem eines formalen Nahverkehrsanbieters anzuwenden.

Das Minibusmodell ist integriert in eine multimodale Multi-Agenten-Simulation. Im Modell konkurrieren verschiedene Minibusunternehmen um die Nachfrage. Während erfolgreiche Unternehmen expandieren und weniger erfolgreiche Unternehmen sukzessive vom Markt verdrängt werden entsteht ein nachhaltiges Netz von Minibusrouten. Die Arbeit beinhaltet mehrere illustrative Szenarien um die Sensitivität des Modells hinsichtlich verschiedener Nachfrageströme, dem Umsteigeverhalten und der Interaktion der Minibusse mit dem Schienenangebot eines formalen Nahverkehrsanbieters zu demonstrieren.

In der Arbeit wird das Modell für zwei verschiedene Arten von Verkehrsplanungsproblemen eingesetzt. Zum Einen wird das Modell verwendet um richtige Minibussysteme in Südafrika zu simulieren und realistische Minibusnetze zu generieren. Zum Anderen wird der nachfragesensitive Charakter des Modells zur Netzgestaltung und Angebotsoptimierung eines formalen Nahverkehrsanbieters genutzt. Das Modell kann einzelne Linien oder ganze Netze betrachten. Beispielhaft werden in der Arbeit zwei Planungsprobleme des Berliner Nahverkehrsunternehmens BVG behandelt. Im ersten Beispiel wird ein Busnetz für den Bezirk Steglitz-Zehlendorf von grundauf neu gestaltet. Das zweite Beispiel behandelt die Schließung des Flughafens Tegels und dessen Einfluss auf das Busnetz der BVG. Das Modell lokalisiert die Einflusssphäre dabei nicht nur auf die unmittelbare Umgebung des Flughafens sondern generiert auch ein der ursprünglichen BVG-Planung für die Flughafenschließung entsprechendes Busangebot.

Zusammenfassend passt das in dieser Arbeit vorgestellte Modell das Angebot automatisch an die Nachfrage an. Das Modell kann dabei nicht nur

Busnetze von grundauf neu gestalten sondern auch bestehende Angebote in ihrer Nachhaltigkeit testen und hinsichtlich der Angebotsfrequenz, Betriebszeit und Route weiter optimieren. Die Optimierung ist dabei in eine verhaltensbasierte Multi-Agenten-Simulation eingebettet. Diese erlaubt es auf die Reaktion sämtlicher beteiligter Akteure wie Passagieren, konkurrierender Verkehrsunternehmen und anderer Nutzer der Infrastruktur zu testen. Das Modell kann daher auch für komplexere Untersuchungen wie die Einführung einer City-Maut oder Umweltanalysen eingesetzt werden.

CHAPTER 1

Introduction

1.1 Motivation and problem definition

The success of a public transport system highly depends on its network design. While transport companies try to optimize a line with respect to running costs, they have to take care of the demand. The best cost structure will not be sustainable if potential customers leave the system and opt for alternatives, e.g. private cars. The basic problem to solve is to find sustainable transit lines which offer the best service possible for the customer. More specifically

- The demand side of the customers asks for direct hassle-free connections. This is commonly referred to as operating door-to-door.
- The supply side of the operators asks for profitable lines to operate. This is commonly achieved by concentrating demand on trunk lines and by establishing a hub-and-spoke network.

Such a market-oriented and moreover self-organizing public transport system can be found in informal public transit systems around the world. These services are often referred to as paratransit and have to be considered as equally important to other modes of transport including the private car. For example, In some regions of Indonesia more than every second vehicle is a paratransit vehicle (Joewono and Kubota, 2007). In the capital city of Indonesia, Jakarta, half of all motorized public transport trips in the city are handled by Jakarta's paratransit services (Cervero, 2000, p. 94). For Manila, the market share of jeepney (minibus) services has been about 75 % of public transport passengers trips in 1989 (Shimazaki and Rahman, 1996) and is still about 40 % in 2000 (Cervero, 2000, p. 74). Despite the great importance of this transport mode it is mainly unsubsidized. Moreover, it often competes with the (subsidized) formal public transit services. Hence, there is an incentive for the government to remove paratransit from the market or if this fails, at least to try to regulate it. However, for sustainable regulation a certain level of understanding is needed which leads to the first objective of this thesis that is:

1. To provide an understanding of the underlying principles of paratransit services, namely minibus services, its stakeholders, fares, route functions, and patterns.

With a decent knowledge on the paratransit mode, the next step is the integration of the mode into existing multi-modal transport planning tools so that transport planners and policymakers can analyze the implications of policy measures. Therefore, the second objective of this thesis is:

2. To develop a model to simulate paratransit, in particular minibus services as the most important type (Cervero, 1997), that allows policymakers to assess the impact of actions before they are implemented.

Also, a regular public transit company can better counteract the competing paratransit if it knows why a certain market niche is successfully filled by paratransit. It can then decide on how to oppose the competitor best.

In addition, the knowledge on paratransit and its ability to identify and fill market niches provides an interesting approach to solve the network design problem of a formal public transit company. A regular task for transport planners of such a company is increasing the overall performance of their service while keeping the budget. In order to do so, it is common practice to shift transport capacity from one line to another one. The according decision is based on expert knowledge and the travel demand forecasts for that line.

If the newly added capacity yields a higher occupancy, the level of service increases while the costs remain the same. Although this method works well for a locally confined area, the impact on other parts of the network is often not predictable as easily. Especially in a dense network, increasing the performance of a single line may well decrease the performance of another line. Thus, the overall gain in performance may turn out to be negative.

Moreover, major changes in travel demand such as are expected with the opening of the new international airport of Berlin and Brandenburg (BER, Germany) are difficult to overcome with traditional expert knowledge. The stepwise local optimization will not be sufficient to restructure the current transit network that is grown over decades. Especially, the existing airport Tegel will cease operations. Thus, transport planners face a completely new situation. Overcoming old habits, they need to recreate the bus network serving the area around the former airport from scratch. The only information available to them is the travel demand forecast and the road infrastructure that is already in place. Thus, the third objective of this dissertation is:

3. To apply this model to the network planning of formal public transit. The underlying demand-responsive algorithm adopted from paratransit needs first to respect the requirements of both the supply and demand side, and second, to rely solely on information on travel demand and road infrastructure.

The model can thus help to tailor the transit company's services to the demand. According to real paratransit, the resulting services are unsubsidized with respect to the cost structure of the company. Operation on loss-making services is ceased while high-demand services are strengthened.

1.2 A brief history of transit optimization

Before redesigning a public transit network, one has to understand how that network works. More specifically, one has to understand how the parts that form the transit network work together. Namely, these are transit stops, transit vehicles, and transit lines connecting the stops by trips of vehicles. Individual trips of a vehicle are characterized by the time the vehicle arrives and departs at a certain stop, and the order of the stops the vehicle serves. In transport planning the combination of stop sequence (route profile) and departure time information (time profile) is called a transit route. The time between the departure of two vehicles serving the same route profile is called the headway. Its reciprocal value is the frequency of that route profile, e.g. measured in departures per hour.

Single line optimization Early research focused on these attributes of a single line with a fixed route profile. For example, Mohring (1972) optimized headways and stop spacing of urban mass transportation services from an economic point of view. Later Jansson (1980) argued that the vehicle size influences the operating costs of a line. Consequently, he proposed a model to optimize service frequency and bus size. In their review article, Jara-Díaz and Gschwender (2003b) reviewed the evolution of microeconomic models for the analysis of public transport services with parametric demand, i.e. the demand is based on passengers per hour values only, and added the disutility of crowding. The cost of a line can be further optimized by allowing some vehicles to serve only a part of the line's route profile. This strategy is known as short-turning (Furth and Day, 1985) and was studied by Furth (1987), Delle Site and Filippi (1998), and more recently by Cortés et al. (2011), who, in addition, added deadheading to the problem. The deadheading strategy allows for faster return trips by not serving any passengers (Furth and Day, 1985). Thus, the vehicle can earlier serve again the direction with the higher demand. Naturally, the passengers still need to be served somehow, e.g. by only letting one out of two buses deadhead. Also, deadheading should take place aside from the vehicle's original route so as not to anger any waiting passengers.

On high demand bus corridors, buses may also operate without timetables. Passengers then only need to know that there is a service with a high frequency. The actual departure time is irrelevant to the passenger, since passenger arrivals at stops tend to be less coordinated for small headways (Luethi et al., 2007). For such unscheduled services, a limited-stop service that serves only some of the stops along the transit line can yield lower travel times due to fewer stops and higher between-stop speeds resulting in shorter bus cycles (Leiva et al., 2010). Thus, the same demand can be served with fewer vehicles. Last, the choice of the fare collection systems can have a serious impact on the travel time of a line (Tirachini and Hensher, 2011). For example, in Berlin boarding is restricted to the first door of a bus, allowing the driver to check and sell tickets. The resulting boarding delay per passenger is found to be about twice as high as the time needed for one passenger to alight (Neumann et al., unpublished).

Network design optimization The deep understanding of single transit line optimization allows going one step further to the optimization of a complete network design. This is by far more complex since the interrelation of individual lines needs to be covered. A condensed summary of network design approaches with focus on bus networks is included in the article of Ceder and Wilson (1986). Baaj and Mahmassani (1995) propose a hybrid route generation algorithm to generate a transit network meeting the demand of a given OD-matrix. This algorithm incorporates the knowledge and expertise of transit network planners to effectively reduce the search space of the algorithm. Since bus networks consist of several lines, the network density, i.e. the distance between parallel bus routes, needs to be considered. For example, Kocur and Hendrickson (1982) studied the role of a supervising controller optimizing the network density, the fares, and the frequency of the service.

Another aspect of networks is the differentiation of services. High-demand bus lines and trains serve mostly (long-distance) corridors. Whereas low-density (residential) areas are linked to those corridors by so-called feeders such as local buses or minibus services. Both types of service can either be optimized in an integrated way, e.g. if local and long-distance bus lines belong to the same stakeholder, or independently. The latter case assumes that the supply of the long-distance service is fixed as it is the case with the infrastructure of train services. The optimal feeder bus network to access an existing rail line was investigated by Kuah and Perl (1988) with focus on bus route spacing, headways, and stop-spacing, and more general for cyclical demand (peak and off-peak) by Chang and Schonfeld (1991). Later, the "joint optimization of a rail transit line and its feeder bus system" was studied by Chien and Schonfeld (1998) who looked also into supplier and user cost minimization. Another research question is whether demand can be better served by direct lines (similar to door-to-door) or by corridor lines (hub-and-spoke). This has been investigated by Jara-Díaz and Gschwender (2003a). They argue that the optimal transit pattern depends on the scenario, i.e. the level and spatial shape of the demand and its perception of transfer delays, waiting time, and in-vehicle time.

The research mentioned so far focused on the optimization of formal public transit with a fixed known demand. More recently, the optimization of feeder transit networks focused on uncertain demand and demand responsive transport systems (DRT), which are related to the dynamic pickup and delivery problem (Savelsbergh and Sol, 1995; Berbeglia et al., 2010). In his dissertation, Cortés (2003) proposed a concept of a high-coverage point-to-point transit system with focus on real-time updates of shuttle routes. This was later developed into a model with point-to-point real-time routing by vehicles operating within one zone as feeder or on one corridor connecting different zones. The travel demand along the corridors was known, whereas the zones were optimized in real time with uncertain demand (Pagés et al., 2006). Fernandez et al. (2008) further developed the model to an integrated system based on a hierarchy of specialized services that complement and coordinate their operations. Again, there is a strict distinction between the corridor service and feeder services operating in a designated target area, and again the system tends to find a system optimum due to the services cooperating. Cortés et al. (2008) added traffic congestion and an adaptive predictive control to the dynamic pickup and delivery problem. Thus, future information regarding unknown demand and expected traffic conditions can be incorporated.

Other approaches solving the dynamic pick-up and delivery problem were using genetic algorithms and fuzzy clustering (Sáez et al., 2008), particle swarm optimization (Cortés et al., 2009), and Benders' decomposition together with a branch and bound strategy (Cortés et al., 2010). Adopting algorithms to solve combinatorial optimization problems from biology can also be taken literally as the more ingenious approach of Tero et al. (2010) shows. They used a slime mold to reconstruct the rail network of greater Tokyo. City centers were represented by portions of nutrition and successfully integrated in the slime mold's transport tubes. They captured the core mechanisms needed for adaptive network formation in a biologically inspired mathematical model.

1.3 Research direction and methodology

The research direction of this dissertation will follow Sáez et al. (2008), Cortés et al. (2009), and Tero et al. (2010) in the application of bio-inspired algorithms and metaheuristics (Osman and Laporte, 1996). But rather than solving one system-wide instance, the dissertation will look at a number of competing elements, each of them evolving according to its own optimization procedure. This is not the same as swarm behavior, where multiple instances cooperate to solve a problem (e.g. Bonabeau et al., 1999), but rather related to co-evolution and evolutionary game theory (e.g. Palmer et al., 1994; Arthur, 1994; Hofbauer and Sigmund, 1998; Drossel, 2001).

A common topic in such investigations is finding circumstances under which cooperative structures can emerge despite the competition (e.g. Axelrod, 1984). The structure of the competition will be inspired by paratransit systems. A common solution concept in such a non-cooperative game is the Nash equilibrium (Nash, 1951). The Nash equilibrium is reached if no participant of the game can improve his solution by opting for a different strategy (e.g. route) while all other players keep their solutions unchanged. That is, players can only improve their situation if they cooperate, i.e. by moving simultaneously to a (supposable) worse solution. However, for evolutionary games, reaching such an equilibrium remains difficult if not impossible.

As stated by Roughgarden (2010) in his review article on "Algorithmic game theory", Chien and Sinclair (2011) prove that for symmetric congestion games natural experimentation strategies can quickly reach a (possibly approximate) equilibrium. Under the assumption that each agent can adapt every nth step, Awerbuch et al. (2008) show that asymmetric congestion games can as well get near despite being exponentially many steps away from the actual Nash equilibrium. Furthermore, Roughgarden (2010) argues that "none of the standard equilibrium notions or the corresponding proofs of existence suggest how to arrive at an equilibrium with a reasonable amount of effort". Indeed, from lectures on game theory "it is known that there are instances of symmetric congestion games in which there are states such that every improvement sequence from this state to a Nash equilibrium has exponential length" (Hoefer, 2013). Thus, with engineering applications in mind, the equilibrium needs to function "as a credible prediction of the long-run state of the system" (Roughgarden, 2010).

From a practitioners point of view, the exact optimal solution of an analytical approach may not be found with the limited resources available (Chakroborty, 2003). This is one of the situations in which Zanakis and Evans (1981) advocate the usage of heuristics, e.g. an evolutionary game as proposed in this dissertation.

The evolutionary game approach of this dissertation is also motivated by the author's practical experience with large-scale scenarios. In an evolutionary game, a clear definition of the involved players is mandatory. In the market of public transport, there are two players, the supply side of the transit operators and the demand side of the passengers. Normally, the passengers face a transit schedule that from their point of view is fixed. Thus, they need to react to that schedule to their best effort. Opposing the schedule by e.g. going the long way on purpose, will usually yield a lower utility for the passenger compared to the least cost path. Hence, the passenger will react by choosing the path with the highest utility, i.e. in most instances this is also the fastest path. Contrarily, the transit operator can change its schedule whenever it needs to optimize its services well knowing that the passengers will react by choosing their individual best paths. That is, the supply side proposes its services and the demand side then reacts. Such a game with a leading player, the transit operator, and a following player in form of the passengers is called a Stackelberg game (von Stackelberg, 2011). In the game proposed in this thesis, the number of passengers is fixed but the amount of collectible fares is not. For example, with a distance-based fare the amount of collectible fares is a function of the distance the passengers traveled. Thus, serving the same trip by a longer distance, i.e. by making a detour, yields a higher utility for the operators. Simaan and Cruz Jr. (1973) argue that in such a nonzero-sum game the Stackelberg solution concept is the most natural way of defining optimality.

Therefore, the focus of this thesis lies on transit network optimization by means of a co-evolutionary algorithm of transit line optimization. Transit line operators compete each other and evolve by applying the genetic operators of mutation and selection to their lines. Mutations include changing the line's route profile, its time of operation, and its service frequency. Selection is represented by each individual line's fitness. Vehicles are removed gradually from unprofitable lines and when no vehicle is left, the line dies out. The algorithm is set up as a Stackelberg game, with the operators as the leading player and the passengers as the followers.

1.4 Outline of the dissertation

This thesis consists of eight chapters. In the following chapter 2, a detailed literature review regarding paratransit is presented. The characteristics and the underlying principles of paratransit systems are described and the various stakeholders involved are identified. The further categorization focuses on jitney/minibus services and aspects of the vehicles used, the price structure, working hours, the route pattern, and the route function are covered. The chapter concludes with the most common characteristics of minibus services.

The proposed evolutionary game presented in chapter 3 is based on the most common characteristics mentioned in the previous chapter. The focus lies on the description of the stakeholders and their interaction. In addition, different types of operators and strategies are discussed. The integration of the evolutionary game into the multi-agent simulation of MATSim is presented in chapter 4. Implications of the implemented minibus model are discussed at the end of the chapter. In the sensitivity studies of chapter 5, the minibus model is applied to different settings in illustrative scenarios. The model is tested with different travel demands, networks, and strategies.

The case study of chapter 6 functions as a demonstrator of the practicability of the approach to simulate minibuses in a South-African context. This is the first application of the minibus model to a real-world scenario. In the second case study of chapter 7, the minibus model is applied to the real-world network design problem of a formal public transit authority. The approach of the evolutionary game is used to create a new bus network from scratch and the solution found is compared to the currently implemented solution of the authority. Special thoughts are given to the quality of the results and the necessary steps to implement the model as a transit planning instrument. The third case study in chapter 8 focuses on analyzing the impact of a massive change in demand. In particular, the closure of the existing airport Tegel and its effects on the bus transit network are analyzed.

The thesis concludes with a summary of the dissertation. Furthermore, chapter 9 contains an outlook for the approach and possible applications of the minibus model.

CHAPTER 2

Paratransit around the world

(I) do not know what the fare for a "bag-o-potatoes" are.

Johan W. Joubert on using South-African minibuses for the occasional freight transport

This chapter begins with a definition of paratransit in the sense of this thesis and proceeds with an introduction to paratransit systems around the world. It closes with a brief summary of the main characteristics in order to derive the requirements for a paratransit simulation model. A condensed version of this chapter was presented earlier at the 91st Annual Meeting of the Transportation Research Board (Neumann and Nagel, 2012a).

2.1 Definition and scope

The term paratransit has two meanings when referring to transport. The first one is a mode of transport specially fitted to the needs of elderly or physically handicapped people. In the United States of America transit authorities were forced to offer services to the disabled by the requirements of section

504 of the Rehabilitation Act of 1973 (U.S. Department of Transportation, 1973; Contributors of the Wikipedia, 2012b). At this time, transit authorities considered it best to offer complementary flexible services to the disabled instead of retrofitting the existing bus fleet.

The second meaning is more common outside the United States where it refers to all kinds of public transport ranging from taxis up to bus lines. In most cases, this is a user-demand-oriented mode of transport mainly used in cities of the developing world. In this thesis, the term paratransit refers to that second meaning and is used as a general term for this kind of service. Additional definitions from dictionaries and books about paratransit are compiled in appendix A.

2.2 Distinction from demand responsive transit

Although paratransit shares some underlying principles with demand responsive transit (DRT), it can be distinguished from such systems by the way its organization takes place. DRT systems heavily rely on a supervising level (controller) which allocates vehicles to individual trips or collective rides (e.g. ENEA, 2004; Jokinen et al., 2011). Paratransit lacks a supervising control level, but nevertheless is not completely unorganized.

2.3 Organisation of paratransit

As seen in section 2.1, paratransit can not be defined easily in one sentence. In this section, paratransit is defined as an abstract system. According to Cervero (2000) the paratransit system can be seen from two sides,

a) The supply side and

b) The demand side.

Not explicitly mentioned but stated indirectly in the case study of Cuba (Cervero, 2000, p. 18) is a third side

c) The marketplace.

Since the marketplace and the demand side are not in the focus of this thesis they are only briefly mentioned here. The supply side is then described in more detail in section 2.4.

2.3.1 The marketplace

The marketplace can consist of the two sides supply and demand negotiating directly, but can also consist of a man-in-the-middle, e.g. a kind of dispatcher working at a parking lot, bringing together both sides. In the case of Cuba, supply and demand side are brought together by official traffic wardens called "Amarillos" forming a kind of state serviced hitch-hiking system. State owned vehicles are forced to fill up empty passenger capacities and halt at certain points mostly located at trunk roads leaving the city. The Amarillo coordinates the demand side on spot by asking for travel destinations of the hitch-hikers in advance (Díaz, 2010). In return, a small refund is paid to the Amarillo (Contributors of Wikitravel, 2012). In South Africa, so-called "rank marshals" or "queue marshals" fulfill a similar role as the example of Pretoria in subsection B.3.4 shows. Typically, the marketplace brings together those willing-to-provide and those willing-to-pay. With transit operators seeking profit and customers searching for a cheap ride, the marketplace comes up with market-determined fares.

2.3.2 The demand side

Paratransit operators serve all kind of passengers. This includes high-class educated people and students, middle-income households (even car owners) as well as lower income classes, especially in cities of India and Africa. The service provided depends on the social class served. Different classes use a different level-of-service. For the most part, the trip purpose is unrelated to work, except for some commuting on peak-hours. On some relations, case studies suggest an asymmetry in trips. For example, people tend to avoid higher fares of the paratransit operators by walking or by taking a bus when going to the marketplace shopping. Returning loaded with goods, they tend to use paratransit services more often. The supply side tries to compensate by offering cheaper fares to the marketplace (Cervero, 2000, p. 33–34). In another example derived from the Bangkok's case study (Cervero, 2000, p. 66), students tend to use paratransit services inbound in the morning, when they are in a hurry, and save money by taking the bus for their return trip home.

2.4 The supply side

The supply side mainly consists of drivers and vehicle owners. In the following they are referred to as operators. There are further players connected to the supply side, like car mechanics and pressure groups. However, these will not be discussed in this thesis, since they are not an important part of the supply side from a traffic engineer's point of view. This thesis focuses on the description of paratransit characteristics from the operators' side.

In his study about informal transport in the developing world Cervero (2000, p. 14) mentions a common core distinction among paratransit services and the vehicles in service:

> "whether they are 'taxi-like', providing door-to-door connections, or 'bus-like', following more or less fixed routes. In general, small-vehicle services, like pedicabs, hired-motorcycles, and microbuses, operate akin to taxis. As passenger loads increase, service-providers begin to ply fixed routes because of the impracticalities of delivering lots of unrelated customers to assorted destinations. Accordingly, 'bus-like' services consist mainly of larger vehicles like commercial vans, pick-up trucks, and minibuses."

Extending this distinction, the following dimensions of the supply side are discussed in this section: the different types of operators, the type of vehicles used, the underlying price structure and working hours, performance figures, and route choice.

2.4.1 Types of paratransit operators

There are many kinds of paratransit operators, starting from one-driver-companies like single car owners and franchisees, up to route associations with hundreds of members. The following description gives a short introduction to the different types of operators. For case studies featuring the different types of operators the reader is referred to Table 2.6.

Single car owner As the name indicates, this type of operator possesses only one vehicle. The owner of the vehicle often runs the vehicle by himself or rents it part-time to another driver. The driver is responsible for his actions and acts as a single person company. He earns all revenue, but at the same moment bears all expense. This often leads to a fierce head-to-head competition with other drivers.

Franchisee Drivers lacking the money to buy a car can lease one on a daily basis. This is a solid business run by former drivers who one day managed to possess more than one car and now make a living out of the franchise business only.

Route association Route associations also known as cooperatives consist of paratransit drivers and are founded in order to fend off renegades and pirate drivers from the association's service area. Route associations are a kind of self-organizing structure in an otherwise highly competitive market. Although, in most cases, protection from open competition is the main objective, there may be other objectives. These include the enforcement of minimum standards, facility sharing, or joint negotiation with the administrative or political sector. Route associations are the most common form of organization. Therefore, the reasons for founding or joining an associations are considered more closely.

- A route association can enforce (unwritten) ground rules and procedures, e.g. penalizing head-hunting of passengers.
- Limiting the access to the market can help balancing supply and demand, avoiding cutthroat competition on the one hand, but on the other hand can lead to cartelization.
- Coordinating routes can prevent head-to-head competition and help avoiding redundancies. A route association can agree on transport hubs shared by all its drivers and negotiate transfer stations between different associations effectively increasing the service quality to the customer.
- A route association can provide a trade name representing a certain level of service. The association can assign duties to its drivers, e.g. maintaining adequate service during slack periods. Losses due to this kind of service can be distributed among its members.
- The members of a route association can share a facility at transit hubs. Sharing of a common place at terminals and pick-up spots can lead

to competitive advantages over other associations and prevent non-members from market entry.

- Members of a route association can act as one group of customers. This can give discounts when buying spare parts or grant access to affordable credits.

- Due to the large number of members, a route association can give protection from law enforcement, e.g. by bribing local police officers, as well as from other associations.

- A route association can lobby for the members' interests, e.g. further deregulation of public transit market.

As mentioned above, route associations can definitely improve the level-of-service. However, when cartels are formed, prices can rise while service remains on the same level or even declines. Also, competition among route associations can lead to unwanted side-effects as the following example taken from Cervero (2000, p. 50) illustrates.

> "Competition heated up so much that a new occupation, sapos (Spanish for 'toads'), formed for purposes of selling information to operators about downstream traffic conditions and locations of waiting customers. Some 3000 sapos worked full-time advising drivers when to overtake competitors and how to avoid police traps."

Route associations with their vast number of members and vehicles are supposed to have an impact on the traffic flow dynamics of roads. While it is true that each vehicle needs some amount of the road's capacity, the actual footprint is quite small compared to individual car traffic. This holds true especially when considering the different occupancy rates. However, the road space use per passenger of a minibus can be twice as high than the one of a public bus (Shimazaki and Rahman, 1995). In addition, paratransit vehicles tend to

> "form the greatest traffic bottlenecks at and around major bus terminals and marketplaces. Thus, their congestion-inducing impacts tend to be spatially confined" (Cervero, 2000, p. 36).

Table 2.1: Classes of paratransit vehicles that operate informally; adopted from Cervero (2000, p. 15)

Vehicle Class	Routes	Schedules	Capacity	Service Niche	Service Coverage
I Conventional Bus	Fixed	Fixed	25–60 pax	Line-Haul	Region/Subregion
II Minibus, Jitney	Fixed	Semi-Fixed	12–24 pax	Mixed	Subregion
III Microbus, Pick-Up	Fixed	Semi-Fixed	4–11 pax	Distribution	Subregion
IV 3-Wheeler, Motorcycle	Variable	Variable	1–4 pax	Feeder	Neighborhood
V Pedicab, Horse-cart	Variable	Variable	1–6 pax	Feeder	Neighborhood

2.4.2 Types of paratransit vehicles

Vehicles used in paratransit are as manifold as services provided. Nonetheless, it is possible to categorize them by key features like capacity and routes served. The categorization for this thesis is derived from Cervero (2000, p. 15) and shown in Table 2.1. In the developed world, class I vehicles are used by official public transport companies. Class IV and class V vehicles lack the prerequisites of an inter-borough service. Therefore, this thesis concentrates on class II and class III vehicles filling the gap between conventional buses and compact vehicles with capacities of 4 to 24 passengers (pax).

2.4.3 Price structure and working hours

Most paratransit operators will adapt their route whenever demand changes. This decision is often based on profit maximization by optimizing the income, cutting down expenses, or by optimizing the working time.

In contrast to typical transit authority bus drivers, paratransit drivers do not work for wages. Their earned income derives from collected fares. In general, there are two models of price structure. The first one is the fixed fare. This can include price steps that decline with distance, e.g. stage fares. Class II and class III vehicles plying a fixed-route mostly charge fixed fares. The second one relies on fares calculated on a per-kilometer basis. In lack of taximeters, the price can be preassigned, e.g. by a route association, or can be negotiated with the driver. Fare calculation may rely on the driver's intuition

(Sapa, 2013) and can also depend on the passenger's outward appearance, goods to haul and weather conditions. Variable fares are more common for taxi-like services as offered by smaller vehicles (class IV and class V). Since prices depend heavily on the region and date of the survey there are no general figures. However, an approximation can be made by comparing the income and fare structure of other means of transport. For example, figures for drivers of Mexico City from 1994 indicate that earnings of drivers of the colectivo minibus "compared closely to what public bus operators made" (Cervero, 2000, p. 31). Other comparisons are included in the case studies of Appendix B, e.g. Rio de Janeiro in B.2.4 and B.2.5, and Accra in B.3.3.

Although paratransit operators may realize an income comparable to formal bus services, the drivers lack the benefits from being employed by a regular company, e.g. job security. Especially drivers not organized in a route association need to rely solely on themselves. But also organized drivers need to cover expenses like their and their family's living costs, refueling, maintenance expenses and maybe vehicle depreciation. Drivers engaged in a route association may be due to a membership fee for the services provided by the association. Independent drivers lacking the membership may have to occasionally bribe officials by themselves.

In addition, the driver may have to pay for licenses or for leasing the vehicle, if the financial background does not allow to buy one.

> "In most cases, drivers pay a set amount each day to lease a vehicle. In other instances, owners and drivers split proceeds based on some mutually agreed-upon formula" (Cervero, 2000, p. 47).

> "Under most lease arrangements, drivers pay a set daily fee (usually equivalent to around 20 to 25 percent of gross daily in-take) and cover all other day-to-day expenses (mainly fueling the vehicle, minor maintenance, and paying off enforcement officers). Rarer are situations where owners bear all financial responsibilities and either pay drivers pre-set salaries or else fold these costs into daily lease rates" (Cervero, 2000, p. 30).

Due to the complex cost structure it may even seem to result in uneconomic behavior as shown in the case of Santa Cruz de la Sierra (Figueroa and Pizarro, 1998). In this case, the majority of operators use second hand minibuses which the study found to be more expensive on a per-kilometer basis than new vehicles. However, operators operate profitably suggesting that not all reasons for running a second hand vehicle are considered and covered by that study.

Also working conditions depend on the region and vehicle class driven. Since the income of the drivers is unpredictable, some drivers are forced to work as long as is needed to earn the minimum wage needed to survive. Therefore, the number of hours a driver has to work varies from 10 to 12 hours a day, 6 to 7 days a week for drivers of motorized vehicles up to 70–80 hours a week for drivers of three-wheelers (Cervero, 2000, p. 26). Sometimes, this means 10 hour shifts, seven days a week for several weeks without a rest (Etherington and Simon, 1996, Table 3).

To conclude, spending mainly consists of living and upkeep costs including fueling and "special" expenses. Revenue derives from fares, typically in form of lump sums or on a per-kilometer basis.

2.4.4 Performance figures

The number of passengers served by paratransit operators varies from region to region. According to figures from secondary sources it is correlated to the vehicle type used. Table 2.2 shows passenger performance figures for the metropolitan areas of Jakarta, Indonesia and Bangkok, Thailand, while Table 2.3 gives estimates of served passengers for hired motorcycles and vans of the city of Bangkok and for motorized three-wheelers and minibuses of the city of Vadodara, India. From the figures listed in Table 2.5, estimates for cities in Sub-Saharan Africa can be calculated.

Comparing the figures of the Tables 2.2, 2.3, 2.4, and 2.5 underscores the variation of results obtained by field studies. Numbers of carried passengers per day and vehicle vary from 60 to 520 pax in the case of Bangkok's minibuses (Cervero, 2000, p. 27). Other Asian cities show similar figures, see Table 2.4. Estimates based on Table 2.5 vary from 73 passengers per minibus and day in the case of Lagos up to 410 passenger per minibus and day in the case of Dakar. Interviews with people from Rio de Janeiro (page 195) indicate 12–15 passengers per trip and van. Examples from Eastern Mediterranean and Egypt (page 202) show common 10–14 seater vans operating at their limits, sometimes exceeding their legal capacity on peak hours by allowing standees or passengers sitting on the floor. In the City of Johannesburg, about every second minibus departs from a taxi rank exceeding the legal capacity (ITP, 2004, Table 3-56). However, the figures give a rough estimation in terms of class II and class III vehicle's passenger performance indicators.

Table 2.2: Passengers performance figures from Jakarta and Bangkok (Cervero, 2000, p. 27)

Jakarta	Human-powered becaks	1.5	passengers of kilometer of service
	Three-wheel bajajs	4	passengers of kilometer of service
	Bemo micro-vans	7	passengers of kilometer of service
Bangkok	Motorcycles	44	passengers a day
	Pickups	60	passengers a day
	Minibuses	520	passengers a day
	Conventional buses	1300	passengers a day

Table 2.3: Passengers served in the cities of Bangkok and Vadodara, India (Cervero, 2000, table 2.4)

		Average number of trips per day	Average number of passengers carried per day	Average number of passengers per vehicle trip
Bangkok	Hired motorcycles	33	44	1.3
	Vans	5	60	12.0
Vadodara	Motorized three-wheeler	34	90	2.9
	Minibus	8	60	10.0

Table 2.4: Performance figures for Asian cities based on unnamed World Bank survey, studies and field reports cited by JICA (1990, table 4.7.2)

City	Vehicle type	Capacity	Performance per vehicle	
Hong Kong	minibus	14 pax	230 km/day	330 pax/day
Istanbul	minibus	20 pax	215 km/day	335 pax/day
	shared taxi	7 pax	110 km/day	100 pax/day
Jakarta	minibus	30 pax	250 km/day	480 pax/day
	vans	15 pax	250 km/day	125 pax/day

Table 2.5: Passengers performance figures from Sub-Saharan minibuses (Trans-Africa, 2010b, p. 19)

Region	Number of units	Capacity per unit	Average rate of occupancy per unit	Annual kilometers per unit	Annual total number of passengers	Daily unit trips
Abidjan	5,370	18	18	86,400	568,940,760	16
Accra	45,883	12	18[1]	79,872	1,458,103,145	6
Addis Ababa	8,911	11	11	57,350	500,887,310	14
Dakar	2,551	39	35	58,006	382,063,850	14
Dar es Salaam	10,000	30	29	70,000	1,115,631,312	11
Douala	550	18	17	50,000	30,197,340	9
Johannesburg	19,600	15	8.5	64,680	2,513,817,600	7
Lagos	80,000	30	18	72,000	2,140,000,000	8
Nairobi	22,733	25	18	18,000	1,590,744,661	11

[1] As indicated in subsection B.3.3, this figure might be inaccurate.

The average trip length of a paratransit trip also varies from region to region and depends on the vehicle class. Citing a somewhat outdated study of the transport system of Manila from 1986, Cervero (2000, p. 27) states that "around 65 percent of bus trips are over 7.5 kilometers in length while an equal share of jeepney (minibus) trips are under 5 kilometers in length." The same cited study (JICA, 1985, table 5.5) also states averages for trip lengths of 10.4 km for jeepney routes and 21.1 km of bus routes. However, the assumption of minibuses serving only considerably short trips is wrong, as can be seen from the case study of Rio de Janeiro on page 195.

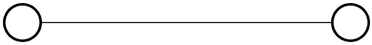
Figures from the JICA (1999, table 3.6) indicate an average travel time of 16.6 min for tricycles trips and 43.0 min for trips by jeepneys. The average trip length of jeepney passengers is 3.0 km for Metro Manila (JICA, 1999, table 3.5). However, Cervero (2000, p. 34) refers to the same city and time stating the average length of a trip ranges from 1–2 kilometers for pedicabs to 2–4 kilometers for tricycles and up to 6–8 kilometers for jeepneys.

To conclude, trip distances correlate with the type of vehicle. However, the trip length of one vehicle type varies significantly in the literature, as the case of Manila's jeepneys demonstrated. Minibuses like jeepneys serve short trips as well as longer commuter runs and inter-borough service.

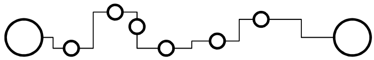
2.4.5 Route choice

Regardless of the type of paratransit operator, the operator has to adapt to the customers. The operator does so by providing a service for a certain time in a certain area or by plying along a corridor. For example, commercial vans tend to operate as commuter service mainly on peak hours, whereas minibuses work all-day along a corridor (Cervero, 2000, p. 27). Route choice can be categorized by a) the route pattern and b) the route function.

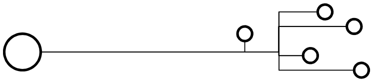
a) Since route patterns heavily depend on the local market, there are as many different types as there are markets in the world. More details about the variety of patterns can be found in the case studies in Appendix B. For a better understanding, some of the most common patterns are visualized in Figure 2.1. One possible way of categorizing them is by the number of destinations they serve. For example, the most flexible taxi-like route pattern serves *Many-To-Many* connections. In the case of class III vehicles, a driver will more likely cruise a neighborhood for more customers to fill up the empty seats. Passengers



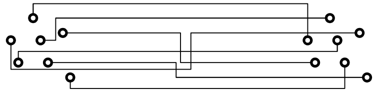
(a) One-To-One: From downtown area to the train station



(b) Corridor: Multiple stops according to demand



(c) One-To-Few or Few-To-One: Distributor or feeder to the marketplace



(d) Many-To-Many: Taxi-like door-to-door service

Figure 2.1: Some examples of different route patterns

already in the vehicle will have to bear the extra ride. If the driver periodically checks the same spots and finally proceeds to the market, the type of route is *Few-To-One*. Class II vehicles tend to ply along a fixed route, e.g. from one city to another or from the township's market to the central business district. This type of route can be called *One-To-One*. Variations may occur in the way that passengers can get on and off along the route or that the driver will make a small detour in order to drop off a passenger. The trip's destination can be preset, e.g. a market, or set by the first customer entering the vehicle. The driver will then seek to pick-up additional passengers heading in a similar direction, e.g. as known from Niamey, Niger (Cervero, 2000, p. 158). To summarize, every kind of combination of *One*, *Few* and *Many* can be found and multiple origins and destinations along a corridor may be served.

b) The route function is determined by the origins and destinations served. A route can function as a distributor connecting the market to residential areas or as a complementary feeder to mainline routes, e.g. connecting to a metro station. Both types are short distance versions of the type *One-To-Few/Many*. According to Cervero (2000, p. 18), in most instances, class II and class III services compete with rather than complement formal bus and rail services. There are two types of competition. First, there is the head-to-head competition with conventional public transport buses along popular routes, effectively duplicating the routes. Paratransit buses arrive at the stop just before the conventional one taking away passengers by offering a faster trip. Second, there is the complementing type of competition. This happens, if headways of the fixed-schedule bus are too long and the paratransit vehicle fills in the gap, shortening the effective waiting time. Another type of complementing competition is realized by offering a higher level-of-service, e.g. guaranteeing seating, serving coffee and providing newspapers.

"Finally, unlike conventional bus service, the paratransit modes have no obligation to provide a service on routes where demands are low. The operator provides service only when profitable for him." (Shimazaki and Rahman, 1995)

2.4.6 Boarding behavior

The boarding behavior depends on the vehicle class with smaller vehicles reacting more often to individual hails whereas larger vehicles tend to serve fixed terminals. For vehicles of the classes II and III, basically two different categories exist. The first one allows boarding and alighting anywhere by hailing a vehicle. A more sophisticated version of this behavior can be found studying the South African minibus taxi. Location-dependent hand signals indicate the passenger's desired destination to the driver (Woolf and Joubert, 2013). The second one uses fixed spots. This can be large facilities dedicated to paratransit only like the South African minibus taxi ranks, see subsection B.3.4, or as it is the case with the highly regulated terminal at the Muang Thong food court, see subsection B.1.2. As the example of South Africa illustrates, combinations of both categories exists as well. Also, the fixed spot may be defined ad hoc by the passengers who start to cluster at intersections, e.g. in Damascus (subsection B.4.3), effectively increasing their probability of being picked-up.

2.5 Summary of paratransit systems

Paratransit systems can be categorized by route pattern and function, by organization of drivers, kind of stops, and fare type. Table 2.6 summarizes the case studies included in Appendix B. Most case studies obtained by personal communication and presented by Cervero (2000) indicate that paratransit services are mainly organized as route associations operating 8-15 seater vans on fixed routes. Most of the services run in direct competition to a public transport system of a public transit authority. The approach presented in this thesis will be based on those most common characteristics.

Such a service—minibuses with fixed routes but without fixed schedule—is often called a jitney service (Cervero, 1997, p. 39). This thesis will use the term minibus service, and refer to the operator as a paratransit operator with the understanding that the jitney/minibus service is one out of many possible paratransit services.

Table 2.6: Overview of the case studies included in the Appendix B

Case Study	Type of operator	Type of vehicle	Fare system	Route choice
Southeast Asia and China				
B.1.1 Philippines/Manila	Route association Route association	Class II Class III	Stage fare	Fixed route, pick-up anywhere Fixed route with detours in fixed area, major pick-up points
B.1.2 Thailand/Bangkok	Route association	Class II–III	Fixed fare per trip	Long-distance commuter runs, many-to-few
B.1.3 Indonesia/Jakarta	Route association	Class II–III	Fixed fare (mainly)	Fixed route, major pick-up points
B.1.4 China/Nanjing–Yancheng		Class I	Fixed fare	Fixed route, stops along the route
South America				
B.2.1 Jamaica/Kingston	Single car owner Single car owner	Class II Class III		Fixed route, pick-up anywhere, pirating on other routes Many-to-many, pick-up anywhere
B.2.2 El Salvador/San Salvador		Class I	Fixed fare	Fixed route, pick-up anywhere
B.2.3 Bolivia/Santa Cruz de la Sierra	Route association	Class I–II	Fixed fare	Fixed route
B.2.4 Brazil/Rio de Janeiro	Route association Single car owner	Class II Class III	Fixed fare	Fixed route, one-to-many Circulator in designated area, feeder, many-to-many
B.2.5 Brazil/Rio de Janeiro	Route association	Class II	Fixed fare	Fixed route
B.2.6 Brazil/São Paulo, Porto Alegre		Class II–III	Fixed fare	Fixed route, pick-up anywhere
Sub-Saharan Africa				
B.3.1 Nigeria/Lagos	Single car owner	Class I–II		Fixed route
B.3.2 Kenya/Nairobi	Route association	Class II–III		Fixed route, pick-up anywhere

Table 2.6: Overview of the case studies included in the Appendix B (cont.)

Case Study	Type of operator	Type of vehicle	Fare system	Route choice
B.3.3 Ghana/Accra	Route association	Class II	Fixed fare based on distance	Fixed route, pick-up anywhere
B.3.4 South Africa/Pretoria	Route association	Class II	Fixed fare	Fixed route, pick-up anywhere, hubs
Eastern Mediterranean				
B.4.1 Turkey/Instanbul, Antalya, Alanya, Bodrum		Class II	Fixed fare based on distance	Fixed route, pick-up anywhere
B.4.2 Turkish Republic of Northern Cyprus	Route association	Class III	Fixed fare based on distance	Fixed route, detours on demand, pick-up anywhere
B.4.3 Syria/Damascus	Single car owner	Class II	Fixed fare	Fixed route, pick-up anywhere
B.4.4 Lebanon, Syria/Damascus–Beirut	Single car owner	Class III	Negotiated	Fixed route, one-to-one, pick-up at terminal only
B.4.5 Lebanon/Beirut	Single car owner Single car owner	Class II Class III	Fixed fare Fixed fare	Fixed route, pick-up anywhere Shared-taxi, many-to-many
B.4.6 Israel/Haifa		Class III		Fixed route
B.4.7 Egypt/Aswan, Luxor, Hurghada, Sinai		Class II Class III	Fixed fare based on distance Fixed fare based on distance	Fixed route, one-to-one, pick-up at terminal only Shared-taxi, many-to-many
B.4.8 Egypt/Cairo	Route associations	Class II	Fixed fare	Fixed route
B.4.9 Tunisia/Tunis	Single car owner	Class III	Fixed fare	Fixed route with some detours
Other regions				
B.5.1 Kuwait	Single car owner	Class III	Negotiated	Many-to-many
B.5.2 Republic of Moldova/Chișinău	Single car owner	Class II	Fixed fare	Fixed route, pick-up anywhere

CHAPTER 3

Paratransit model

Evolutionary algorithm design remains an art.

C. Patvardhan's final remark about his talk on quantum-inspired evolutionary algorithms

Based on the requirements stated in section 2.5 the proposed model needs to cover the following features to reflect the main characteristics of minibus services:

- Individual paratransit operators: Each paratransit operator reflects a route association managing its own fleet of minibuses.
- Competition: Paratransit operators need to be able to engage in head-to-head competition. The operator with the most competitive routes should prevail.
- Fixed route service: The paratransit operator's offer services on fixed routes. At the same time, the routes need to be flexible enough to be adapted to a changing demand.

- No fixed schedule: The passengers need to know at which time of day a service will be available, but the schedule should only reflect the frequency of the service, i.e. departures are not fixed, but a passenger knows that there will be a vehicle departing e.g. every five minutes. The paratransit operators need to be able to change their operating times, if demand changes.
- Flexible vehicle-fleet size: The number of vehicles each paratransit operator puts into service needs to reflect the income of its routes. If a route is unprofitable, the operator should withdraw vehicles from that route. Likewise, operators should increase the number of vehicles on profitable routes.

In addition, there are minor features to consider. These features only apply to some regions of the world and therefore help to apply the model to those regions. The following optional features will be covered:

- Franchise system: Sometimes, paratransit systems are regulated in the sense that paratransit operators need some kind of a license. Licenses may be valid for a region, e.g. a neighborhood, or for a relation, e.g. between two major hubs or a mall and the central business district. The licenses are also an instrument to limit the number of operators on the market. A license may be issued with additional requirements like offering services for a minimal period of time per day.
- Restricted areas: Paratransit operators may be restricted to certain areas. This can be due to protection of publicly founded public transit investments or as a result of traffic issues, e.g. minibus services tend to clutter the most frequented transport hubs. The model also needs to ensure that operators do not serve certain formal public transit stops.

The proposed paratransit model uses a co-evolutionary algorithm. More precisely, it is inspired by the core mechanics of genetic algorithms. While genetic algorithms are the third best way of doing just about anything (Russel and Norvig, 2010, p. 621) they are computationally inefficient but extremely flexible in the way they can be applied and extended. Solutions of genetic algorithms are not guaranteed to be optimal as is the case with most heuristics. However, the genetic algorithms proved to generate plausible solutions when solving transportation problems. For example, Charypar and Nagel (2005) applied genetic algorithms to generate complete all-day activity plans.

Thus, the model in this thesis is probably not the most advanced evolutionary algorithm but will nearly always generate plausible and good-enough solutions and can be easily extended.

The next section starts with an introduction to genetic algorithms as their core mechanics are found throughout the proposed paratransit model. The following sections will first describe the overall paratransit model and how the supply side and the demand side interact with each other. Next, there will be a more detailed description of the main characteristics and how they are covered by the model. This chapter concludes with the model's optional features.

3.1 The quintessence of genetic algorithms

Genetic algorithms belong to the field of machine learning research and are sometimes also referred to as evolutionary algorithms. They adopt the survival of the fittest principle from nature's way of evolving successful organisms. Well adapted organisms reproduce and give their genes to their offspring. Organisms not fitting their environment die out. Occasionally, genes are modified and the mutation prevails if it gives an advantage over competing organisms. Non-successful mutations are likely to be removed from the selections process (Darwin, 1859; Wallace, 1889).

In genetic algorithms, individuals are scored according to a fitness function. Individuals that are better adapted to their environment are rewarded by a higher score. A higher score allows for a higher rate of reproduction. Genetic algorithms can solve reinforcement learning problems (Kaelbling et al., 1996; Moriarty et al., 1999; Whiteson, 2012). However, the genetic algorithm needs to ensure that also low-scoring but surviving individuals have a probability to reproduce. Otherwise, the hill climbing way of selecting only the most promising individuals would ignore slower evolving solutions and thus the genetic algorithm may get stuck on a local maximum.

Once allowed to reproduce, individuals apply one of the two genetic operators *cross-over* or *mutation* to their genes. *Cross-over* means combining the genes of two parents in a way that, for example, the first n genes are taken from parent A and the remaining genes are taken from parent B. *Mutation* can be achieved without parents by simply changing a gene randomly. Note that in this thesis only *mutation* is used and that mutation operators are labeled as "route modification strategy". The label "operator" is intentionally not used to avoid ambiguity with paratransit and minibus operators.

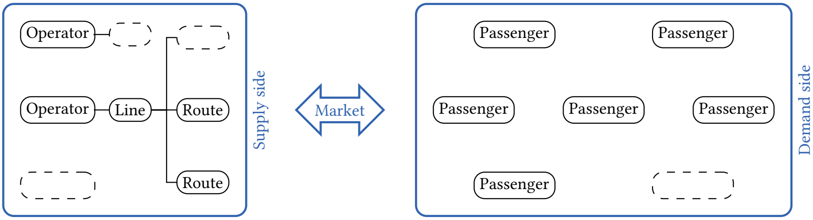


Figure 3.1: The model's representation of the supply side and the demand side

3.2 Overview of the paratransit model

This section describes the paratransit model in the most general way. It is considered to be an introduction to facilitate the understanding of the more detailed descriptions of the following sections.

The paratransit model consists of two sides interacting with each other as depicted in Figure 3.1. The supply side comprises paratransit operators offering minibus services. The passengers of the demand side use these services. Both sides interact with each other through the market. In this model, the market is realized by an individual scoring of each side and a mobility simulation in-between. The next subsections cover the paratransit operators, the passengers and the mobility simulation in more detail.

3.2.1 Paratransit operators

The paratransit operators reflect the route associations of the real world. Thus, operators form the most important part of the model.

In the model, paratransit operators do not communicate with each other. There is no explicit coordination or cooperation between the operators, except for the fact that passengers using one operator can transfer to a different operator. Different operators together can thus form a hub if this emerges from the optimization process, but otherwise are engaged in competition with each other.

Each paratransit operator manages one *line*. This *line* is similar to the transit line of a public transit authority or to a route association's service corridor. A *line* can consist of multiple *routes*. Each *route* has a number of vehicles and stops associated with and each *route* can have a unique time of operation. While the bundle of an operator's *routes* form its *line*, the *routes*

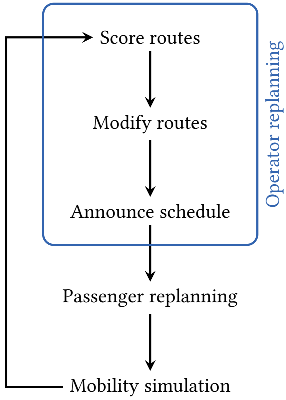


Figure 3.2: The operator replanning in the context of the passenger replanning and the mobility simulation

do not have to overlap. Thus, a paratransit operator may provide minibus services in otherwise unrelated areas.

Paratransit operators are subject to a changing environment due to a changing demand for transit services. Operators will thus have to react to their environment and adapt their *lines*. If an operator cannot successfully adapt, it cannot prevail and will eventually leave the market. Operators can adapt by the so-called *operator replanning* process which is illustrated in Figure 3.2 and Algorithm 3.1. An operator replans by first scoring its *routes*, second modifying its *routes* and finally announcing its *routes* to the passengers of the synthetic population. After the *passenger replanning*, both sides interact through the *mobility simulation* until the next *operator replanning* is triggered.

Paratransit operator scoring

An paratransit operator has to assess its *routes* so that it can focus on the more profitable ones. For each of its vehicles the operator calculates the (net) income or profit. The revenue derives from collecting fares whereas the vehicle-related expenses can be split into different categories. To express the public transport operating costs, the Australian Transport Council (ATC, 2006) recommends a function of three variables:

1. The fixed costs induced by the number of vehicles in the fleet, e.g. depots and depreciation.
2. Costs depending on the distance traveled, e.g. fuel and tires.
3. Costs depending on the time the vehicle is in operation, e.g. driver and crew.

As for minibus services, it can be argued that a driver needs to earn enough money to make a living. The driver needs a certain amount of income per day rather than per hour. If earnings per hour are rather low the driver needs to compensate by working longer shifts. However, for transport planning purposes, drivers are assumed to work under contract and thus the proposed cost structure including costs per hour is used.

After determining the profit of each vehicle separately, the profit of each *route* is calculated by summing up the individual profits of the vehicles associated with the *route*. The operator can then start modifying the *routes* using the profit as performance metric. This can be the total profit of that route or a per-vehicle based value.

Modifying routes

During the route modification part of the *operator replanning* process, the paratransit operator needs to decide which *routes* to maintain further, which ones to drop and whether new *routes* will be proposed or not. To prevail in the competition with other operators, each operator needs to maximize its profit. Essentially, the operator needs to strengthen profitable *routes* and to weaken unprofitable ones. This can be done by dropping *routes* entirely or by shifting vehicles from unprofitable *routes* to profitable ones. Since profitable *routes* seem to fit the market requirements better, they are a candidate for creating a new *route*. New *routes* can be created by altering one or more attributes of an existing *route*, e.g. by shifting the time of operation or by adding/removing stops.

Announcing the schedule

Finally, the paratransit operator has to announce its set of offered *routes* to the demand side. In this model, it is proposed to create a transit schedule with all *lines* of the paratransit operators. This schedule can be fused with an existing schedule of a public transit authority. This ensures a transparent integration of minibus services with other public transit services, e.g. trains and formal bus lines. The schedule created by the paratransit operators does not have to follow the same strict rules as the schedule of a public transit authority. The schedule of the paratransit operators needs only to reflect the general service frequency and not the actual departures, see the discussion at the end of subsection 3.2.4.

Linkage to genetic algorithms

In terms of genetic algorithms, *routes* represent the individuals. A paratransit operator's line is akin to a collection of individuals (*routes*) with similar genes. The properties of a *route*, i.e. the sequence of served stops and the time of operation, form the genes. Operators select individuals for reproduction based on the profit per *route* (fitness function). Reproduction is achieved by a) cloning a *route*, i.e. effectively duplicating the genes by allowing more vehicles to serve the same *route*, and b) *mutation*. In the latter case, one of the genes of the *route* is altered and a single copy of that *route* is released to the environment. That is, the *route* is served by one vehicle only and the *route* is announced in the schedule and thus executed in the mobility simulation.

3.2.2 Passengers

The passengers form the demand side of the model. Ideally, the passengers are represented by synthetic individuals each reacting to its environment individually. These so-called agents need to be able to conduct trips. A trip connects two points of interest, normally activities, and consists of one or more legs. For this model, only legs using public transport as transport mode are of interest. Agents search the routes of their legs based on the transit schedule available. If this transit schedule includes minibus services, agents can conduct trips using minibus as well as formal public transport. Using a multi-agent simulation, agents are provided with a similar replanning process as the paratransit operators are. That is, agents will score their trips, modify them and publish their new intended trips to the mobility simulation.

3.2.3 Mobility simulation

The mobility simulation lets both supply side and demand side interact with each other. The offered *routes* of the supply side are transformed into infrastructure like stops and minibuses. The intended trips of the demand side's passenger agents are then executed. Agents and minibuses interact at transit stops. Minibuses can be delayed by boarding and alighting passenger agents as well as by other minibuses, e.g. when caught in a traffic jam. Since the capacity of a minibus can be limited, passengers influence each other as well. This is especially the case with the smaller capacity of minibuses when the boarding of a passenger is denied due to a fully loaded vehicle. In the end, the outcome of the mobility simulation is fed back and founds the basis for the paratransit operators and passengers replanning as is illustrated in Figure 3.2 and Algorithm 3.1. One such cycle is commonly referred to as an iteration.

3.2.4 Discussion

The design of the paratransit model allows both sides, paratransit operators and passengers, to replan in each iteration. The operators assess their *routes* based on the passengers' decision of the last iteration. The passengers' replanning is based on the schedule announced by the operators. The passengers do not know how the operators will change their services in the next iteration. They only know what the decision for the current iteration is.

In terms of game theory, the paratransit model is related to a Stackelberg game[1] (Fisk, 1984; Chen and Ben-Akiva, 1998; van Zuylen and Taale, 2004; von Stackelberg, 2011). The operators, as the leader, state their quantities in form of the capacity. The passengers, as the follower, choose their best response in form of the least cost path. Passengers not choosing the least cost path as response will score worse. Thus, this is not a valid option for the passenger side. The leading side of the operators can then proclaim the new quantities of the their schedule well knowing that the passengers have to follow.

However, in terms of the model this only holds true if all passengers choose their best response in every single iteration. That is, all passengers search for

[1] In contrast, the paratransit model would be at a Cournot Nash equilibrium (Cournot and Fisher, 1897) if the following would hold: a) Paratransit *routes* are optimal given that the passengers' behavior is fixed. b) Passengers' behavior is optimal given that the paratransit *routes* are fixed. The difference lies in point a).

Algorithm 3.1: The minibus model's core algorithm

```
begin Initialization
    Init first operators

foreach Iteration do
    begin Operator replanning — Part I
        Update available route modification strategies
        Handle bankrupt operators
        if Too few operators left then
            Create new operators

        forall the Operators do Modify routes
            Try to improve the operator's solution. Note that this
            modification depends on the route modification strategies
            available and the actual type of the operator

        Announce the schedule of all operators

    begin Passenger replanning
        ⋮

    begin Mobility simulation
        ⋮

    begin Operator replanning — Part II
        foreach Operator do Score each route and vehicle
            if Budget is negative then
                if Budget can not be balanced by selling vehicles then
                    Declare operator bankrupt

        Note that the scoring information is available during route
        modification of the next iteration
```

Note that in contrast to Figure 3.2, the operator replanning is split into two parts. However, the next iteration will close the cycle and thus the route modification starts immediately after the scoring of the *routes*.

new *routes* under the assumption that the *routes* found represent indeed the optimal solution. If some of them stick to their old *routes*, their knowledge is incomplete, i.e. a passenger may have a *route* in its choice set which may not exist anymore or a better route may be proposed which the passenger is not aware of. As a result, the operators' assessment may be based on irrational decisions of the passengers, thus yielding irrational decisions of the operators. To solve this, operators have to either wait a certain number of iterations until the demand side has fully adapted or to keep suboptimal *routes* in their choice-set.

For economic markets, Nagel et al. (2004) found out "that a well-defined market only emerges when prices adapt on a much slower time scale than consumption." In the minibus model, prices are directly linked to travel times. Travel times derive from the *routes* offered. Thus, operators need to adapt their *routes* on a much slower time scale than the "route consuming" agents. In summary, the model needs to ensure that the demand side replans faster than the supply side. The easiest way of achieving this is by forcing every single passenger in each iteration to search for a new *route*.

The route planning by the passenger is similar to a schedule-based transit assignment. That is, the minibus is included in the passenger's route plan by the assumption that there will be a certain minibus at a certain stop at a certain time. Especially with minibuses ignoring the timing of their schedule and driving as fast as possible, the minibus may be far away from its schedule. However, for typical minibus services running at high frequencies, this is not a serious issue since the passenger will just take the first approaching minibus heading to the desired destination. Moreover, as laid out in section 1.2, passengers tend to arrive less coordinated for high frequency services (as minibuses are), a behavior found as well in multi-agent simulations (Neumann et al., 2013).

3.3 Different types of operators

Each operator has to handle his own operator replanning process as described earlier in subsection 3.2.1. This process is independent from other operators. The scoring of *routes* can be seen as an operator's assessment while the announcement of the final schedule reflects the operator's reaction to its assessment. Both steps function as the interface to the passenger side. Thus, both steps are standardized following the same procedure for each operator.

However, during the route modification step, the operator has the opportunity to apply different strategies to its *routes*, see section 3.4. In addition, the operator can manage the number of *routes* offered and the number of vehicles put into service. Basically, the route modification process is responsible for the behavior of the operator. This behavior is not restricted in any way and depends solely on the actual implementation. For illustrative purposes, some behavioral designs are discussed in the following subsections and in more detail in chapter 4.

3.3.1 Single route operator

This is probably the most simple type of operator. Its *line* consists of one *route* only. This *route* is served by all vehicles the operator owns. Every new vehicle bought or every vehicle sold will be added or removed from that *route*. The operator adapts to its environment due to a second *test route*. The *test route* is a copy of the *route* that is modified by a route modification strategy. Only one single vehicle shifted from the *route* is serving the *test route*. The operator announces the *route* and the *test route* in its schedule allowing both to be used by passengers. During the next operator replanning process, *route* and *test route* are assessed. The combined score of both *routes* is then compared to the combined score of the last iteration. If the combined score has increased, the *test route* is considered to improve the operator's *line*. The *test route* becomes the new *route* and the old *route* is dropped. All vehicles are transfered to the new *route*. If the combined score has decreased, the *test route* is considered to worsen the operator's *line*. Consequently, the *test route* is dropped and its vehicle transfered back to the *route*.

Although this type of operator proved to work (Neumann and Nagel, 2012a,b), there are two issues to discuss. First, while this type of operator can react to its environment, it does so by randomly trying new routes. The decision to accept a modification or not depends on the assessment of one iteration only. This iteration's outcome is influenced by the other operators' decisions and some randomness of the mobility simulation, e.g. competing operators may steal passengers from each other depending on a first-come first-serve principle at transit stops. As a result, all else being equal, a driver may serve more passengers than in the last iteration and the modification of a *test route* may be accepted leading to an overall worse *line*. However, this happens only if the score of the *test route* is more or less indifferent, i.e. the modification of the *test route* does not really improve or worsen the *line*. Contrarily, if the *test route* has an impact on the combined score, a clear decision can be made. Second, this type of operator cannot modify its *route* any longer once its vehicle fleet size has dropped to one vehicle. This may raise problems during the operator's first iterations when it is still in the process of claiming a market niche. A possible solution is to initialize such an operator with more than one vehicle allowing the operator to prospect for more iterations.

3.3.2 Multiple route operator

This type of operator does not only have one *route* and one additional *test route*, but can have an infinite number of *routes*. This allows the operator to diversify the time of operation and the *routes* in service. An operator can thus offer different *routes* and/or offer a different service frequency on different parts of a *route* by overlapping variations of one *route*.

The operator starts with one single *route* as the single route operator does and then slowly extends the number of *routes*. Instead of relying on a *test route*, the operator copies one of its existing *routes* and modifies it with one route modification strategy. This new *route* is served by one vehicle taken from one of the already existing *routes* or from a spare vehicle pool. All *routes* of the operator are announced in the schedule. The route scoring assesses each *route* individually. This allows for comparison of the *routes* and thus for identification of the most profitable ones. Since each *route* has a certain number of vehicles associated with it, a score per vehicle can be calculated. *Routes* with the highest score per vehicle are considered to be the most promising ones and thus are candidates for increasing the number of vehicles on them. Any newly bought vehicle should preferentially be put in service on those *routes* whereas vehicles subject to be sold should be withdrawn from the least profitable *routes*.

As a consequence, operators can cut losses by removing vehicles from *routes* with a negative score per vehicle. Eventually, a *route* is dropped when the last vehicle is removed. Contrarily, *routes* with a positive score per vehicle will receive additional vehicles from the generated income. With an increasing number of vehicles serving a *route* the score per vehicle will start to decrease, because the higher frequency of the *route* will not attract enough passengers to sustain the rate of profit (Kaddoura et al., 2012). By redistributing the vehicles to the most profitable *routes*, eventually, all *routes* generating profit will have a similar score per vehicle. This does not mean that *routes* with the same score per vehicle are equally important. The number of vehicles associated with each *route* may vary significantly and thus, the total income generated per *route*. *Routes* with the same score per vehicle but with more vehicles have to be considered as more important. An operator can then use the vehicle fleet size of each *route* as the *route's* weight. When choosing a *route* as basis for a route modification, the operator can, for example, decide to use that weight for a weighted random draw among its *routes*. This focuses the operator's *line* optimization on the *routes* with the most valuable assets, hence focusing on *routes* with the highest potential increase in profit.

Similar to the single route operator, this operator cannot create a new *route*, if each of its *routes* is served by one single vehicle and no unassigned vehicles are available. Otherwise, one of the existing *routes* would be dropped risking to loose profitable and established solutions. However, due to the redistribution and closure of nonprofitable *routes* and, in case all *routes* are profitable, assigning newly bought vehicles to the most profitable *routes* first, this is not really an issue.

3.3.3 Operators with fixed strategies

The strategies applied for route modification can be chosen randomly. Because of the *route* selection process, profitable solutions will prevail. Instead of this random modification, a fixed sequence of strategies may speed-up the selection process or result in a more straight-forward optimization. There are basically two different approaches to this.

The first one uses a fixed set of strategies which is applied when the operator is founded. Since the operator starts with a randomly drawn *route*, a possible first strategy is to reduce the *route* to transit stops with the highest profit. This immediately cuts losses due to not serving stops not providing any revenue and due to reducing the vehicle-kilometer traveled. A possible second strategy is reducing the time of operation to the most profitable period of day. After applying those two strategies, the operator should either have found a profitable *route* which can then be extended again or the current *route* will not allow the operator to remain in business.

The second approach uses a fixed set of rules that describe when to use a strategy. The basic idea is to choose one strategy randomly and to apply the counteractive strategy in the following iteration. An example for such a rule is extending the time of operation in one iteration and then reducing the time of operation immediately in the next iteration. Extending the time of operation will first induce more costs as the vehicles will have to travel longer. However, the operator explores the market by means of its vehicles and afterwards knows what the potential demand in the newly served period of day is. In the next iteration, it can use that knowledge to change its *route* to a more profitable one by reducing the time of operation. This new *route* may incorporate the explored period of day or not. In any way, the operator can immediately reduce the losses related with the exploration to a minimum. The same rule can be applied to the spatial search. Extending a *route* is followed immediately by the route reducing strategy.

Both approaches can be combined, i.e. initializing an operator with a fixed sequence of one set of strategies and then proceeding with a set of rules for the application of a second set of strategies. Although both approaches have been implemented in the model, they are not extensively used. This is mainly due to the definitions of reasonable rules becoming more and more complicated with each newly added rule. In addition, a rule based strategy has to be tested for undesired side effects and may only be valid for a certain scenario.

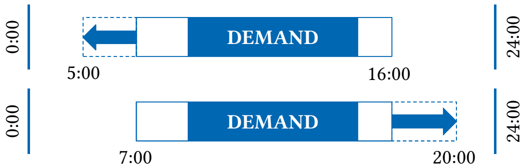
3.4 Route modification strategies

Route modification strategies are strategies which can be applied by an operator to one of its *routes* in order to modify it. Basically each attribute of a *route* is subject to modification. The following subsections cover modification strategies implemented and used in this thesis. Further strategies have been developed and tested by Röder (2013).

3.4.1 Extension of the time of operation

An operator's knowledge of the potential demand is limited by the *routes* of its vehicles. Due to its vehicles an operator knows at which stops and what time passengers board and at which stop and what time they alight. The operator is not aware of any demand in time periods not covered by one of its services. Hence, the operator cannot predict the potential demand in these periods. There is no educated guess. An operator trying to expand its service needs to conduct some market research. In the example of Figure 3.3a, the operator offers services from 7:00 to 16:00. Its vehicles report that they only served passengers from 9:00 to 15:00.

(a) Illustration of an operator's time of operation from 7:00 to 16:00. The operator serves demand within the blue period, i.e. approx. from 9:00 to 15:00.



(b) Two ways of extending the time of operation, setting a new first departure time, e.g. to 5:00, and setting a new last departure time, e.g. to 20:00.

(c) Reduction of the time of operation according to the actual demand served from 9:00 to 15:00.

Figure 3.3: Temporal modification of a *route*

Not knowing anything about the demand, the operator can only randomly pick a new time of operation. This can be a new first departure time, i.e. the operator will start its service earlier, or a new last departure time, i.e. the operator will terminate its service some time later. In case of the new first departure time, this can be done in two ways. First, the operator can choose any time from midnight to its current first departure time. For example, the operator in Figure 3.3b chooses a new first departure time of 5:00. This covers the whole search space available, but may induce a lot of losses due to serving long slack-periods. The second way reduces the risk of serving slack periods by limiting the search space to a short period of time, i.e. the operator may only pick randomly between 6:00 and 7:00. This allows for slowly extending the time of operation by smaller time steps. The repetition in further iterations make larger adaptations possible.

The second way imposes a restriction on the operator's ability to optimize. For illustrative purposes, consider an example with two demand segments divided by a slack-period. The operator does only serve one of the segments. If the operators chooses to extend its time of operation while limiting its search space, it may not be able to incorporate the second segment in its *line*. In order to accept the new extended *route*, the *route* needs to generate enough revenue to cover the expenses imposed by having to serve the slack-period as well. In the worst case, the small search space may only allow to additionally cover a small part of the slack-period. As a result, only the expenses are increased and the operator will discard that less profitable *route*. Thus, the time step size needs to be large enough to bridge the slack period completely. Not limiting the search space offers the operator the possibility to cover the second demand segment at once. Therefore, the demand of the second segment may generate enough income to run a more profitable *route* although the slack-period in-between has to be compensated.

3.4.2 Reduction of the time of operation

Since operators try to run a profitable line, they need to be able to avoid losses, e.g. induced by serving slack-periods. Each operator knows about the demand pattern served by its vehicles. Therefore, the operator can analyze which periods of the day are the most profitable ones. The analysis can simply be based on the number of trips, implying that each trip generates more revenue than it costs, or, more sophisticated, can be based on the cost structure of the operator. The first version may yield suboptimal solutions if passengers pay a fixed fare for boarding a vehicle and then travel very long distances. Thus, each new passenger will increase the losses. However, since it serves more trips, the scoring will consider the solution as favorable and suboptimal *routes* survive. Hence, the second version is to be preferred whenever possible.

3.4.3 Reduction of the stops served

With the same argument that an operator needs to reduce its time of operation, an operator may want to reduce the stops it serves. Stops not generating enough revenue to cover the associated costs do not add to the operator's profit. Therefore, the operator analyzes the demand pattern served by its vehicles. In particular, it analyzes how many passengers boarded at a certain stop and where they alighted. Assuming that each trip of a passenger will add to the profit, the operator can decide solely on the number of trips. However, the profit depends on the fare structure and thus an operator should make its decision based on the actual revenue generated. Otherwise, trips not covering the related costs with their fares will result in ruinous *routes*. Once the operator knows which stops to drop, it can reroute through the remaining stops which likely results in less vehicle-kilometer traveled by its vehicles and thus a further cut in losses.

3.4.4 Extension of the route

Whenever an operator has found a profitable *line* it may want to extend it in order to further increase its profit. However, the operator does not know what kind of demand to expect outside the area its vehicles already serve. This is similar to the extension of the time of operation discussed earlier. Hence, the operator needs first to extend one of its *routes* and can then assess its additional demand.

The probably most simple way of achieving this is adding another stop at one of the *route's* ends. While this would work with every randomly chosen stop, the probability to fail due to a mis-located stop can be reduced significantly by limiting the search space. For instance, picking stops which lie next to one of the existing *route's* stops will add a u-turn to the *route*. This may turn out favorable in case navigating the landscape is tricky, e.g. a road over a mountain pass will cause drivers to change the direction multiple times. But in terms of urban street networks, this will more likely yield in a detour due to a shorter direct path often being available. As a consequence, the new stop should be in the general direction of the existing *route*.

Similar to the extension of the operating time, the exploration of the new part of the *route* involves spending, e.g. covering the losses due to more vehicle-kilometers traveled. With spending comes the risk of investing a lot of resources in a *route* which may turn out to generate no revenue. Again, as with the time of operation, this risk can be reduced by limiting the distance between the new stop and the rest of the *route*, effectively limiting the amount of resources spent for exploration. Similar to serving slack-periods, extending a *route* may yield serving stops without any demand turning the whole *route* unprofitable. However, a more distant stop may turn out to be an established hub with enough demand to serve intermediate no-demand stops and still run a more profitable *route* than before. In summary, a small limited search space allows for inexpensive low-risk exploration of the surroundings while a larger search space may find more interesting demand spots.

In contrast to the temporal exploration, spatial exploration may find intermediate solutions due to the flexibility of the passengers. For example, if the newly added stop is not the actual stop forming the hub but merely in its proximity, then passengers will fill the gap by walking. An operator will then keep this *route* in service and eventually, by continuing the search, find the actual hub. However, it should be noted, that this applies for all operators. Thus, two operators serving roughly the same *route* will force each other to both serve the hub directly. If one operator has its terminus not directly at the hub, passengers will opt for its competitor saving the intermediate walk from the hub to the terminus. Thus, the "missing link" will result in the shifting of demand leaving one operator to serve the hub, and the other one in shortening its *route* to cut losses.

In addition to the extension of a *route's* end, the *route* may be extended in-between. With the example of the hub, an existing operator's *route* may just pass by the actual hub. The hub is only connected by an intermediate walk or not at all. For the operator, it may be profitable to incorporate a small detour to the hub and back to its original *route*. Therefore, an operator needs to be able to shift its *route*. It does so by searching sideways. The new stop needs to be inserted into the current *route's* stops minimizing the length of the detour and thus, minimizing the associated costs. Again, there is the problem of defining the search space, with a huge search space resulting in large exploration cost and a small search space limiting the potential stops. Furthermore, inserting a new stop in-between can be done in both directions of the *route* or only in one direction whereas adding a new terminus has a predefined insertion point.

In combination with the route reduction strategy, adding a new stop may replace an old stop of the *route*. If the new stop/terminus is considered more favorable by the passengers, they shift to the new one leaving no demand left for the old stop. Thus, an operator may drop the old stop when it applies the route reduction strategy for the next time.

3.4.5 Further strategies

This subsection includes strategies not implemented and tested in this thesis. However, they can be found in minibus systems around the world and may therefore yield in further extensions of the model.

Splitting a line

The assessment of an operator's *route* may indicate several separate demand segments, i.e. the analysis reveals a demand pattern where trips are isolated on two different parts of the *route* with no trips going from one part to the other part of that *route*. Given that serving both parts and the demandless part in-between is not profitable, the operator has to decide on which part it continues to offer services and which part to drop. The strategies discussed so far force the operator to serve the whole *route* or to stick to one part of the *route* only. However, it may be more profitable to split the *route*, eventually offering services on two unconnected *routes*. By the definition of this thesis' model, an operator's *routes* do not need to overlap. However, since these *routes* are completely unrelated, the strategy should found a new operator. This new operator would get one part of the *route* and some of the vehicles associated with this *route*. From that point on, the new operator acts independently as a new competitor.

This strategy has not been implemented due to complexity and dynamics involved. The newly found operator needs some vehicles to start its business. It is not clear how many vehicles the new operator will need to be successful. It may turn out, that the fixed cost per day associated with each vehicle will render the new (shorter) *route* unprofitable. However, it is clear that these vehicles are lost to the old operator. This operator will need some time to recover. It may even suffer from competition due to the lower service frequency offered. Therefore, splitting of the original *route* may result in even more losses than offering services on both parts of that *route* but with the same vehicles.

Minor detours

Instead of only picking up agents with a destination served by the predefined *route*, the minibus driver can consider to incorporate a small detour. The minibus will then deteriorate from its *route*, deliver the new agent and return to the *route* at the point of the next stop, defined by one of the in-vehicle passengers' destinations. If that detour is no longer than, for example, 1.5 times the predefined *route* to that stop, the agent will be delivered. Otherwise, the minibus will proceed as planned. This strategy has not been implemented due to the necessity of rerouting the vehicle on-the-fly. This is related to within-day replanning and a separate research field.

Short turning

Another form of adapting the predefined *route* is adding short turning. If a minibus can make more profit in the opposite direction, it will make a u-turn going the opposite direction. The minibus driver will have to check waiting passengers on the opposite link of the network. In Kingston, Jamaica, drivers were known to force passengers out of their vehicle, then running in the opposite direction (Talvitie, 1999; Cervero, 2000). In Damascus, Syria, passengers may be asked to change for the next vehicle, if load can be optimized by concentrating. The next vehicle will depart immediately and passengers get a fare refund of the first one (Ihab Kaddoura, personal communication, May, 2011). Again, this strategy involves within-day replanning and thus has not been implemented.

Equal headways

Another strategy applied are equal headways, instead of operating according to schedule or circulating as fast as possible. This mode of operation is known for slack periods in cities of Turkey, where drivers tend to delay their departure in order to avoid bunching. This allows for more passengers to aggregate along the route. The operator can then adapt the frequency according to demand reported by its vehicles. The same mode of operation is applied to formal bus lines with high frequencies (Welding, 1957; Daganzo, 2009) and is already implemented in MATSim (Neumann and Nagel, 2010).

3.5 Summary

This chapter presented the underlying mechanics of the minibus model and its linkage to genetic algorithms. Operators and passengers are described as two sides, namely the supply side and the demand side, interacting through the mobility simulation. Special attention is paid to various types of operators and their possible strategies with which they react to their environment. The modularity of the minibus model allows to develop own types of operators and more complex strategies if needed. The next chapter will discuss the implementation of the minibus model as used in this thesis.

CHAPTER 4

Implementation

There is always one more bug.

Lubarsky's Law of Cybernetic Entomology

This chapter contains a short introduction on simulation frameworks. Also, reasons for why the multi-agent simulation MATSim has been chosen for the realization of this thesis are given. The chapter continues with a brief overview on MATSim itself and the implementation of the minibus model.

4.1 Choosing a simulation framework

From the requirements stated earlier in section 2.5 and chapter 3, the simulation framework needs to be microscopic in the sense that it needs to be able to handle individual trips with individual pick-up and drop-off locations as well as individual departure times. In addition, travel requests need to distinguish between alternative public transport services regarding travel time, transfers, and access and egress walks. From the operator side, vehicles need to be simulated individually in order to allow for a detailed cost-benefit analysis. Interaction with other minibuses and a strict capacity limit are additional requests.

With similar requirements in mind and the same wish for future development as to allow for multi-model simulations with mode choice, Maciejewski and Nagel (2013) stated that the model has to be embedded into a microscopic, behavior-oriented traffic simulation where regardless of the transport mode all travelers are simulated individually. The conclusion of their work was, that

> "although several companies offer micro- or "nano"-simulations (Aimsun, 2013; Azalient, 2013; DynusT, 2013; Paramics, 2013; SavannahSim, 2013; PTV, 2013b), they are either not able to perform network loadings with millions of persons/vehicles, or they do not trace persons or vehicles throughout the whole day. Non-commercial approaches include TRANSIMS (2013), SUMO (Behrisch et al., 2011), Mezzo (2013), and MATSim (2013). Out of these, MATSim is arguably the one with least focus on traffic flow realism but with the highest computing speed and the best behavioral model on the trip planning side."

Macroscopic simulations have been further developed recently, e.g. in PTV VISUM (PTV, 2013c) capacity limits for public transport were added. Nevertheless, MATSim is chosen for its potential to investigate large scenarios while still tracking individuals on both demand and supply side.

4.2 Integration in MATSim

In MATSim (2013), each traveler of the real system is modeled as an individual agent. Initially, all agents independently generate daily plans that encode among other things their desired activities during a typical day as well as the transport mode. Agents typically have more than one plan. The original approach consists of an iterative loop that has three steps:

1. Traffic flow simulation (synthetic reality): All selected plans are simultaneously executed in the simulation of the physical system.

2. Scoring: All executed plans are scored by a utility function.

3. Replanning: Some agents are allowed to modify their plan.

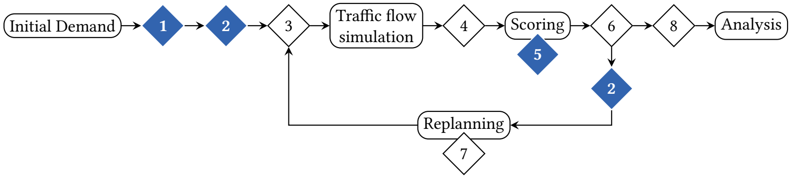


Figure 4.1: Notifications within one MATSim run (based on MATSim, 2013)
1 — Simulation Starts, 2 — Iteration Starts, 3 — Before Mobsim, 4 — After Mobsim,
5 — Scoring, 6 — Iteration Ends, 7 — Replanning, 8 — Simulation Ends

The iterative loop is embedded in the complete structure of a MATSim run as depicted in Figure 4.1. Starting with the initialization, one run at least once triggers the traffic flow simulation and the scoring. After the scoring, the run is either complete, i.e. the post analysis can begin, or a new iteration starts with the replanning of the agents. As a consequence, the iterative loop is basically optional but mandatory for implementing any learning behavior.

MATSim provides several notifications to inform about the current state of the run. The minibus model uses some of them, namely *Simulation Starts*, *Iteration Starts*, and *Scoring*, in order to register its own replanning process as illustrated in Figure 3.2.

At the point of *Simulation Starts* the minibus model registers with the rest of the simulation. That is, the stock transit schedule is replaced by a modifiable version to allow for transit line modifications between iterations. In addition, the stock transit agent is replaced by an own version with a different boarding behavior, see subsection 4.3.8 for details. Furthermore, the model registers the following modules:

Time provider Provides the operators with common knowledge of the departure time distribution of the agents, see subsection 4.3.1.

Minibus stop provider Defines the potential minibus stops and provides the operators with common knowledge of the agents' spatial trip distribution, see subsection 4.3.2.

Strategy manager Provides the operators with route modification strategies, see subsection 4.3.3.

Operator provider Creates new operators, see subsection 4.3.4.

Initial operators Creates the initial operators of the very first iteration either from scratch or based on a given transit schedule, see subsection 4.3.5.

Operator scoring Calculates and distributes the fares collected from the agents, calculates and imposes the costs for each vehicle on its operator, and transfers the fares calculated to the corresponding agent, see subsection 4.3.6.

Franchise system Prevents two operators from offering the same service, see subsection 4.3.7.

After the initialization, the operators publish their services by inserting their schedules into the centralized regular schedule of MATSim. The traffic flow simulation can then execute these services in the same way as the regular public transit.

After completing the traffic flow simulation, the agents score their executed plans. At the same time, the minibus model is triggered to score the operators' routes due to the *Scoring* notification. This can be done in parallel to the agents' scoring since all agents and all operators are scored on an individual basis.

With the *Iteration Starts* notification, bankrupt operators are terminated and new operators are founded. All other operators can update their routes based on the route modification strategies available. In the end, the operators republish their schedules into the central MATSim transit schedule and all removed services are removed from the schedule as well. Agents can then replan taking the new transit schedule into account. Note that the very first *Iteration Starts* notification right after the initialization is ignored since operators cannot replan due to a lack of assessment.

Because of the transparent integration of the minibus services into the public transit schedule, agents using public transport can use minibus services as well as formal services like trains and buses of a public transit agency. Regular transit vehicles and minibuses are indistinguishable from the perspective of the traffic flow simulation. The current default version of the MATSim public transit passenger router (Rieser and Nagel, 2009; Rieser, 2010) minimizes travel time (including walk), with an additional penalty for a line switch which is equivalent to an additional 60s of travel time. Other properties as fares and congestion do not play a role in that version of the router. As a survey for the Berlin case shows, travel time is indeed by far the most important factor exceeding safety, comfort, and others that account for 12 %, 4 %, and 7 %, respectively (Reinhold, 2006). For experiments with a more realistic routing the reader is referred to the recent work of Moyo Oliveros and Nagel (2012) and Moyo Oliveros (2013).

The model allows for different modes of operation. Regular transit vehicles and minibuses can a) be forced to circulate strictly according to the schedule. A delayed vehicle will try to run as fast as possible to catch up with the schedule. Vehicles can b) be forced to await departure time at certain stops only. Finally, the vehicles can c) be allowed to drive as fast as possible eventually ignoring the timing information in their schedule. This thesis uses version a) for formal transit services and version c) for the minibus. However, the minibus operators announce a schedule that reflects the average realized travel time, see subsection 4.3.3 for details. Thus, the behavior of the minibus is similar to version a) once a stable network has emerged. Minibuses can overtake each other and other buses at stops. A fully loaded minibus will not try to pick up additional passengers and instead proceed as fast as possible to the next stop determined by one of the passengers' desire to alight. A minibus with empty seats left will ask the waiting agents at each stop it passes by for their destination. The agent can then decide whether to be picked up or not.

The other transport modes offered, i.e. walk, bike, and car, are not altered. Each agent can have different legs in its plan, each using a different mode of transport, as with the standard MATSim implementation. However, agents throughout this thesis' scenarios are not allowed to change the mode. That is, the transport modes are fixed but agents can opt for alternatives within one mode, e.g. bus and minibus. Without a mode choice model in place, the minibus model does not need an alternative-specific constant for the minibus services to represent the cost of the first trip. However, the minibus services are modeled as a submode of public transport and the alternative-specific constant of public transport is applied to the scoring of minibus trips. The same holds true for consequent trips with the disutility of line switch representing implicitly the cost of the next boarding, regardless whether bus or minibus.

4.3 Model implementation

This section provides further details on the implementation of the various modules of the minibus model. For the actual implementation, the reader is referred to the code repository of MATSim (2013, revision 22806).

4.3.1 Time provider

During the operator replanning, operators need to decide when to offer services. However, they only know about the demand served by their own vehicles. There is no information on non-served areas and time periods. Early implementations as used by Neumann and Nagel (2012a, 2013) forced the operators to probe the demand by means of their vehicles. As a result, many iterations were wasted by the simple trial-and-error approach. To keep reasonable run times for larger scenarios, operators need to make educated guesses on their surroundings. To do so, it is assumed that the operator knows roughly about the traffic pattern of the agents, e.g. due to its drivers living in the area. The time provider provides the operators with that common knowledge. By collecting the activity end times of all agents, the time provider knows how often trips start at the various times of the day, e.g. divided into time slots of 15 minutes. If an operator needs to determine its operating time for a route, it can do a weighted random draw based on the number of activities in each time slot. Time slots with more activities have thus a higher probability to be picked, while low demand time slots are not ignored entirely.

4.3.2 Minibus stop provider

Similar to the time provider, the stop provider enables the operators to make educated guesses on where to offer services. Minibus stops can be restricted to a certain area, effectively forcing minibuses to operate in a designated area only. Stops can be limited by the allowed maximum speed of a link, so that minibuses cannot serve passengers on certain links, e.g. interstates. Furthermore, stops can be limited to a given set specified by the transport planner. This hybrid solution approach (Baaj and Mahmassani, 1995) couples the knowledge of the transport planner with the minibus model's algorithm and thus significantly reduces the search space of the operators.

Regardless of the set of stops available, the stop provider provides the operator with a randomly drawn stop. This is initially done by giving all stops the same weight. In later iterations, the weight depends on the number of activities in the vicinity of a stop. For that, all activities and minibus stops are mapped to a grid. The number of activities within one cell of the grid is the weight of that cell. The weight of a cell is then divided among the number of minibus stops of that cell. Thus, the more activities and the less minibus stops in a cell, the higher the weight per minibus stop within that cell. Stops situated in an area with a high density of activities have a higher probability to serve as a terminus for a new minibus operator. This includes activities related to public transit like boarding and alighting a vehicle or transfers. Especially areas functioning as a transit hub for conventional public transit and minibus services get a higher weight. Thus, areas where trips are naturally interrupted are an attractive opportunity to be served by a new operator. In later iterations, the pattern may change. For example, with a growing minibus network, new hubs may evolve. These hubs become more attractive with more passengers transferring, e.g. from minibus to minibus. With the demand shifting to new hubs, new operators will more likely pick the new hubs as termini making the hub even more attractive. Lower demand at the formal hubs will drive minibus operators to reduce or even cease operation on them. Eventually, the demand may shift to minibus services only and the minibus network becomes completely detached from the formal public transit network. An example from South Africa features a trunk road running parallel to a train service. Train stations are not situated directly at the trunk road but request a small detour. Once the demand is shifted from the train to the minibus taxis on the trunk road, the minibus taxi operators do not need to serve the train stations any longer. Minibus operators do not detour any longer, making the trip with the minibus even faster and more attractive (Daniel Röder, personal communication, October, 2012).

Note that cells without any activities start with a weight of zero. Thus, they cannot be drawn as termini for a new *route*. However, with operators serving also unimportant intermediate stops, passengers can start transferring within such a cell. In later iterations, the weight of that cell increases, because transfers account as activities, too. Thus, it is possible to establish a hub in the "midst of nowhere" as long as two *routes* pass by close enough in order to allow for transfers. The example shown in subsection 5.1.1 and the example of two intersecting roads in section 5.2 both illustrate such a situation.

4.3.3 Strategy manager

The strategy manager provides the operators with route modification strategies. A route modification strategy is configured in the config file. Common parameters are the weight of the strategy to be chosen and the iteration in which the strategy is removed from the available strategies. When asked for a strategy, the strategy manager does a weighted random draw. If a strategy is removed from the set of available strategies, its weight becomes zero. Accordingly, the weight of the remaining strategies increases. If no strategy is defined or left, the operators cannot replan and have to work with the *routes* already known.

Once a strategy is chosen, the strategy is provided with one *route* of the operator. This *route* functions as a blueprint for a new *route*. Depending on the strategy one of the following *route* attributes is modified:

- Time of the first departure, see subsection 4.4.1 and subsection 4.4.2 for the description of the route modification strategies.
- Time of the last departure, see subsection 4.4.1 and subsection 4.4.2 for the description of the route modification strategies.
- The minibus stops to be served, see subsection 4.4.3, subsection 4.4.4, and subsection 4.4.5 for the description of the route modification strategies.

After the modification, the new *route* is returned to the operator which allocates one or more vehicles to this *route* and integrates it into its schedule. Since this schedule demands a well defined transit route as specified by Rieser (2010), the operating time and the sequence of the served stops need to be transformed into a complete transit route. The example given in Listing 4.1 is taken from subsection 5.1.1. The operator's sole *route* is defined as serving the stops 2 and 3 from 6 to 10 o'clock (line 16).

From the sequence of served stops the circular route is created by calculating the shortest path from the first stop to the second one, from the second one to the third one, and so forth. The circle is completed by routing from the last stop back to the very first one. The resulting links define the actual path the minibus will go. Each minibus stop lying on one of the links is inserted in the resulting *routeProfile*. For the example of Listing 4.1, the resulting stop order is 2–3–2 even if the way back (3–2) is considered as unimportant (lines

Listing 4.1: Example transit schedule of a minibus

```
1  <?xml version="1.0" encoding="UTF-8"?>
2  <!DOCTYPE transitSchedule SYSTEM "http://www.matsim.org/files/dtd/transitSchedule_v1.dtd">
3
4  <transitSchedule>
5   <transitStops>
6    <stopFacility id="1" x="1000.0" y="1000.0" linkRefId="1" isBlocking="false"/>
7    <stopFacility id="2" x="2000.0" y="1000.0" linkRefId="2" isBlocking="false"/>
8    <stopFacility id="3" x="3000.0" y="1000.0" linkRefId="3" isBlocking="false"/>
9    <stopFacility id="4" x="4000.0" y="1000.0" linkRefId="4" isBlocking="false"/>
10   <stopFacility id="5" x="5000.0" y="1000.0" linkRefId="5" isBlocking="false"/>
11   <stopFacility id="6" x="6000.0" y="1000.0" linkRefId="6" isBlocking="false"/>
12   <stopFacility id="7" x="7000.0" y="1000.0" linkRefId="7" isBlocking="false"/>
13  </transitStops>
14  <transitLine id="para_0_1">
15   <transitRoute id="para_0_1-347_286">
16   <description>Plan 347_286, score: 62.54, score/veh: 6.25, trips: 8000, vehicles: 10, Operation
         time: 06:00:00-10:00:00, Stops: 2, 3, line budget 103.226</description>
17    <transportMode>pt</transportMode>
18    <routeProfile>
19     <stop refId="2" arrivalOffset="00:00:00" departureOffset="00:00:00" awaitDeparture="false"/>
20     <stop refId="3" arrivalOffset="00:01:46" departureOffset="00:01:46" awaitDeparture="false"/>
21     <stop refId="2" arrivalOffset="00:03:34" departureOffset="00:03:34" awaitDeparture="false"/>
22    </routeProfile>
23    <route>
24     <link refId="2"/>
25     <link refId="23"/>
26     <link refId="3"/>
27     <link refId="32"/>
28     <link refId="2"/>
29    </route>
30    <departures>
31     <departure id="0" departureTime="06:00:00" vehicleRefId="para_0_1-347_286-0"/>
32     <departure id="1" departureTime="06:04:34" vehicleRefId="para_0_1-347_286-0"/>
          .
          .
33        .
34    </departures>
35   </transitRoute>
36  </transitLine>
37 </transitSchedule>
```

19–21). Therefore, a minibus will also serve stops which the operator has not defined as important, but which it will pass-by anyway.

The path calculation is based on an empty network. That is, delays induced by other vehicles, e.g. private cars, buses, or even minibuses are not considered. Therefore, a minibus operator will always ply the same *route*, regardless of the traffic conditions. This is different from the route searching behavior of MATSim's other agents, especially private car users. They search for a least cost path with the knowledge of the realized travel times of the last iteration. Thus, due to the learning mechanism of MATSim, they are able to circumvent traffic jams by making a detour. As a consequence of the different route searching behavior of minibus operators and other road users, minibus operators can oust other vehicles from certain road sections if the operators maintain enough vehicles. This behavior is known from real minibus systems, e.g. around Cairo's main train station (Cervero, 2000).

For public transport planning purposes a different behavior might be desirable. For example, a bus company may decide to offer services on a secondary road running in parallel to the main/trunk road for various reasons, e.g. faster services due to less traffic. In this case, the route searching can be switched to the standard MATSim behavior. Minibus operators will then alter their *routes* with regard to the travel times of the last iteration. However, this might result in an odd behavior for large numbers of minibuses serving the same *route*. Since the minibuses influence the realized travel time in the same way as other vehicles do, the operator might induce a traffic jam with its own minibuses. Consequently, the operator will reroute its vehicles in the next iteration. This removes the jam from one road segment and most likely creates a new one on the alternative route. During the next iterations the minibus route flip-flops between both alternatives. To conclude, using MATSim's standard route searching behavior might have some use-cases but will only yield to a relaxed state if the number of vehicles per *route* is considerably small, i.e. the vehicles' own impact on the realized travel times can be neglected.

After defining the *route*'s path and the sequence of served stops, the *routeProfile* is completed by calculating the arrival and departure offsets of the stops. For that, the travel time needed to travel from one stop to the following stop is derived from the previous iteration. The travel time of all vehicles of the same *route* is averaged. Thus, the promised travel times published in the schedule reflect the average travel time on that *route* from the last iteration. Note that the history of a *route*'s travel time is an average containing all trips of a day. Thus, it may underestimate the travel time during peak-hours and overestimate the travel time during slack periods. If no travel time history is available for a particular *route*, e.g. it's a new *route*, the free speed travel time together with a planning speed factor serves as an estimate. A planning speed factor close to 1.0 or even greater than 1.0, gives new *routes* an advantage over established *routes*. From the passenger agents' point of view, the travel time is the most important factor. Hence, announcing faster travel times attracts more passengers. Contrarily, a smaller planning speed factor gives new *routes* a disadvantage over existing *routes* due to stating a longer travel time. However, the planning speed factor is only considered, if there is no data available from previous iterations. Newly found *routes* will thus only have an advantage or disadvantage for their very first iteration. The total impact on other *routes* is furthermore limited, since new *routes* start with one vehicle only.

Finally, the number of departures is calculated and vehicles are allocated to each departure. Based on the *routeProfile* and the therein contained departure offsets, the time needed for one vehicle to complete a tour is known. At the terminus, a slack time is added. Vehicle departures are added with respect to the number of vehicles allocated to that *route*, the time needed for one round trip, and the service end time. The service end time determines the last departure of a vehicle. Thus, service may be offered beyond the time of operation. Departures are distributed equally resulting in equal headways.

Comparison to the state-of-the-practice

The decision to use a circular route pattern has been driven by the more generic design. Adding and removing stops can be done in a flexible and straight forward way. However, state-of-the-practice in the public transit planning consists of defining at least two *routes* going from one terminus to the other one and the way back. Consequently, this pattern is called “back and forth”. This type of pattern requires a more complex vehicle scheduling and timetabling since both *routes* are interlinked, i.e. served by the same vehicles. As a further consequence, the *routes* of an operator cannot be scored independently, see subsection 4.3.6. The fixed costs of a vehicle must not be covered by the *routes* but by the operator. *Routes* that cannot cover the fixed costs of a vehicle can still yield a contribution margin. Consequently, the operator can decide to allow a vehicle to operate on two *routes* that both would not be sustainable when scored individually, i.e. each *route* has to cover the fixed costs of a vehicle. For further reference on the optimization of back-and-forth-style transit schedules the reader is referred to the German Operations Research Society (GOR, 2013) and especially to the work of the research group for optimization of Ralf Borndörfer at ZIB (2013), see, e.g., Borndörfer et al. (2007, 2012) and Borndörfer and Karbstein (2012).

4.3.4 Operator provider

The operator provider creates new operators whenever operators need to be replaced or the total number of operators is increased. The operator is founded and initialized with two stops provided by the stop provider, the operating time drawn from the time provider and the number of starting vehicles as configured.

All types of operators share the same interface with the rest of the minibus model and have the same abstract operator as a common basis. This abstract operator knows about its name, the number of iterations being allowed to exist without making profit, the cost of buying one vehicle, the refund for selling one vehicle, the minimum operation time specified, and the franchise system in place. The initialization process and the scoring is also the same for all types of operators. Each operator is initialized by setting its initial state of operation to *prospecting*, the initial budget, the iteration the operator is founded, the route provider for this operator, and the initial transit line offered. The scoring of an operator sums up the score of all of the operator's *routes*. If an operator exceeds the number of iterations it is allowed to run nonprofitable, the operator's state changes from *prospecting* to *bankrupt*. If the total score is greater than zero, the operators state of operation is set to *in business*. The total score is added to the operator's budget. If the budget of an operator is negative and it can not balance the budget by selling vehicles, the state of that operator is also set to *bankrupt*. The score of one iteration is stored for comparison reasons until the next iteration.

New operators are founded whenever the share of profitable operators exceeds a given threshold α. The number of new operators N_{new} is derived by the following equation

$$N_{new} = \max \begin{cases} 0 \\ \left\lfloor \left(\alpha^{-1} - 1\right) \cdot N_{in\,business} \right\rfloor - N_{prospecting} \end{cases} \tag{4.1}$$

For example, setting the threshold to 50 % allows for a second operator once the initial operator starts to make profit. Consequently, the third operator is founded if the other two operators' state has changed to *in business*. A threshold of 90 % requires at least nine operators *in business* to create a new (tenth) operator.

Furthermore, the model allows to specify a minimum number of operators N_{min}. This guarantees that at least N_{min} operators probe the market at all time, i.e. their state is *prospecting*. Thus, the number of additional operators N_{add} is calculated as

$$N_{add} = \max \begin{cases} 0 \\ N_{min} - N_{in\,business} - N_{prospecting} - N_{new} \end{cases} \tag{4.2}$$

The value of N_{min} depends on the scenario. Although more operators allow for faster prospecting, the operators may run into a cut-throat competition once their supply exceeds the potential demand. Thus, setting N_{min} too high yields unstable behavior.

The types of operator differ in the way they react to their environment. By extending the abstract operator, the operator's replanning behavior can be altered. The following paragraphs describe three different designs of operator replanning with the multi route operator being used throughout this thesis.

Basic operator

The basic operator is the most simple one. Although the operator follows a rather simple strategy, it has been successfully applied to early versions of the model (Neumann and Nagel, 2012a, 2013). An operator of this type has only one main *route* and may have one additional test *route*. When triggered to replan, the operator will first sell vehicles if it has to balance the budget. The operator determines the number of vehicles to be sold and removes them from its main *route*. Second, the operator determines how many vehicles it can buy from its budget. These vehicles are added to the main *route*. Third, the operator draws one strategy for route modification from the strategy manager. If the strategy can be successfully applied, the returned *route* becomes the test *route* and one vehicle is moved from the main *route* to that test *route*. Otherwise, the replanning ends. Finally, the operator reinitializes the main *route* and the test *route* in case it exists and publishes both to MATSim's central transit schedule.

If there is a test *route*, the operator will check in the next iteration's replanning, whether its total score has improved compared to the last iteration or not. In case of improvement, the test *route* is considered to improve the overall situation of the operator. The test *route* then becomes the new main *route* and all remaining vehicles of the former main *route* are transfered to the new main *route*. In case the total score did not improve, the test *route* is deleted and its vehicle transfered back to the main *route*.

Fixed strategy operator

This type of operator uses the same mechanic with main and test *route* as the basic operator. However, the fixed strategy operator uses a preset set of strategies during its first three iterations of existence. The operator will buy as many vehicles as possible during its first iteration. During the second iteration, it will use the strategy to reduce the stops served to the stops most profitable, see subsection 4.4.5. In the third iteration, the operator will restrict the time of operation to times with the most demand served, see subsection 4.4.2. After the first three iterations, the operator reacts in exactly the same way as a basic operator. Due to the special replanning strategy in the initial three iterations, an operator can restrict its service to profitable routes and times faster. Thus, it can reduce losses and has a higher probability to find a market niche.

This fixed strategy approach can be further extended to later iterations. The operator then has to remember the last strategy used and applies its counterpart during the next replanning. For example, if the last strategy increased the time of operation, its counterpart is a strategy that reduces the time of operation. In this way, an operator can extend its time of operation, checks whether there is enough demand, and can then reduce immediately its time of operation to the demand actually served. The same strategy is applied to route modifying strategies. If a strategy enlarges the route served, e.g. by adding a new stop, the next strategy will reduce the route served to the stops with the most profitable demand. This way the operator can more likely reduce the costs associated with prospecting. However, defining the set of strategies and its counterparts needs careful attention and can become quite complex. It might not be clear beforehand which receipt of strategies will actually give the best results. Moreover, an ill-configured set of strategies can completely bar operators from successful solutions.

Multi route operator

This is the type of operator used throughout this thesis. It does not rely on one main *route* and one test *route* but rather uses an infinite number of *routes*. This allows the operator to diversify the time of operation and the service area. An operator can thus offer different areas and/or offer a different service frequency on different parts of the same corridor by means of overlapping *routes* with the same sequence of stops.

When triggered to replan, the operator reduces the number of vehicles allocated to negatively scored *routes* by transferring one vehicle from each of these *routes* to its spare vehicle pool. It then determines how many vehicles need to be sold in order to balance its budget. Vehicles are first sold from the spare vehicle pool. In case this isn't sufficient, the operator sells one vehicle from its worst scored *route* based on the average score per vehicle of that *route*. This procedure is repeated until the budget is balanced. If the last vehicle of a *route* is sold, the *route* is deleted. Note that the average score per vehicle of a *route* changes whenever a vehicle of that *route* is sold. However, selling a vehicle further worsens the average score per vehicle of that *route*. Thus, vehicles tend to be sold from one *route* only until its vehicles are depleted. This mechanism effectively prevents the operator from selling vehicles from profitable *routes*, whenever there is at least one negative scored *route* present. However, focusing on (slightly) negative *routes* only is not really an issue since a) an operator may only sell a small number of vehicles, e.g. 1 or 2, or b) the worst scored *route* is very likely the source of the incurred costs that force the operator to sell large numbers in the first place.

Contrary to selling vehicles, the operator might have sufficient budget to buy new vehicles. If the budget exceeds the cost to buy a new vehicle, the operator determines the number of new vehicles it can afford to buy from the budget. The newly bought vehicles are added to the spare vehicle pool. All positive scored *routes* get their vehicle fleet increased by one additional vehicle. This is done by starting with the most profitable *route*, again based on the score per vehicle. If there are more *routes* with a positive score than spare vehicles available the least positive scored *routes* are left out.

After balancing the budget and redistributing its vehicles, the operator might have some spare vehicles left. These vehicles are used for newly created *routes*. The number of new *routes* is limited to half the number of vehicles already in service. This limits the risk involved in prospecting, as the operator saves enough vehicles to compensate potential losses in the next iteration. For each new *route* to be created, the operator has first to choose which *route* will be taken as the blueprint. The blueprint is chosen randomly from all present *routes* of the operator. This random draw is weighted by the number of vehicles, i.e. a *route* with more vehicles will have a higher probability of being chosen. This accounts for the fact, that a *route* will be served by more vehicles the more asset-creating it proved to be in former iterations. The operator then draws a route modification strategy from the strategy manager. The returned new *route* is validated by the franchise system in place, see subsection 4.3.7. In case it is rejected by the franchise system, the *route* is deleted immediately. Otherwise, the *route* gets one vehicle from the spare vehicle pool and is added to the operator's set of *routes*. Drawing the next blueprint thus includes *routes* created in the very same iteration. However, the probability to draw such a *route* is quite low due to its single vehicle.

Note that at the end of the operator's replanning process, the spare vehicle pool does not need to be empty for various reasons. First, not all vehicles are spent for prospecting. Second, a new *route* might be rejected by the franchise system in which case the vehicle remains in the pool and will not be used in the current iteration. Third, a strategy might not be able to create a new *route* from the provided blueprint. This can be the case when a new first departure time is asked for, but the blueprint already includes an operating time starting at midnight. In this case, the vehicle remains in the pool, too. However, the pool grows not indefinitely. Vehicles in the pool impose fixed daily costs on the operator, even though they are not put into service. Hence, the size of the pool is limited by the surplus generated by the active *routes*. Since profitable *routes* increase their vehicle fleet as long as they remain profitable, this surplus decreases over time. Accordingly, the vehicle pool size is not only reduced by retrieving vehicles directly for profitable lines, but also by forcing the operator to sell vehicles whenever the vehicle pool's cost is higher than the surplus of its *routes*.

Finally, all *routes* of the operator are reinitialized using the the operator's route provider and are published to MATSim's central transit schedule.

4.3.5 Initial operators

The initial operators are the operators of the very first iteration. In difference to later iterations, they cannot rely on data collected in previous iterations. Therefore, the time provider and the minibus stop provider decide completely randomly on which operating times and with which stops those first operators start with. To facilitate the evolution of the minibus network, operators of the first iteration can be initialized by a preset *route*. The *route* can derive from former runs of the minibus model or from a transit schedule of a public transit authority. In the first case, the routes can be directly reconverted into minibus *routes*. In the latter case, all routes contained in the transit schedule are transformed into an operator with the same *stopProfile*. As discussed earlier, the state of the practice uses a back and forth type of route design. Therefore, the routes cannot be transformed into the circular design of the minibus model directly. The two given routes forming a back and forth pair are closed implicitly. For simplicity, the route's vehicle fleet size is set in a way it matches approximately the number of departures. As a result, twice as many vehicles will serve most of the *routes*, since the vehicles of the back route and the forth route add up. In the following iterations, the extra capacity is reduced through the operators' replanning process. To conclude, the initialization of operators with a given route can speed-up the evolutionary process and allows for a systematic analysis of a given route or corridor. In addition, both forms can be mixed, so the minibus model can be initialized by some operators with preset *routes* and additional operators searching freely.

4.3.6 Operator scoring

The operator scoring contains the infrastructure for scoring the operators as well as for scoring the passenger agents. For the operator, transport planners normally consider costs associated with distance, with time, and on a daily basis, i.e. costs per vehicle-kilometer traveled, costs per vehicle-hour in service, and fixed costs per day and vehicle (ATC, 2006). Assuming minibus drivers have to earn enough in order to cover the daily costs, an alternative approach is possible which omits the costs per hour in favor of higher daily fixed costs. Thus, drivers will be forced to drive as long as necessary and not as long as specified by an employee's working contract. However, for transport planning purposes, the complete cost function is implemented, allowing to set each parameter individually.

The data for calculating the operator's cost is collected centrally. This is in contrast to minibus systems in the real world, where often the vehicle crew is in charge of collecting the fare and of covering the direct costs. Afterwards, the vehicle owner reimburses the crew and collects the (reported) fare. However, this more object-oriented design has been dropped in favor of the faster centralized approach.

Scoring takes place at the end of the iteration. The $score$ of an operator's vehicle consists of revenue rev and expenses exp:

$$score_{Veh} = rev_{Veh} - exp_{Veh} \tag{4.3}$$

The revenue of a vehicle is calculated by collecting fares. The fare is based on a stage related data set, which contains

- the stop the passenger boards,
- the time of boarding,
- the number of kilometers traveled in-vehicle,
- the stop the passenger alighted the vehicle,
- the time of alighting, and
- the operator and route associated with the vehicle boarded.

One such data set is generated for each trip of an agent using public transport. Each data set is then transformed into a fare and added to the revenue of the vehicle. The calculated fare is based on a combination of per boarding $f_{boarding}$ [monetary units (¤)] and per kilometer f_{km} [¤/km]. With l [km] being the trip length of one passenger and N_{pax} being the number of passengers the vehicle served, the total revenue of one vehicle is calculated as

$$rev_{Veh} = \sum_{i=0}^{N_{pax}} (f_{boarding} + f_{km} \cdot l_i) \tag{4.4}$$

Note that the typical paratransit fare system of the case studies listed in Table 2.6 relies on the fixed fare only. In future, a more formalized paratransit may shift to more sophisticated fare systems as known from formal public transit, e.g. distance-based fares and combinations of both. Based on the data set collected for each passenger trip, other fare systems can be implemented as well, e.g. zone-based fare systems and peak-hour pricing that rely on the boarding/alighting stop and the boarding/alighting time, respectively. These fare systems may also play an important role in case the minibus model is used as a planning tool for formal public transit authorities that need to put their own cost structure into the model.

Vehicle expenses consist of fixed costs, time based costs, and distance based costs. Fixed costs c_{fix} [¤] cover expenses related to the vehicle, e.g. an official operating license. Time based costs c_h [¤/h], e.g. drivers, are summed up for each hour the vehicle is in service. Distance based costs c_{km} [¤/km], e.g. fuel, are summed up for each kilometer traveled by the vehicle. With t [h] being the service time of the vehicle and m [km] being the distance traveled by the vehicle the vehicle's expenses are calculated as

$$exp_{Veh} = c_{fix} + c_h \cdot t + c_{km} \cdot m \tag{4.5}$$

The $score$ of a route is then calculated by summing up the $score$ of all vehicles N_{veh} assigned to that route.

$$score_{Route} = \sum_{i=0}^{N_{veh}} score_{Veh,i} \tag{4.6}$$

Thus, an operator can assess each route individually. Moreover, the implementation allows for operator designs which assess individual vehicles.

The total score of one operator

$$score_{Operator} = \sum_{i=0}^{N_{routes}} score_{Route,i} \quad (4.7)$$

can be seen as the operator's (net) cash flow. Profitable operators end up with a positive cash flow, non-profitable operators with a negative cash flow. At the end of the scoring, the cash flow is added to the budget of the operator and can be spent according to the operator's design, see subsection 4.3.4.

In the current implementation, the calculated fare is only handed over to the operator. The passenger agent is not charged, although the methods for that are implemented. Charging the passengers as well would mean adding the fare to the agents' scoring. However, since the current public transit router does not consider the fare in its least-cost-path calculation, the agents cannot adapt their routes. In consequence, an agent might be well aware of the high costs associated with its route due to the scoring, but cannot opt for a different "cheaper" connection, because the router will always provide him with the same route. Thus, the current implementation of collecting virtual fares can be assumed as some kind of subsidization. For example, a state owned institution reimburses the operator for each passenger-kilometer served.

4.3.7 Franchise system

The franchise system ensures that operators do not offer the same service twice. The systems checks every newly created *route* regardless of the *route*'s operator and grants permission to offer this *route* according to a first-come first served principle. A *route* is rejected, if an identical *route* is already in service. Two *routes* are considered identical if they satisfy the following three criteria:

Same start time. The start time of the service is mapped to a time slot as provided by the time provider.

AND Same end time. The end time of the service is mapped to a time slot as provided by the time provider.

AND Serves the same corridor. The stops of the *route*'s *stopProfile* are mapped to the grid cells of the minibus stop provider. Two *routes* serve the same corridor, if the resulting grid cell sequences match.

With these checks, similar *routes* are possible as long as at least one criteria differs, e.g. another start time slot or a detour in the *routeProfile* linking another grid cell. *Routes* no longer offered are removed from the franchise system and can be applied for by another or the same operator.

4.3.8 Boarding behavior of the transit agents

MATSim's standard transit agent will only board transit vehicles belonging to the transit line stated in the agent's plan. Thus, agents comply with the result of the transit router. Agents will not board any other line, although this line's solutions might be indifferent from the planned one. While this behavior may hold true for most situations in public transport, it is debatable in terms of the common lines problem (Chriqui and Robillard, 1975). In MATSim, two lines plying the exact same route with the exact same travel time face no competition from each other. It solely depends on the transit router to distribute the agents among the lines, i.e. the router will allocate an agent to the next departing vehicle depending on the agent's departure time. Therefore, high frequency services get a higher load and agents stick to the chosen line until they are allowed to replan. As a consequence, an agent not able to board, e.g. due to a lack of free capacity, will wait for the next vehicle of the intended line, although empty vehicles of other lines may pass by.

In the minibus model, an agent boards a vehicle, if a) the vehicle's *route* is the intended one of the agent's plan or b) the vehicle's *route* serves the desired stop and the planned travel time to that stop is not longer than the travel time of the originally intended *route*. However, a minibus operator may have ceased service on the intended *route*. Thus, the intended *route* of the agent does not exist anymore and the travel time comparison becomes impossible. In the standard MATSim model, the agent is stranded at the stop and has no opportunity to react until it is chosen again for replanning. In the minibus model, the agent skips the travel time comparison and boards anyway as long as the destination stop is served. The next time the agent is chosen for replanning, the agent can react to the new situation by asking the transit router to update the route information of its plan.

4.4 Route modification strategies

This section describes the implemented route modification strategies of the thesis' model. Alternative implementations of strategies are described by Neumann and Nagel (2012a) and Röder (2013).

4.4.1 Extension of the time of operation

This route modification strategy extends the operating time of a given route. The actual implementation consists of two strategies. The first one searches for a new first departure time and the second one searches for a new last departure time. Both strategies rely on the time provider for the search. The time provider returns a randomly drawn time slot as described in subsection 4.3.1 and the beginning of that time slot becomes the new first/last departure of the route. The time provider's search is limited to the time period

- from midnight to the current first departure in case of a new first departure search, and
- from the current last departure to the following midnight in case of a new last departure search.

Since both strategies can be configured independently, the probabilities for choosing one of the strategies during the operator's replanning process can be different, too.

4.4.2 Reduction of the time of operation

Due to the operator scoring, each operator has detailed knowledge of the *routes*' individual demand. Thus, the operator can reduce operations at slack times by adapting its *route* to the demand's travel pattern. For that, the strategy uses a threshold to distinguish the important periods of the day from less important ones. The strategy's algorithm includes the following steps:

1. All trips served by the *route* are classified depending on the trip's departure time and on the trip's arrival time. The travel times are mapped to time slots. Each start-time-slot-to-end-time-slot combination has a weight based either on the number of trips linked to that combination or the amount of collected fares of that combination.

2. The standard deviation is calculated over all time slot combinations and is used as the threshold.

3. All time slot combinations with a weight greater than the standard deviation are considered as important. These combinations are candidates to be served again.

4. The start time slot and the end time slot of all important time slot combinations are fused into one data set. The resulting data set is sorted in ascending order. Note that the time slots may be discontinuous, i.e. the resulting data set may contain the time slots 2, 3, 4, 7, and 8 which are detached from each other due to the time slots 5 and 6 being classified as unimportant. The strategy allows then for two different behaviors to determine the new operating time from this data set. This can be:
   a) Cover as much time slots as possible. This takes the earliest and the latest time slot. In consequence, all time slots in-between are covered as well. From the example above, the time slots 5 and 6 will be served since the strategy defines 2 and 8 as the first and the last time slot.
   b) Choose one of the continuous time slot blocks. Each continuous time slot block, 2–3–4 and 7–8 from the example, is weighted by the number of time slots it holds. One of the blocks is picked by a weighted random draw, e.g. 2–3–4. Therefore, the operator does not have to serve slack periods but can rather choose one of the more profitable periods of the day.

5. The resulting time of operation is derived by setting the new start time slot's start time as the new first departure time and the new end time slot's end time as the new last departure time. That is, for the example of 2–3–4, the new first departure time is set to the start time of slot 2 and the new last departure time to the end time of slot 4.

Note that an operator still holds the original *route* in its transit schedule. It can thus offer services on both *routes* and both *routes* can be used to replan again. Therefore, the operator may choose differently in a later iteration, and may eventually offer a third route, e.g. 7–8 in case of strategy 4b. In consequence, the operator has split its *route* into two detached *routes* and may even drop service on the original *route*.

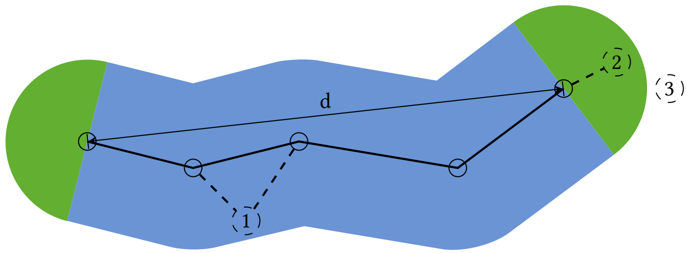


Figure 4.2: Search space for extending the route — The search space for extending the route at its ends is restricted to the green end caps, e.g. stop 2. Stops for a sideways extension are searched in the blue area only, e.g. stop 1. Stop 3 cannot be found by either strategy.

4.4.3 Extension of the route at its end

For extending the *route*, the strategy searches for possible candidate stops, chooses one stop and incorporates it into the existing *routeProfile*. The candidates are found by computing a buffer of the given *route*'s actual path. For extending a *route* at its ends, only the buffer's end caps are used. In the example of Figure 4.2, the end caps are filled green. In the example shown, only stop 2 lies in the end caps' area and is thus the sole candidate. The remaining unserved stops 1 and 3 are not considered as a candidate. From all candidate stops, one stop is chosen by a weighted random draw. The weights are provided by the minibus stop provider, see subsection 4.3.2. The chosen stop is then either added before the very first stop of the *routeProfile* or added right after the stop with the largest distance from the first stop, i.e. whichever of the two is closer.

The size of the computed buffer can be specified by an absolute number, e.g. 500 m, or is based on the *route*'s length, denoted d in Figure 4.2, e.g. 20 % of the *route*'s length. If both are specified, the larger buffer size is selected.

4.4.4 Extension of the route at its sides

Extending the *route* sideways works similar to the *route* end extension strategy. Again, a buffer is computed defining the candidate stops. This time, the end caps are ignored and the area marked blue in Figure 4.2 is taken as the search space. Candidate stops are drawn randomly based on the weights provided by the stop provider. After choosing one stop from the candidates, e.g. stop 1 in the example, the new stop needs to be inserted in the *routeProfile*. For this, the *route* is converted into two back and forth sub-routes. For each sub-route, the distance between the new stop and all the existing stops is calculated. The strategy then inserts the new stop between the two nearest existing stops of both sub-routes. Thus, the new stop will be served in both directions. At the end, the two sub-routes are fused into one regular circle *route*.

From the perspective of the minibus operator, it would be sufficient to insert the stop only once into the circular *route*. The stop is then served in one direction and the division into sub-routes would not be needed. However, the minibus model can as well be applied to planning problems of a formal public transit authority. The predominant route pattern of formal bus lines is serving a corridor in both directions. Hence, the new stop needs be to served in both directions in order to maintain the shape of the corridor.

4.4.5 Reduction of the stops served

Similar to the operating time reduction strategy, the served stop reduction strategy fits the *routeProfile* to the travel pattern of the *route*'s demand. Again, the operator knows where agents have boarded and where they have alighted. The individual trips are classified with respect to the trip's departure stop and the trip's arrival stop. The trip's departure time is not regarded. Thus, the analysis is based on a complete iteration, normally a whole day. The threshold to distinguish important stops from less important ones is again the standard deviation of the stop combinations' weight. This can either be based on the number of trips served by the stop combination or the amount of collected fare. All stops of the stop combinations with a weight greater than the threshold are finally fused into one single *route*. The stops keep the order of the old *routeProfile*. Thus, all (important) trips served by the old *route* can still be served with the new *route*. Finally, a new *route* is calculated from the new *routeProfile* linking all remaining stops by shortest paths, see subsection 4.3.3 for details. Stops of unimportant stop combinations may thus be dropped from the *route*, e.g. stop 1 of the example of subsection 4.4.3. However, if the new *route* passes by such an unimportant stop anyway, it is again served by that *route*.

Note that the strategy can yield different results in different iterations. For example, from *route* A a new *route* B is created that only serves the most attractive stops of *route* A. Since the operator offers services on *route* A as well as on *route* B, both *routes* run in direct competition to each other. Thus, *route* B attracts passengers from some parts of *route* A. If the same *route* reducing strategy is applied to *route* A for a second time, the analysis of the *route* A's travel pattern may result in a different threshold. In consequence, the important stop combinations can be others and the newly created *route* can be different from *route* B.

4.5 Discussion

The operators described in this thesis all buy as much vehicles as they can afford. As long as there is enough budget left to buy one more vehicle, the operator will buy one. Depending on the type of operator, these vehicles are put into service or put into the spare vehicle pool. Regardless which one is chosen, the vehicles impose costs on the operator. Especially with the vehicles of the spare vehicle pool not adding anything to the operators profit, one could argue that the operator should not buy more vehicles but rather save the budget. However, this imposes the problem of loss-making operators which are not removed from the market but rather live on the savings accumulated earlier. These operators will die out in the long run. But as long as they stay in the market they compete with other operators resulting in an unnecessary long relaxation process. For this reason, the model's design forces operators to offer as much service as possible, although the operator's return may decline. If the operators need to guarantee a certain rate of return, the model can be extended to deduct an investor's share of profits from the operator's (net) cash flow. The operator has then to buy vehicles from the remaining budget and can thus, only afford a smaller vehicle fleet.

The vehicle fleet is also important for the variety in the operator's replanning. Operators with a huge vehicle fleet can afford to operate many *routes* at the same time. Since the number of vehicles an operator owns defines how many new *routes* per iteration it can create, operators with many vehicles can probe the market faster. In terms of genetics, these operators have a higher mutation rate and can therefore adapt faster to their environment. However, being successful depends on the individual circumstance of an operator, i.e. time of the market entry and the direct competition in place. The example of Figure 4.3 shows how the operator's evolve and what the impact of the two factors is. Each dot represents the creation of a *route*. Since each *route* is derived by altering one of its attributes, each *route* can be linked to its predecessor. The big dots mark *routes* which survived until the last iteration.

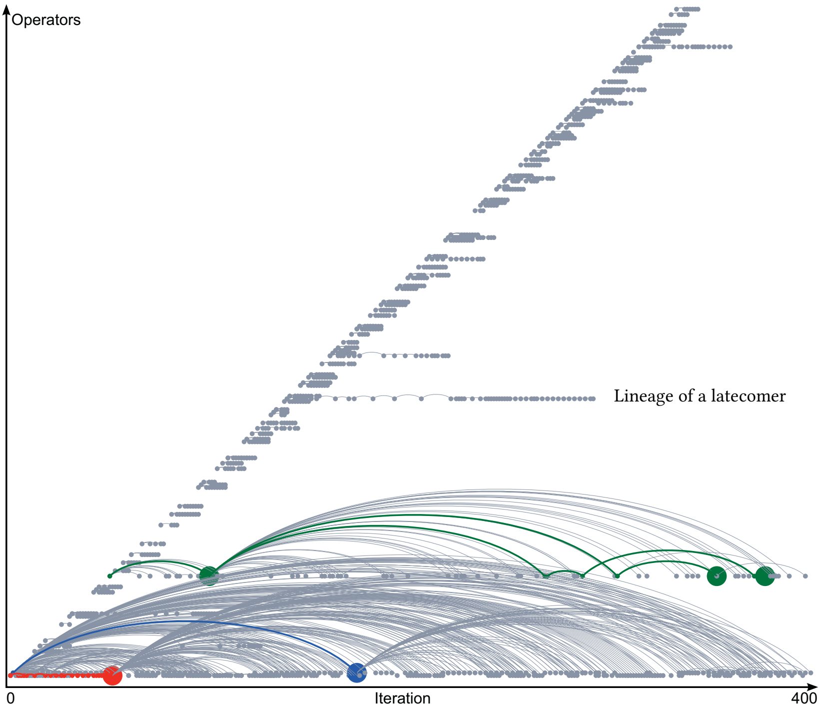


Figure 4.3: Lineage of operator routes — Each node represents a route and is placed according to the iteration it is created in and the operator it belongs to. The three surviving operators marked red, blue, and green offer five different routes in the last iteration (marked with bigger nodes). Each node is linked to its predecessor eventually tracing back to the operator's initial route.

Their lineage is colored accordingly and can be followed back to the very first initial *route* of the operator.

All three surviving operators evolved differently. The red one, founded in the initial iteration, has been mutated about twenty times in quick succession, before the final *route* has been found. However, the operator further tried to optimize its *route*, but none of its mutations survived. Unlike the red operator, the blue operator found its final *route* by a direct mutation of a *route* dating back to the first iterations. This is possible due to an early market entry that allows to claim a decent *route* right a the beginning of the run. Further iterations and mutations of a first iteration *route* or even the final *route* did not yield any further improvements. The third operator has three surviving *routes* marked green. Two of them are indirect offsprings of the third one. This operator is an example for a latecomer finding a market niche. It cautiously improves and diversifies its *routes*. Operators with an even later market entry have a lower probability to fill successfully one of the left (smaller) market niches with their initial *route*. Although some operators stay in business for some time, the majority goes bankrupt once the initial budget is spent. There is one operator surviving quite long until iteration 217. However, this operator is forced to cease service when the green operator starts to extend service. To conclude, an early market entry allows to claim niches more easily, giving pioneers an advantage over latecomers.

A computational performance improvement can be achieved by limiting the rerouting of the population's plans to public transit legs only. That is, legs with the transport mode walk, bike, and car will not be routed again but simply copied. With the population of the real world scenario of chapter 7, an average speedup of a factor of two has been achieved. The drawback of this approach consists in the incompatibility of the other existing population replanning strategies. For example, the time allocation replanning strategy needs to reroute all modes of transport after shifting the activities' end times in order to allow for any routing reaction, e.g. an agent starts early and can thus take a different route with its car. Consequently, rerouting public transit legs only needs to be implemented as a standalone replanning strategy to be compatible with existing strategies. The time allocation replanning strategy can then rely on its own rerouting strategy that routes all transport modes.

CHAPTER 5

Sensitivity analysis

If you don't care about quality, you can meet any other requirement.

Gerald M. Weinberg

This chapter will use the model implementation as described in chapter 4 and apply it to a number of small illustrative scenarios. The model is tested for sensitivity with respect to time and space. The first sensitivity tests use a simple corridor network. These tests are followed by more complex ones using an intersection of two roads and a grid network, which allows the paratransit operators to alter their *routes* in two dimensions. For the sensitivity to the charged fare the reader is referred to the Sioux Falls scenario of Appendix C.

5.1 Tests within a corridor network

In the sensitivity tests of this section, paratransit operators have first to react to a spatially distributed demand and then to temporarily distributed

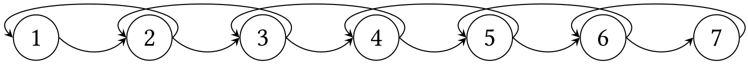


Figure 5.1: Corridor network featuring seven transit stop facilities labeled 1 to 7

demand peaks. All tests of this section use the same corridor network depicted in Figure 5.1.

This network contains 12 car links, each with a length of 1000 meters and a capacity of 10,000 vehicles per hour. The speed-limit is set to 10 meters per second. In addition, there are 7 special links, denoted 1 to 7 which represent transit stop facilities. In this scenario, each transit stop facility is modeled as one car link with start and end node having the same coordinate. The effective delay for passing such a link is one second, i.e. the length is set to 10 meter and the speed-limit is the same as for the other links. Each of those links connects all of its ingoing links with all of its outgoing links. Therefore, each vehicle going from stop 1 to stop 3 will pass stop 2. The same vehicle will loop over stop 2 again when heading back to stop 1. Thus, stop 2 can serve passengers heading in both directions.

The complete configuration of the scenarios of this section is listed in Table 5.1. Initially, there is only one operator starting with three vehicles. New operators are founded whenever the share of profitable operators exceeds 90 %. An operator has 10 iterations to at least break even. If it does not at least break even, it is declared loss-making and closed down, i.e. the operator's state changes from *prospecting* to *bankrupt* as described in subsection 4.3.4. This is independent of the actual amount of money the operator may still possess.

The minibuses used in this section have a capacity of 11 seats allowing to carry 10 passengers and the driver. The operators have to pay 0.30 monetary units [¤] for each vehicle-kilometer. Revenue is 0.10 ¤ per passenger boarding a vehicle. Since an operator has to cover a fixed cost per vehicle and day/iteration of 10 ¤ and an additional 10 ¤ per vehicle-hour, operators need more than an average load of 50 % to run a profitable business. Note that this assumes an average travel distance of the passengers of 1000 meters. The price of a minibus is set to 100 ¤, regardless whether bought or sold. In order to remove any side-effects, all other parameters like the minimal time of operation or the delay per boarding passenger are set to zero or in such a way that they do not influence the outcome of the model.

Table 5.1: Overview of the parameters used in this section. The parameters of the route modification strategies are listed in Table 5.2.

Parameter	Value
Minimum number of operators	1 operator
Target share of profitable operators	90 %
Number of iterations for prospecting	10 iterations
Initial number of vehicles	3 vehicles
Service area	Not restricted
Franchise system	Installed
Passengers per vehicle	10 pax
Passenger car equivalents	1.0 PCE
Delay per boarding passenger	0.0 s/pax
Delay per alighting passenger	0.0 s/pax
Cost per vehicle and day	10.00 ¤
Cost per vehicle and hour	10.00 ¤
Cost per vehicle-kilometer	0.30 ¤/km
Price per vehicle bought or sold	100.0 ¤
Earnings per boarding passenger	0.10 ¤
Earnings per passenger-kilometer	0.00 ¤/km

Table 5.2: Overview of the route modification strategies used in this section

Sec.	Route modification strategy	Probability and parameters
4.4.1	Search for a new first departure time	10 % — none
4.4.1	Search for a new last departure time	10 % — none
4.4.2	Reduce the time of operation	30 % — 15 min time bins, Splitting allowed
4.4.3	Extend the route at its end	10 % — MAX(1500 m, 20 % of route length)
4.4.4	Extend the route sideways	10 % — MAX(1500 m, 20 % of route length)
4.4.5	Reduce the served stops	30 % — none

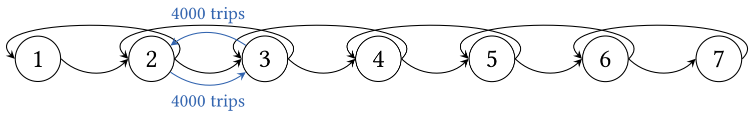
During replanning, the operator's probability to increase the time of operation by trying a new first or last departure time is 10 % each, see Table 5.2 for a listing of all strategies. The probability to decrease the time of operation by setting the first and last departure time according to demand is 30 %. The operator's probability to add a new stop at the beginning or the end of its *route* is 10 %. The probability to restrict the *route* to profitable stops is 30 %. There is an additional 10 % probability to extend the *route* sideways. However, this will not have any effect, since all possible stops are either already part of the *route* or can only be added at its end, i.e. those stops are not situated at one of the *route*'s sides. The type of operator used is the multi route operator described in section 4.3.4.

All scenarios have the same configuration, except for the synthetic population, and run each 1000 iterations. At the end of each iteration, all passengers are allowed to search for a new route. Passengers are only allowed to change their route, but not the transport mode. This allows to change to different minibus *routes*, or to walk directly in case this is the least cost path. Due to the set-up of the scenario, passengers going from stop 2 to stop 3 would need to walk 1000 m. Hence, this functions as a backup strategy only.

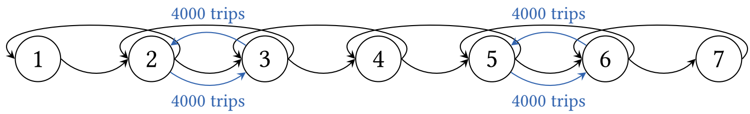
Since the minibus model itself is deterministic, the randomness within the simulation is scripted. That is, once initialized, the random number generator will provide the same sequence of random numbers. Running the same set-up several times thus yields the exact same outcome. To ensure that the outcome is not biased, the same configuration is run 10 times each with a different initialization of the random number generator, also called random seed. Thus, the sequence of random numbers is different in each run. If the outcome of the runs is still the same it is not due to the implementation but due to the minibus model being attracted by the same solution. Such a set of runs with identical configurations except for the random seed is further referred to as "ensemble run".

5.1.1 Spatially distributed demand

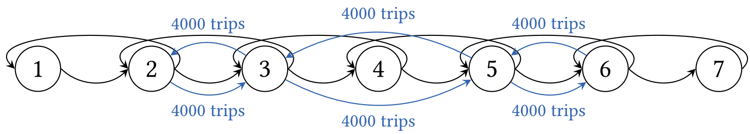
The sensitivity tests S1, S2, and S3 of this subsection each use a demand of 1000 trips per hour and destination. The demand's departure times are uniformly distributed between 6 and 10 o'clock. In each of the scenarios the demand pattern is spatially distributed in a different way. The distribution used is depicted in Figure 5.2.



(a) Demand distribution of scenario S1



(b) Demand distribution of scenario S2



(c) Demand distribution of scenario S3

Figure 5.2: Demand distribution of the scenarios S1, S2, and S3 - The passengers' departure time is uniformly distributed between 06:00 and 10:00

S1 – Scenario with one demand segment

As illustrated in Figure 5.2a, scenario S1 features 4000 trips from node 2 going to node 3 and 4000 trips in the opposite direction. The total number of trips is 8000 and the departure times are uniformly distributed between 6 and 10 o'clock.

The results of the ensemble run of scenario S1 are listed in Table 5.3. With the exception of run number 4, only one operator survived. There are basically two resulting *routes* which differ only in the order of the termini, i.e. starting at stop 2 or at stop 3. Operating times are all the same. However, in run 9, the operator offers a second *route* with only two vehicles and a slightly shorter time of operation. The exact same *route* results in the same profit per vehicle, which is +6.3 starting at stop 2 and +6.4 starting at stop 3. The majority of operators agreed on putting 10 vehicles in service. Using 11 vehicles render the business unprofitable as run 3 illustrates. This operator would have changed back to 10 vehicles in the next iteration, too. With the head-to-head competition of run 4 the operators put more vehicles into service decreasing the overall profit per vehicle. Overall, the result of run 0

Table 5.3: Results of scenario S1

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 0	347	06:00–10:00	2–3	10	8000	+6.3
1	O1 – 1	3	06:00–10:00	2–3	10	8000	+6.3
2	O1 – 0	189	06:00–10:00	3–2	10	7999	+6.4
3	O1 – 12	516	06:00–10:00	3–2	11	7999	−1.0
4	O1 – 11	602	06:00–10:00	2–3	10	7408	+0.3
	O2 – 858	858	07:45–09:15	2–3	2	592	−4.5
5	O1 – 0	166	06:00–10:00	3–2	10	7999	+6.4
6	O1 – 9	106	06:00–10:00	3–2	10	7999	+6.4
7	O1 – 8	58	06:00–10:00	2–3	10	8000	+6.3
8	O1 – 1	213	06:00–10:00	2–3	10	8000	+6.3
9	O1 – 10	382	06:00–09:45	3–2	2	1488	+4.2
		493	06:00–10:00	3–2	8	6493	+7.5

may be considered as optimal. All passengers are served and the operator runs a profitable business.

From the results, it can be concluded that the scenario is indeed not perfectly symmetric. Operators starting at stop 3 serve only 7999 out of the total of 8000 passengers, e.g. as in run 2. The reason lies within the demand itself. The agent 7592 departs at 9:59.59 and would arrive one second later at stop 3. However, the algorithm is such that operators can only shift the operating times by whole time bins, i.e. they can either run until 10:00, or until 10:15, see subsection 4.4.1 and 4.4.2. Running until 10:00 means that every vehicle arriving at the terminus until 10:00 will depart again, every vehicle arriving there after 10:00 will stop. Thus, in order to transport an agent arriving at 10:00.00, a vehicle would have to arrive exactly at 10:00.00. This is highly improbable. Also, extending the service period for this single agent clearly is inefficient. Thus, this agent is not served. The situation is different if the terminus is at the stop 2, e.g. as in run 0. Here, any vehicle arriving until 10:00 will be turned around, and any vehicle arriving after 9:58.20 will be late enough to pick up the agent at the stop 3 on its way back. Since the demand is the same for all runs, this agent misses the last departure whenever the terminus is at the stop 3.

The iterations in which the surviving *routes* are found seem rather high. For example, in run 0 the sole surviving operator's *route* is found in iteration 347.

From that iteration on, the *route* is kept unmodified except for the number of vehicles. However, analyzing iteration 347 in more detail reveals that the operator offered a similar *route* before. That is, since iteration 14, the operator offered the very same *routeProfile* with a different time of operation of 06:00–10:15. The same situation can be found in the other runs, e.g. run 2 with the predecessor *route* found in iteration 21 (06:00–10:30) and run 3 in iteration 12 (06:15–09:45). Thus, the overall solution is found quite early and is only further optimized in later iterations.

S2 – Scenario with two disjoint demand segments

In addition to the demand of scenario S1, the scenario S2 features an additional demand of 4000 trips from node 5 to node 6 and 4000 trips the way back, see Figure 5.2b for an illustration.

The results depicted in Table 5.4 show multiple operators serving the demand for all runs. Again, 10 vehicles result in a profitable *route*, while one vehicle more results in slight losses. The result of run 3 may be considered as optimal. Depending on the terminus, some of the agents might be late for the last departure. For instance, operator 2 of run 3 faces the very same situation as in scenario S1 with agent 7592 being forced to walk.

The results of the other runs show similar solutions, sometimes however with duplicate lines. The duplicates are offered by different operators or as different *routes* within the same operator, e.g. run 4. If these duplicates are merged, the resulting *routes* are essentially always the same, i.e. one *route* serving the demand from 5–6 and back and one *route* for the demand between 2 and 3.

S3 – Homogeneous demand density split into three segments

This scenario increases the synthetic population of scenario S2 by adding one additional demand segment. In total 8000 trips are added going from node 3 to node 5 and back as depicted in Figure 5.2c. All three demand segments do not overlap, but form a homogeneous density of demand from node 2 to node 6.

As shown in Table 5.5, the time of operation of the operators match the corresponding demand segments. With the exception of run 5, there are essentially two different *routes* evolving. The first one is going from stop 2 to stop 4 and the second one is going from stop 4 to stop 6. The interesting fact is, that there is no demand at stop 4 to be served. However, both lines agreed

Table 5.4: Results of scenario S2

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 0	524	06:00–10:00	2–3	11	8000	−1.1
	O2 – 26	220	06:15–10:00	6–5	11	7995	+3.1
1	O1 – 1	3	06:00–09:45	3–2	3	2040	−1.8
		90	06:00–10:00	3–2	8	5940	+0.6
	O2 – 90	325	06:00–10:00	6–5	10	7371	−0.1
	O3 – 454	454	07:45–09:30	6–5	1	476	+8.7
2	O1 – 0	226	06:00–10:00	6–5	11	8000	−1.0
	O2 – 65	106	06:00–09:45	2–3	11	7521	−1.4
3	O1 – 12	536	06:00–10:00	5–6	11	7992	−1.1
	O2 – 35	91	06:00–10:00	3–2	10	7999	+6.4
4	O1 – 1	715	06:00–10:15	2–3	2	1833	+13.6
		794	06:00–10:00	2–3	7	6112	+13.6
	O2 – 159	773	06:00–09:45	6–5	10	6981	+0.1
	O3 – 890	893	07:15–10:00	5–6	1	618	+7.1
5	O1 – 1	435	06:00–10:00	3–2	9	6312	−3.7
	O2 – 11	362	06:00–10:00	5–6	11	7992	−1.0
	O3 – 704	704	06:00–09:45	3–2	2	1581	+8.9
6	O1 – 1	170	06:00–10:00	6–5	10	8000	+6.4
	O2 – 64	112	06:00–09:45	2–3	3	1984	−3.7
		433	06:00–10:00	2–3	8	5986	+1.2
7	O1 – 8	450	06:00–10:00	5–6	8	6194	+3.8
	O2 – 71	74	06:00–09:45	2–3	9	6505	+2.7
	O3 – 678	692	06:30–10:15	3–2	1	717	+1.4
	O4 – 832	832	06:00–09:15	5–6	3	1768	−2.9
	O5 – 891	899	07:15–09:00	3–2	1	405	+1.5
8	O1 – 1	56	06:00–09:45	6–5	2	1571	+8.4
		258	06:00–10:00	6–5	9	6322	−3.7
	O2 – 669	678	06:00–09:45	3–2	10	7508	+5.6
9	O1 – 8	232	06:00–10:00	2–3	10	8000	+6.3
	O2 – 18	280	06:00–10:00	6–5	11	7513	−5.4
	O3 – 896	899	07:45–09:15	6–5	1	395	+5.4

on that stop as a transfer station. Demand going from stop 3 to stop 5 or in the opposite direction is forced to transfer. Since this solution depends on the cooperation of both minibus operators, the surviving *routes* tend to be found in the same or nearly same iterations.

The reason for this transfer station lies within the fare system. Passengers pay a fixed fare of 0.1 ¤ per boarding. This does not depend on the actual distance traveled. Since operators optimize their *route* with focus on profit maximization, they try to serve as short as possible trips. From their point of view, any extra passenger-kilometer traveled means losses. In case of run 5, the single operator solution results in about 10 vehicles less put in service

Table 5.5: Results of scenario S3

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 15	286	06:00–10:15	4–5–6–5	18	15066	−2.1
	O2 – 106	282	06:00–09:30	2–3–4	20	14164	−1.7
1	O1 – 0	64	06:00–10:00	6–5–4	19	15998	+3.1
	O2 – 1	67	06:00–10:00	2–3–4–3	20	15997	−1.2
2	O1 – 23	720	06:00–10:00	4–5–6	19	15944	+2.6
	O2 – 195	456	06:15–10:00	2–3–4	21	15897	−1.1
3	O1 – 0	102	06:00–10:00	2–3–4	19	16000	+3.0
	O2 – 26	172	06:00–10:00	6–5–4	20	16000	−1.2
4	O1 – 27	298	06:15–10:00	6–5–4	21	15966	−0.8
	O2 – 193	298	06:15–10:15	2–3–4	20	15956	−1.4
5	O1 – 16	33	06:00–09:45	2–3–5–6–5–3	28	23061	+0.8
6	O1 – 0	437	06:00–10:15	6–5–4	18	16000	+3.3
	O2 – 1	437	06:15–10:00	2–3–4	21	15953	−0.9
7	O1 – 73	217	06:15–10:00	6–5–4	17	14045	+5.7
		876	06:15–10:00	6–5–4–5	2	1618	+3.7
	O2 – 90	720	06:00–10:00	2–3–4	19	15824	+2.0
8	O1 – 5	560	06:00–10:15	4–3–2	18	15535	+0.6
	O2 – 78	253	06:00–09:45	6–5–4	20	15117	−1.2
9	O1 – 6	223	06:00–09:45	2–3–4	20	15111	−1.3
	O2 – 63	223	06:00–10:00	6–5–4	20	15538	−3.5

while still serving nearly all the demand. That is, the higher number of served trips in the other runs is induced by forcing 8000 passengers to transfer once. Consequently, the number of potential trips is increased to 32000.

Putting less vehicles into service means offering a lower service frequency, and thus longer average waiting times at the access stop. For example, both *routes* of run 0 offer a frequency of 21–23 s while the headway for the solution of run 5 is 30 s.

However, when shortening their *routes*, operators have to pay attention to the needs of the demand side. Passengers will change for a competitor's *route* if this yields in more convenient trips, i.e. the transfer penalty in the public transit router does not compensate for the faster trip. In reality, passengers would consider the fare as an additional criterion for choosing the *route*. However, this is not included in the transit router yet. See section 4.2 for details on that and the current work in progress.

In conclusion, operators can form a transfer hub in an area with no demand. This depends on the fare system in place. Given that agents search for a least-cost-path but do not consider the fare, transferring once may result in shorter trip travel times due to higher service frequencies provided by the higher operators' income.

In case the fare system is based on the passenger-kilometer traveled only, e.g. 0.10 ¤/km but no per-boarding fare is installed, the surviving solution is completely different. It is expected to have three independent operators, each serving one demand segment. The *route* from 3 to 5 is twice the length of the other two connections. Thus, a vehicle needs approximately twice the time for one turn and can thus only serve half the number of passengers in the same period of time, e.g. 06:00–10:00. Since the generated revenue depends on the passenger-kilometer served, the profit per vehicle remains the same, i.e. serving half the number of passengers over twice the distance results in the same profit per time. As a result, the operator of the middle segment is able to maintain about twice the number of vehicle than the operators of the other two segments.

S4 – Scenario S1 with a different probability of rerouting

This scenario uses the same set-up as scenario S1 with the exception of the agents' probability to search for a new route in each iteration. In scenario S1, this probability is set to 100 %. Therefore, all agents use a *route* which matches the current transit schedule offered by the operators. In this scenario, the probability is decreased to 30 %. The probability for an agent to choose the plan of the last iteration is 70 %. Thus, some agents will try out plans containing *routes* which might not be offered any more or in a different way, e.g. a different service frequency. An agent might even get stuck, if there is no substitute for the *route* intended to board. However, the probability to be forced to stick to an old plan decreases to 49 % after two iterations, and 34.3 % after three iterations. After 12 iterations, the probability to never be able to reroute drops below 1 %.

Compared to the average running time of scenario S1, this scenario needed about 3 minutes less per run, i.e. the total running time of scenario S1 is 16 min. For more agents and a more complex transit network and thus schedule, the savings might be even larger. In conclusion, decreasing the probability to reroute gives a considerable advantage in computational speed while the overall results, see Table 5.6, remain roughly the same – although individual agents might get stuck somewhere on route.

Table 5.6: Results of scenario S4 with 30 % probability to reroute

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 0	10	06:00–10:00	3–2	10	7344	−0.2
	O2 – 642	642	06:00–07:45	3–2	2	655	−5.5
1	O1 – 1	3	06:00–10:00	2–3	10	8000	+6.3
2	O1 – 20	22	07:00–09:45	2–3	7	4338	+8.3
	O2 – 748	754	06:00–07:15	2–3	5	1653	+2.8
	O3 – 832	832	06:30–10:00	3–2	2	1633	+15.5
3	O1 – 0	11	06:00–10:00	3–2	11	7999	−1.0
4	O1 – 5	9	06:00–10:00	2–3	11	8000	−1.1
5	O1 – 10	245	06:15–10:00	3–2	9	6636	+4.2
	O2 – 519	519	06:15–07:45	3–2	2	684	+0.1
	O3 – 839	839	08:00–09:45	3–2	2	671	−4.8
6	O1 – 0	13	06:00–10:15	2–3	9	7142	+1.7
	O2 – 606	606	06:00–08:30	2–3	1	650	+15.2
7	O1 – 0	12	06:00–10:00	3–2	9	7254	+7.0
	O2 – 209	209	06:00–08:15	3–2	1	576	+11.4
8	O1 – 1	4	06:15–09:45	2–3	9	6175	+2.9
	O2 – 305	305	06:15–09:15	2–3	1	723	+14.1
	O3 – 899	899	06:30–08:30	3–2	1	516	+9.0
9	O1 – 0	21	06:00–10:00	3–2	11	7999	−1.0

5.1.2 Temporally distributed demand

All trips of the scenarios T1, T2, and T3 are space-wise the same connecting the same two stops 2 and 6 as shown in Figure 5.3. The trip density is set to 1000 trips per hour and destination. However, the exact number of trips varies from scenario to scenario due to overlapping demand segments. Since the distance each passenger travels is increased to 4 km, the fare is increased as well to 0.40 ¤ per boarding.

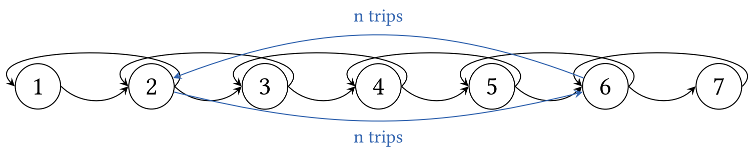
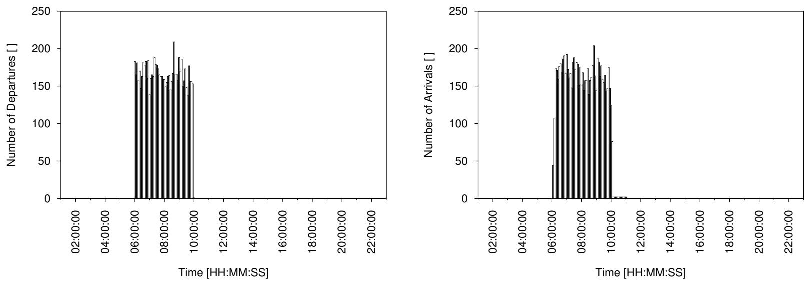


Figure 5.3: Demand distribution of scenarios T1, T2, and T3. The actual demand is listed in Tables 5.7, 5.9 and 5.11.



(a) Departures of agents

(b) Arrivals of agents - Average of all 10 runs

Figure 5.4: Histograms of scenario T1

T1 – Scenario with one demand peak

As in all scenarios, there are 1000 trips per hour and direction summing up to a total of 4000 trips going from stop 2 to stop 6 and 4000 trips going in the opposite direction. The two demand segments are listed in Table 5.7. In total, there are 8000 trips. The passengers' departure time is uniformly distributed between 6 and 10 o'clock. The actual demand distribution is shown in Figure 5.4. Basically, this scenario is the same as scenario S1, except for the distance each passenger travels which is four times the distance of scenario S1.

Table 5.7: Demand segments of scenario T1

Number of trips	From Stop	To Stop	Departure Time
4000	Stop 2	Stop 6	06:00–10:00
4000	Stop 6	Stop 2	06:00–10:00

The results listed in Table 5.8 show that in all runs the majority of passengers is served by one operator. All lines ply the whole distance from stop 2 to stop 6. In contrast to scenario S1, the time of operation is less tailored to the demand, i.e. while the majority of operators starts at 6 o'clock the last vehicle departs well after 10 o'clock.

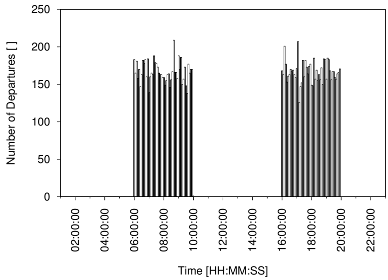
For further analysis, the histograms of Figure 5.4 show the distribution of departures in Figure 5.4a and as an average of all ten runs the distribution

Table 5.8: Results of scenario T1

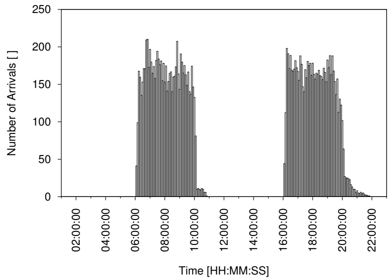
Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 6	14	06:45–09:45	2–6	25	4218	−0.2
	O2 – 17	152	06:00–08:45	6–2	19	3033	+1.0
	O3 – 875	892	06:30–09:30	2–6	2	296	−10.1
1	O1 – 1	3	06:00–09:45	6–2	33	6922	+2.0
	O2 – 721	819	06:00–11:00	6–2	3	956	+21.1
2	O1 – 7	14	06:15–10:00	6–2	33	6710	−0.6
	O2 – 530	664	06:00–10:00	6–2	6	1285	−1.7
3	O1 – 0	5	06:00–11:00	2–6	30	8000	+0.8
4	O1 – 0	40	06:00–10:45	2–6	31	8000	+2.1
5	O1 – 0	13	06:00–10:30	2–6	33	8000	+0.8
6	O1 – 0	6	06:00–11:00	2–6	27	7878	+10.8
	O2 – 871	899	06:30–08:00	2–6	1	120	+4.8
7	O1 – 0	24	06:00–10:15	6–2	35	8000	+0.0
8	O1 – 0	6	06:00–11:00	2–6	27	7307	+2.3
	O2 – 862	899	06:00–09:30	2–6	2	455	+12.3
9	O1 – 0	5	06:00–11:00	2–6	30	8000	+0.8

of arrivals in Figure 5.4b. The distribution of departures does not show any departures for 10 o'clock or later. The distribution of arrivals show a significant number of passengers arriving after 10 o'clock — until 10:10 and a few arrivals until 11 o'clock. Those late arrivals are induced by run 1 which has only three vehicles to serve the demand after 9:45. The lack of vehicles forces passengers to wait longer for an empty vehicle to pass by. Furthermore, there are 122 agents who plan to board a vehicle but fail to do so due to the service closed after 11:00. In case of the missing trips of the other runs the agents either just walk because there is no service or the intended *route* has too few vehicles available to serve all agents before the service's end time.

The comparison of the clear solutions of run 0 of scenario S1 with run 3 of scenario T1 show the same number of trips served in both scenarios. However, the vehicle fleet in scenario T1 is three times the size as the one of scenario S1. Due to the longer distance each vehicle has to travel, each tour needs more time and the number of departures per vehicle is lower than in scenario S1. The transit line of scenario S1 run 0 has a total of 526 scheduled departures compared to 606 departures in scenario T1 run 3. Note that the vehicles of run 3 of scenario T1 circulate one hour longer than the ones of scenario S1 run 0. Thus, the service frequency is about the same. In T1, each vehicle



(a) Departures of agents



(b) Arrivals of agents - Average of all 10 runs

Figure 5.5: Histograms of scenario T2

offers about 20 tours which translates to a maximum of 200 passengers per destination. To be still able to serve all the demand the operator needs more vehicles or allow for extra tours per vehicle. One tour takes about 15 min. Since the fixed cost per vehicle and day is the same as the cost per hour, the operator can decide to add an extra tour to each of its 30 vehicles, e.g. increasing the time of operation by 15 min, or to buy one more vehicle which will then cost the daily charge plus 20 tours times 15 min. For comparison, the operator of run 7 offers 600 departures with 35 vehicles.

The comparison of runs 3 to 5 of scenario T1 further illustrates the relation of fleet size and operating time. With a shorter time of operation the operator needs more vehicles to still serve the same number of passengers. However, there is no distinct tendency for more vehicles or service time. Run 3 and 5 indicate a trade-off of 3 vehicles for 30 min while still scoring exactly the same. In conclusion, the variety of operating times can be explained by the scoring function and the lack of an unambiguous optimal solution.

T2 – Scenario with two demand peaks

In addition to the morning demand peak in T1, the scenario T2 features a second demand peak from 16:00 to 20:00. As shown in Table 5.9, the total number of trips is doubled. Again, the trips are uniformly distributed, see Figure 5.5 for the agents departure histogram.

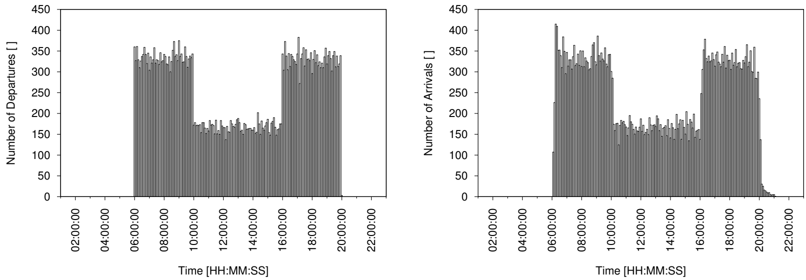
The results of the scenario T2 in Table 5.10 show a similar result as in scenario T1. The correct stops are always found. The beginning of the time of operation matches the first departures of agents with a more diffuse ending.

Table 5.9: Demand distribution of scenario T2

Number of trips	From Stop	To Stop	Departure Time
4000	Stop 2	Stop 6	06:00–10:00
4000	Stop 6	Stop 2	06:00–10:00
4000	Stop 2	Stop 6	16:00–20:00
4000	Stop 6	Stop 2	16:00–20:00

Table 5.10: Results of scenario T2

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 0	667	06:00–10:45	2–6	5	1182	−7.3
	O2 – 5	5	06:30–09:45	2–6	31	5982	+4.9
	O3 – 6	9	16:00–19:15	2–6	32	5836	+0.7
		874	16:00–19:30	2–6	4	755	−2.0
	O4 – 310	310	19:00–20:45	2–6	13	1460	+1.0
	O5 – 729	729	06:00–07:00	6–2	11	779	−1.1
1	O1 – 1	7	16:00–20:30	6–2	28	6995	+3.6
		582	16:00–20:15	6–2	6	1024	−23.8
	O2 – 4	4	06:30–10:00	2–6	35	6489	−2.9
	O3 – 521	564	06:00–08:45	6–2	9	1489	+3.0
2	O1 – 0	5	06:00–11:00	6–2	31	8000	−2.6
	O2 – 1	758	16:00–20:45	2–6	6	1619	+6.3
	O3 – 7	31	16:15–19:45	2–6	32	6361	+2.3
3	O1 – 2	2	06:30–09:30	2–6	27	4961	+5.9
	O2 – 3	9	16:00–19:30	2–6	34	6356	−2.4
		577	16:00–20:30	2–6	4	1078	+11.3
	O3 – 651	685	06:00–11:00	6–2	10	3037	+15.3
	O4 – 881	896	19:30–21:15	6–2	4	499	+5.5
4	O1 – 0	7	06:00–11:00	2–6	30	8000	+0.8
	O2 – 2	9	16:00–21:15	2–6	29	8000	−0.4
5	O1 – 0	27	06:00–10:15	6–2	35	8000	+0.0
	O2 – 1	11	16:00–20:00	6–2	36	8000	+2.3
6	O1 – 0	6	06:00–11:00	2–6	31	8000	−2.8
	O2 – 26	26	16:00–19:30	6–2	33	6257	−1.3
		785	16:00–21:45	6–2	5	1698	+15.0
7	O1 – 0	5	06:00–11:00	2–6	31	8000	−2.8
	O2 – 14	21	16:00–20:00	6–2	37	8000	−0.2
8	O1 – 0	6	06:00–11:00	6–2	30	7793	−2.0
	O2 – 1	1	18:00–20:00	2–6	31	3870	+1.5
	O3 – 383	385	16:00–18:00	2–6	34	4103	−0.1
	O4 – 877	889	06:30–09:30	6–2	1	197	+7.2
9	O1 – 0	5	06:00–11:00	2–6	30	7823	−1.6
	O2 – 6	14	16:00–19:45	2–6	33	6720	−0.4
		855	16:00–21:00	2–6	5	1267	−5.3
	O3 – 876	885	06:30–09:00	2–6	1	177	+8.7



(a) Departures of agents

(b) Arrivals of agents - Average of all 10 runs

Figure 5.6: Histograms of scenario T3

The reasons are the same as in scenario T1. Morning and afternoon peak show the same pattern with arrivals lagging behind the actual demand, see Figure 5.5. The solutions are more diffuse with similar *routes* offered by different operators, e.g. run 0 operator 1 and operator 2, or even by the same operator, e.g. as in run 0 operator 3. Overall, merging similar solutions yields in essentially two different solutions. The first one is operating from 6:00 to 10:00/11:00 and second one from 16:00 to 20:00/21:00.

T3 – Scenario with overlapping demand

In addition to the exactly same demand of scenario T2, this scenario features a third demand segment between 6:00 and 20:00, see Table 5.11. The total synthetic population consists of 44,000 agents. The departure times are uniformly distributed and there are again two demand peaks, but this time with a smaller slack-period in-between, see Figure 5.6 for an illustration of the departure time distribution.

Table 5.11: Demand distribution of scenario T3

Number of trips	From Stop	To Stop	Departure Time
4000	Stop 2	Stop 6	06:00–10:00
4000	Stop 6	Stop 2	06:00–10:00
4000	Stop 2	Stop 6	16:00–20:00
4000	Stop 6	Stop 2	16:00–20:00
14000	Stop 2	Stop 6	06:00–20:00
14000	Stop 6	Stop 2	06:00–20:00

Table 5.12: Results of scenario T3

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 0	5	06:00–11:00	2–6	65	16611	−3.5
		86	10:45–20:00	2–6	53	24724	−0.6
		721	06:00–11:15	2–6	4	1111	+0.5
	O2 – 26	51	15:30–20:00	6–2	5	1233	+2.4
1	O1 – 1	10	06:00–10:15	6–2	74	16705	−1.0
	O2 – 4	94	10:30–20:00	2–6	50	24563	+4.5
		869	10:30–20:15	2–6	3	1681	+26.2
	O3 – 859	879	15:45–20:15	6–2	4	1051	+8.6
2	O1 – 0	9	06:00–11:30	2–6	66	19162	+0.8
	O2 – 7	32	16:00–20:00	6–2	63	13924	+1.8
		138	11:30–17:00	6–2	36	10290	−1.1
		777	16:00–20:15	6–2	2	493	+5.7
3	O1 – 0	5	06:00–11:00	2–6	67	17832	+0.8
	O2 – 6	23	16:00–19:30	6–2	61	12000	+1.7
		860	16:00–20:15	6–2	4	810	−10.7
		897	16:30–20:45	6–2	2	466	+0.3
	O3 – 140	151	11:00–16:30	2–6	38	10880	−0.9
	O4 – 242	258	19:30–21:00	6–2	14	1432	+2.2
	O5 – 894	898	07:15–09:45	2–6	2	273	−5.1
4	O1 – 0	6	06:00–11:00	2–6	68	18151	+1.1
	O2 – 3	55	11:00–19:45	6–2	47	20515	−3.1
		843	11:00–20:00	6–2	4	1760	−6.9
	O3 – 717	731	16:30–20:15	2–6	16	3473	+4.8
5	O1 – 0	5	06:00–11:00	2–6	68	18148	+1.1
	O2 – 1	52	15:30–20:15	2–6	1	213	−19.6
	O3 – 58	139	11:00–19:45	6–2	55	24910	+3.6
6	O1 – 0	12	06:00–11:30	2–6	67	19170	−0.9
	O2 – 3	17	16:00–20:00	6–2	70	14565	−3.3
		594	15:45–20:15	6–2	5	1252	+3.0
	O3 – 553	561	11:30–15:45	6–2	38	8537	−1.6
7	O1 – 0	7	06:00–11:15	2–6	67	18717	+1.3
	O2 – 7	17	11:15–20:15	2–6	56	25283	−1.7
8	O1 – 0	7	06:00–11:15	2–6	63	17599	+1.2
		177	11:15–15:45	2–6	38	8987	−1.7
		855	06:00–11:30	2–6	4	1152	−1.3
	O2 – 8	28	16:00–20:00	2–6	70	14539	−3.5
		813	16:00–20:15	2–6	5	1141	−0.2
9	O1 – 0	5	06:00–11:00	2–6	69	18136	−0.5
	O2 – 91	142	11:00–20:15	6–2	54	24814	−3.3
	O3 – 860	869	10:45–19:30	6–2	2	1044	+30.6

The results in Table 5.12 show that there are solutions with only two operators, e.g. run 0, 2, 7, and 8, and solutions with up to five operators. Overall, the solutions tend to consist of 3–5 *routes*, regardless of the number of operators. Solutions with fewer operators, provide similar *routes* within one operator. For example in run 2, there are two operators. The first one serves the first peak from 6:00 to 10:30. Again, the operating time exceeds 10:00 because of the same reasons as in scenario T1. The second operators starts its service exactly at the end of O1's operating time. This service has fewer vehicles due to a lower demand density of only 1000 trips per hour. O2 cancels this service with the starting time of the second demand peak. This time there is an overlapping period of time from 16:00 to 17:00 when both services run in parallel. However, there is no real competition between both services. One service is still serving the slack-period demand which lags as in the other scenarios. The other service serves the additional peak hour demand with its 2000 trips per hour. Both afternoon peak services merged result in the same vehicle fleet size as the morning peak service of O1. Other runs perform similar with roughly the same solution found in run 3, 6, and 8.

Another solution emerges in the runs 0, 1, 5, 7, and 9. The *routes* of these runs do not show a clear distinction between the slack-period and the second peak of the afternoon. The *routes* overlap both periods, merging the slack-period *route* with the afternoon peak *route*. An intermediate solution with an increased overlapping service time survived in run 4.

In conclusion, the surviving *routes* are reasonable in terms of the given demand and the cost structure of the operators. Given the doubled demand density during the peak hours, the *routes* operated result in the same vehicle-to-demand ratio as in scenario T1.

T4 – Scenario T1 with self-inflicted traffic jam

As described in subsection 2.4.1, the route associations' fleet size can become considerably large. With each additional vehicle, the self-inflicted traffic impact increases. At a certain point, an operator evaluating its *routes* will find that an additional vehicle bought will not return enough revenue to cover the fixed daily costs associated with it. The main reason for this lies in the increased time needed for one turn due to the more congested roads and, thus, in the increased opportunity costs.

This integration test demonstrates how operators react to self-inflicted traffic jams. It uses the same input data as scenario T1, except for the network. The four links to and from node 4 have a reduced capacity of one vehicle per minute or 60 veh/h. This simulates other road users. For example, node 4 may be a train station which is served by several competing minibus operators cluttering the area around node 4. Thus, operators passing through this area, e.g. from node 2 to node 6, are affected as well.

The results of Table 5.13 show all operators serving the complete corridor from node 2 to node 6 as in scenario T1, see Table 5.8. However, the operators manage to only put half the number of minibuses into service. In addition, operating times are much longer with some operators operating up to 14:15. This clearly shows that the operators are not able to serve the complete demand in the same time as in scenario T1. Increasing the vehicle fleet size only adds to the traffic jam and thus increases the associated costs. Although the underlying cost function of the operators has not changed, the average occupancy increased from 67.9 % to 93.2 %. Overall, the solutions are evolving less stable as the foundation iteration of the surviving operators indicate. With the severe traffic jam in place, surviving becomes a game of chance. Established operators get no advantage over new-comers, because being first through the bottleneck is the only factor that matters. Thus, there is no way of planning ahead and the services become more unstable.

Table 5.13: Results of scenario T4 with bottleneck

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 854	895	06:00–14:15	2–6	15	7402	+18.0
	O2 – 877	898	06:15–11:15	6–2	2	548	−2.8
1	O1 – 814	893	06:00–14:15	6–2	11	7150	+91.1
	O2 – 894	898	06:15–10:15	6–2	2	587	+30.5
2	O1 – 829	898	06:00–12:45	6–2	9	4910	+78.6
3	O1 – 833	899	06:00–13:00	2–6	20	8000	+25.6
4	O1 – 830	899	06:00–12:00	2–6	19	7590	+39.9
5	O1 – 878	898	06:00–11:30	6–2	4	1324	+9.2
	O2 – 885	898	06:00–11:30	2–6	14	5830	+44.0
6	O1 – 867	881	06:00–11:00	6–2	21	7530	+28.0
7	O1 – 883	896	06:00–12:00	2–6	18	7370	+45.5
8	O1 – 833	895	06:00–12:30	6–2	20	8000	−0.8
9	O1 – 882	892	06:00–10:45	6–2	23	5830	+24.3

5.2 Crossing scenario

This scenario uses the network depicted in Figure 5.7. It consists of eight links, each with a length of 1000 m, a speed limit of 10 m/s and a capacity per link of 10,000 vehicles per hour. There are five transit stop facilities depicted as A, B, C, D, and X which are modeled the same way as in section 5.1. The parameters used in this scenario are the same as shown in the Tables 5.1 and 5.2 with the exception of the fare set to 0.2 ¤ per boarding passenger. The demand of the scenario is listed in Table 5.14 and consists of two segments intersecting at stop X and one smaller segment going from A to C and the way back. The departure time of all agents is, as before, equally distributed between 6 and 10 o'clock.

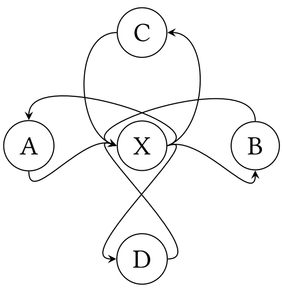


Figure 5.7: Crossing network

Table 5.14: Demand distribution of the crossings scenario

Number of trips	From Stop	To Stop	Departure Time
4000	Stop A	Stop B	06:00–10:00
4000	Stop B	Stop A	06:00–10:00
4000	Stop C	Stop D	06:00–10:00
4000	Stop D	Stop C	06:00–10:00
400	Stop A	Stop C	06:00–10:00
400	Stop C	Stop A	06:00–10:00

As shown in Table 5.15, there are mainly two *routes* evolving. One is serving the demand between A and B and the other one is serving the demand

Table 5.15: Results of the crossing scenario

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 1	786	09:00–11:00	C–D	6	1264	−3.6
	O2 – 9	52	06:00–10:45	A–B	19	8800	−2.4
	O3 – 272	304	06:00–09:30	D–C	20	7536	+2.8
1	O1 – 1	15	06:15–10:00	D–C	18	6871	−0.7
		813	06:15–10:00	D–X–C–X	4	1521	−1.3
	O2 – 21	581	06:15–10:00	A–B	22	8384	−0.8
	O3 – 864	893	06:00–07:45	A–X–C–X	3	754	+8.4
2	O1 – 1	7	06:15–09:45	A–X–B	14	4901	−2.7
		882	06:15–10:15	A–X–B	9	3560	−2.5
	O2 – 31	312	06:15–10:00	D–C	22	8565	+0.8
	O3 – 797	885	06:00–07:30	C–X–A–X	3	544	−0.8
3	O1 – 2	20	06:00–08:15	C–X–D	1	318	+13.0
		55	06:00–09:30	C–D	19	7129	+2.5
	O2 – 22	520	06:15–10:00	B–A	18	7363	+4.7
		757	06:15–10:15	B–A	3	1377	+10.3
	O3 – 405	410	09:00–10:30	D–C	7	1353	+1.7
4	O1 – 0	388	06:00–10:00	C–D	21	8798	+2.0
	O2 – 18	27	06:00–10:30	A–B	15	6783	−0.2
		790	06:00–10:00	A–B	5	2017	−0.9
5	O1 – 0	609	06:00–10:00	D–C	22	8797	−1.8
	O2 – 2	27	06:15–10:00	A–B	22	8778	+2.7
6	O1 – 0	148	06:00–10:15	B–A	21	8800	−2.3
	O2 – 1	726	09:00–10:15	D–C	14	2150	−1.8
	O3 – 4	32	06:00–09:00	C–X–D–X	21	6650	−0.4
7	O1 – 2	7	06:45–10:00	C–D	19	6640	+1.7
	O2 – 3	314	06:00–07:45	C–D	10	2157	+1.6
	O3 – 17	34	06:15–10:00	B–A	16	6722	+7.0
		816	06:15–10:00	B–X–A–X	5	2062	+5.2
8	O1 – 17	334	06:15–10:00	B–A	20	8226	+5.1
	O2 – 52	77	06:15–10:00	C–D	20	8230	+5.1
	O3 – 817	894	06:00–09:30	C–X–A–X	3	955	−9.2
9	O1 – 0	11	06:00–10:15	D–C	20	8797	+1.9
	O2 – 6	815	06:15–10:00	A–X–B	18	7255	+3.5
		889	06:15–09:15	A–B	5	1548	−2.0
	O3 – 864	898	06:00–07:00	A–X	2	146	−11.5

between C and D. Again, there are duplicates of *routes* either operated by the same operator or a different one. With the exception of run 1 and 2, the smaller demand of A–C needs to transfer at stop X. Only run 1 and 2 provide a direct service but nonetheless this service does not serve all of the 800 trips. In conclusion, the demand of A–C is too low to provide a feasible direct service. Due to the high demand of the other relations, their high-frequency services allow for traveling from A to C with only a small delay when transferring at stop X. Thus, transferring is faster than waiting for a low-frequency direct service. In addition, most of the *routes* serving the high demand relations do not consider stop X as important. Stop X is not part of the *routeProfile* and only served because each *route* needs to pass by anyway. In case a faster bypass was available, e.g. stop X is modeled as an off-street bus terminal, all *routes* without stop X encoded in their *routeProfile* would not serve that stop any longer. Thus, these *routes* would ignore the extra demand of A–C since stop X cannot serve as a transfer station.

5.3 Gridnet scenario

In this section, the thesis' model is compared with simpler models published earlier. To facilitate comparison with former publications, it uses the same multi-modal network that has been introduced in Neumann and Nagel (2012a) and has been further used in Neumann and Nagel (2012b). Whenever possible, this section uses the same parameters as in Neumann and Nagel (2012b) from which parts of the scenario description are taken.

5.3.1 Scenario description

The multi-modal network is shown in Figure 5.8. It contains 16 nodes connected by 48 car links, each with a length of 1200 meters and a capacity of 2000 vehicles per hour. The speed-limit is set to 7 meters per second to compensate for traffic lights and other obstacles. Four additional car links, called A, B, C and D, are included to locate demand at the nearby nodes directly. These links have a length of 100 meters, a speed-limit of 100 m/s, and a flow capacity of infinity. Since these links loop, the actual coordinates of the passengers located on those links are identical with those of the nearby node. The minibuses have a capacity of 11 seats allowing to carry 10 passengers and the driver. The minibuses stop at the end of each link. This allows for transfers at the node, since every incoming link is a possible minibus stop. For each person boarding, the minibus is delayed by 2 seconds, for each person alighting, the minibus is delayed by 1 second.

Furthermore, there is one train line running from node 1 via node 2 to node 3 and back via node 2 to node 1, marked with a dashed line in Figure 5.8. Trains run between 5:00 and 13:00; the train frequency is varied (see below). The capacity of the train is set to 100 passengers per train; the delay per person boarding or alighting is set to half a second. On the connection from

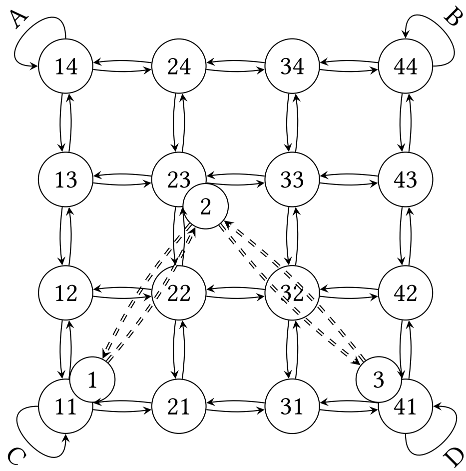


Figure 5.8: Grid road network with one transit line marked with a dashed line

C to D, the train is about 20 % faster than the minibus. Conversely, minibuses tend to run more often than the train. Since the travelers' departure times are fixed, the shorter waiting time for the minibus may compensate for the longer travel time, and the traveler may select the minibus.

Minibuses are allowed to operate in addition to the train. In contrast to Neumann and Nagel (2012b), the target share of profitable operators is set to 90 %. Passengers are only allowed to change their route, but not the transport mode. This allows to change to different minibus *routes*, to the train, or to walk directly in case this is the least cost path.

The operators pay 10 ¤ per day for every minibus they own, and 0.30 ¤ for each vehicle-kilometer. Revenue is 0.05 ¤ per passenger-kilometer and 0.20 ¤ per passenger boarding. This mixed fare system is a combination of the earlier per-boarding fare scenarios of this thesis and of the scenarios in Neumann and Nagel (2012b) which have used a distance-based fare only. Therefore, an operator needs approximately an average load of 80 % to run a profitable business, i.e. 3 passengers to balance the running costs, 4 passengers to cover the vehicle hourly costs and at least one additional passenger to make enough profit in order to pay for the fixed daily costs. The average load to break even in Neumann and Nagel (2012b) has been 50 %. The price of a minibus is set to 100 ¤, regardless whether bought or sold. At the end of each iteration, 100 % of the passengers are allowed to search for a new route. Newly found operators have 10 iterations to break even.

Due to the slightly changed model, the operators' set of possible strategies are changed as well. All strategies are substituted by new ones with a similar behavior. That is, the strategies and parameters used are the same as in Table 5.2 with one exception. Extending a *route* sideways is disabled due to a missing counterpart in the former runs of Neumann and Nagel (2012b). Consequently, the 10 % probability is equally distributed among the remaining strategies. In contrast to Neumann and Nagel (2012b), there is no explicit strategy to buy new vehicles. Due to the vehicle management introduced with the multi route operator, see subsection 4.3.4, that became obsolete. Instead the operator decides by itself whether to buy new vehicles or not.

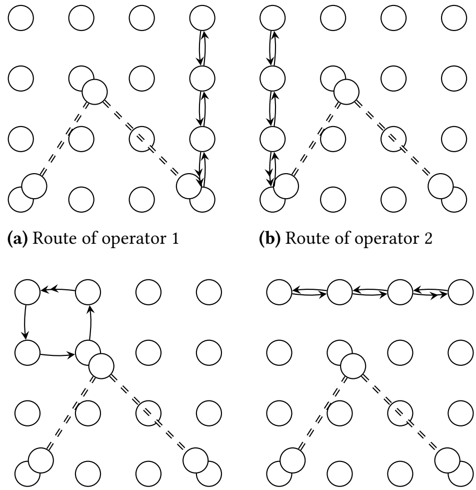
The demand is exactly the same as in Neumann and Nagel (2012b), that is, 1000 trips for every origin-destination combination of ABCD, resulting in a total of 12,000 trips. The passengers' departure time is uniformly distributed between 6 and 10 o'clock.

The same scenario is run for three ensemble runs with the same configuration, except for the schedule of the train. The schedule of the train is altered in each ensemble run. In the first ensemble run, the train will depart every minute. In the second ensemble run, the train departs every 10 minutes and in the last ensemble run, the train departs every hour only. Again, each run lasts 1000 iterations.

5.3.2 Results and comparison

Overall, the results are the same as in Neumann and Nagel (2012b). The Tables 5.16, 5.17, and 5.18 show the variety of the results for all ensemble runs with train schedules of 1min, 10min, and 60min.

With a train's headway of 1 minute, a direct minibus connection from C to D is missing. The solutions for the feeder service from A and B to the train station 2 are less obvious. One solution is to operate two different *routes* from A and B, respectively, to the train station. However, as run 4 shows, those two feeders can also be combined into one *route* plying from A to the train station and further on to B, effectively serving all the feeder demand as well as the demand from A to B. With the former model of Neumann and Nagel (2012b), this kind of *route* could not be found.



(a) Route of operator 1 **(b)** Route of operator 2

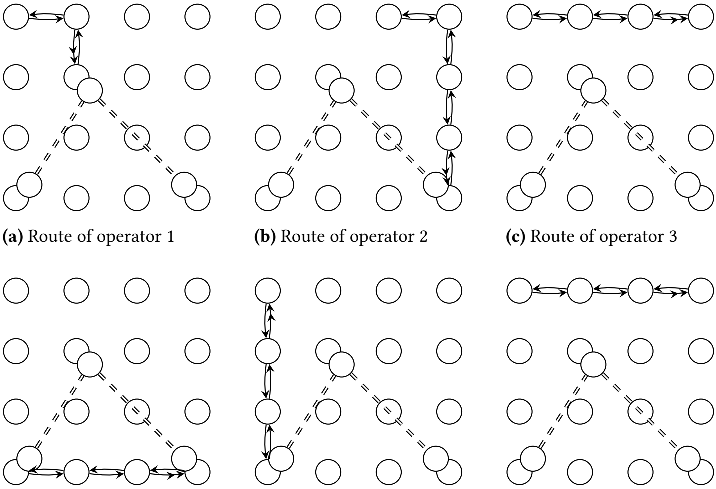
(c) Route of operator 3 **(d)** Route of operator 4

Figure 5.9: Resulting routes and flows of scenario 1min — Double arrows indicate termini

The 60 min runs give a clear solution with essentially four different *routes* plying along the outer edges of the network. The train is completely ignored and a direct minibus competition between C and D is established. Only run 3 offers a feeder to the train which serves only 482 passengers, but the majority of the missing trips just walks directly.

With a train schedule of 10 min, a mixture of solutions occurring in the other two cases is found. For example, with the exception of run 7, all runs offer a direct service from C to D. At the same time, the majority offers additional feeders to the train. In particular, comparing the final *routes* of run 0 of each scenario, see Figures 5.9, 5.10 and 5.11, demonstrates that the case of 10 min has the feeder of 1 min as well as the direct connection between C and D common to the 60 min case.

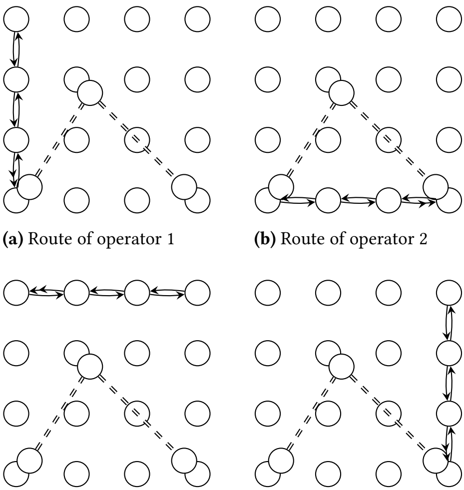
To conclude, the thesis' model is able to reproduce results of earlier publications. In addition, the model is able to find new more complex solutions.



(a) Route of operator 1 **(b)** Route of operator 2 **(c)** Route of operator 3

(d) Route of operator 4 **(e)** Route of operator 5 **(f)** Route of operator 6

Figure 5.10: Resulting routes and flows of scenario 10min — Double arrows indicate termini



(a) Route of operator 1 **(b)** Route of operator 2

(c) Route of operator 3 **(d)** Route of operator 4

Figure 5.11: Resulting routes and flows of scenario 60min — Double arrows indicate termini

Table 5.16: Results of grid scenario 1min

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 0	102	06:00–11:00	4241–4344	16	4007	+2.8
	O2 – 72	255	07:00–10:15	1211–1314	9	1559	+2.3
	O3 – 199	202	06:15–10:30	2414–1323	11	2729	+1.2
	O4 – 576	589	06:30–10:15	3444–2414	12	1993	−9.0
1	O1 – 12	185	06:00–10:00	1323–1314	12	2629	−4.0
	O2 – 73	307	06:30–09:30	1211–1314	10	1533	−1.4
	O3 – 76	182	06:00–10:00	3444–2414	12	2299	−3.3
	O4 – 139	157	06:15–09:30	2423–3444	21	3402	−2.1
2	O1 – 75	83	06:00–10:30	1314–1211	9	2002	+0.4
	O2 – 135	444	06:15–11:15	3444–2414	8	1491	−21.0
	O3 – 156	353	06:00–10:00	2414–1323–2324	9	2531	+15.1
	O4 – 397	397	06:00–09:45	4344–2423	10	2202	+11.1
	O5 – 552	561	06:15–10:45	4344–4241	9	2054	+2.6
3	O1 – 47	113	06:15–10:15	1314–1211	9	1900	+4.0
	O2 – 93	169	09:00–10:15	2414–1323	7	728	+2.1
	O3 – 100	165	06:00–09:00	1314–2423	9	1679	+1.3
	O4 – 137	482	06:15–09:15	3444–2414	10	1622	+1.1
	O5 – 345	355	06:00–10:00	2423–4344	16	3148	−2.0
	O6 – 417	424	06:15–08:00	4241–4243–4344	10	967	−2.3
4	O1 – 0	0	04:30–10:45	4344–4241	7	2140	+2.8
	O2 – 96	142	06:00–09:00	1314–1211	11	1669	−1.8
	O3 – 109	165	06:15–10:00	3444–2423–2414	20	4030	−3.7
	O4 – 154	226	06:45–09:45	2414–1323–4344	15	2404	−2.4
5	O1 – 85	132	06:00–10:15	1323–2414	11	2631	−2.6
	O2 – 94	114	06:00–09:30	3323–3444	11	1994	+0.8
	O3 – 96	104	06:30–09:45	1211–1314	9	1660	+6.4
	O4 – 179	183	06:15–09:00	4344–4241	10	1476	+0.5
	O5 – 228	238	06:15–09:00	2414–2434–4434	10	1477	+0.4
	O6 – 290	309	09:00–11:00	2414–3444	7	830	+0.0
6	O1 – 51	124	06:45–10:15	1211–1314	10	1641	−5.0
	O2 – 112	209	06:00–11:30	3444–3323–2324–1424	10	2432	+0.2
	O3 – 181	442	06:00–10:15	2414–2423	6	1732	+13.5
	O4 – 408	885	06:00–11:30	3444–3323	11	2911	−0.1
	O5 – 459	463	07:45–09:30	4241–4344	9	972	+2.1
7	O1 – 1	71	06:00–09:45	3444–3323–2414	22	4284	−1.5
	O2 – 196	320	06:15–09:45	2414–2324–3444	20	3725	−0.6
	O3 – 369	375	06:45–10:15	1314–1211	11	1801	−5.1
8	O1 – 160	184	06:15–11:00	4241–4344	8	2025	+7.8
	O2 – 285	300	06:30–09:45	2414–3444	10	1720	+1.1
	O3 – 365	375	06:15–10:30	3323–3334–4434	10	2257	+5.8
	O4 – 432	457	06:00–09:30	1314–1323	10	2081	+0.6
	O5 – 516	536	07:30–12:00	1211–1314	2	550	+19.1
	O6 – 844	869	06:15–09:45	1211–1314	8	1534	+5.2
9	O1 – 19	111	06:30–10:00	4344–4241	11	1896	−1.9
	O2 – 272	420	06:00–09:45	3444–2423–2414	16	3259	−0.2
	O3 – 619	645	06:00–10:00	2414–1323–2324	13	3043	−0.5
	O4 – 771	778	06:45–10:00	1323–3444–2414	13	2164	−3.3

Table 5.17: Results of grid scenario 10min

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 1	30	06:00–10:00	2423–2414	5	1223	+2.6
	O2 – 29	41	06:15–12:15	4241–3444	7	2054	+1.9
	O3 – 101	108	06:00–08:45	3444–3424–2414	17	2744	+5.4
	O4 – 339	342	06:15–09:45	3141–2111	15	2230	−10.9
	O5 – 767	845	06:00–10:30	1314–1211	17	3841	+1.6
	O6 – 879	897	08:15–11:45	3444–2414	5	929	+2.0
1	O1 – 0	104	06:00–11:00	4241–4344	15	3839	+4.5
	O2 – 74	107	06:00–09:30	3444–2414	18	3169	−0.7
	O3 – 128	360	06:15–10:30	2414–1323	5	1336	+5.5
	O4 – 833	891	06:15–10:45	1211–1314	14	3293	+5.2
	O5 – 854	858	07:15–10:00	2111–3141	15	2455	+6.4
2	O1 – 18	27	06:15–10:00	1211–1314	16	3550	+11.1
	O2 – 32	90	06:30–09:30	4241–4344	20	2857	−4.8
	O3 – 33	167	06:45–09:45	3444–3424–2414	14	2397	+5.4
	O4 – 73	206	06:00–10:00	2414–1323–3444	11	2585	+9.2
	O5 – 544	548	06:45–09:30	2111–3141	15	2084	−2.7
3	O1 – 0	293	06:00–11:00	4344–4241	16	3720	−3.9
	O2 – 5	238	06:15–11:30	2414–4344	4	1020	+0.2
	O3 – 108	108	07:30–09:15	3141–2111	18	1895	+1.1
	O4 – 208	214	06:45–10:00	1314–1211	13	2345	+4.9
	O5 – 809	838	06:15–10:15	2414–1323	8	1800	−2.3
4	O1 – 18	122	06:00–10:45	1211–1314	18	4121	−0.8
	O2 – 76	121	06:00–10:30	4241–4344	20	4403	+0.0
	O3 – 95	159	06:45–09:45	3444–2414	20	3119	−0.2
	O4 – 116	124	06:15–09:45	2111–3141	21	3726	−0.3
5	O1 – 39	56	06:30–09:30	1314–1323	5	1099	+11.4
	O2 – 102	267	06:15–10:00	2414–3444	16	3009	−2.2
	O3 – 176	187	06:00–10:15	1314–1211	18	3576	−4.2
	O4 – 263	267	06:15–10:15	4344–2423	17	3387	−1.4
	O5 – 720	720	07:30–09:45	2111–3141	12	1485	−0.1
6	O1 – 13	385	06:15–11:15	1314–1323	6	1561	−7.4
	O2 – 33	692	06:15–09:45	1211–1314	21	3383	−6.4
	O3 – 197	213	06:00–10:00	2414–3444	22	4194	−3.3
	O4 – 367	728	06:15–09:30	4344–4241	15	2971	+11.5
	O5 – 563	563	07:15–09:45	2111–3141	12	1636	+0.3
7	O1 – 14	380	06:15–10:30	1314–1413–1211	16	3570	+4.5
	O2 – 51	564	06:00–10:30	3444–2414	19	4497	+5.8
	O3 – 63	128	06:30–10:45	4241–4243–4344	10	2720	+22.5
	O4 – 704	841	06:00–10:15	2414–1323	7	1437	−12.1
8	O1 – 32	230	06:00–10:15	3444–3323	17	3518	−1.5
	O2 – 69	108	06:30–10:15	3444–2414	13	2453	−0.1
	O3 – 106	167	06:15–10:30	2414–1323	8	2183	+8.9
	O4 – 764	774	06:30–11:00	1314–1211	12	2681	+1.2
	O5 – 858	867	08:30–11:00	3141–2111	6	842	+1.8
9	O1 – 27	44	06:30–10:15	2111–2131–3141–4131	13	2540	+2.5
	O2 – 42	469	06:00–11:00	2414–2333–4344	29	6911	−1.5
	O3 – 369	390	06:15–10:30	1211–1213–1314	22	4498	−3.1
	O4 – 582	835	06:30–10:45	2324–2423	4	1155	+2.4

Table 5.18: Results of grid scenario 60min

Run	Operator Est. in I.	Iteration of Opening	Time of Operation	Route	Veh	Trips	Profit per Veh [¤]
0	O1 – 36	166	06:00–09:45	1211–1314	22	3958	−3.4
	O2 – 42	138	06:15–10:30	3141–2111–2131	17	3265	−6.5
	O3 – 239	315	06:15–10:45	2414–3444	19	4692	+9.6
	O4 – 313	324	06:30–10:30	4241–4344	20	3946	−0.7
1	O1 – 0	26	06:00–11:15	4241–4344	16	4010	−1.0
	O2 – 39	278	06:00–10:00	2414–2434–3444	21	4417	+3.8
	O3 – 190	256	06:30–10:30	1314–1211	21	4045	−2.5
	O4 – 197	201	06:15–09:30	3141–2111	19	3184	+0.3
2	O1 – 0	541	06:00–10:30	4344–4241	17	3939	+4.0
	O2 – 17	787	06:15–10:15	1314–1211	19	3892	+1.6
	O3 – 42	688	06:00–11:45	3444–2414–1314	9	2543	+1.8
	O4 – 109	145	06:00–10:15	2111–3141	22	5004	+6.2
3	O1 – 43	153	06:00–10:15	1211–1314	23	4970	−0.1
	O2 – 86	120	06:15–10:15	2414–3444	23	4483	−1.8
	O3 – 774	774	06:45–09:15	1314–2313	3	482	+0.8
4	O1 – 0	165	06:00–11:00	4241–4344	17	4295	+3.2
	O2 – 37	103	06:00–10:00	2111–3141	26	4967	−3.2
	O3 – 45	198	06:15–12:15	2414–3444–4344	8	2320	+1.2
	O4 – 61	167	06:00–09:15	1211–1314	18	3186	+3.7
5	O1 – 4	47	06:30–10:00	1211–1314	23	3966	−2.1
	O2 – 29	330	06:15–10:15	4241–4344	22	4487	+1.6
	O3 – 162	336	06:15–10:15	3444–2414	25	4960	−0.4
	O4 – 228	318	06:15–09:00	3141–2111	18	2680	+1.1
6	O1 – 4	118	06:15–10:30	2414–3444	22	4479	−2.2
	O2 – 71	238	06:00–15:30	1314–1211–2111–1213	7	3036	−4.3
	O3 – 707	840	06:15–10:15	4241–4344	26	5360	+2.4
	O4 – 791	797	06:45–10:45	2111–3141	14	3221	+10.5
7	O1 – 13	47	06:30–09:45	1211–1314	24	4065	+0.6
	O2 – 66	266	06:00–09:45	4241–4344	18	3707	+6.6
	O3 – 134	228	06:45–10:00	2111–3141	21	4036	+9.3
	O4 – 146	279	06:00–09:15	2414–3444	22	3296	−6.4
8	O1 – 53	374	06:00–12:00	3141–2111–1211	10	2755	−2.3
	O2 – 87	155	06:15–12:00	4344–4241–3141	10	2782	+1.5
	O3 – 417	442	06:00–10:00	2414–3444	23	4178	−6.7
	O4 – 453	561	06:15–10:45	1211–1314	18	3839	−4.2
9	O1 – 0	178	06:00–11:15	4241–4344	17	4080	−5.0
	O2 – 61	187	06:15–10:45	3141–2111	15	3818	+12.3
	O3 – 179	402	06:15–10:45	1211–1314	19	4069	−2.3
	O4 – 776	845	06:15–09:45	3444–3424–2414	23	4062	−0.3

5.4 Summary

The sensitivity studies of this chapter demonstrated that the model is able to generate plausible *routes* in illustrative scenarios. These transit lines reflect the most important characteristics such as finding market niches and operating demand-oriented under severe competition. The high number of iterations used in the sensitivity studies may not be feasible for larger real-world scenarios. However, the high number was chosen for demonstration purposes and earlier iterations proved to provide similar and sufficient solutions. With the basic functionality proved, the following two chapters will apply the model to larger real-world scenarios.

CHAPTER 6

Case Study I: The South African case

What time is it? Who cares, it's African Time.

Caraline Harshman (2011) on the perception of time in general and the unreliability of minibus services in particular

The sensitivity analyses in chapter 5 demonstrate the functionality of various parts of the minibus model when using illustrative networks. This chapter summarizes the minibus model's first application to a large-scale scenario. The work started as a master thesis of Daniel Röder (2013) supervised by the author of this thesis. An enhanced version got finally published in Neumann et al. (2015). During his stay at the University of Pretoria Daniel Röder has set up the minibus model to work with Johan W. Joubert's existing scenario of the Nelson Mandela Bay Area Municipality. Thus, credits for the scenario itself and its integration into a South African context go to Johan W. Joubert and Daniel Röder, respectively. Since the focus of this thesis lies on public transport planning and not on the simulation of real minibus networks, the following sections give only a summary of the work done. For the full description, the reader is referred to Röder (2013) and Neumann et al. (2015).

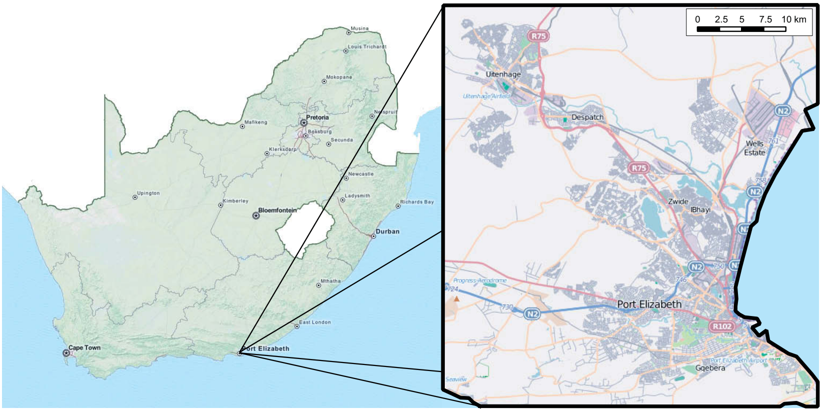
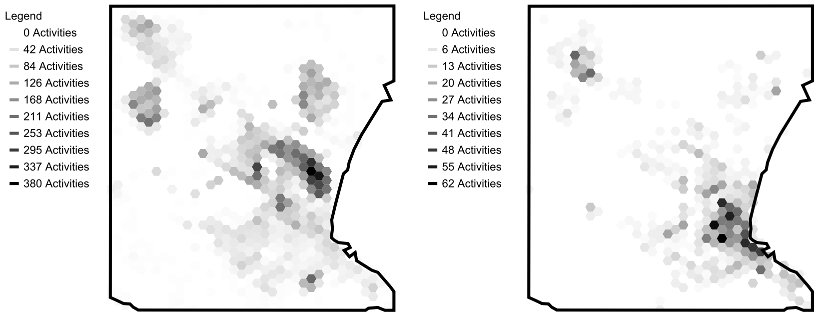


Figure 6.1: The location of the scenario area at the south-eastern coast of South Africa. The map data is taken from OpenStreetMap (2012).

6.1 Scenario description

The scenario is situated in the Nelson Mandela Bay Area Municipality (NMBM) and comprises the city of Port Elizabeth and its surroundings, see Figure 6.1 for an overview of its location within South Africa. The travel demand of the scenario includes 11,498 agents conducting about 3,600 trips by car and 9,300 trips by minibus. This is a 1 % sample drawn from a larger 100 % scenario of the NMBM. The original 100 % scenario features about about 1.2 million agents and is based on Census data and a 24-hour trip diary of approximately 1 % of NMBM's population. The 1 % sample has been drawn with respect to the characteristics of the population, i.e. age, sex, and mode share.

One of the legacies of the former *Apartheid* regime in South Africa is the location of informal and semi-formal townships on the periphery of cities and towns. These settlements are mainly occupied by low-income (black) citizens who cannot afford private vehicles for their daily commute. In the absence of reliable formal transit, minibus services emerged as the dominant mode of transport serving these townships. Due to the remote location of townships, there is a high spatial diversification of home activities and work activities as the density plots of Figure 6.2 reveal. The townships show the highest density of home activities whereas the central business district (CBD) of Port Elizabeth located in the south-east shows the highest concentration of work activities.



(a) Activity type home

(b) Activity type work

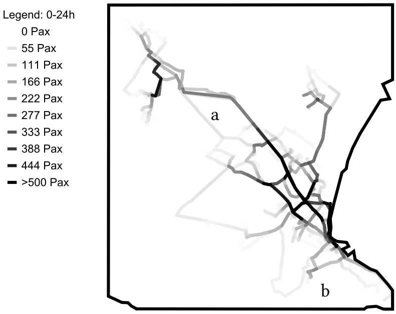
Figure 6.2: Distribution of activity types within the scenario area

The scenario's network is generated from OpenStreetMap (2012) data and contains 39,507 links. Minibuses are allowed to stop at all road sections with a speed limit of 80 km/h or less. The minibus model is set up with 35 operators, each starting with 21 minibuses. Each minibus can hold two passengers. Note that the actual capacity of 16 passengers could not be scaled down to 1 %, i.e. 0.16 pax, mainly for two reasons. First, the multi-agent simulation of MATSim treats passengers as agents. Thus, only whole passengers can be simulated. Second, a capacity of 1 pax does only allow for two different states of the vehicle, i.e. fully loaded or completely empty. Thus, the capacity has been further increased by one passenger in the master thesis.

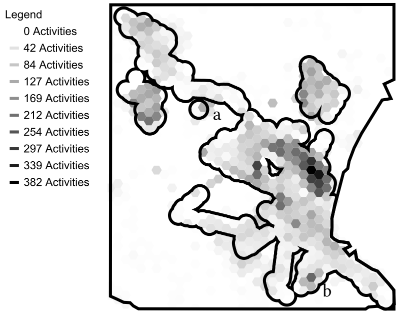
In contrast to the model description of subsection 3.2.2, agents using minibus services cannot transfer to different public transport modes. This design has been motivated by the fact that in the South African context minibuses serve a completely different segment of customers than for example bus rapid transit (BRT) systems. Thus, the public transport mode of an agent's trip is preset and cannot be altered or be mixed with other modes.

6.2 Results

The final minibus network consists of 87 *routes*. Three different types of *routes* can be distinguished by their pattern. Local *routes* access neighborhoods through a dense network. Feeders provide services from nearby townships to the city's center. Long distance services connect the north-western part of the



(a) Resulting minibus network and the combined number of passengers served by overlapping minibus routes



(b) Area within a 1000 m walking distance from a minibus stop with underlying combined density of home and work activities

Figure 6.3: Passenger volumes and coverage of minibus services

scenario area to the CBD. Since passengers board every minibus regardless of its pattern, all minibus *routes* form one single network. Consequently, the frequency of the services is additive, i.e. two *routes* serving the same road section with the same headway effectively double the frequency on that road section. The maximum number of passengers served per road section is 1276 passengers. However, this occurs only at one single intersection. Therefore, to have a better overview, the maximum in Figure 6.3a is set to 500 pax. For trunk roads, numbers range from 300 to 800 passengers which roughly scales up to 30,000 to 80,000 passengers per day for the 100 % scenario.

Comparing the minibus network with the density plots of Figure 6.2 demonstrates how the minibus connects the activity centers. High-demand areas are served as well as low-demand areas whereas areas without any demand are left out completely. Moreover, nearly all areas showing activities can be reached within a 1000 m walk from a minibus stop, see Figure 6.3b. This also includes high-density remote areas like Khaya Mnandi and the Walmer-Township, depicted with a and b in Figure 6.3, respectively.

Note that the minibus will not stop at road sections with a speed limit of more than 80 km/h. Thus, road sections may not be covered by the shown catchment area despite indicated otherwise by the passenger loads in Figure 6.3a.

Overall, from personal knowledge of Johan W. Joubert and through verbal confirmation with the areas only formal bus operator, Algoa Bus (2014), the *routes* seem very plausible. The network evolves according to the constraints of the input data given. The results of the ensemble run (Röder, 2013; Neumann et al., 2015) show a similar number of *routes*, passenger loads and service coverage. The network density and variety of minibus *routes* are a function of the given fare structure and cost structure of the operators, see Appendix C for experiments with fares.

The minibus-specific behavior is, arguably for the first time, integrated into an existing multi-modal transport model. The model can test for reactions from all types of stakeholders, e.g. route associations for different fare schemes. Drivers and vehicle owners react to their environment by changing their routes, operating times, and number of vehicles. Transport planners and policymakers can use the minibus model to analyze the implications of policy measures like the currently debated implementation of a minibus (taxi) subsidy (van Rensburg, 2013). Furthermore, Joubert (2013) points to a case in which the newly introduced formal BRT is jointly operated, and owned, by the minibus operators. Normally, introducing a new high-capacity BRT line raises the question of how many minibus drivers and owners are concerned, e.g. face unemployment. The model can help to give an answer and can thus, support negotiations on the number of minibuses that will be removed from the BRT line's corridor.

6.3 Discussion

The minibus model is able to grow networks that represent the coverage and the main characteristics of the real minibus system of the NMBM. Moreover, it reflects the minibus users' travel pattern. However, validation data is sparse and thus the actual results have to be regarded as a demonstrator. With more reliable validation data being available the model's accuracy can be further improved and validated. For example, the research group of Johan W. Joubert is currently conducting field studies to explore the minibus network in Pretoria, South Africa. However, first results indicate that parts of the network are too dangerous to be logged by students with GPS devices because of conflicts among taxi associations.

With the focus on South African minibuses, the model can be further enhanced to incorporate more local specific travel behavior. This includes, for example, ceasing service outside the peak hours or a more sophisticated boarding behavior at the taxi ranks (termini) to reflect the drivers' tendency to depart only with nearly fully loaded minibuses. Furthermore, minibuses in South Africa may need a license before serving a certain relation, so future implementations should depict for the fact that it is not an open market, i.e. operators are not allowed to extend their services at will but only according to the license hold.

Last, while minibuses in the model show a certain diversification of service types, the boarding passenger does not mind. In South Africa, different services may charge different fares. Thus, passengers pick their minibus based on destination and related costs. Knowing that the fare is charged per boarding regardless of the distance traveled, passengers are more willing to board a local minibus if it serves the same trip with equal or better quality. A first step into that direction is the recent implementation of fares into MATSim's router architecture. A second step would be the implementation of a detailed decision model – based on intrinsic motivation and personal income – to represent the agents reaction to changes of the system.

CHAPTER 7

Case study II: The first transit authority case

> The existing travel demand models have a substantial focus on transportation issues and they observe the society from that limited perspective. That is the reason that people from fields other than transportation look at the disaggregate integrated transportation and land use models, which are the most complex framework in analyzing the transportation system, as a handicapped creature which has a large organ in one part but inappropriately developed organs for other parts.
>
> *Rashidi and Kanaroglou, 2012*

The minibus model's first application to a real world scenario in chapter 6 focused on the creation and simulation of real minibus networks in South Africa. This chapter features the application of the model to a real world planning problem of a public transport company in Berlin, Germany.

7.1 Background

The Berliner Verkehrsbetriebe (BVG) is Berlin's main public transport company and runs all kind of services with the exception of the S-Bahn urban rail system. This includes bus services, the subway network, the largest tram network of Germany as well as ferry services. The bus network consists of 149 different lines, 6468 directed stops and a vehicle fleet of 1316 buses (BVG, 2012b). In total, about 937 million trips were served by BVG in 2012, 41 % of them by bus.

With the opening of the new international airport of Berlin and Brandenburg BER, Berlin is expecting some major changes in travel demand. Especially, the existing airport Tegel, currently exclusively served by buses operated by BVG, will cease operations. BVG had thus a large interest in a new transport model for the Berlin area. Due to the big changes, the model should not only deliver the basis for future planning of the regional transport system, but has to provide detailed information about passenger flows of different user groups as well. Such user group specific analyses are considered of high importance for the BVG in order to provide a basis for their future business strategies, which is why an agent-based model was specifically requested. Two scenarios were actually asked for, one for the year 2008 (actual state), and one for the year 2015 (prediction). To fulfill the needs mentioned above, the team of PTV (2013a), Senozon (2013) and VSP (2012) at Technische Universität Berlin (TU Berlin) offered a combined model consisting of both a static macroscopic model built with PTV VISUM (PTV, 2013c) as well as an integrated activity-based demand and dynamic traffic assignment model built with MATSim (2013). During the project, attention was given that both models were based on the same data sources and that both modeling processes interact with each other to allow data exchange between the two models.

In this thesis, the MATSim model for the year 2008 is used. In brief, the model contains about 115,000 links, about 15,000 directed stops, 6.0 million agents, and 539 public transport lines operated by BVG and other companies of the city of Berlin and the state of Brandenburg. For a more in-depth description of the model, its generation and its calibration, the reader is referred to the work of Neumann et al., 2014.

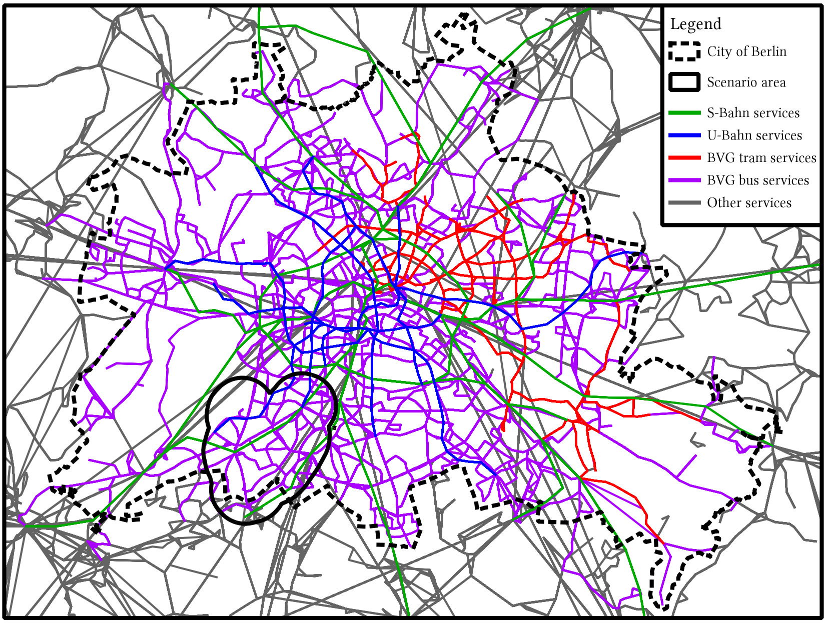


Figure 7.1: Public transport network of the city of Berlin — The category "other services" includes bus and tram services not operated by BVG as well as ferry services and non-commuter rail services.

7.2 Scenario description

As depicted in Figure 7.1, the model includes public transport services all over the city of Berlin as well as some parts of Brandenburg. The scenario area is located in the south-west of Berlin. It covers the eastern part of the district of Berlin Steglitz-Zehlendorf and the town of Teltow in Brandenburg.

Based on the relaxed model of the actual state of 2008 (Neumann et al., 2014) a diluted 100 % scenario is created. That is, compared to the original scenario, only the demand changes. Infrastructure like network and public transport supply are used without any further adaptation. For the demand, all agents "touching" the scenario area as depicted in Figures 7.1 and 7.2 are kept in the population of the scenario. All agents not "touching" the scenario area are removed. An agent "touches" the scenario area, if it passes over one of the scenario area's street sections. This includes all agents using a private car or one of the public transit vehicles but not agents using one of MATSim's

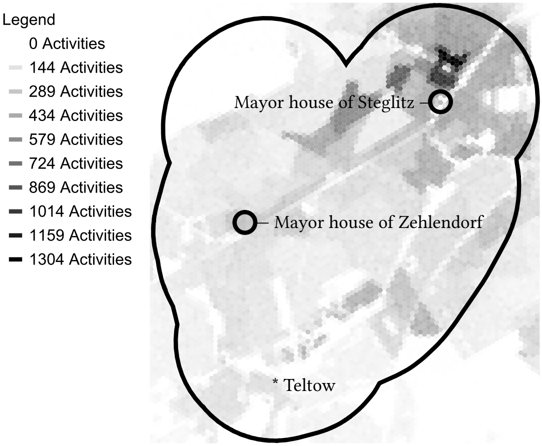
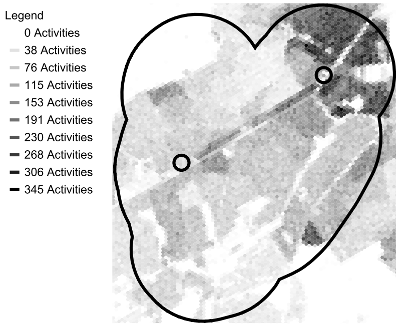


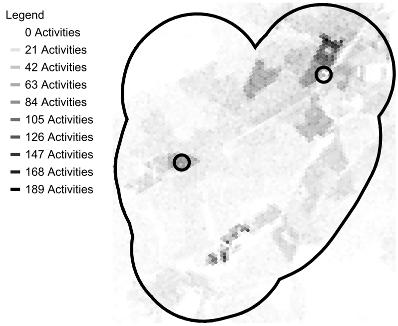
Figure 7.2: Distribution of activities within the scenario area

teleported modes, i.e. walking, cycling, and long distance access and egress walks to access public transport. This does not automatically include all agents with an activity within the area. For example, activity types defined by the underlying household survey may be linked by walking trips only. In this case, the agent has no impact on other agents and thus can be removed. Contrarily, activities related to public transport, e.g. boarding, transferring, and alighting, imply using a transit vehicle and are thus included. With this definition, the total demand can be reduced to about 10 percent, i.e. from about 6 million to 593,337 agents.

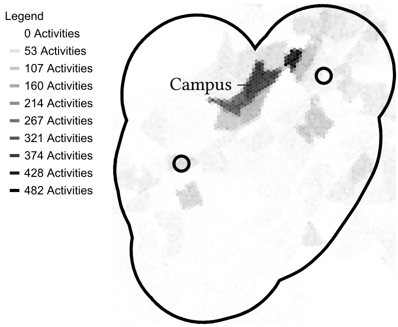
To better understand the demand of the scenario area, Figure 7.2 features the density plot of all activities of the scenario's demand and for later reference the two mayor houses of Steglitz and Zehlendorf. The area is divided into hexagonal zones and all types of activities of the household survey are counted per zone. Activities related to public transport are omitted. From the distribution one can clearly see that the area is mono-centric with the commercial district along Schloßstrasse north of the mayor house of Steglitz featuring the highest densities of up to 1304 activities per zone. Furthermore, activities outside the scenario area are preserved, if they belong to an agent "touching" the area. The complementary figures of Figure 7.3 reveal the different distribution patterns for the activity types home, work, education,



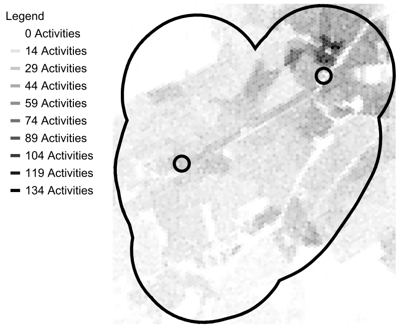
(a) Activity type home



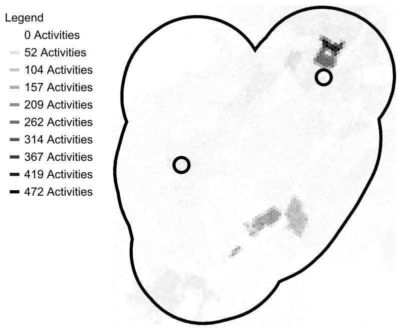
(b) Activity type work



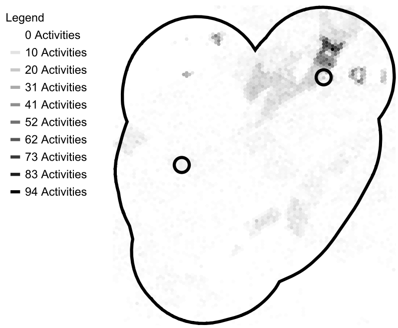
(c) Activity type education



(d) Activity type leisure



(e) Activity type shopping



(f) Activity type tourist

Figure 7.3: Distribution of activity types within the scenario area

leisure, shopping, and tourist. With the help of those figures one can distinguish high-density living quarters from more rural places, and identify shopping centers, remote tourist hotspots as well as the main campus of Freie Universität Berlin.

Discussion of the diluted scenario approach Extracting a scenario from a calibrated model always poses the problem of where to cut and which demand to preserve. Thus, the easiest way is to simply simulate the complete demand and later on restrict the analysis to the actual scenario area. However, this comes with the heavy price tag of computational resources. The alternative of the diluted scenario approach as used in this thesis tries to distinguish between agents with and without impact to the scenario area. However, some agents might influence the traffic within the scenario area indirectly. This is especially the case, if a removed agent frees capacity on an alternative route which circumvents the scenario area. In consequence, other agents might opt for the alternative route freeing capacity now within the scenario area itself. However, the scenario area is chosen in such a way as to not be largely affected by this issue, e.g. the inner-city motorway of A100 running north-west of the area does not provide a real alternative to passing through the area directly. The same argument holds for the public transport services running in parallel to the motorway. Their capacity can be regarded as infinite and their impact thus be neglected.

7.2.1 Configuration of the scenario

The configuration for the diluted scenario uses the same MATSim configuration of the base model (actual state of 2008) with the exception of the agents' replanning modules. In contrast to the base model, agents in the diluted scenario cannot change the mode of transport anymore. The remaining strategies include searching for a new least cost path (30 %) and choosing one of the plans of the agent's choice set (70 %) with respect to a multinomial logit model. In total, the simulation runs for 400 iterations. After the 350th iteration, the rerouting option is discarded and the agents will always choose among their existing plans. The configuration of the minibus model is listed in Table 7.1. The scenario uses the same configuration for the route modification strategies as listed in Table 5.2 of chapter 5. The strategies of the minibus model are disabled in iteration 300. Afterwards, minibus operators can only manage the vehicle fleet and/or cease service on some of their *routes*. After

Table 7.1: Overview of the parameters used for the Berlin scenario. The parameters of the route modification strategies are listed in Table 5.2.

Parameter	Value
Minimum number of operators	10 operators
Target share of profitable operators	90 %
Number of iterations for prospecting	10 iterations
Initial number of vehicles	5 vehicles
Service area	see subsection 7.2.2
Franchise system	Installed
Passengers per vehicle	10 pax
Passenger car equivalents	1.0 PCE
Delay per boarding passenger	2.0 s/pax
Delay per alighting passenger	1.0 s/pax
Cost per vehicle and day	100.00 ¤
Cost per vehicle and hour	10.00 ¤
Cost per vehicle-kilometer	0.30 ¤/km
Price per vehicle bought or sold	500.0 ¤
Earnings per boarding passenger	0.50 ¤
Earnings per passenger-kilometer	0.00 ¤/km

iteration 250, no new operators are founded, i.e. there is no more competition from new operators entering the market.

7.2.2 Three different setups

The same input data and configuration is used with three different setups of the scenario called *Reference*, *Corridor*, and *Area*.

Reference The first setup uses the unmodified transit schedule and disables the minibus model. The derived travel pattern reflects the status quo and is later compared to the *Corridor* and *Area* setup.

Corridor The second setup removes one single bus line from the transit schedule – namely line 285. The removed line and all its subroutes are depicted in Figure 7.7b. Minibuses can only serve passengers within a 100 m buffer around the removed line. That is, they can serve all formal transit stops within that buffer. Otherwise, they are not restricted. A minibus operator can decide to ply outside the buffer. In this case, its vehicles are not allowed to pick up or drop off any passengers as long as the vehicle is outside the buffer. Therefore, it is possible to offer a direct non-stop connection between the two termini of the removed bus line 285. However, this connection needs to attract enough direct demand to be profitable.

Area The third setup removes all bus lines operated by BVG from the scenario area. That is, lines operating only within the scenario area are removed completely. Lines starting or ending within the area are truncated so that they start and end at the first stop of the scenario area. The departures of the remaining parts of the lines are modified in such a way that the transit supply outside the scenario area isn't altered compared to the original transit schedule. The transit network of the *Reference* setup and the final transit network of the *Area* setup are shown in Figure 7.4a and Figure 7.4b, respectively.

An ensemble run is performed for the *Corrdior* and the *Area* setup. Each ensemble run consists of ten runs with identical configuration and input data. Only the initial random seed is varied. The heuristic of the minibus model is then able to produce different results with the same initialization. The results of the ten runs of one ensemble run are fused to allow for a more reliable analysis and to identify stable and repeating solutions.

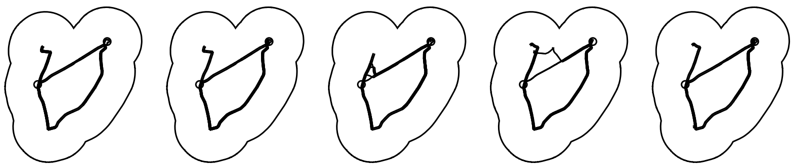
7.3 Results of the Corridor setup

The *Corridor* setup with its 100 m buffer restriction does not allow for numerous network designs. Figure 7.5 shows the final minibus networks of each of the ten runs for this setup. In nearly all runs, the combined *routes* cover the same street sections as the original bus line 285. However, in three out of ten runs, run 2, 5, and 8, the section from Oskar-Helene-Heim northbound to Am Waldfriedhof is missing, see Figure 7.7b for this section's actual location. This clearly emphasizes the necessity of ensemble runs. From the results of run 0 alone, one would probably establish an additional bus service to cover this section as well. The ensemble run indicates that there should be a further analysis. In addition, a direct non-stop connection between the two mayor

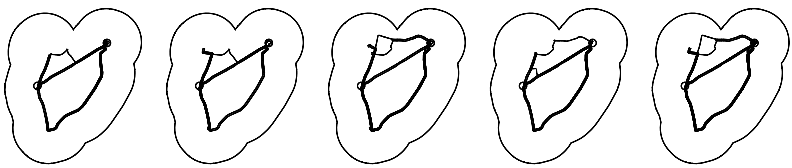
(a) Public transport services in the *Reference* setup

(b) Public transport services in the *Area* setup. All bus lines operated by BVG within the scenario area are removed.

Figure 7.4: Comparison of public transport service of the *Reference* setup and the *Area* setup. Scenario area (black), U-Bahn services (blue), S-Bahn services (green), BVG bus services (purple) and other services (orange).



(a) Run 0 **(b)** Run 1 **(c)** Run 2 **(d)** Run 3 **(e)** Run 4



(f) Run 5 **(g)** Run 6 **(h)** Run 7 **(i)** Run 8 **(j)** Run 9

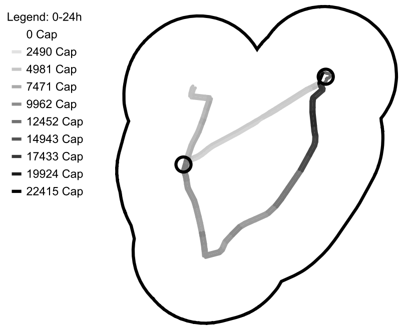
Figure 7.5: Resulting lines for the *Corridor* setup. Minibus services are restricted to a buffer of 100 m around the removed bus line 285.

houses prevailed in all runs. This indicates that there is enough demand preferring a direct connection to run a profitable minibus service and that the minibus in the model can compete the parallel bus and S-Bahn services.

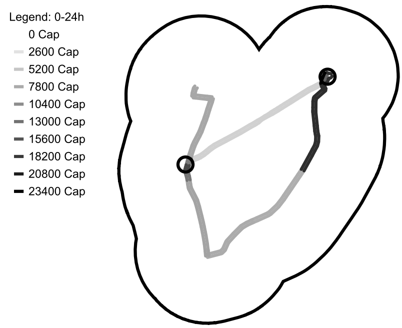
The final networks give a rough estimate of where to put a new bus line replacing the 285. However, the network alone gives no further information on the quality of the service. For example, bus lines not operated by BVG often form a network of high coverage, see the orange lines in the southern part of the scenario area in Figure 7.4a. But in terms of service frequency, some of those lines may only feature a few departures per day. The reason lies in the rural character of the service area. Some special locations as schools need to be linked to residential areas. However, this needs only be done during the morning hours when school starts and occasionally in the afternoon. Thus, the demand can be served with at most two departures. To estimate the quality of service, Figure 7.6 shows the provided capacity per street section and day. Knowing that the vehicle capacity is 10 pax per vehicle, the service frequency can be calculated by dividing the total capacity by ten. Thus, the figures show the different level of service for the corridor and sections with a high service frequency can be distinguished from low frequency sections.

Analyzing all capacity plots individually suggests high fluctuations of the results, e.g. the maximum value is 20,610 in run 8 and 25,830 in run 3. However, this is a direct result from minibus *routes* running in parallel, and, thus, stacking their capacity. For example, the extreme capacity of 25,830 in run 3 actually only occurs on one single intersection near the mayor house of Steglitz. The remaining sections provide a capacity of about 18,000 pax per day or less.

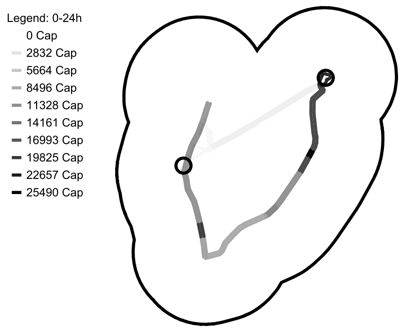
The capacity of the western trunk is only about the half of the eastern one. In addition, all runs provide further increments in capacity on the eastern trunk with higher capacities towards the mayor house of Steglitz. However, all runs basically reestablish the removed bus line 285. That is, the whole corridor is served and the provided capacity is about the same for all sections. The additional capacity of the eastern trunk is induced by pirating passengers from existing parallel running bus lines. Minibus *routes* have the advantage of the high service frequency effectively luring away passengers from low frequency lines. The same holds true for the direct non-stop connection which attracts passengers from the various lines running in parallel. Since intermediate stops are not allowed for the minibus, the effective travel time is about 10 minutes shorter than the 16 minutes of the competing bus, resulting



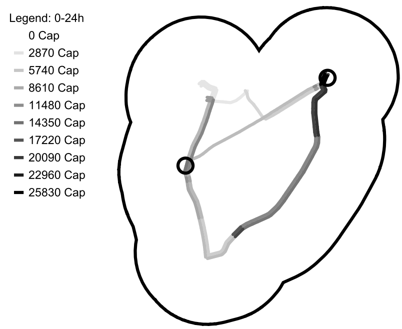
(a) Run 0



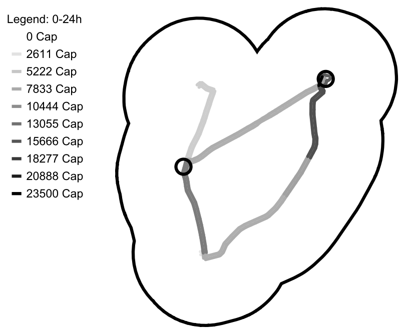
(b) Run 1



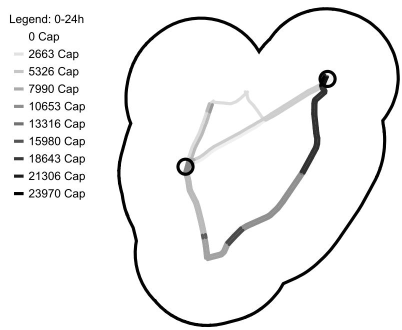
(c) Run 2



(d) Run 3

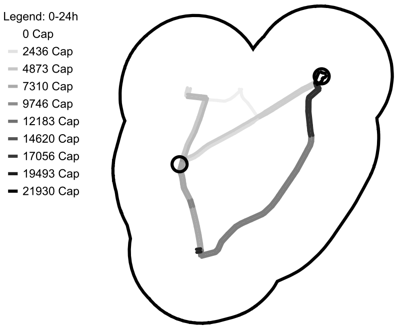


(e) Run 4

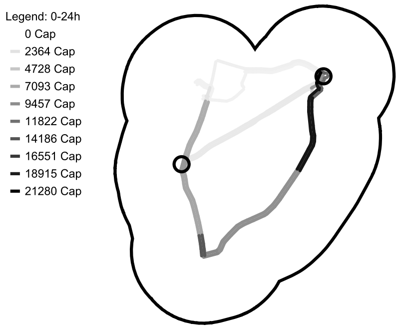


(f) Run 5

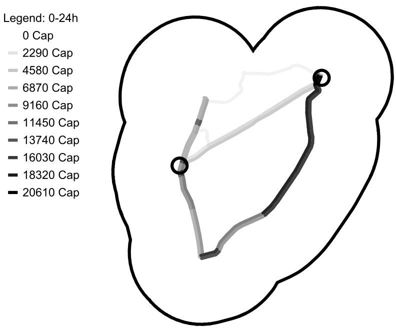
Figure 7.6: Provided capacity per street section for the *Corridor* setup



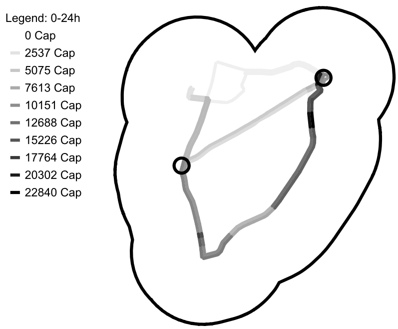
(g) Run 6



(h) Run 7



(i) Run 8

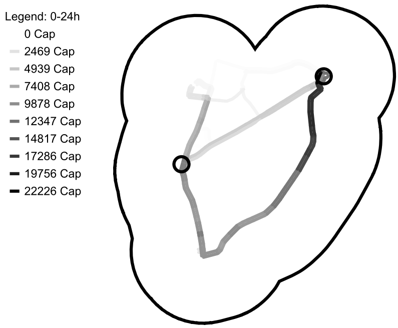


(j) Run 9

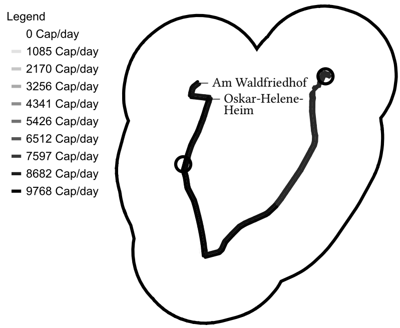
Figure 7.6: Provided capacity per street section for the *Corridor* setup (cont.)

in an even more attractive minibus. In fact, the minibus is even 2 minutes faster than the S-Bahn service offered on the same corridor.

Identifying the relevant corridors and services gets easier, if the ten individual solutions are fused into one plot. Figure 7.7a shows the average capacity of all ten runs for each street section. One-time solutions as the various alternatives to the direct non-stop connection from Steglitz to Zehlendorf have a considerably smaller resulting capacity compared to reoccurring solutions like serving the eastern trunk. As stated in the model's discussion of section 4.5, operators offer as much service as they can afford. This means that any capacity offered is also asked for. With the information given by the activity density plots of the Figures 7.2 and 7.3, the figure clearly shows how the



(a) Average provided capacity per street section of all ten runs of the *Corridor* setup

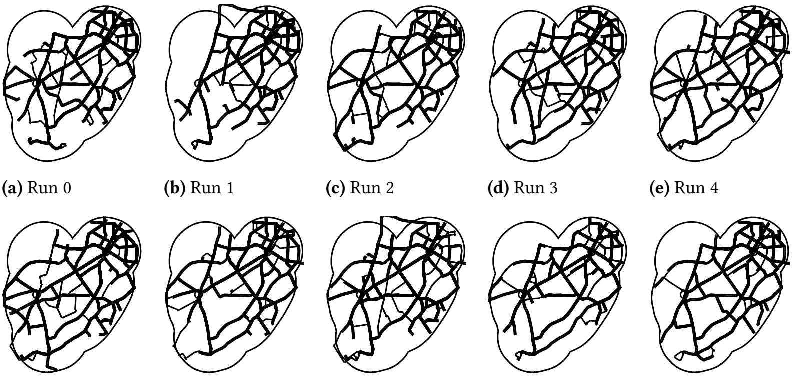


(b) Provided capacity per street section of the removed bus line 285

Figure 7.7: Comparison of provided capacity per street section — *Corridor* setup

minibus model adapts to the mono-centric demand by offering an asymmetric service on this corridor. Street sections towards the center around the mayor house of Steglitz have the highest capacity of about 17,000 pax per day and thus the highest demand. The capacity drops to 12,000 pax per day towards to south and further drops to about 10,000 pax per day northwards to the mayor house of Zehlendorf. The most northern trunk starting at Zehlendorf allows only for a minibus capacity of about 7,000 pax per day. This supports the consideration of dropping service of the bus line 285 entirely in favor of the remaining bus lines. Furthermore, the result of Figure 7.7a shows clearly that the northern variations of the direct non-stop service have no relevance compared to the other street sections.

For comparison, Figure 7.7b shows the same kind of plot for the removed bus line 285. The provided capacity of the western trunk is about the same as in the minibus solution. Accounting for the parallel lines on the eastern trunk, the capacity of the removed line 285 is somewhat lower. This is in contrast to the minibus, which does not head for a system optimum within the bus system, but tries to attract as much passengers as possible. Thus, the minibus does not account for existing capacities of other operators and, in consequence, offers higher capacities.



(a) Run 0 **(b)** Run 1 **(c)** Run 2 **(d)** Run 3 **(e)** Run 4

(f) Run 5 **(g)** Run 6 **(h)** Run 7 **(i)** Run 8 **(j)** Run 9

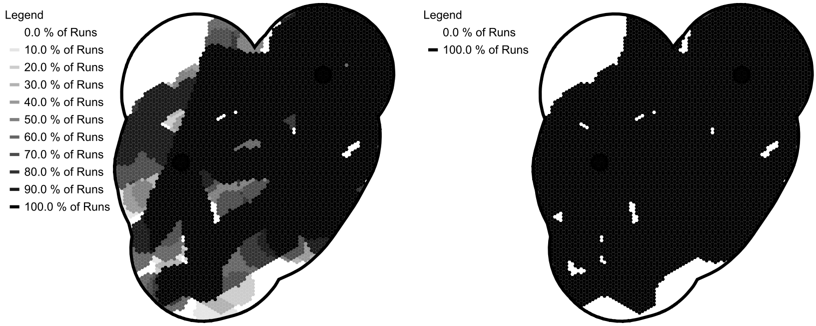
Figure 7.8: Resulting lines for the *Area* setup — Minibus services are restricted to the whole scenario area.

7.4 Results of the Area setup

In this setup, the minibus services can serve passengers within the complete scenario area. Passengers can board and alight a minibus at any formal bus stop within the area. Bus lines operated by BVG are truncated as described in subsection 7.2.2. Otherwise, the model runs with the same configuration and input data.

The resulting minibus networks of all ten runs of the ensemble run are shown in Figure 7.8. The plots show a dense network of minibus services in the area of the mayor house of Steglitz for all ten runs. Services in the south-west around Teltow face some competition by bus companies of Brandenburg. Accordingly, a more sparse minibus network evolves in this area. The majority of trunk roads is served in most runs. However, the secondary network which accesses the residential areas shows a variety of solutions.

Figure 7.9 shows the coverage of the minibus services and the *Reference* of BVG's bus lines. An area is considered as covered by a service if it can be reached by a short walk of 500 m or less. This definition derives from SenStadt (2007). The ten runs of the minibus model are merged into one figure, Figure 7.9a. A coverage of 100 % can only be reached if that particular area is served in all ten runs. Accordingly, the coverage decreases with each run the area is not served. 0 % means the area is not served in any run. For the western part of the scenario area, only trunk roads are served steadily.



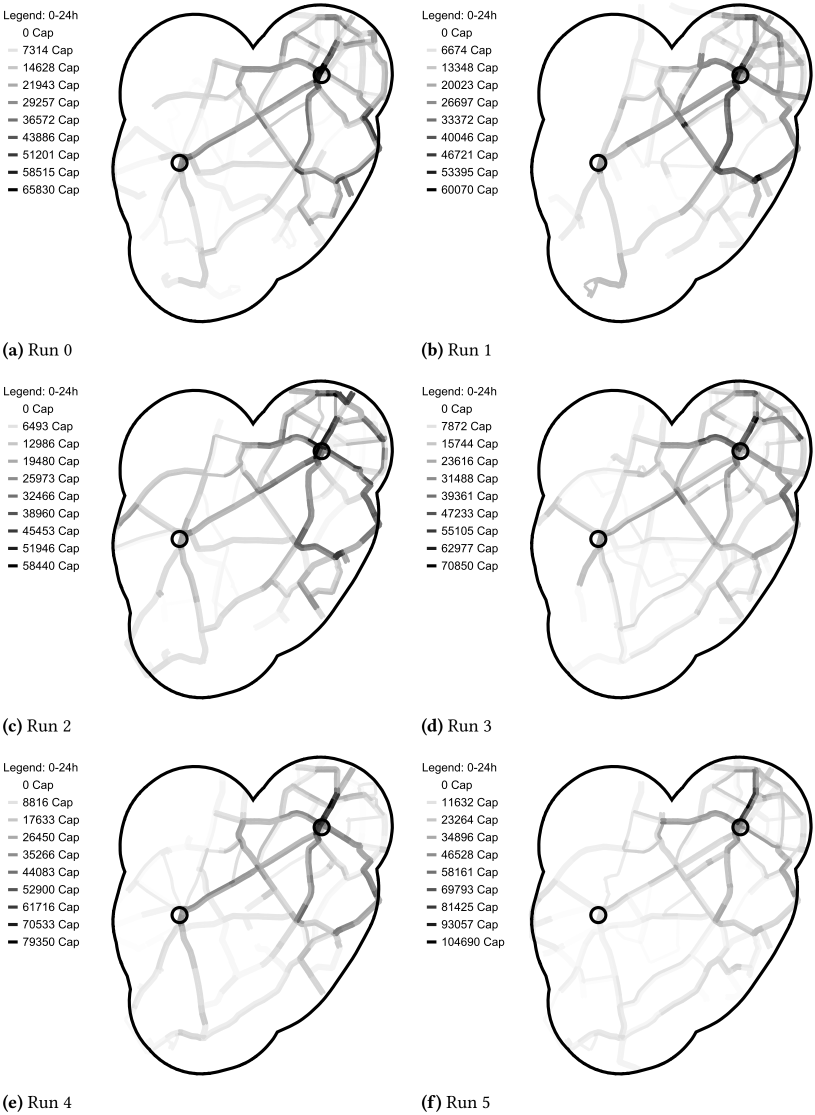
(a) The north-east is served in each run whereas the low-density areas in the south-east have a lower probability of being served by the minibus.

(b) Coverage of BVG's bus line in the reference setup

Figure 7.9: Coverage of minibus and BVG bus lines

This is mainly due to the lower density of activities. High density areas like the eastern part are served entirely. The comparison of the *Reference* setup in Figure 7.9b illustrates how BVG is forced to provide a constant coverage of bus services for the complete area. Note that in the single run of the *Reference* setup, an area can either be covered or not, i.e. 0 % or 100 %. Overall, the minibus yields the same coverage for the high-density areas. Low-density areas are served with a lower probability.

Since the network plots do not allow for assessing the quality of the service provided, Figure 7.10 features the same kind of capacity density plot for each run as in the *Corridor* setup. The plots reveal that the provided capacity on trunk roads is much higher than on secondary roads. This derives directly from the minibus model. Trunk roads are expected to be faster also in an empty network. Thus, the route searching algorithm of the operators has a higher probability to pick those roads. As in many cities, the major street network of Berlin and the centers of activity co-evolved over centuries (e.g. Levinson et al., 2007; Levinson, 2011, and the references therein). In consequence, trunk roads tend to link the centers of activity. With minibus operators having a higher probability to try out a stop near an activity center, the probability to connect centers and thus using trunk roads increases. However, it is still possible that an operator opts for secondary roads linking low density areas to the rest of the network. For example, an operator offering a service from the mayor house of Steglitz to the mayor house of Zehlendorf



(a) Run 0

(b) Run 1

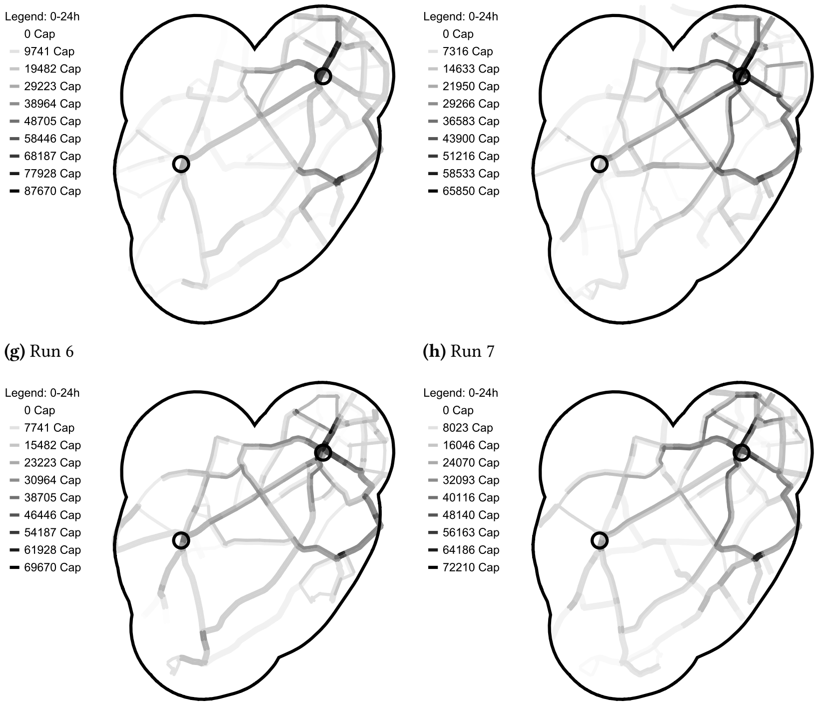
(c) Run 2

(d) Run 3

(e) Run 4

(f) Run 5

Figure 7.10: Provided capacity per street section for the *Area* setup — Minibus services are restricted to the scenario area.



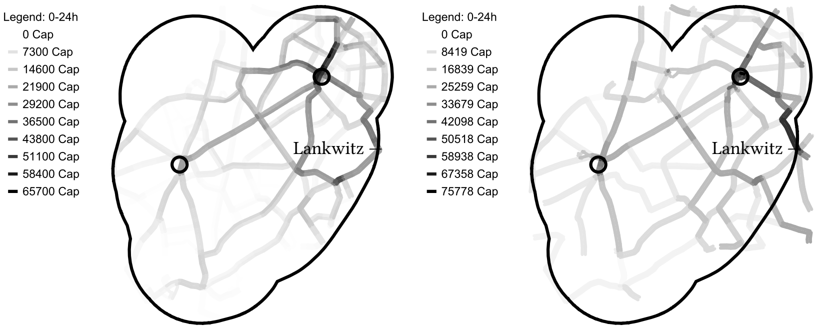
(g) Run 6 **(h)** Run 7

(i) Run 8 **(j)** Run 9

Figure 7.10: Provided capacity per street section for the *Area* setup — Minibus services are restricted to the scenario area. (cont.)

might try to detour by searching for a new stop located sideways of its *route*. Depending on the demand, this new *route* might be less profitable due to the additional distance traveled and the demand opting for a faster and more direct line of a competitor. Consequently, the detouring *route* offers larger headways and provides a lower capacity. Overall, a supplemental secondary minibus network might evolve, but this is more unstable in terms of the offered *routes*, i.e. the actual *route* may vary in each run.

Combining the individual runs of the ensemble run by averaging the capacity per day clearly illustrates which are the important corridors to provide service on. The combined plot in Figure 7.11a proves the area around the mayor house of Steglitz to be the main center of the scenario area. Again,



(a) Average provided capacity per street section of all ten runs of the *Area* setup

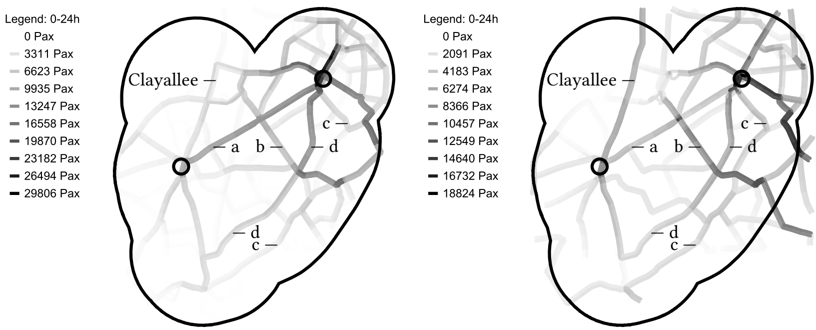
(b) Provided capacity per street section of all bus lines operated by BVG of the scenario area

Figure 7.11: Comparison of provided capacity per street section

the eastern trunk of bus line 285 has a similar capacity of 10,000 pax per day for street sections where the 285 has been the only service. On the farthest north-eastern section with competing lines of M85 and 283 the capacity is about 22,000 pax per day. To recall, in the *Corridor* setup, those competing lines were still present. In the *Area* setup, the minibus model compensates those missing services.

For comparison, Figure 7.11b shows the capacity per day plot for all bus lines operated by BVG as included in the *Reference* setup. Combined with the illustration of the transit network in place (Figure 7.4b) one can identify which market niches the minibus can possibly fill. For instance, the corridor from the S-Bahn train station of Lankwitz to the mayor house of Steglitz is a well established public transit service in both the minibus model and the real bus network. Unfortunately, the capacities provided cannot be compared directly. The minibus model comes up with capacities asked for. While the BVG bus network in place is limited by the vehicle fleet available and political constraints. However, the final combined capacity plot of the minibus model gives a good approximation as where to offer capacities.

The comparison of the number of passengers served in Figure 7.12 reveals similarities, e.g. along Berliner Strasse/Drakestrasse (depicted a and b, respectively) with 6,000–10,000 passengers in both the minibus model and the *Reference* setup. Deviations can be found along Clayallee (express bus line X10) and on the southern corridor (c) from Teltow to the mayor house of Steglitz



(a) Average number of passengers served per street section of all ten runs of the *Area* setup

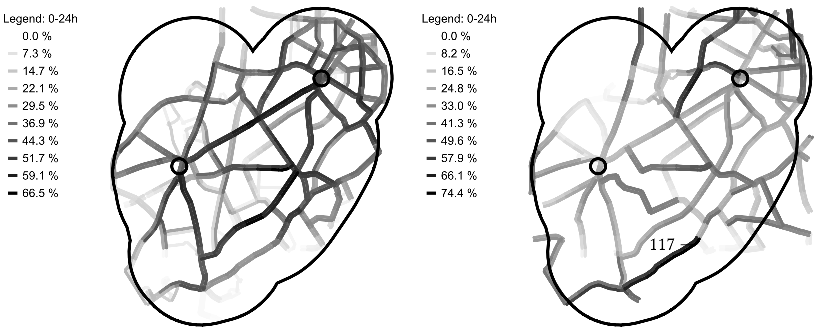
(b) Number of passengers served per street section of all bus lines operated by BVG of the scenario area

Figure 7.12: Comparison of the number of passengers served per street section

(bus lines 117 and 186). In the latter case, the demand switches to the northern corridor (d) which runs in parallel. Thus, there is an extra demand of about 2,000 passengers on the eastern trunk of the 285 compared to the *Reference*.

With some exceptions, the occupancy rate in the *Reference* setup is lower then the average occupancy in the minibus model, see Figures 7.13b and 7.13a. One exception is the aforementioned bus line 117 starting in Teltow with an occupancy of up to 75 % in the reference model. This is a low frequency line whose demand opted in the minibus model for the alternative northern corridor. The rest of the bus network shows an occupancy of about 25 to 40 %. This is slightly higher than figures from 2006 indicate (Reinhold, 2006). However, the distribution of high-occupancy and low-occupancy road sections show the same pattern. While the city-wide average of BVG's buses is about 16.5 %, figures for the area of Steglitz-Zehlendorf range from 10 % for the secondary network to over 35 % around the mayor house of Steglitz. Nonetheless, data derived from the Berlin scenario has to be compared with data from the same scenario. Thus, using the same input data, occupancy rates in the minibus model are higher and vary from 50 to 60 % for the primary network and about 40 % for the secondary network. Note that the average occupancy rate of 50 % is the direct result of the underlying cost function of the minibus operators.

As stated earlier, the heuristic approach of the minibus model demands multiple runs. The supply structures of the individual runs differ in details but the overall structures are similar. For instance, the histograms of Fig-



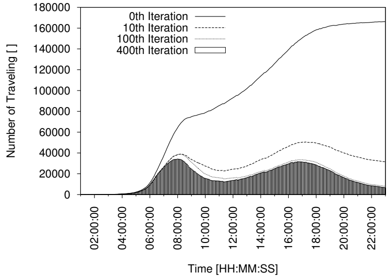
(a) Average occupancy per street section of all ten runs of the *Area* setup

(b) Occupancy per street section of all bus lines operated by BVG of the scenario area

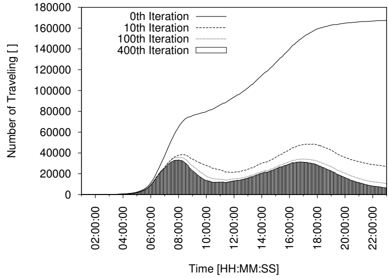
Figure 7.13: Comparison of the occupancy per street section

ure 7.14 show the number of passengers for the runs 0 and 1. In the very first iteration 0, both curves are identical since no minibus network evolved yet. As a consequence, many agents must walk. This results in long travel times and therefore large numbers of traveling agents in the evening. In later iterations, a minibus network evolves and the number of traveling agents in the evening decreases. However, the minibus networks of run 0 and run 1 evolve differently. Consequently, the curves of iteration 10 differ as well. Towards the last iterations, the different runs result in similar supply structures with nearly identical curves for the last iteration 400. For further comparison, Figure D.22 shows the histograms for the runs 2 to 9.

From the passengers' point of view, the resulting supply structures are nearly identical. The average score of the population of all ten runs only varies during the early iterations when the minibus network is still evolving, see Figure 7.15a. In later iterations, the variation diminishes. Note the small peak at iteration 350 when agents stop searching for new routes. The average score increases due to the agents less experimenting. Looking at the number of trips served in Figure 7.15b, the minibus services loose about 31,000 trips starting in iteration 350. This is caused by the agents opting for different *routes*. In particular, agents now stick to *routes* already in their choice set and manage to increase their score. On the other hand, the minibus operators do loose some trips and thus income. Consequently, the operators react by selling vehicles, see Figure 7.15d. The number of *routes* offered is not affected by the

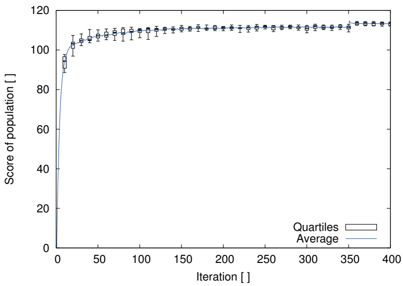


(a) Run 0

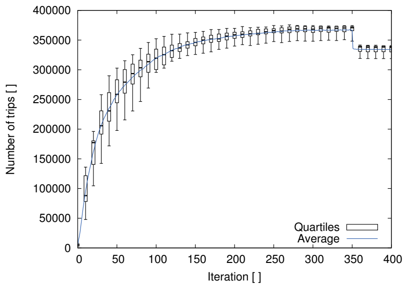


(b) Run 1

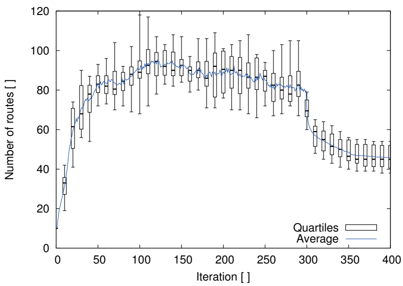
Figure 7.14: Histograms of traveling public transport users



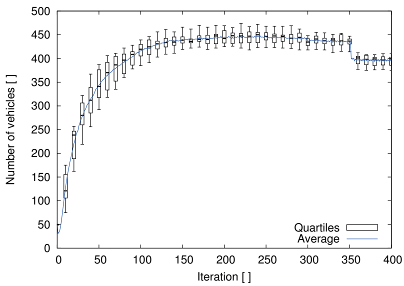
(a) Agent score



(b) Number of trips served by minibuses



(c) Number of routes offered by minibus operators



(d) Number of minibuses put into service

Figure 7.15: Population score and performance indicators of the minibus services averaged over all runs. Recall that operators stop offering new *routes* in iteration 300 and that agents stop searching for a new least cost path starting with iteration 350.

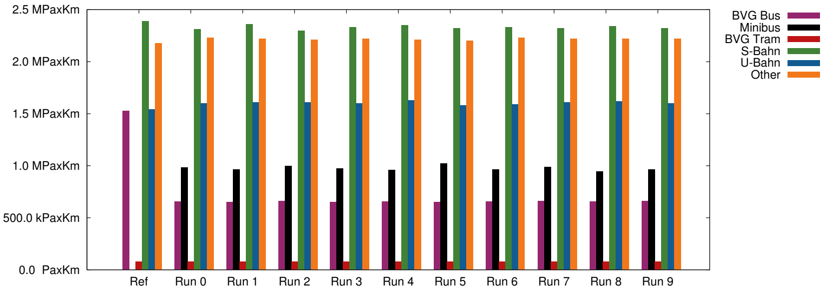


Figure 7.16: Passenger-kilometer served in the *Reference* setup (Ref) and the *Area* setup (Runs 0–9)

loss of passengers. Only the deactivation of route modification strategies has an effect. When the operators stop optimizing their *routes*, they resort to the management of the *routes* they have in their choice set. *Routes* created for exploration stop service. With iteration 250, no new operators are founded. However, this does not have any impact on the score of the population or the minibus operators.

Regardless of the particular solution, the minibus fully compensates the removed bus lines of BVG. Figure 7.16 lists the passenger-kilometer served as performance indicator for all public transport modes of the ensemble run and the *Reference* setup. For all ten runs of the *Area* setup, the minibus served approximately one million passenger-kilometer. That is about the amount BVG's bus lines lost due to the removal of lines. The figure shows values for the whole simulated area and not only for the scenario area. Accordingly, tram services of BVG are listed as well although no tram services are present in the scenario area. Compared to the average of all ten runs, S-Bahn services loose some transport performance, about 60 kPaxKm, whereas U-Bahn services gain about 70 kPaxKm. The reason for that is not completely clear. One reason can be the different integration of both types of rail services with the minibus. S-Bahn stations within the scenario area tend to be offside whereas U-Bahn stations are usually located directly at intersections. With the minibus preferring trunk roads, transfer distances to the S-Bahn services become larger. Bus lines of the *Reference* setup compensate this by detouring and serving secondary roads. For example, the bus terminal at the mayor house of Steglitz is tightly integrated with the S-Bahn station. However, U-Bahn services are closer to the trunk roads and activity centers.

Table 7.2: Performance figures of the *Reference* setup and the *Area* setup

	Reference setup	Minibus model Mean	SD σ	Minimum	Maximum
Figures represent trips starting and ending within the scenario area only					
Avg. number of transfers	0.198	0.475	0.018	0.427	0.506
Avg. door-to-door travel time	28.3 min	26.8 min	2.3 min	23.5 min	32.3 min
Avg. access walk time	8.3 min	5.5 min	0.1 min	5.4 min	5.6 min
Avg. transfer walk time	0.1 min	0.0 min	0.0 min	0.0 min	0.1 min
Avg. egress walk time	7.0 min	5.4 min	0.1 min	5.3 min	5.6 min
Avg. waiting time at first stop	3.1 min	7.1 min	1.6 min	4.4 min	10.7 min
Avg. waiting time at transfers	4.6 min	6.2 min	1.5 min	4.6 min	9.8 min
The following figures include all trips of the population					
Avg. score per agent	115.810	113.163	0.798	112.076	114.154
Avg. score per non-stuck agent[1]	116.069	114.844	0.270	114.371	115.274
Avg. number of agents stuck	151.000	2408.300	852.022	1289.000	3672.000
Percentage of stuck agents	0.02 %	0.41 %	0.14 %	0.22 %	0.62 %
Circuity[2] of transit trips	1.333	1.354	0.003	1.349	1.359

[1] An agent is excluded if it is stuck in at least one run. In total 18670 agents are removed.
[2] Circuity is defined as the ratio of network to Euclidean distance. Its reciprocal is Directness.

Overall, public transport services of the *Area* setup serve about 150 kPaxkm more than the ones of the *Reference* setup. This indicates that passengers travel longer distances, since the underlying population cannot alter their activity locations nor change the mode of transport. This is further backed-up when calculating the circuity of public transport trips (Contributors of Wikibooks, 2013). The ratio of network to Euclidean distance increases slightly in the runs of the minibus model, see figures in Table 7.2. Moreover, the more detailed figures of Table 7.2 indicate a considerably higher number of transfers. The average travel time decreases by 1.5 minutes. This means, agents need to transfer more often, but can nevertheless travel faster than in the *Reference* setup. This is mainly due to shorter access and egress walking distances. The minibus offers a higher coverage with more stops close-by. However, the longer waiting time at stops compensates some of the advantage. The average score per agent decreases slightly for two reasons. First, the number of agents stuck increases due to more low capacity minibuses in service and the minibus operators thinning out services earlier in off-peak periods. Second, agents crossing the border of the scenario area are forced more likely to transfer due to the interruption of the BVG's bus lines. With an alternative rail service missing, agents have no choice but to bear the extra inconvenience/disutility of the transfer. An early step to solve the stuck problem of public transit users can be found in Grether (2014). To summarize, the bus network derived from the minibus model shows a good performance when compared to the *Reference*. Some penalty to the scoring is induced by the restriction of the scenario area.

7.5 Discussion

The results presented in this chapter are based on the reality of the model. That is, the demand acts fully rational in terms of the model. Thus, agents can react in a different way than expected, e.g. transferring at a certain station might be more complicated and thus, impose higher costs in reality than in the model. Another discrepancy arises from missing demand. This is the case with the cluster of schools located at 285's terminus of Am Waldfriedhof. The significant demand of type education is not present in the model, compare Figures 7.3c and 7.7b. This demand has played an important role in BVG's bus network planning process as it is the political consent to provide public transit services to schools. Since the minibus model lacks both, the political constraint as well as the educational demand, it reacts accordingly and drops the service of the northern branch of line 285. Thus, one might be inclined to drop the service in reality as well. However, as this example demonstrates, transferring the minibus model's results back to the real world needs careful consideration as to what flaws of the model's data might lead to false conclusions.

As mentioned before, the minibus model tends to connect activity hubs preferably using trunk roads. Unprofitable services are left out. In this regard, the minibus model is no different from real minibus systems throughout the world (Cervero, 2000, p. 8). However, from a transport planning perspective, "cream-skimming" is not a valid option. A regulated transport company like BVG is forced to offer services on profitable routes as well as on unprofitable routes in order to fulfill the political constraints. For the city of Berlin this includes (SenStadt, 2007):

- No direct competition between rail services and bus services. Bus services running in parallel to tram, S-Bahn, and U-Bahn need to be well justified.

- The walking distance to the next public transit stop is less than 300–400 m for high-density areas and about 400–500 m for more sparsely populated areas.
- Service frequency is 20 min or more often. This allows for a reliable service, but for the price of wasted capacity in case a headway of 30 min would be sufficient.

Therefore, BVG is forced to cross-subsidize its lines and to offer services in areas the minibus model would not suggest. However, further constraints like serving a certain stop can be easily implemented into the model. For example, granting operators a subsidy for each departure will compensate for low-demand stops or periods of the day. Thus, the model can be adapted to the local constraints of the area of interest.

Furthermore, the realized travel times of minibus services are shorter than the ones of competing public transport services. This derives mainly from not serving stops whenever the vehicle is full, see section 7.3 for an example. In that case, the minibus' travel time is only limited by the speed limit of the road network, i.e. a minibus will travel as fast as a private car or a taxi. Contrarily, the limiting factor for the competing transport services is their time profile included in the transit schedule. The transit schedule is directly received from BVG's planning experts who incorporate average delays induced by traffic signals and boarding delays, e.g. strollers and purchasing tickets. However, these delays are not explicitly modeled in the current implementation of the Berlin model; rather, buses travel slower than physically possible because of the schedule. In contrast, the minibuses can move as fast as the simulation allows. The minibus schedule is based on the realized travel times only. Thus, the announced time profile of a *route* respects boarding delays but not the missing traffic signals. Currently, there are two solutions to this problem. Either the Berlin model needs to be improved by taking traffic signals into account, or the minibus model needs to be enhanced by a planning speed factor similar to the one described in subsection 4.3.3. The latter solution is similar to adding a speed limit to minibuses only, e.g. to the half of the maximum velocity allowed. A first estimation of the minibus model's reaction to the implementation of a speed limit can be obtained by the experiments of Appendix E. Enhancing the model by signal systems is more an issue of getting the data. The underlying simulation framework of MATSim is already capable of integrating signal systems (Grether et al., 2012).

Last, as shown in the example of the *Corridor* setup, the minibus aggressively competes the formal bus services by attracting as much passengers as possible. These passengers are lost to competing services of the formal bus system. In consequence, the amount of fares collected by the formal bus decreases and the combined capacity of minibus and formal bus is too high for the given demand. If the minibus model is used as a planning tool for a public transit authority, the transport planner in charge is likely searching for a system optimum within the combined bus system consisting of formal bus and minibus services. Thus, the transport planner should bear in mind that any additional profit generated within the minibus may impose losses on the competing formal bus services. For this fact to be considered in the analysis, the cost structure of the formal transit services needs to be incorporated into the minibus model.

7.6 Summary

Overall, the example of the Berlin scenario demonstrates that:

- The model can be used to evaluate a single transit line.
- The model can be used to evaluate a larger area.
- The model identifies service niches and fills in minibus services.
- The model reduces or cuts services on nonprofitable corridors.

Furthermore, the minibus model replicates profitable services of a reference network. The capacities offered by the model reflect the demand served. Nonprofitable services are not reproduced. The resulting minibus *routes* of a single run can provide a basis for designing formal bus services. In fact, BVG was more interested in individual runs than in combined plots and averages. Individual *routes* can be analyzed using state-of-practice methods, e.g. as illustrated in Figure D.21. Further development includes:

- The model's application to other areas and corridors.
- An in-depth analysis of the demand using public transport to increase the result's reliability.
- Further variations of the used parameter sets.
- Implementation of further requirements like preset termini and restricted areas.

- Improving the operator's optimization process by further limiting the search space, e.g. further reducing the number of potential stops.
- Allowing for a transit system wide cost-benefit analysis by incorporating the cost structure of formal transit services into the minibus model.

To summarize, the application to the Berlin scenario demonstrates that the model can be used for real world planning problems within the public transport domain.

7.7 Computing performance

The runs of this chapter were conducted on the computing cluster of the mathematics faculty. The resources of the cluster, namely the computing nodes and the file system, are shared by the users. This allows to allocate resources in a flexible way. However, it does not guarantee an exclusive access to a certain resource. Thus, the performance of the system varies depending on the load of the overall system and the particular computing node used. For example, the heavy IO of one user can prevent another user from using the CPU up to the full potential. In consequence, the time needed to complete one single run varies from 90 to 100 hours on an Intel® Xeon® Processor E5-2640 and 110 to 120 hours on an Intel® Xeon® Processor X5550. While the E5-2640 features 6 cores that allow to run 12 threads in parallel, the number of threads was limited to 8 in order to use the same configuration on both CPU. Regardless of the CPU used, the JAVA virtual machine (JVM: 1.6.0_26; Sun Microsystems Inc.; mixed mode; 64-bit) could allocate up to 32GB of memory allowing to use compressed object pointers, which reduced the running times significantly.

The most expensive operation of the minibus model is the replanning process of the agents (synthetic travelers). Fortunately, this process scales linearly with the number of available CPU cores. A different hardware architecture can thus significantly improve the computing time. Further improvements include the exclusive usage of resources, e.g. a computing node, and the software implementation of MATSim. Especially the software has a lot of potential as the example of the public transit router shows. For the runs of this chapter, the stock router of MATSim has been replaced by a reimplementation of Senozon (2013). As a result, the rerouting of agents can be reduced to about 11 minutes while still giving the same results, i.e.

a speed-up of factor 7 to 8 compared to the stock router of MATSim can be achieved.

Further potential speed-up lies in the implementation of the minibus model itself. That is, currently all legs of a person are rerouted. However, this may be restricted to the public transit legs only. Depending on the actual mode share, first tryouts show a further speed-up of factor 2–3.

CHAPTER 8

Case study III: The second transit authority case

I'm going to be guarded about picking a date now

Klaus Wowereit, Governing Mayor of Berlin,
refusing to announce a new opening date of the
Berlin Brandenburg airport (NYT, 2013)

This chapter provides a planning case of a public transit authority similar to the one in the previous chapter. Instead of reconstructing a bus network from scratch, a major change in the demand and its effects on the bus transit network are analyzed. The relocation of the airport Tegel (TXL) to the new airport of Berlin and Brandenburg (BER) provides a background for this scenario.

8.1 Scenario description

As depicted in Figure 8.1, the scenario area is situated more to the center of Berlin. The detail shows the bus network for the scenario area and the location of TXL. Note that TXL is exclusively served by buses operated by BVG.

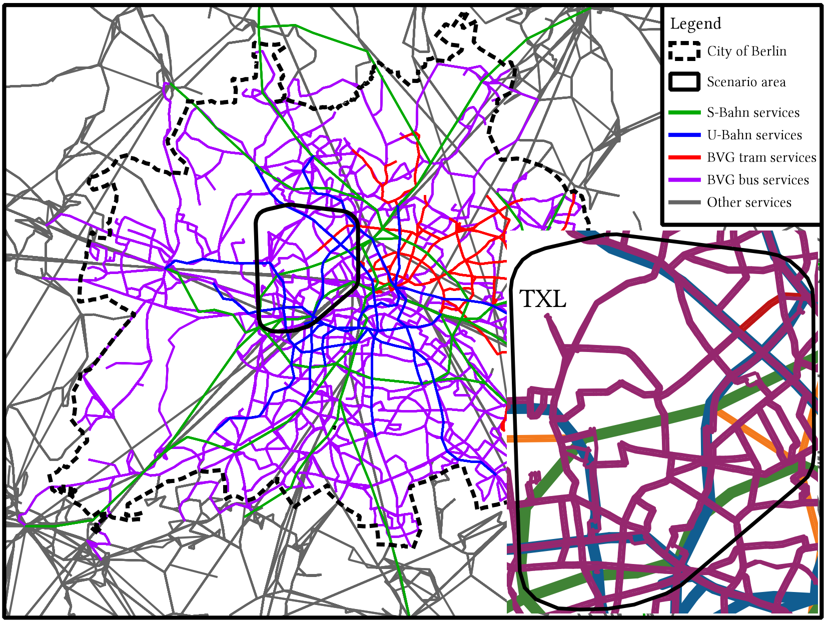


Figure 8.1: Location and close-up of the TXL scenario area showing the public transport network — The category "other services" includes bus and tram services not operated by BVG as well as ferry services and non-commuter rail services.

The scenario of this chapter uses the same input data as the scenario of chapter 7. To keep the running time of the simulation in bounds, the scenario is reduced to a 25 % sample of the population. The data is prepared in the same way as described by Neumann et al., 2014 and in chapter 7. All agents not passing through the scenario area are again removed from the population. The remaining population consists of 306,842 agents. Since each of these agents actually represents four agents of the full population (100 % sample) the public transport supply is also altered: The capacity of each vehicle type is reduced to one quarter. The boarding and alighting delays for each vehicle type are increased by a factor of 4 accordingly.

In the base scenario, TXL is still operational. For further reference, this is called the *TXL* case. In the altered scenario, TXL is supposed to be closed. All activities located at TXL are relocated to BER. This assumes that travelers as well as employees will simply move to the new airport. The altered scenario is referred to as the *BER* case.

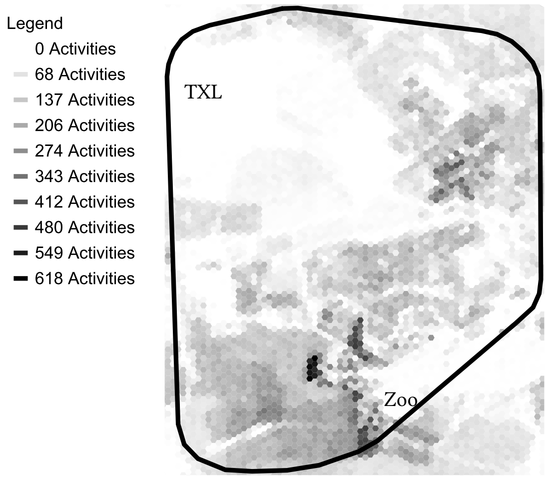


Figure 8.2: Distribution of activities within the scenario area — *BER* case. A total of 7,672 activities are relocated from TXL to the new airport BER.

Figure 8.2 depicts all activities for the *BER* case. A total of 7,672 activities are relocated from TXL to the new airport of BER and are therefore not shown in the figure. In the *TXL* case, these activities form a singular source of demand which would by far dominate in Figure 8.2. Note that large parts of the scenario area surrounding the airport feature only a low density of activity. Thus, the high density spot at TXL is isolated from the rest of the city, e.g. the City West around the transit hub of Zoologischer Garten (Zoo).

Configuration of the scenario

With the following exceptions, the configuration of the scenario uses the same parameters as chapter 7 given in the Tables 5.2 and 7.1:

- To compensate for the larger scenario area, the minimum number of operators is increased to 20.
- The earnings per boarding passenger is scaled by a factor of 4 to 2.00 ¤.
- The capacity is reduced to 3 passengers. Note that this is slightly higher than a fourth of the initial capacity of 10 passengers since MATSim simulates whole passengers only.

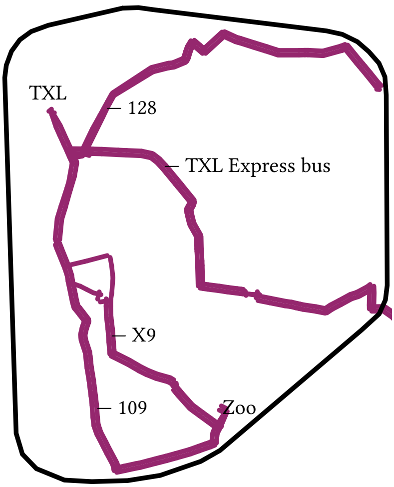
Setups

The same input data and configuration is used with two different setups of the scenario called *Corridor* and *Area*.

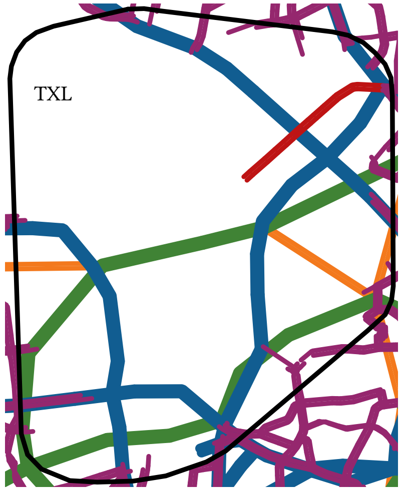
Corridor The *Corridor* setup follows the same basic idea as in chapter 7. Instead of the removal of one single line, all four lines serving TXL are removed, see Figure 8.3a. Namely these are 109, 128, the express bus X9, and the airport express TXL. Note that 109 and X9 both connect the transit hub at Zoo to TXL. Minibuses can only serve passengers within a 100 m wide buffer around the removed lines. That is, they can serve all formal transit stops within that buffer. They are not restricted otherwise. A minibus operator can decide to ply outside the buffer. In this case, its vehicles are not allowed to pick up or drop off any passengers as long as the vehicle is outside the buffer. In order to test for stability, the four removed bus lines serve as seeds for the initial minibus operators. That is, for each bus line one operator is initialized with approximately the same *route*, operating time, frequency, and capacity. Note that the remaining 16 operators and all operators founded in later iterations are created from scratch as described in chapter 4.

Area The *Area* setup removes all bus lines operated by BVG from the scenario area as described in chapter 7. The final transit network of the *Area* setup is shown in Figure 8.3b. Again, the four removed bus lines function as seeds.

Again, an ensemble run is performed for the *Corridor* and the *Area* setup. Each ensemble run consists of ten runs with identical configuration and input data. Only the initial random seed is varied. The heuristic of the minibus model is then able to produce different results with the same initialization. The results of the ten runs of one ensemble run are fused to allow for a more reliable analysis and to identify stable and repeating solutions. With the two different populations of the *TXL* case and the *BER* case the total number of runs increases to 40.



(a) All bus lines serving TXL are removed in the *Corridor* setup. These lines serve as seeds for the initial minibus operators.

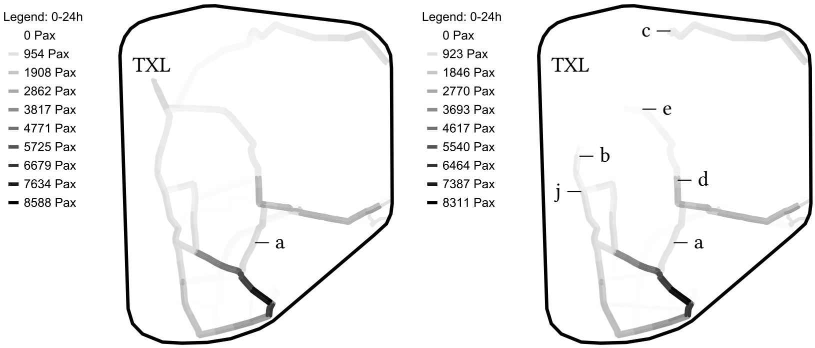


(b) Public transport services in the *Area* setup. All bus lines operated by BVG within the scenario area are removed.

Figure 8.3: Comparison of public transport service of the *Corridor* setup and the *Area* setup. Scenario area (black), U-Bahn services (blue), S-Bahn services (green), BVG bus services (purple) and other services (orange).

8.2 Results of the Corridor setup

The results of the *Corridor* setup are depicted in Figure 8.4. For the *TXL* case, all four transformed bus lines serving TXL prevail. In addition, there is a non-stop connection from the corridor of the TXL Express bus to the X9, denoted (a). This implies that from the point of view of the model, the formal service on this corridor, the bus line 245, could be improved. While this is not done, it is vulnerable to competition by minibuses. In the *BER* case, this non-stop connection is operated as well. However, the bus stop at TXL is not served anymore. The terminus of 109 and X9 is relocated to the U-Bahn station of Jakob-Kaiser-Platz (b), compare Figure 8.3b. The bus line 128 is reduced to the part between the U-Bahn station of Kurt-Schumacher-Platz (c) and its eastern terminus. The airport express is shortened to the S-Bahn station of Beusselstraße (d) and only about half the capacity is offered onwards to the light industrial park (e). Apart from TXL, the rest of the network is unaffected by the closure of the airport. That is, in both cases, the same demand is served on the same corridors.



(a) *TXL* case **(b)** *BER* case

Figure 8.4: Comparison of the average number of passengers served per street section of all ten runs — *Corridor* setup

Since the opening of BER has been postponed only a few days before the planned opening date, information on the planned bus lines and routes is available. With the closure of TXL on 3 June 2012, BVG had scheduled the following changes for bus lines serving TXL (BVG, 2012a):

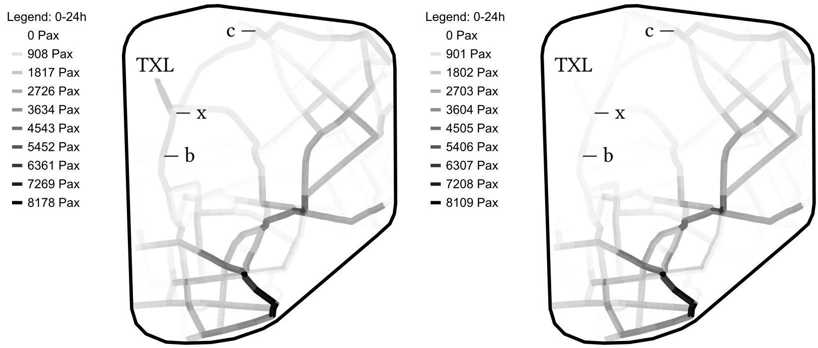
109 The terminus is relocated from TXL to the S-Bahn and U-Bahn station of Jungfernheide, denoted (j) in Figure 8.4b.

128 The terminus is relocated from TXL to the U-Bahn station of Kurt-Schumacher-Platz (c).

X9 This line is canceled.

TXL The TXL Express bus is substituted by a regular bus line. The terminus is relocated from TXL to the S-Bahn station of Beusselstraße (d).

Overall, the scheduled changes of BVG match the outcome of the minibus model. However, the minibus model indicates that there is enough demand for maintaining X9.



(a) *TXL* case

(b) *BER* case

Figure 8.5: Comparison of the average number of passengers served per street section of all ten runs — *Area* setup

8.3 Results of the Area setup

For the *Area* setup, the results, depicted in Figure 8.5, are basically the same. Although the minibus operators are allowed to search freely in the complete scenario area, the resulting networks look similar. Again, with the exception of TXL itself, the same demand is served on the same corridors. Differences occur on the branches from TXL to the nearest train station. While the TXL Express bus shows the same pattern as in the *Corridor* setup, the other bus lines do not cease service completely. Recall that in the *Corridor* setup some formal bus lines are still present. These lines provide a direct connection from Jakob-Kaiser-Platz (b) to Kurt-Schumacher-Platz (c). In the *Area* setup, these lines are missing and their demand is served by the minibus. However, the minibus solution differs in one detail. It still serves the bus stop at TXL although TXL itself does not provide any source of demand. The reason lies within the road infrastructure and the available transit stops. TXL itself and large parts of the corridor from (b) to (c) are served using an inner-city motorway. The initial solutions of the seeded minibus operators, namely bus lines 128 and 109, do not serve any stops near the motorway junction denoted (x). Thus, the bus stop at TXL serves as a transfer station connecting the minibuses going northbound with those going southbound. A direct connection that by-passes TXL prevailed in four out of ten runs. In three other runs, the advantage of the seeded operators is too large to be successfully challenged by a newcomer. Note that the seeded operators yield a higher income by forcing the passengers to pay an additional boarding fare at the transfer station of TXL. Since the additional income is spent on increasing the vehicle fleet, the established solution via TXL can afford to provide a much higher frequency compared to a solution that bypasses TXL. The situation would be completely different with a distance-based fare system in place, see the discussion in section 5.1.1 starting on page 83. Further note that in the remaining three runs the corridor is not served completely or is not served at all because of the overall low-demand on that corridor.

8.4 Discussion and summary

The *Corridor* setup demonstrates that the closure of TXL does not affect the remaining bus network. Only the branches from TXL to the nearest train station are affected. Essentially, the *Area* setup provides similar results. The remaining network is unchanged showing very stable results with reoccurring solutions throughout the individual runs of the ensemble run. The impact of TXL on the public transport network is thus locally confined. The comparison with the projected changes of BVG reveal a close match with the minibus model's solution. However, information on the planning instruments and data used by BVG is not available.

Furthermore, the results of the *BER* case indicate that effective bus lines should connect centers of activity. A bus line may pass through low-demand areas, but still be profitable by offering more transfers to the rest of the transit network. Furthermore, this may provide a direct connection, e.g. between otherwise unconnected train stations as in the example of the corridor from (b) to (c). This further increases the connectivity of the network. In contrast, a hub-and-spoke pattern more likely looses this connectivity because of each bus serving only as a feeder. For example, the TXL Express bus terminates in the light industrial park and functions as a one-sided feeder to the train station of Beusselstraße. It would attract more passengers if the terminus was relocated to a train station in the northwestern part of the scenario area. Examples from border communities, e.g. Blankenfelde, show that BVG's buses as well as buses operating in Brandenburg both provide access to the same S-Bahn service. However, buses stop right at the border of Berlin and Brandenburg without providing a transfer to the other side. A much faster trip could be provided if the feeder service started at the S-Bahn station in Berlin and then proceed to the S-Bahn station located in Brandenburg.

In conclusion, the minibus model reacts to changes in demand. The provided solutions are plausible. In the scenario, the impact of the massive change in demand is locally confined. Transit lines have a higher probability of surviving if connecting two different activity centers, e.g. transit hubs. Following a hub-and-spoke approach by letting the line end in low-demand areas renders a line less attractive because of a reduced connectivity, e.g. to one train station only. This chapter further demonstrated how the minibus model can be initialized by some operators with preset/transformed routes and additional operators searching freely. Existing transit lines can thus be explicitly seeded in the minibus model and be further optimized to fit the demand. Finally, this chapter showed that the minibus model still provides meaningful results when applied to a reduced scenario of a 25 % sample of the full population.

CHAPTER 9

Summary and further challenges

9.1 Summary of the dissertation

In developing countries, a substantial number of public transport trips is served by informal, so-called paratransit services. Since these often compete with officially approved (and subsidized) transit services, it is often tried to ban paratransit from the market or, if that fails, at least to regulate it.

Following this observation, this dissertation investigates paratransit services around the world, in particular the stakeholders involved and the main characteristics as seen from a transport planner's perspective. Minibuses are identified as the most important mode of paratransit. Commonly, an unscheduled service along fixed routes with 8 to 15 seater vehicles is offered. The predominant form of organization is the route association.

Based on this investigation, a model capable of simulating minibus services is developed. This includes the various stakeholders involved, in particular the supply side formed by drivers and vehicle owners and their customers as the demand side. The model is integrated in a multi-agent simulation that already incorporates other transport modes like formal public transit and private car. Competing minibus operators start exploring the public transport market offering their services. With more successful operators expanding and less successful operators going bankrupt, a sustainable network of minibus services evolves. The model is tested with various illustrative scenarios representing different demand patterns: along a simple corridor as well as in the more complex scenarios of an intersection and a grid network. The latter also includes a fixed train line as a formal competing operator. Here, the interaction of minibus and train services are analyzed. The minibus model is capable of finding the optimal solution for the corridor scenarios. This is not guaranteed to happen within a certain given search time and the probability declines with the complexity of the scenario. However, in the more complex scenarios, the model still finds close-to-optimal networks within a reasonable runtime.

From the perspective of paratransit

Moreover, the model is able to create "close-to-reality" minibus networks. Although its application has been only shown in a South African context it can as well be applied to other regions with similar characteristics. Essentially, the model serves two different purposes. The first one is to evolve the networks according to the constraints of the input data given. Especially, the network density and variety of minibus lines are a function of the given fare structure and cost structure of the operators. The second one is to simulate a fixed minibus supply along with the other transport modes assuming a decent knowledge on routes, headways, and fares. In both cases the minibus-specific behavior is integrated into an existing multi-modal transport model for the first time.

Transport planners and policymakers can thus analyze the implications of policy measures like the currently debated implementation of a minibus (taxi) subsidy (van Rensburg, 2013). Furthermore, Joubert (2013) points to a case in which the newly introduced formal bus rapid transit (BRT) is jointly operated and owned by the minibus operators. Normally, introducing a new high-capacity BRT line raises the question of how many minibus drivers and owners are concerned, e.g. face unemployment. The model can thus support decisions on the number of minibuses that will be removed from the BRT line's corridor.

In general, through the model the reactions of all types of stakeholders can be tested. For example, if route associations implement a different fare scheme, drivers and vehicle owners react by changing their routes, operating times, and number of vehicles. In particular, the following questions can be answered by using the model:

- Depending on the agreed fare, what will be the coverage of the minibus services? Are there neighborhoods without access to this mode? Which groups of the population are more likely to use paratransit?
- How many vehicles are needed to serve all the demand? Is this feasible? Does the road capacity allow for any supplemental load induced by minibuses? Do certain areas, e.g. train stations, suffer from severe congestion?
- What vehicle size suits the demand best?
- Can minibuses successfully serve off-peak periods?
- Which formal transit lines are successfully challenged by minibus services? Under which circumstances does the minibus cooperate with other transport modes, e.g. by forming a transfer hub?
- What are the implications of the introduction of road pricing? Are there any unintended consequences like newly congested areas being created as a result of other road users diverting? Are operators forced to increase the fare to cover the additional costs? Will low-income users of the minibus consequently pay the toll in an indirect way? Does the paratransit thus need to receive subsidies?

Especially the last point of the unintended consequences may bring attention to matters policymakers were not aware of before. These can then be further analyzed, e.g. using the minibus model, and finally be addressed.

From the perspective of formal transit operators

Moreover, the unsubsidized paratransit does not only compete formal transit, but often does so by serving the passengers in a more demand-oriented way. This is an interesting feature also applicable to the typical transport planning problem of a formal transit operator. More precisely:

> How can the demand be served best while still covering the associated costs at the same time?

Consequently, the minibus model is applied to real world planning problems of a public transit authority. For a designated area the fixed line bus services are removed, leaving a market niche for the minibus services. Again, a network of minibus services emerges. This network can be analyzed macroscopically, with focus on individual operators, or with focus on individual minibus services. Transforming a single minibus service into a fixed formal bus line allows to apply state-of-practice single line optimization methods. Minibus services can thus be used as blueprints for formal fixed-route bus services.

Furthermore, the model can be used the other way around. A single transit line can be transformed into a minibus service with approximately the same route, operating time, frequency, and capacity. The minibus model is then allowed to run letting the transformed bus line adapt to its environment. The easiest set up tests for the line's sustainability and does not change any of the line's parameters except its frequency. A profitable service will put more buses into service, hence increasing the service's frequency and capacity. An unprofitable service will start selling vehicles and eventually may even be forced to cease operation completely. Allowing for more strategies, the line can also be optimized regarding its time of operation, its length, and its route.

Both forms can be mixed, so the minibus model can be initialized by some operators with preset/transformed routes and additional operators searching freely. This allows to speed up the optimization process and for a more systematic analysis of a given route or corridor.

Again, the optimization process is fully integrated into the behavior-rich environment of a multi-agent simulation reflecting the reactions from the passengers as well as from competing transit services and other road users. Thus, the minibus model can be used along with more complex scenarios like city-wide tolls or pollution analyses (e.g. Kickhöfer, 2014).

In summary, the application to the Berlin scenario demonstrates that the model can be used for real world planning problems within the public transport. In particular, from the formal transit operator's perspective, the model can be applied to the transit network design problem. The example of the Berlin scenario demonstrates that:

- The model evaluates a single formal transit line.
- The model evaluates a larger area.
- The model identifies service niches and fills in minibus services.
- The model reduces or cuts services on nonprofitable corridors.

Furthermore, the model replicates profitable services of a reference network of formal bus services. The capacities offered by the minibus model reflect the demand served. Nonprofitable services are not reproduced. The model reflects large shifts in demand. The resulting minibus lines can provide a basis for designing formal bus services.

To conclude, the minibus model developed in this dissertation is dual-use in the way that it can be applied to two different fields of transport planning. First, there is the simulation of real paratransit that aims to help understanding the implications that lie within the relationship of the different paratransit stakeholders. Second, the same model provides a demand-driven approach to solve a network design problem. Thus, it can be used as a planning tool for the optimization of single lines or networks of a formal transit authority. However, the model is not restricted to those two applications. For Germany, the recent liberalization of long-distance bus services promises an interesting field for the model. Newly found bus operators just started to offer inter-city routes attracting passengers from train services and car-sharers. These operators have to probe the market and compete each other as well as train services with their individual cost structures.

9.2 Further challenges

Due to the dual-use character of the minibus model the further research depends on the audience addressed. The audience interested in simulating minibuses as a form of paratransit is probably more interested in the implementation of more minibus related behavior. The audience that wants to solve the network design problem may have more interest in solving the problem more straightforward while preserving the minibuses' behavior.

Thus, the **paratransit modeler** can enhance the model by incorporating more local specific behavior like ceasing service outside the peak hours or a more sophisticated boarding behavior at the stops, e.g. to reflect the driver's tendency to depart only with a nearly fully loaded vehicle. Ceasing service can be implemented by offering two identical routes with one serving the morning peak and the other one serving the afternoon/evening peak only. Delaying departures involves vehicle holding strategies as known from high frequency bus lines. Neumann and Nagel (2010) tested this with the focus on formal bus lines. However, the approach can also be used with paratransit. Sometimes, a driver also delays its departure to avoid bunching. Thus, there is more time to allow customers to aggregate. This strategy is also subject to the vehicle holding problem. Finally, drivers short turn to boost their income. Similar to detouring, this demands some kind of within-day replanning. Otherwise, the driver would not be able to recalculate its route and therefore, could not pick up/drop off the passenger. This behavior is more related to taxi drivers and currently under development by Maciejewski and Nagel (2013).

The **transport planner** is probably more interested in optimizing parameters of formal transit systems like including the vehicle type into the operators' decision. The operator can then decide on the vehicle's capacity and thus its related costs as well as the mix of vehicle types within its vehicle fleet. Also motivated by the practitioner is the approach to guide the optimization process. Often, there are given requirements that need to be met. This includes certain termini or stops that have to be served as well as restricted areas.

Both, the **transport planner** and the **paratransit modeler**, may want to increase the minibus model's computing performance, i.e the time needed for a minibus network to emerge. Although operators can optimize in parallel in different areas of the network, the time needed for optimization depends directly on the size of the search space. Therefore, limiting the search space yields the most easily achievable gain in performance, e.g. by reducing the number of potential minibus stops. Further improvements can be achieved by changing the most time consuming process, the transit router. Currently, a schedule-based routing approach is used. With minibuses ignoring the schedule and passengers waiting for an empty vehicle to board, the departure time encoded in the transit schedule can only give a rough estimate on when to expect a vehicle to arrive. More important to the passenger is information on routes and transfer points. Thus, a frequency-based router might be accurate enough.

The second largest time consuming process is the mobility simulation. Dropping the mobility simulation entirely in favor of an approximation could therefore result in a significant speed-up. For example, fare calculation could be derived from the transit router only. The feedback is only obtained by the passengers' rerouting process. The operators score their routes as usual and publish their optimized services back into the transit schedule. However, this completely neglects the advantage of the multi-agent simulation. The unreliability of the service is not reflected by the router-only-based approach. Thus, agents are assumed to board a vehicle at their will, i.e. there are no denied boarding events due to vehicles operating at their capacity limit. Moreover, there are no vehicle delays. Both phenomena are known to be important and are reflected within multi-agent simulations, e.g. Neumann et al. (2013).

Furthermore, the confidence in the model needs to be addressed. This is more likely to be questioned by practitioners who occasionally attend personally in court due to some project being on trial. Thus, increasing the confidence in the model is probably the most important step for disseminating the model into practice. For the Berlin case, this includes a) an in-depth analysis of the underlying public transport demand, b) the model's application to other scenarios, and c) the variation of the used parameter sets. Especially, the Berlin scenario has been calibrated with a certain set of travel behavior parameters by performing an experimental design method. Thus, the behavioral parameters of the underlying demand should be reviewed with focus on public transit routes. Especially the recent work of Manuel Moyo Oliveros (2013) promises improvements in calibrating a given public transit demand to counts data, e.g. as derived from electronic ticketing (Roth et al., 2011).

Finally, the individual route choices of agents can be improved by using a taste-variation router (e.g. Graf, 2013). Agents can then have individual sets of parameters and thus may choose different routes for the same pair of origin and destination, e.g. avoiding transfers or certain types of services. In conjunction with a fare-dependent transit router this may even allow for a diversification of transit services. Agents can then react to changes in the transit system based on intrinsic motivation and personal income, e.g. to bear longer access/egress walking distances in order to pay a lower fare. This also includes the full mode choice. While the current model allows to change between different public transit modes, agents cannot leave the system, e.g. from public transport to car and vice versa. With a recalibration of the model this should become possible. However, the enabling of the full mode choice requires further research on the underlying game mechanics and particularly on the interaction of the supply and the demand side. Otherwise, minibus operators will find it difficult to establish a first network of minibus services, if the passengers already opted for the private car due to a missing minibus alternative. Thus, full mode choice may only be allowed in later iterations once a primary minibus network has evolved.

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A certain "agent" for always complaining about M45 and stubbornly ignoring a transport planners advice on route choice.

[1] Rosa, Don. "The Life And Times Of Scrooge McDuck", Chapter 3: "The Buckaroo of the Badlands", e.g. ISBN: 978-0911903966, Gemstone Publishing, June 2005

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Appendices

APPENDIX A

Lexical definitions of paratransit

The following excerpts are definitions of the term paratransit taken from different dictionaries and publications. It should be noted that most dictionaries do not feature an entry for paratransit.

Adopted from the Contributors of the Wikipedia (2012a)

> “Paratransit is an alternative mode of flexible passenger transportation that does not follow fixed routes or schedules. Typically minibuses are used to provide paratransit service, but share taxis and jitneys are also important providers. Paratransit services may vary considerably on the degree of flexibility they provide their customers. At their simplest they may consist of a taxi or small bus that will run along a more or less defined route and then stop to pick up or discharge passengers on request. At the other end of the spectrum—fully demand responsive transport—the most flexible paratransit systems offer on-demand call-up door-to-door service from any origin to any destination in a service area. Paratransit services are operated by public transit agencies,

community groups or not-for-profit organizations, and for-profit private companies or operators."

Adopted from the online version of Merriam-Webster (2012)

"transportation service that supplements larger public transit systems by providing individualized rides without fixed routes or timetables"

Adopted from the online dictionary Dictionary.com (2012)

"public or group transportation, as by automobile, van, or minibus, organized to relieve the congestion of mass transportation."

"any type of public transportation that is distinct from conventional transit, such as flexibly scheduled and routed services such as airport limousines, carpools, etc."

Adopted from the book "Informal Transport in the Developing World" written by Cervero (2000, p. 3)

"These privately operated, small-scale services are varyingly referred to as "paratransit", "low-cost transport", "intermediate technologies", and "third-world transport". The term adopted in this study is "informal transport", for this term best reflects the context in which this sector operates - informally and illicitly, somewhat in the background, and outside the officially sanctioned public transport sector. While private, small-vehicle, for-hire services, such as taxis, can be found in all cities of the world, what separates informal transport operators from others is that they lack, to some degree, official and proper credentials. That is, they are unsanctioned. In some instances, operators lack the necessary permits or registration for market entry in what is a restricted, regulated marketplace. In other instances, operators fail to meet certification requirements for commercial, common-carrier vehicles - such as minimum vehicle size, maximum age, or fitness standards. Other violations include lack of liability insurance, absence of a commercial driving permit, and operation of a unclassified or substandard vehicle.

In spite of such transgressions, in many cases the informal transport sector is tolerated by public authorities, allowed to exist as long as it remains more or less "invisible" to most motorists, confined to low-income neighborhoods. Often, however, patrol officers and local "bosses" must be paid off for the right to operate in their "turf". Informal transport is just one of many sectors of the underground economy that thrives in many third-world countries.

Informal transport is about as close to laissez-faire transportation as can be found. Through the invisible hand of the marketplace, those who are willing-to-pay for transport services make deals for lifts with those who are willing-to-provide. Thus, informal transport involves commercial transactions which distinguishes them, as transportation services, from the provision of free lifts, whether by friends, acquaintances, or truck- drivers back-hauling with empty loads from the marketplace, all common forms of mobility in many poor, rural areas."

Adopted from the book "Urban public transportation; systems and technology" written by Vuchic (1981, p. 87)

"*Jitneys* are privately owned passenger cars or vans (5- to 15-seat vehicles), which operate on a fixed route (in some cases with minor deviations) without fixed schedules. They pick up and drop off passengers along their route by request. Because of their small capacity, jitneys operate in large numbers; their frequent stopping often contributes to traffic congestion. Jitneys typically offer less safety and comfort than regular transit does. They are used primarily in countries that have inadequate transit service."

Adopted from the book "Urban public transportation; systems and technology" written by Vuchic (1981, p. 648)

"PARATRANSIT — modes of passenger transportation consisting of small or medium capacity highway vehicles offering service adjustable in various degrees to individual users' desires. Its categories are:

PUBLIC — paratransit services available to any user who pays a predetermined fare. Examples: taxi, jitney, dial-a-ride.

SEMIPUBLIC — paratransit services available only to persons of a certain group, such as a company, neighborhood, etc. Examples: vanpools, subscription buses."

Adopted from the article "Paratransit — Existing issues and future directions" written by Roos and Alschuler (1975)

"Jitney/Route Deviation Service — A vehicle travels a basic fixed route picking up or dropping off people anywhere on the route. In addition, the vehicle will deviate a specified distance off the route, on request, to pick up or drop off a passenger. Jitney services are common outside North America and route deviation services have been implemented in Mansfield, Ohio (Guenther, 1970) and Emmen, The Netherlands (Hupkes, 1972)."

APPENDIX B

Case Studies

This section includes condensed information from case studies around the world. Information about paratransit is difficult to obtain, due to its nature of being often illegal. The book "Informal Transport in the Developing World" (Cervero, 2000) contains a great number of first and second-hand material. Even though, some may be outdated, it is a valuable resource to study the general principles of paratransit systems. Further examples by Cervero (1997) present material for the cities of Buenos Aires, Belfast, Mexico City, Puerto Rico, and Hong Kong. In addition, some up-to-date case studies are included featuring first-hand information from interviews or own experiences. The focus of this section lies on the different dimensions of paratransit introduced in section 2.4. The following ones are checked for each case study:

Type of operator Single car owner, franchise or route association

Type of vehicles Size and capacity of vehicles in service, class I to class III. Due to their technical limitations, vehicles of the classes IV and V will be ignored in the case studies.

Price structure and working hours Earnings and spending of the operator

Performance figures Number of passengers served per trip or day, average trip distances and travel times

Route choice Route pattern and route function

The different studies are compiled into an overview table which can be found in section 2.5 on page 26.

B.1 Southeast Asia and China

This section features case studies from the Philippines, Thailand, Indonesia, and the province of Jiangsu, China.

B.1.1 Philippines/Manila

This case study is derived from Shimazaki and Rahman (1995, 1996), Talvitie (1999) and Cervero (2000), which, for the most part, rely on material dated from the nineties of the last century. In contrast to other paratransit cities, Manila features no truly informal transit — at least on the road network (Favila, 2008). Most drivers are registered with government one way or another mostly by franchise. Nevertheless, drivers may lack a license or drive vehicles without a proper registration. Primarily, it is the way of privatized organization and free-for-all competition which qualifies it as paratransit.

Type of operator Most drivers lease a vehicle from "absentee" owners for a set fee. The owners are members of a route association and registered with national security and exchange commission. New routes can be licensed when market demand is demonstrated. The license is valid for 5 years. For the first 3 years of a new route no other franchises are allowed on that route.

Type of vehicles Operators use class II type of vehicles. Jeepneys seat between 14 and 26 passengers and up to 30 on peak hours. Additional 10 seater Tamaraw FX vans.

Price structure and working hours Fares are calculated as fixed fares of 20 pesos for the first 2–3 kilometers and 10 pesos for each additional kilometer. Drivers have to pay fees to authorized franchise-holders and for the occasional bribing. Jeepney operators work 13 h per day on average.

In 1993, 87 % of Jeepney drivers rented their vehicles paying, on average, 334 pesos per day. The average gross was 695 pesos per day, resulting in net earnings of 361 pesos without operating expenses subtracted. 36 % of vehicle owners owned just one vehicle.

In 1996, a Jeepney driver's gross income per day was, on average, 940 pesos. Taking in account operating expenses of 611 pesos results in net earnings of 329 pesos (35 %). Leasing a vehicle cost another 364 pesos per day. This considerable high rate is due to over-supply of drivers resulting in aggressive competition. Still, it is possible to make a living, since not every driver has to rent a vehicle and thus adds to the average in the same way. In both cases the driver pays for fuel and the car owner pays for licenses, insurance and maintenance.

Performance figures On average, 15 passengers per vehicle were served in 1996. In 1989, Jeepney services carry about 75 % of public transport passengers. Jeepney routes range in length from 1.9 to 30.6 km with the average being around 7 km. 65 % of trips are shorter than 5 kilometers. On average, Jeepney drivers serve 7.8 round trips per day. In 1996, average travel time of a Jeepney trip was 43.4 minutes.

Route choice Class II vehicles ply a fixed route, stopping anywhere along the route. The paratransit services of class II compete and complement public bus service. They operate as feeders to high-capacity mainline Jeepney and conventional bus routes. According to own calculations based on Cervero (2000, table 5.2), inter-modal transfers involving Jeepneys split as follows: to/from tricycle 35.4 %, to/from other Jeepneys 33.5 %, to/from bus 25.3 % and to/from other modes of transportation 5.8 %. Most terminals are situated on-street. The frequency of Jeepneys services is about 3.5 times higher than the frequency of the public bus giving the Jeepney an competitive advantage over the bus for shorter trips.

Besides class II vehicles, class III vehicles are bound to certain areas, serving major pick-up points and are more likely to deviate from the route.

The case study of Manila features some figures about the number of vehicles involved in public transit. In 1996, about 57.400 Jeepneys plied along 399 routes picking up passengers at 210 terminals. According to census, in 1995 about 9.5 million people lived in Metro Manila which extends over an area of 639 square kilometer.

B.1.2 Thailand/Bangkok

This case study is derived from Cervero (2000), which, for the most part, relies on material dated from the nineties of the last century.

Type of operator The paratransit in Bangkok is arranged by about 300 route associations. Each driver plying a route has to pay an entry fee to the route's associations. The head of the association manages services, sets the working schedules, the route and "pays of public officials, for the right, de jure, to operate illegally". In addition, a route association can employ "queue managers", who manage the queue process at pick-up points.

Type of vehicles Vehicles of class I, e.g. buses, are owned and operated by the public sector only. The vehicles of paratransit modes belong to the classes II to III. Class II consist of 18 seater minibuses, 14 seater pick-ups and vans and 7 seater microbuses. Bangkok features a lot of other modes, especially of the classes IV and V, which are not considered here.

Price structure and working hours The fare is fixed, paid per trip and depends on the route. Most drivers operate between 5:00 and 23:00 resulting in working hours of 10 to 12 hours a day. However, most time the driver spends lined up in a queue. The driver pays dues to the head of the route association and parking fees for certain pick-up points. In the case the driver does not own the vehicle he is driving, he is responsible for daily lease payments. Tolls are paid instantly, leaving an income of $43 per day. This results in net earnings of $15 per day (34 %).

Performance figures Paratransit vehicles serve 60 to 520 passengers per day, depending on the vehicle used. Class II vehicles serve more passengers than vehicles of class III. For comparison, class I buses serve 1300 passengers per day. In the case of vans, about 3000 vehicles operating at 80 different routes hauled around 150.000 passengers per day or, on average, serve 10 passengers per trip. During peak hours, demand exceeds the supply. The whole area of Bangkok is served by trips up to 30 kilometer in length. Since the average speed can be as slow as 8 kilometers per hour, this results in considerable long travel times. However, Shimazaki and Rahman (1996) mention a study from 1990, which estimates the passenger market share of minibuses to be about 13–14 %.

Route choice Expressways and primary roads are served by class II and class III vehicles. Feeder services are served by class IV and class V vehicles on secondary roads. Class II vehicles operate long-distance commuter runs from suburban enclaves to major in-city transportation terminals. The route pattern is many-to-few. Headway frequency depends on the time of day and is 5 to 15 minutes during peak hours and 20–30 minutes at off-peak. In addition, there are non-radial trips like cross-town and suburb-to-suburb. Vehicles depart at major pick-up points and departure takes place whenever the vehicle is full. The routes function as a premium-quality point-to-point service, focused on work and school trips during peak hours. 30 % percent of trips including at least one van trip follow the pattern walk-van-walk and 23 % are of the pattern walk-van-bus. The average access time is 16 minutes, whereas, on average, 13 minutes are needed for egress. In-vehicle time is 41 minutes on average.

In the case of the town of Muang Thong, service is highly regulated. The number of vehicles allowed to operate on the route from Muang Thong Food Court to Bangkok is limited to 30 vehicles. The food court features a terminal allowing for three vans to queue up. Additional vans have to wait on some remote holding pin. A van must depart after 20 minutes, regardless off its load. The route's association demands a considerable high entry fee, but the route is considered comparatively profitable. A driver can make 6 to 8 round trips per day, each 20 kilometers in one direction.

B.1.3 Indonesia/Jakarta

This case study is derived from Shimazaki and Rahman (1995, 1996), and Cervero (2000), which, for the most part, rely on material dated from the end of the eighties and the nineties.

Type of operator Basically, there are two route associations of microbuses focusing at inner-city areas and at suburban markets, respectively. The associations' members own multiple vehicles, which they lease to drivers. In the case of minibuses, a member possesses two vehicles on average.

Type of vehicles Class II and class III paratransit vehicles consist of 6–8 seater microvans in the form of three-wheelers, 10–15 seater microbuses and 20–30 seater minibuses.

Price structure and working hours Data is only available for microvans. Microvans operate on a fixed fare and drivers may pay a set leasing fee on a daily basis.

Performance figures The average trip distances depends on the vehicles' size, with larger vehicles having an higher average trip distance. The microvan trip averages 4.5–10 km per trip or 70 km per day. Trips of microbuses average 5.0–12.0 km in length and these of minibuses 8.0–15.0 km.

Route choice Microvans and microbuses both ply a more-or-less fixed route. Microvans hey mainly traverse back roads. Microbuses operate on short distance trips within the core city, to suburbs and along major commercial streets in the suburbs. Micro- and minibuses will try to depart fully loaded at terminals extend their dwell time at proceeding major pick-up points to further increase the load. There are 48 urban routes and 70 suburban routes operated by microbuses. Minibuses function as feeder and mainline service and operate on 110 routes.

B.1.4 China/Nanjing, Yancheng

This data is obtained by interviews with Yu Chen (personal communication, May, 2011) and his experience dated from about 2007.

Type of operator There is no operator in the sense of the operators specified in subsection 2.4.1. The driver employed by a bus company decides to earn an extra by picking-up additional passengers pocketing their fares.

Type of vehicles Conventional class I long haul buses/coaches.

Price structure and working hours The fixed fare goes directly to the driver and does not include taxes. Fares are considerably lower than at the official ticket office of the bus terminal.

Performance figures Buses often serve more passengers than the capacity allows for.

Route choice The route is fixed and preset by the official bus route of the bus company, e.g. going from the terminal of Nanjing to the terminal of Yancheng. "Paratransit" passengers have the opportunity to enter the bus right after its departure when the bus has left the terminal. The bus may stop along its route to pick up additional customers outside official stops.

B.2 South America

This section features case studies from Jamaica, El Salvador, Bolivia, and Brazil.

B.2.1 Jamaica/Kingston

This case study is derived from Cervero (2000), which, for the most part, relies on material dated from the eighties. Kingston has a long history of paratransit services. Concentrating on peak-hour, high-demand corridors sedans started to compete head-to-head with public bus services as well as with official minibus feeder services. At the beginning of the eighties, the illegal sedans accounted for 27 % of total passengers, leaving 19 % to public buses and the remaining market share, for the most part, to legal minibuses. A more detailed description of the decline of formal bus services and the boom of informal services can be found in Alton Fletcher's contribution to the 1999 World Bank Seminar (Talvitie, 1999, p. 53) and in an article written by Cervero and Golub (2007).

Type of operator The majority of drivers are single bus owners.

Type of vehicles The paratransit consists of 12–24 seater minibuses (class II) and sedans (class III).

Price structure and working hours Minibus drivers may not complete their routes, e.g. in case of a higher demand in the opposite direction the driver may empty the bus and turn around. Drivers work between 13 and 16 hours a day, 6 days per week. Figures from 1985 indicate that an employed bus driver earns 3 Jamaican dollars an hour or 200–300 per week. If the bus driver owns the vehicle he is driving, he earns 700–1200 per week.

Performance figures No detailed data available

Route choice The drivers of minibuses operate fixed routes stopping anywhere. They do not tend to follow a timetable. Headways are based on the drivers' "instinct". Especially during slack periods, pirating on other routes is quite common, regardless of the franchise license owned by the driver.

Sedans serve rural and fringe parts of the urban area and operate as shared-ride taxi. They take up the slacks at nights and along risky sections of highways, e.g. risk of robbery and less profitable routes.

B.2.2 El Salvador/San Salvador

This data is obtained by interviews with Severin Gierlich (personal communication, May, 2011) and his experience dated from 2011.

Type of operator The drivers are employed by bus companies.

Type of vehicles The paratransit services in El Salvador use 20–30 seater minibuses and 50-70 seater buses.

Price structure and working hours All services charge a fixed fare. Unfortunately, data on revenue or the motivation of the driver to maximize profit could not be obtained.

Performance figures The load depends on the time of day, but tend to be around 90–120 % of capacity. Inner-city routes are served by minibuses with trip lengths around 10–12 km. Buses operate routes from San Salvador to the whole country.

Route choice Minibuses ply fixed routes defined by companies according to demand. All inner-city routes connect two suburbs and pass the city center once in a time. Boarding and alighting takes place anywhere along the route. Buses ply between two cities and allow boarding and alighting anywhere.

B.2.3 Bolivia/Santa Cruz de la Sierra

This data is derived from Figueroa and Pizarro (1998), which, for the most part, rely on a study carried out between October 1995 and June 1996. Although not informal, Santa Cruz de la Sierra features a public transport system completely liberalized with features of paratransit services. The Santa Cruz municipality, responsible for the public transport, grants permissions to offer services on a given route. However, the routes are proposed by private companies and the permits usually granted as presented. Eventually, the companies define the route and the quality of service. Only the price is fixed by the municipality, though negotiated with the companies' umbrella organization.

Type of operator Individual operators are organized as route associations based on the route they serve. Route associations belong to an umbrella organization which negotiates the entry of new operators with the municipality. Route organizations coordinate the service of the route, e.g. frequency and time of operation, to ensure profitability for all individual operators.

Type of vehicles Officially, about 1600 13 seater and 25 seater minibuses operate along 82 routes. However, the study gives an estimate of 3200 vehicles.

Price structure and working hours The fare is preset by the municipality. Analyzing the operators' cost structure, the study shows operating a second hand vehicle, as the majority of the operators does, costs more on a per-kilometer basis than a new vehicle would cost. However, the higher fixed costs associated with the new vehicle may turn this advantage into a disadvantage.

Performance figures The average driver does 12 one way trips per day, each 15.5 km in length lasting about 1 hour. In average, each vehicle serves about 513 passengers per day.

Route choice Since, most of the trips start or end within the center of the city, the majority of the routes passes through the center as well serving two or more origin-destination pairs. Although there is a morning as well as an evening peak with unidirectional demand towards the city's center, operators put the same number of vehicle into service in both directions.

B.2.4 Brazil/Rio de Janeiro

This case study is derived from Cervero (2000), which, for the most part, relies on material dated from the late nineties. A more detailed overview of the emergence of paratransit in Rio and its importance to the region can be found in the article written by Cervero and Golub (2007).

Type of operator Most drivers are single car owners. On some routes, they are organized in route associations, especially to defend the route from pirates and secure downtown terminal space. The route associations, in turn, are organized in an umbrella organization lobbying for the interests of all associations serving a certain region, e.g. all terminals around Rio's central train station.

Type of vehicles Paratransit service is handled by 14–16 seater minibus vans and 8 seater kombis.

Price structure and working hours Most van drivers work 12 hours a day, 6–7 day per week. Work shift starts whenever the driver leaves home. Some drivers rent a van on a fixed daily rate and try to compensate by longer work shifts. For example, they may start as early as 4 o'clock. and work on weekends when they get the vehicle for free. The route association pays a monthly lump sum for a designated space at a privately owned terminal. In addition, there is a charge for each van entering the terminal. An calculation example from Cervero (2000, footnote 36) shows a fee of 2 Reais per vehicle entrance. In this example, the driver charges 2.5 Reais per passenger with an conservative estimate of 11 passengers on average per departure.

Performance figures A van driver averages 12 one-way trips or six round-trips per weekday with at least 11 passengers at each trip. Van routes are considerable long. Some drivers of routes plying from the suburbs to downtown drive as far as 40 kilometers in one direction or 1 hour. Going six round-trips, this sums up to about 480 km per day.

Route choice Vans tend to ply on radial and fixed routes between downtown terminals and suburban neighborhoods. They compete directly with franchised buses. Vans circulate within a neighborhood picking up customers. Once the vehicle is fully loaded, which takes about 5–10 minutes, it goes directly to a terminal at the edge of downtown Rio.

Most terminals are situated near a formal bus terminal or the central train station. In the evening, the van goes the same route in the opposite direction. During off-peak hours, a van may leave the terminal with only 8 passengers, which takes up to 20–25 minutes in time. The second kind of vehicle, the kombi, functions as a circulator especially in favelas.

B.2.5 Brazil/Rio de Janeiro (revisited)

This data is obtained by personal communication with Nicole Scherer (personal communication, June, 2011). In 2011, Rio de Janeiro inhabits about 7 million people with two-thirds living in favelas or using the politically correct term in "comunidades". These areas, are often controlled by paramilitary groups (milícia) and bootleggers (traficante) which (re-)sell, for example, gas connections, cable TV and Internet connections. In terms of abiding traffic rules, general traffic behavior and safety, vans services do not differ from formal bus services. Formal buses stop nearly anywhere, e.g. at intersections, allowing for boarding and alighting. As of June 2011, the government tries to drop a number of bus lines in favor to concentrate demand on some major trunk lines serving the city center exclusively. The passenger is then forced to transfer to one of those lines at the periphery. Concerning paratransit services, Rio's transport market is characterized by a glut of vans.

Type of operator According to de Bias Almeida (2011) and Oliveira (2009), some van services were legalized. In theory, routes connecting Rio to its surrounding cities are not allowed to serve Rio's center. Passengers are expected to transfer to another van or bus line. In practice, as of June 2011, they serve Rio's center according to demand stopping anywhere. Vehicle owners are organized in umbrella organizations like the "Sindicato dos Proprietários de Vans e Kombis" lobbying for their interests.

Type of vehicles One still finds the old 9 seater VW Bulli. Other models plying the streets are 12–15 seater vans like the Fiat Ducato. Especially on routes leaving Rio, vans are colored indicating the relation served.

Price structure and working hours The driver may have to buy a "license" when operating in areas controlled by milícia. Fares are normally fixed and depend on the route. A trip by normal bus costs R$ 2.5 and by bus featuring air conditioning R$ 2.8. Van services charge from R$ 2.5 to R$ 5.0 per trip.

Performance figures The drivers tend to wait until no seats are left empty. Sometimes the official capacity will be exceeded by allowing some additional standees or by sitting on the floor. Trips vary in distance with shorter trips around 13 kilometers and longer one up to 70 kilometers.

Route choice The majority of vans is not legal and serves low income neighborhoods. Illegal vans are sometimes referred to as pirates (de Bias Almeida, 2011). Vans stop or queue up at formal bus stops luring passengers away from bus services. Vans duplicate bus lines, but also serve otherwise unserved areas or offer services to areas controlled by milícia. Some drivers are legalized and allowed to ply fixed routes. Nonetheless, they lure passengers away from the bus system by illegal stopping at bus stops or stopping anywhere blocking the traffic. In general, boarding and alighting takes place anywhere, but most passengers change at major pick-up points. Some drivers serve a corridor allowing for smaller detours or switch to an alternative route on-demand. Especially vans not legalized may transform into a taxi-like service, whereas drivers of legalized vans are afraid of loosing their license when doing so.

B.2.6 Brazil/Multiple cities

This case study is derived from Cervero (2000), which, for the most part, relies on material dated from the late nineties. The study features some data about the number of vehicles in use. In the 8.000 square-kilometer area of São Paulo live about 18 million inhabitants. They are partially served by 16.000 clandestine vans. The streets of Porto Alegre are plied by 400 vans under 260 private operating licenses, which carry about 100.000 passengers per day or around 10 % of transit ridership on 41 routes.

Type of operator In most cases the driver does not own the vehicle he is driving.

Type of vehicles The most common vehicles are 14–16 seater vans and 8–10 seater kombis.

Price structure and working hours The most common fare at van services is the fixed one. In Porto Alegre, for instance, clandestine vans charge around twice as much as conventional buses for trips over comparable distances, and in Rio de Janeiro prices are sometimes four to five times as high.

Performance figures No data available

Route choice Vans tend to ply fixed routes, picking up passengers at any point along the route. The routes compete with formal bus lines, but may branch into otherwise poorly served neighborhoods, too. Some function as feeders to formal bus and train services. In Porto Alegre, van service has been legalized as complement of formal streamlined bus services.

B.3 Sub-Saharan Africa

Paratransit is widely used in Sub-Saharan African cities. The Trans-Africa Consortium of the International Association of Public Transport compiled an overview of Sub-Saharan public transportation in general covering formal transit as well as paratransit modes (Trans-Africa, 2008). More recently, they conducted various studies collecting public transport related data, again with some coverage of paratransit modes (Trans-Africa, 2010a,b). The cases presented in this section focus on paratransit only, relying on different sources and some first-hand experience of people interviewed. In particular, this section features case studies from Nigeria, Kenya, Ghana, and South Africa.

B.3.1 Nigeria/Lagos

This case study is derived from Cervero (2000), which, for the most part, relies on material dated from the nineties.

Type of operator Most drivers own their vehicles. There are no route associations, but unions whose members share space at one terminal.

Type of vehicles Besides the omnipresent “danfo” van (class II), Lagos features the class I 25–100 seater truck-like “molue”.

Price structure and working hours No data available

Performance figures No data available

Route choice In theory, the vans ply fixed routes, but in lack of enforcement it is free-for-all.

B.3.2 Kenya/Nairobi

This case study is derived from Cervero (2000), which, for the most part, relies on material dated from the late nineties.

Type of operator 1/3 of the drivers owns the vehicle he is driving. The rest of the drivers leases the vehicle from absent owners. Route associations exist at terminals and most routes are operated by cartels.

Type of vehicles The most common paratransit vehicle in Nairobi is the 8–14 seater van.

Price structure and working hours Paratransit vans charge about the same fare as formal bus services. In 1993, drivers earned about US$ 2500 on average. The driver has to pay fees for parking at terminals and has to buy in a route cartel.

Performance figures About 5.000 vans carry 400.000 riders a day or 70 % of all passenger trips. Paratransit vans serve inner-city trips as well as long-hauls, e.g. to Mombasa.

Route choice The vans ply a fixed route, stopping anywhere along the route. They compete with the formal bus service by duplicating routes and on the same time complement it by serving neighborhoods not served by formal bus services.

B.3.3 Ghana/Accra

This data is obtained by interviews with Ty Frazier (personal communication, October, 2010) and his experience dated from 2012 and earlier. Beside the minibus service of the so-called “tro-tro” Accra offers a bus rapid transport (BRT) system. The system consists of about four routes limited to trunk roads to the central business district. Other streets are not wide enough to be used by the BRT’s regular class I buses. BRT buses have to use mixed-lanes and get further slowed down by roadside vending. However, the BRT system tends to be crowded.

Type of operator There are single-car owners and drivers who lease their vehicles from owners for a week. Drivers organize as route associations offering services on corridors. Drivers need to settle an agreement with the route association's "chief" in order to be allowed to become a member.

Type of vehicles Mainly old second-hand 10–19 seater minibuses called "tro-tro" (Okoye, 2010).

Price structure and working hours "Tro-tro" services are cheaper than BRT and cheaper than taxi services. To get a rough estimate on the different pricing levels for a similar route the prices are about 50 cents for the "tro-tro" compared to 150 cents for BRT and 300–400 cents for the taxi. Regardless of the customer, the price is fixed and depends on the distance traveled. "Tro-tro" drivers are subject to pay some taxes depending on their income.

Performance figures Concerning commuting, about 70 % of Accra's residents rely on "tro-tro" while 10 % use their own car, 8 % use a taxi and 0.3 % use the formal bus transport. The missing 11 % just walk to work and to shop (World Bank, 2010). "Tro-tro" are responsible for about half of the vehicles circulating. Most vehicles are packed to their limit, but will also leave on time, i.e. with some seats left empty. This decision is made by the driver but is influenced by his current customers and thus may be subject to negotiation, e.g. the customers may start complaining about the price or start leaving for a different vehicle. The typical "tro-tro" trip runs to the working-place in the morning, e.g. the central business district, and back to residential areas in the evening. According to Trans-Africa (2010b), a minibus runs 6 round-trips per day and about 80.000 kilometer a year.

Route choice There is no real competition between "tro-tro" services and the BRT system. "Tro-tro" services serve different destinations and are complemented by inner-city walks. "Tro-tro" vans can be flagged-down and alighted wherever the driver decides to do so, but most will stick to designated "stops". Probability to find a "tro-tro" heading the desired direction is far higher at designated hubs like the "37" (named after a military hospital, located on state property, claimed 10–20 years ago) or the circle. Hubs are self-organizing. Queues of vehicles form up depending on their destinations and customers find their queues by word of mouth. “Tro-tro” drivers may offer detours, but normally stick to their route/corridor. In case of a negotiated detour, the driver may just curb without leaving its route and give the passenger general directions when he leaves. However, a driver will detour from its route in order to avoid intense traffic (Okoye, 2010).

B.3.4 South Africa/Pretoria

This data is obtained by personal communication with Daniel Röder (personal communication, October, 2012) and his first-hand experience. Additional information is taken from the blog entry of Tim the hedgehog (2011). For an in-depth study of the minibus taxi industry around Pretoria in general and the working conditions of the drivers in particular the reader is referred to the master thesis of Mpho Manoagae Mmadi (2012).

Type of operator Route associations,e.g. the Menlyn Taxi Association serves the area of Pretoria.

Type of vehicles Old and brand-new 16–22 seater vans. A uniform/corporate design identifies the vehicles as minibus taxi.

Price structure and working hours The fare of a minibus taxi is paid per boarding. The fare depends on the total length of the driver’s route, i.e. a passenger will always have to pay the full price regardless of actual distance traveled. Depending on the route’s length the price is about 5–12 ZAR, e.g. 12 ZAR for a distance up to 25 km. Due to a lack of competing public transport and taxi services the fare can only be compared to the Gauteng’s Metrorail monthly subscription which is about 100 ZAR per month. Goods can be carried along, but need to be paid extra when not placed on one’s lap. The driver works without a tout, but there are marshals organizing trips at the taxi ranks.

Performance figures The model split of minibus taxi services in Pretoria’s region of Gauteng is about 31.8 % and the highest among the South African regions (DoT-SA, 2005). Out of 43,570 minibuses registered in Johannesburg, Trans-Africa (2010b) estimates that 19,600 minibuses operate as public transport vehicles. Minibus taxi drivers drive as fast as drivers of private cars often exceeding speed limits. The major hubs of the minibus taxi network are taxi ranks. Most passengers board at taxi ranks and vehicle tend to depart fully loaded. Many trips cover the whole length of a route, but passengers can also board and alight at traffic lights and intersection by demand. Potential passengers will indicate their desired destination by hand signs (City of Johannesburg, 2005).

Route choice The route is predetermined by two fixed termini (taxi ranks) and drivers need a license to offer services on that route. Drivers will stop anywhere, but will not detour. Instead, passengers will have to walk to the wished route in order to be picked-up. Essentially, minibus taxis ply every trunk road, thus the network of minibuses is roughly known to people knowing the street layout. Since the formal public transport offers only a few services, minibuses do not really compete with it, but rather form a public transport system in itself. Minibus routes connect the townships, the airport and the malls to the city center's taxi rank, e.g. the central business district.

Beside the capital region of Gauteng, there are other cities with similar minibus taxi services which differ in some aspects. For example, Durban's minibus taxis are about the same size and their drivers demand the same type of fixed fares as in Pretoria, but the vehicles themselves may come in an individual style often featuring a noisy permanently enabled stereo system. In Durban, there are two types of service patterns. First, there is the hub-and-spoke with feeders offering services from smaller taxi ranks at malls or in residential areas to the central city center's taxi rank. Second, there are inner-city routes forming a grid network. This second type is engaged in direct competition with the inner-city public bus system and drivers engage an accompanying tout. The tout is responsible for luring passengers from the sidewalk by shouting the vehicle's destination. The tout may even leave the vehicle when stuck in traffic and walk ahead in order to address potential passengers directly (Daniel Röder, personal communication, October, 2012).

B.4 Eastern Mediterranean, Turkey, Egypt, Tunisia

This section features case studies from Turkey, the Turkish Republic of Northern Cyprus, Syria, Lebanon, Israel, Egypt, and Tunisia.

B.4.1 Turkey/Instanbul, Antalya, Alanya, Bodrum

This data is obtained by interviews with Ihab Kaddoura (personal communication, May, 2011) and his experience dated from 2010.

Type of operator Most drivers do not own the vehicle and individual decoration of the vehicle is not allowed. Service in an area is organized by a corporation.

Type of vehicles The typical paratransit minibus seats 14–24 passengers and is called "dolmus".

Price structure and working hours The drivers carry an agreed wage. The fare is fixed and depends on the distance traveled. It is about the same fare as is charged for traveling by formal bus or tram. The driver collects the fare, but transfers it directly to the corporation. Vehicle related expenses like maintenance and refueling are paid by the corporation.

Performance figures No data available

Route choice The minibuses ply a fixed route, duplicating formal bus and tram routes. Sometimes, they complement a route by offering a different level-of service. The drivers do not follow a fixed timetable. Headings are determined according to demand. The driver may depart with some seats empty and stops anywhere along the route allowing for passengers to board and alight. Groups of potential customers will be given priority to in order to facilitate the process. At major intersections and terminals the driver will stop regardless of passengers alighting or not.

B.4.2 Turkish Republic of Northern Cyprus/Multiple Cities

This data is obtained by interviews with Ihab Kaddoura (personal communication, May, 2011) and his experience dated from 2008.

Type of operator The vehicle is owned by the driver, who is organized in a route association.

Type of vehicles A common vehicle is an altered 7 seater stretch limousine.

Price structure and working hours Fixed fares depending on distance. Paratransit charges about the same fare as formal bus services.

Performance figures No data available

Route choice The paratransit vehicles compete the formal bus services. Although they have a fixed destination, the route will be adapted to individual demands. Quite common is the avoidance of trunk roads and the occasional detour in order to increase chances to pick-up additional passengers. For example, the vehicle departs from a village with at least 3 or 4 passengers or after 20 minutes of cruising as the case may be. Passengers may board and alight anywhere.

B.4.3 Syria/Damascus

This data is based on first-hand experience by Ihab Kaddoura (personal communication, May, 2011) dated from 2007. Besides a minibus based paratransit the city of Damascus features a kind of paratransit with full-sized buses. The formal inner-city bus system plies fixed-routes but allows to board and alight at any time the bus stops, e.g. at traffic lights or when caught up in a traffic jam.

Type of operator Most vehicles are owned by the driver.

Type of vehicles Most vehicles in use are 12 seater vans.

Price structure and working hours The driver is entitled to ply one route by paying a license fee. Fares are fixed and paid per ride. Paratransit vans charge less than taxi services, but slightly more the formal bus services.

Performance figures Conventional taxis and paratransit services serve the majority of trips. Passengers may be asked to change for the next van, if load can be optimized by concentrating on one vehicle. The next vehicle will depart immediately and passengers get a fare refund of the first one. The paratransit service area covers the city of Damascus.

Route choice The fixed routes form a dense network. There are no detours, except for the first and the last trip of day. The vehicle speed correlates with the vehicle load, e.g. a driver starts cruising at the curb lane providing an opportunity to fill up empty seats. Boarding and alighting takes place anywhere. Passengers tend to form a bus stop by clustering at intersections, which increases chances to catch a ride.

B.4.4 Syria/Damascus, Lebanon/Beirut

This data is based on first-hand experience by Ihab Kaddoura (personal communication, May, 2011) dated from 2007 and Severin Gierlich (personal communication, May, 2011) dated from 2011.

Type of operator The majority of drivers own their car.

Type of vehicles The most commonly used vehicle is the 4–5 seater sedan. In 2011, the brand-new Hyundai Sonata emerged the market.

Price structure and working hours The driver pays for the license, a fee when departing the terminal in one of the two cities and for maintenance and refueling. The fare is negotiated with the driver and paid per trip. Going by sedan is less expensive than taking a conventional taxi.

Performance figures Since vehicles depart whenever fully loaded, the average passenger load is 4–5 passengers. The sedans only ply between the cities of Damascus and Beirut, which is about 90 km in distance.

Route choice There is only one route between the bus terminal of Damascus and the one of Beirut. Departure is whenever the vehicle is fully loaded or someone pays up for any seats left empty. Alighting along the route essentially takes never place, except for the frontier on rare occasions.

B.4.5 Lebanon/Beirut

This data is based on first-hand experience by Ihab Kaddoura (personal communication, May, 2011) dated from 2007 and by Severin Gierlich (personal communication, May, 2011) dated from 2011.

Type of operator Sedans are normally owned by the driver and operate as taxi or as shared-taxi sometimes lacking a proper identification. Most vans are owned by the driver, too. The rest is leased from a small companies, e.g. from a student who owns five vans.

Type of vehicles Sedans and small vans up to 14 seats ply the street of Beirut.

Price structure and working hours Drivers of sedans pay a license fee and charge negotiated fares based on distance and time of day. In the case of "service" (see Route choice) each additional passenger pays the full price. There is no discount for the first passenger nor the additional ones. The vehicle upkeep and refueling is at the expense of the driver as well. Van drivers have essentially the same expenses. In April 2011, a driver paid a daily leasing fee of 25 €, 5 € per day to get a route license, 0,90€/l for refueling and charged about 0,50 € per passenger and trip. If he drives his own vehicle, he is responsible for upkeep and maintenance.

Performance figures The average passenger load depends on the kind of trip. Sedans serve two purposes. One is the conventional taxi, the other one is a kind of shared-taxi. Vans tend to be loaded to the limit. Both types of paratransit operate in the city's area. The average van trip is 5 km in length or 20 min in time.

Route choice Sedans have two modes of operation and switch between both modes at the start of each new trip. The first one, is the common taxi. Drivers charge slightly more and offer many-to-many services. The second one is a kind of shared-taxi called "service". This mode of operation offers many-to-many connections, too, but allows the driver to pick-up additional passengers along the route heading more or less in the same direction as the initial passenger. With each additional passenger boarding, the driver can set a new final destination serving the rest of passengers by making small detours. If a passenger demands for "service" the driver decides whether to pick-up that passenger or not. The decision is based on the destination demanded and depends on the chances to pick-up additional passengers along the way. On a profitable route the driver may depart with a sole paying customer. If it is unlikely to pick-up additional passengers, the driver may refuse to operate as "service" and instead may offer to operate as taxi.

Vans ply fixed routes. The passengers know the routes and ask the driver for verification. Each route demands a valid license issued on a daily basis. Drivers could change the route at each day by buying a different license, but stick to "theirs".

B.4.6 Israel/Haifa

This data is obtained by personal communication with Oded Cats (personal communication, May 19, 2011).

Type of operator No data available

Type of vehicles The vehicle commonly used has a capacity of 10 seats.

Price structure and working hours No data available

Performance figures The driver waits until the vehicle is full. Paying off empty seats is very uncommon. As a result, customers play sitting duck to enter a "full" vehicle so that the trip starts immediately. Nearly empty vehicles are avoided to minimize individual waiting time.

Route choice The routes are more or less fixed. Paratransit services are engaged in head-to-head competition with legal buses, running ahead the buses.

B.4.7 Egypt/Aswan, Luxor, Hurghada, Sinai

This data is obtained by interviews with Ihab Kaddoura (personal communication, May, 2011) and his first-hand experience dated from 2007.

Type of operator Most drivers drive vehicles of absentee owners mostly companies.

Type of vehicles The vehicle used is the 12 seater minibus.

Price structure and working hours License fee and refueling is paid by the driver. Vehicle maintenance is paid by the vehicle owning company. Fare is calculated based on the distance traveled and is slightly more expansive than formal bus services on the same route.

Performance figures The average passenger load is about the vehicle's capacity of 12 passengers.

Route choice The minibuses ply between fixed termini, e.g. the bus terminals of two cities. Headways are more frequent than those of the formal bus on the same route. In addition, the minibuses offer shorter travel times. A minibus departs whenever the vehicle is fully loaded or on rare occasions only one to two seats are left empty. The driver may switch to a taxi mode of operation when paid an extra. Boarding and alighting usually takes place at the termini.

Beside the minibus service, the region offers a second complementing paratransit service. It is served by 6–10 seater sedans and pick-ups owned by the driver himself or owned by a company. The fare is based on the distance and the time of day. The mode of operation is shared-taxi serving many-to-many connections. Compared to minibuses the headways are more frequent.

B.4.8 Egypt/Cairo

This data is obtained from two newspaper articles (Nkrumah, 2003; El-Rashidi, 2004) and by interviews with Ihab Kaddoura (personal communication, May, 2011) and his experience dated from 2007.

Type of operator Drivers are organized in route associations, but engaged in competition to each other.

Type of vehicles The most commonly used vehicle in Cairo is the 14 seater microbus.

Price structure and working hours The driver pays for refueling, the vehicle license and a passenger license. Minibus service is more expensive than formal bus services and charges a fixed fare per trip.

Performance figures In 2003, 8.880 microbuses were registered within the city of Cairo and about 20.000 in Greater Cairo serving about two million trips per day. Microbuses are considered to have a 20 % share of the total of 18 million journeys per day within Greater Cairo.

Route choice There are 34 fixed route associations in Greater Cairo. Microbuses compete the government-run minibus services (26 seater) offering a faster and more reliable trip. Terminals of formal bus and train stations used as major pick-up points.

B.4.9 Tunisia/Tunis

This data is obtained by interviews with Leila Soltani (personal communication, June, 2011) and her research dated from 2011.

Type of operator Most vehicles are owned by the driver or leased from private owners. Drivers are engaged in head-to-head competition.

Type of vehicles The most common vehicles is the 8 seater van called "stafette". Most vehicles are old.

Price structure and working hours Fares are fixed and paid to the driver directly or to a cashier employed by the driver. A trip about 6 kilometers costs about 600 millimes. That is a quarter to one-fifth of a trip by taxi (2200 millimes) and about the same as going by bus. For an incomplete trip, e.g. half of the complete route's distance, the driver may give a discount. The driver pays for refueling and, in case it is his own vehicle, for the vehicle's upkeep. Van drivers need to buy a license, but this is much cheaper than the taxi driver's one bought once or twice a year, which lead to some stoppage.

Performance figures Especially after 16:00, most vans are fully loaded, thus serving 9-10 passengers per trip. It used to be up to 20, but overloading got prohibited and enforced. Trip length varies in distance and travel time. A common trip is from La Marsa to Ariana, which takes about 6 minutes or 10 kilometers. Another route is from Carthage next to the center of Tunis, which takes about 15 minutes or 17 kilometers. Services in the center of Tunis itself, is restricted to formal taxi services and public transport.

Route choice Most services ply a fixed corridor along trunk roads. Smaller detours are possible, sometimes for a little extra. There is a head-to-head competition with bus and train lines running the same corridor. Vehicles stop anywhere allowing for boarding and alighting. Stopping at bus stops and termini is quite common. Van services provide a faster, more reliable and more comfortable trip than bus services. Although train services provide the same travel time and reliability as van services, they lack in comfort, e.g. guaranteed seating.

B.5 Other regions

This section features case studies from Kuwait and the Republic of Moldova.

B.5.1 Kuwait

This data is obtained by interviews with Leila Soltani (personal communication, June, 2011) and her experience dated from 2011. The formal Kuwaiti public transport system consists of a bus network used by commuting workers and taxi services. Besides private cars mainly used by Kuwaitis, there are company cars and buses offered to employees for commuting. Company cars sometimes find a second usage as clandestine ride-sharing cars in the private sector for relatives and close friends.

Type of operator Private car owner, possessing one or more vehicles, and holding a license for them. Driver may be the car owner himself or an sub-employee.

Type of vehicles Sedans and 7–9 seater vans without any identification or labeling.

Price structure and working hours The price is negotiated with the driver and depends on the distance traveled and the number of passengers carried. For example, a trip from Kuwait City to Al-Fintas costs DK 4–5 or about 12 Euro (30km). For comparison, a trip by taxi from Kuwait International Airport to Al-Fintas costs DK 6 (24km). Although equipped with a taximeter, taxi drivers will charge based on distance but more than according to tariff.

Performance figures Depending on the agreement with the driver, a driver will accept a sole passenger, but more likely demand a higher price. Thus, vehicles are not necessarily packed. The driver will only serve customers with the same sex or otherwise related. The sex of the driver does not matter. Service are is restricted to the state of Kuwait and for the most part to the city itself.

Route choice The service is taxi-like and serves many-to-many connections. It needs to be called by phone in advance. Route, departure time and price are negotiated with the driver. Thus, the route is preset. If the driver receives another call on tour, he may pick that new customer up, if first he has the same general direction and second the passengers on-board agrees. Except for calls, there will be no detours or additional passengers picked-up along the route. The service tends to be used by customers with a repeating travel pattern, who have a longterm agreement/subscription with the driver, e.g. every Monday to Thursday 20:00 from A to B.

B.5.2 Republic of Moldova/Chișinău

This data is obtained by interviews with Joschka Bischoff (personal communication, June, 2013) and his experience dated from 2010.

Type of operator Supposedly private car owners.

Type of vehicles Old 10 seater Mercedes Sprinter vans with an additional room for 15–20 standees called "maxi-taxi". Destination boards indicate the route served.

Price structure and working hours The routes are operated from 6:00 to 23:00. For a typical route length of 10 km the van needs about 40 minutes. In 2010, the fare had been fixed at 3 Lei per trip within the city. This is more expensive than the formal (trolley) bus, 2 Lei, but far cheaper than a taxi ride, about a negotiated 20 Lei. The driver needs a license for its route and is responsible for collecting the fare.

Performance figures Most vans are fully loaded. The drivers do not wait for a fully loaded vehicle at the termini and decide individually when to depart. Headways depend on the route and vary from 3 up to 15 minutes. Roughly half of the public transit demand is served by the vans.

Route choice The routes are fixed and defined by the city's administration. Originally, most routes run in parallel to formal bus lines. According to the Primăria Municipiului Chişinău (2013), 67 minibus routes has been in service in June 2013. Basically, vans serve all neighborhoods, but are restricted from serving the main boulevard (Bulevardul Ştefan cel Mare şi Sfînt). Passengers can board and alight anywhere along the routes.

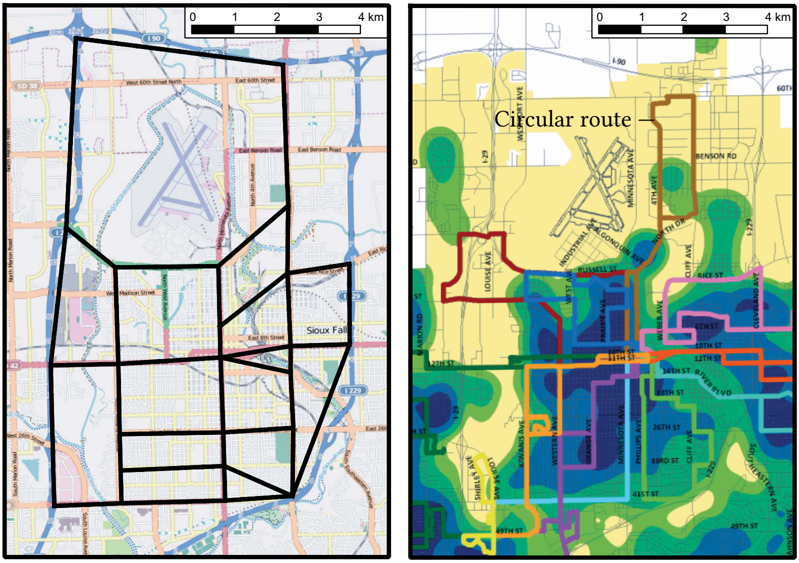
APPENDIX C

Application to the Sioux Falls scenario

In case of public transit optimization, solutions are often benchmarked using an agreed scenario. For analytic studies, this has been the Mandl's Swiss network (Mandl, 1979; Chakroborty and Dwivedi, 2002; Zhao and Gan, 2003) and the Sioux Falls scenario (Morlok et al., 1973; LeBlanc et al., 1975). Recently, Chakirov (2013) transformed the macroscopic Sioux Falls scenario into a microscopic version applicable to the multi-agent simulation of MATSim. The minibus model is applied to this adapted version. Since the author is not aware of any paper optimizing the Sioux Falls transit supply from scratch this section aims to provide data for future comparisons.

C.1 Scenario description

Essentially, the geometry of the original road network is changed to match the real city of Sioux Falls, South Dakota, see Figure C.1a. Furthermore, the 76 original links are replaced by shorter link chains. As a result, activities are no longer tied to one of the original 24 nodes, but can be accessed from any of the in-between nodes linking the new, 500 m long links. The assumed transit supply of Abdulaal and LeBlanc (1979) is integrated as well, see Figure C.3a.



(a) Sioux Falls with simulated road network. The map data is taken from OpenStreetMap (2012).

(b) The fixed route services of the city of Sioux Falls with underlying population density (SAM, 2012)

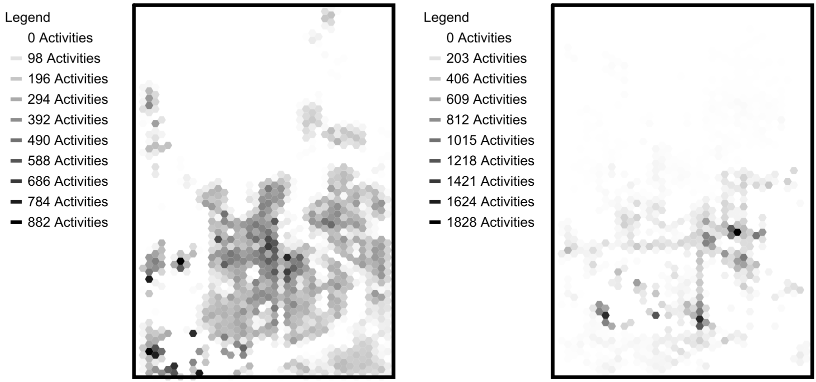
Figure C.1: Sioux Falls scenario and the actual city of Sioux Falls

Consequently, the adapted Sioux Falls scenario is multi-modal featuring the transit modes private car and bus. The actual transit routes of the city of Sioux Falls are depicted in Figure C.1b. Note that these routes also serve streets that are not present in the Sioux Falls scenario of MATSim. In addition, routes in the outskirts are circular routes serving only in one direction.

The demand of the original OD-matrix is transformed into individual agents. Activities are distributed within the original zones. The resulting demand features two main activities. Their distributions are depicted in Figure C.2. In total, there are 81764 agents following a home-work-home pattern.

The configuration of the minibus model is the same as in chapter 7. The parameters of the route modification strategies are listed in Table 5.2, additional parameters are listed in Table 7.1, and the remaining configuration of MATSim is described in subsection 7.2.1. The supply of the formal public transport is removed completely. Thus, the minibus is the only public transit mode.

There are three setups that only differ in the charged fare. In the first setup



(a) Activity type home

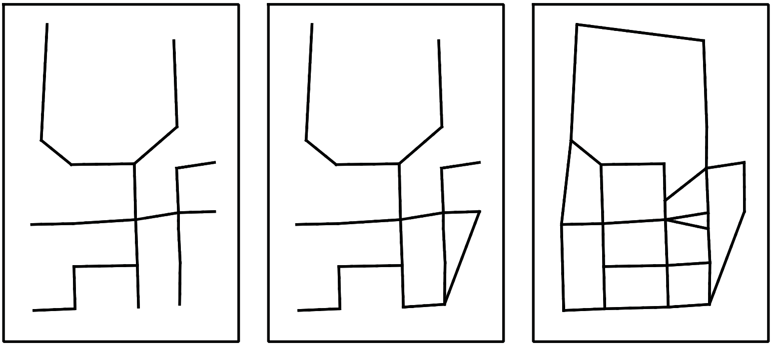
(b) Activity type work

Figure C.2: Distribution of activity types within the scenario area

Normal, the fare is set to 0.5 ¤ per boarding. In the second setup *Doubled*, the fare is set to 1.0 ¤ per boarding and in the third setup *Tripled* to 1.5 ¤ per boarding. An ensemble run is performed for each setup. The results of the ten runs of one ensemble run are fused to allow for a more reliable analysis and to identify stable and repeating solutions.

C.2 Results

The results of the three setups are fused in the same way as described in chapter 7. The results of the *Normal* setup in Figure C.4a show that the minibus is concentrating on the two main streets with the highest concentration of work activities. In addition, the high-density residential area in the southwest are served as well. With an increased fare, operators can serve more low-demand streets. Consequently, the minibus network grows in the *Doubled* and the *Tripled* setup, see Figures C.4b and C.4c respectively. In the *Tripled* setup, the network of minibus services resembles the hypothetical transit supply of Figure C.3a. Note that this transit supply is not optimized in any way. The same holds true for the other two hypothetical transit networks.

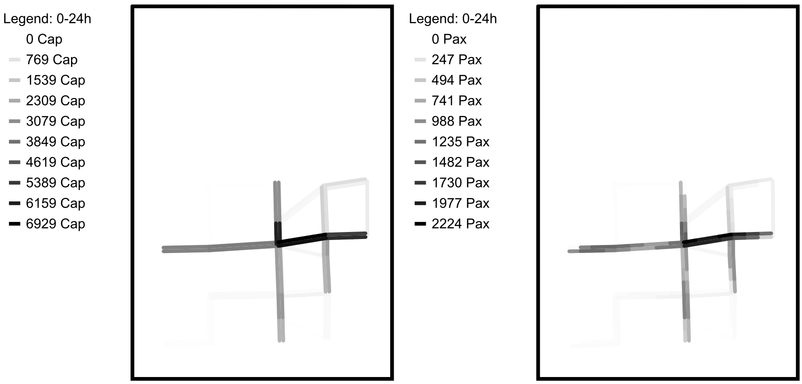


(a) Based on Abdulaal and LeBlanc (1979) **(b)** Based on LeBlanc (1988) **(c)** Based on Samimi et al. (2009)

Figure C.3: Hypothetical transit networks of the Sioux Falls scenario

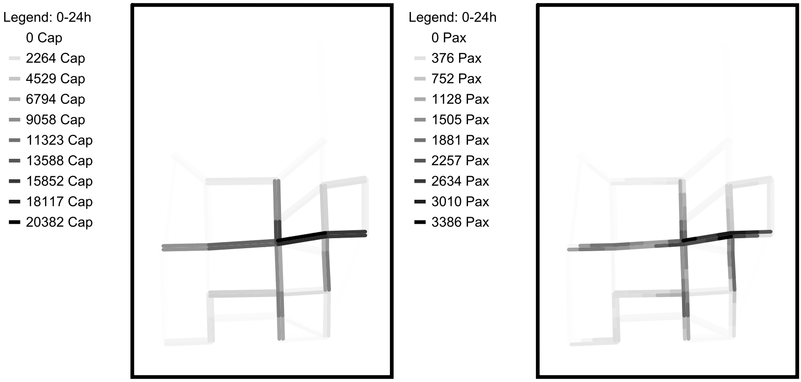
C.3 Conclusion

The overall solution found by the minibus model is stable. That is, there is a clear hierarchy of the served streets. Starting with the lowest fare of the *Normal* setup, each evolved network is a subset of the higher fare's setup,

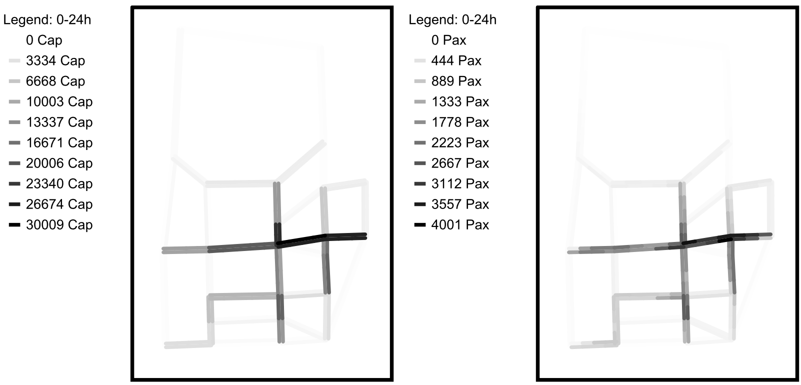


(a) Provided capacity and served passengers – *Normal* setup

Figure C.4: Average provided capacity and average number of passengers served per street section i.e. the network of the *Tripled* setup covers at least the same streets as the network of the *Doubled* setup. Charging a higher fare allows to serve more (less profitable) road sections and thus the minibus network becomes more dense and larger. The actual transit supply of the real city of Sioux Falls as depicted in Figure C.1b could not be mimicked mainly due to a less detailed underlying road network.



(b) Provided capacity and served passengers – *Doubled* setup



(c) Provided capacity and served passengers – *Tripled* setup

Figure C.4: Average provided capacity and average number of passengers served per street section (cont.)

APPENDIX D

Further results of the case study II

This chapter includes the supplemental plots of the *Corridor* setup and the *Area* setup of the transit authority case described in chapter 7. The *routes* of the *Corridor* setup are shown in Figures D.1 to D.10. The *routes* of the *Area* setup are shown in Figures D.11 to D.20. The histograms of the runs 2 to 9 of the *Area* setup are shown in Figure D.22.

Furthermore, Figure D.21 gives an example of a state-of-practice analysis of a minibus *route*. The example *route* is taken from run 0 of the *Area* setup. The highest density of boardings and alightings occurs along the Schloßstrasse north of the mayor house of Steglitz. The average load decreases towards the southern terminus at the mayor house of Zehlendorf (S-Bahn rail station of Zehlendorf/Gartenstrasse). Note that the minibus *route* follows a circular pattern. Thus, the plots show a continuous sequence of stops from Steglitz to Zehlendorf and the way back to Steglitz. Consequently, the load pattern is mirrored at the terminus of Zehlendorf.

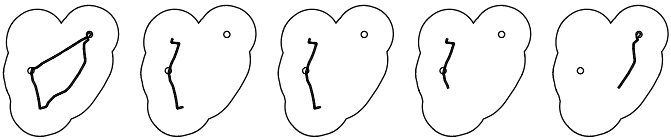


Figure D.1: Resulting *routes* of the *Corridor* setup — Run 0

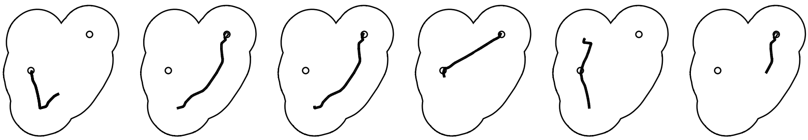


Figure D.2: Resulting *routes* of the *Corridor* setup — Run 1

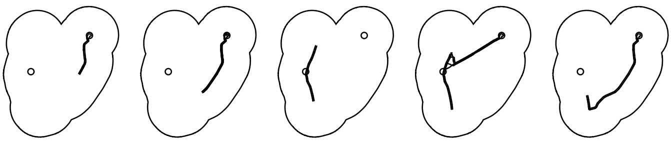


Figure D.3: Resulting *routes* of the *Corridor* setup — Run 2

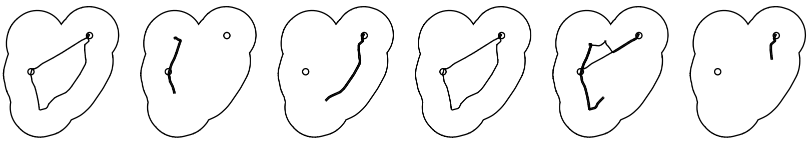


Figure D.4: Resulting *routes* of the *Corridor* setup — Run 3

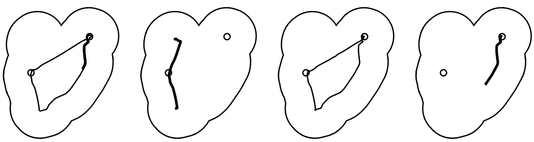


Figure D.5: Resulting *routes* of the *Corridor* setup — Run 4

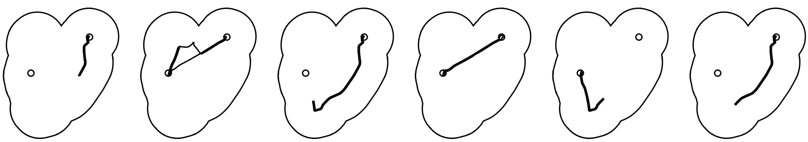


Figure D.6: Resulting *routes* of the *Corridor* setup — Run 5

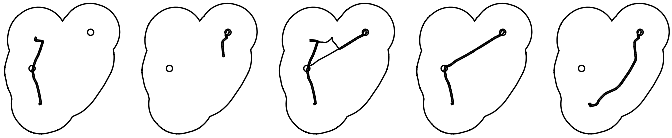


Figure D.7: Resulting *routes* of the *Corridor* setup — Run 6

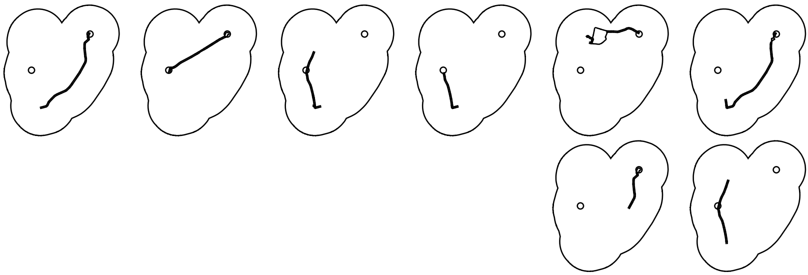


Figure D.8: Resulting *routes* of the *Corridor* setup — Run 7

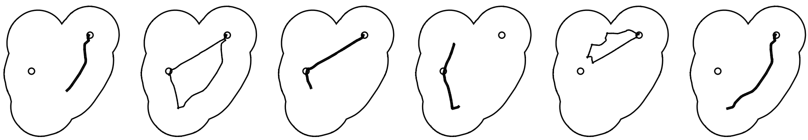


Figure D.9: Resulting *routes* of the *Corridor* setup — Run 8

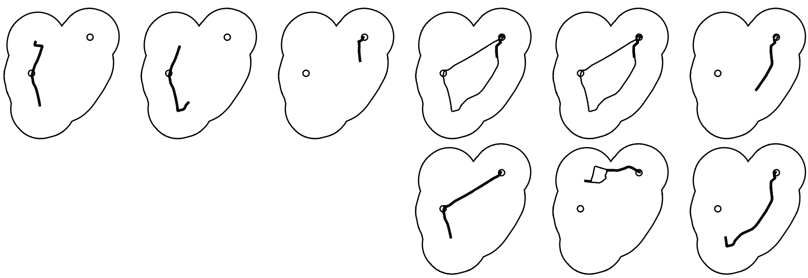


Figure D.10: Resulting *routes* of the *Corridor* setup — Run 9

Figure D.11: Resulting *routes* of the *Area* setup — Run 0

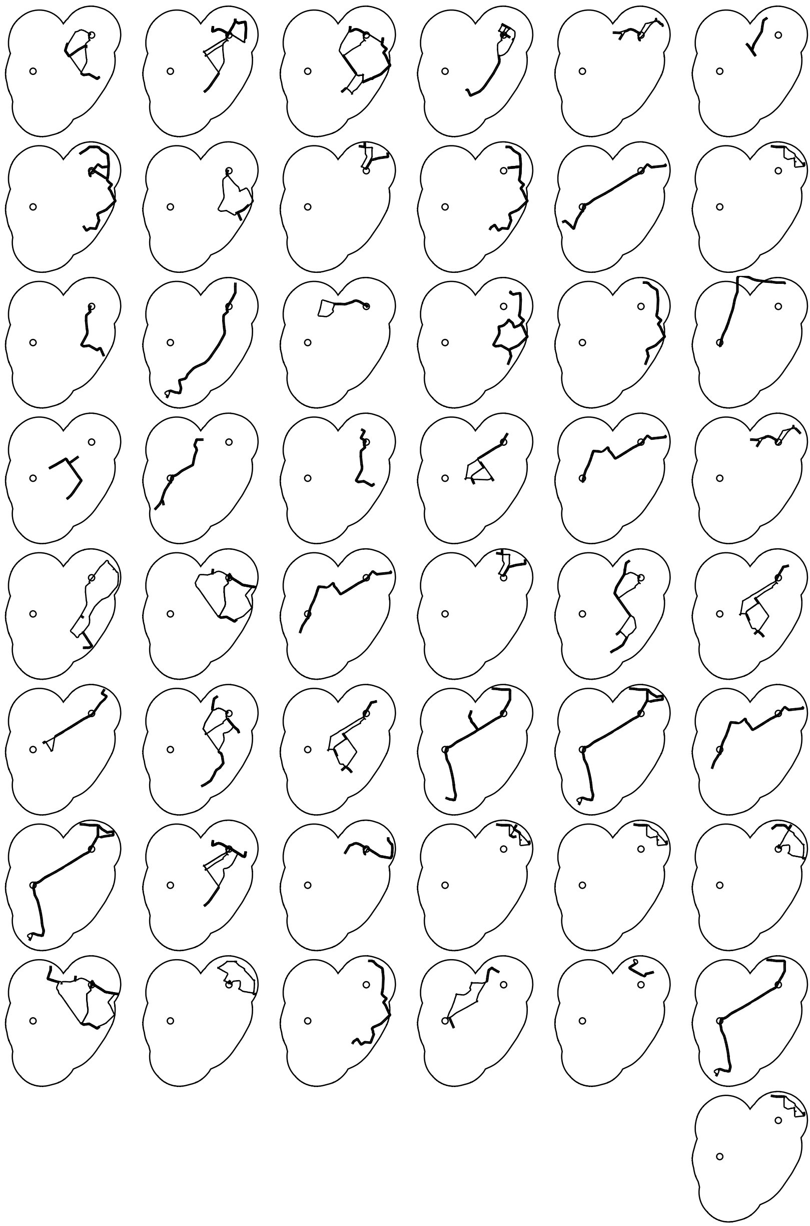


Figure D.12: Resulting *routes* of the *Area* setup — Run 1

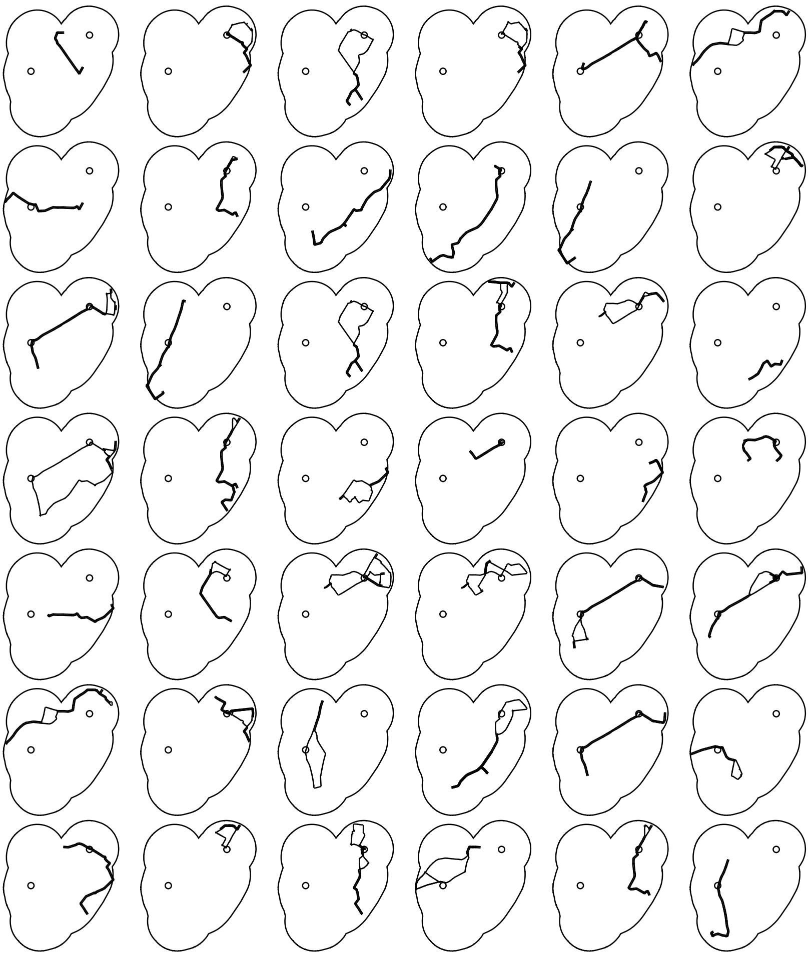


Figure D.13: Resulting *routes* of the *Area* setup — Run 2

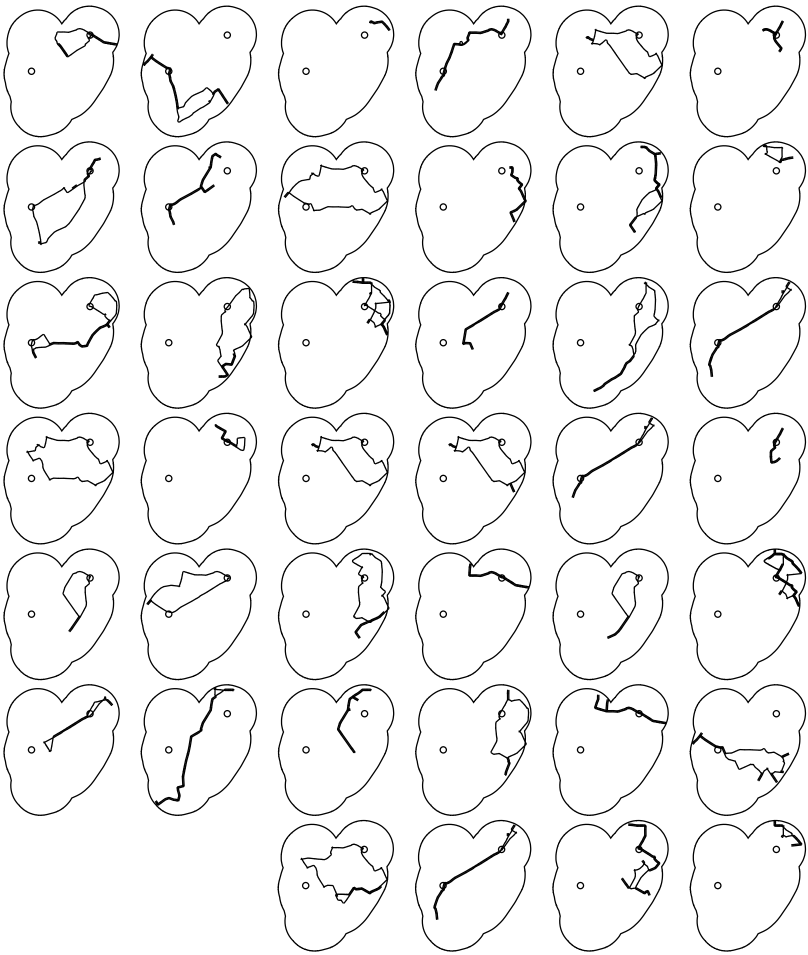


Figure D.14: Resulting *routes* of the *Area* setup — Run 3

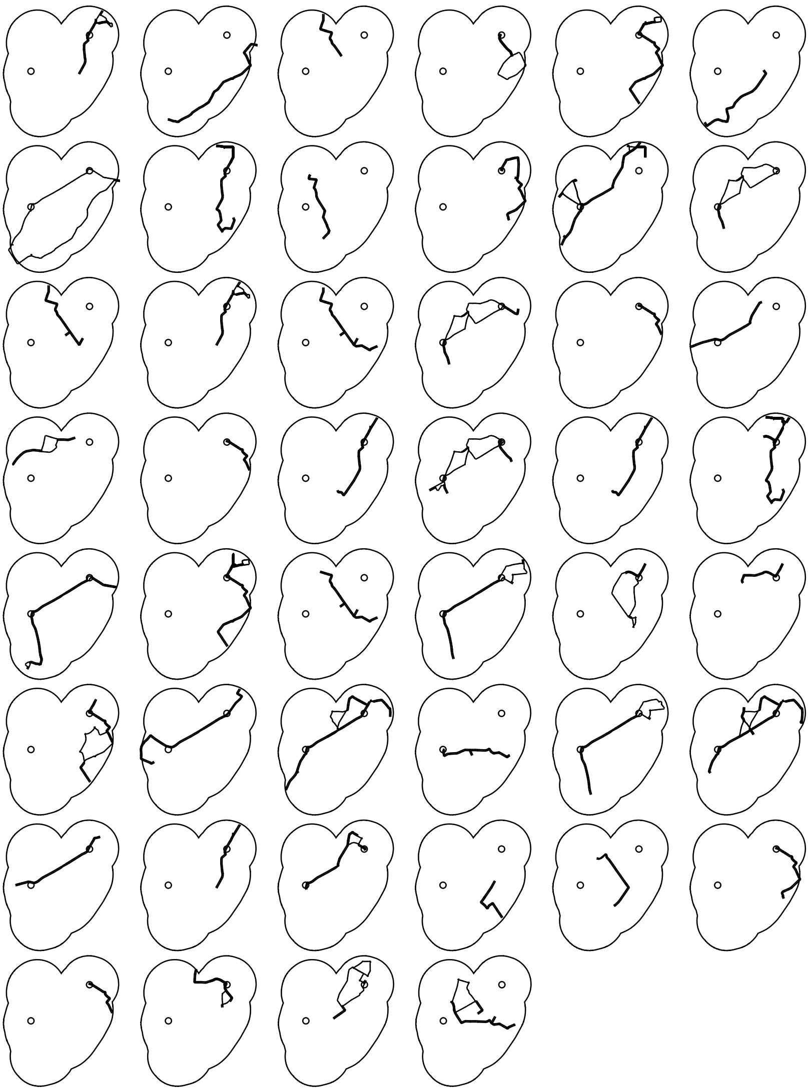


Figure D.15: Resulting *routes* of the *Area* setup — Run 4

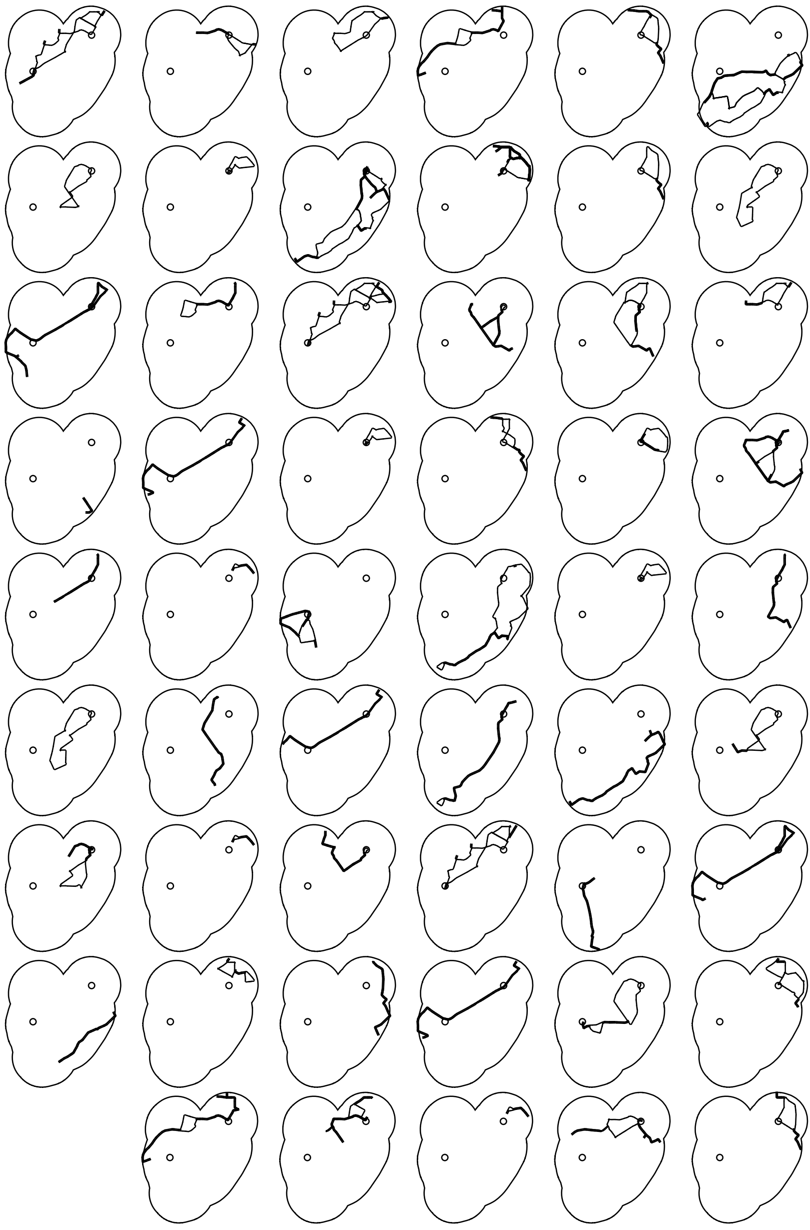


Figure D.16: Resulting *routes* of the *Area* setup — Run 5

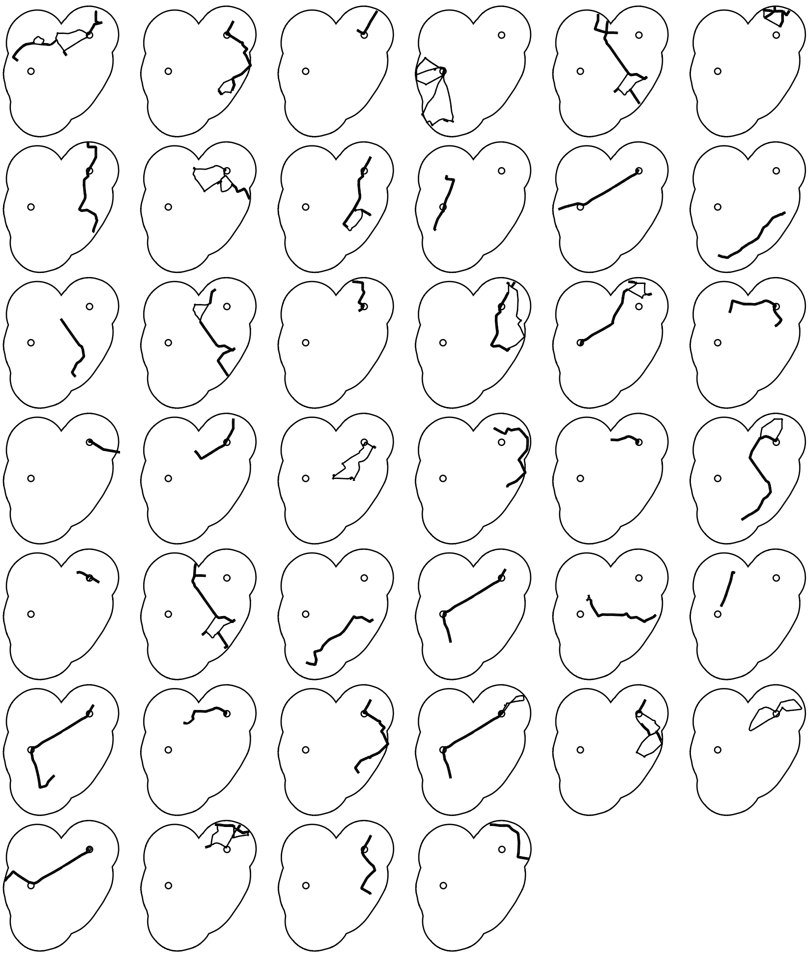


Figure D.17: Resulting *routes* of the *Area* setup — Run 6

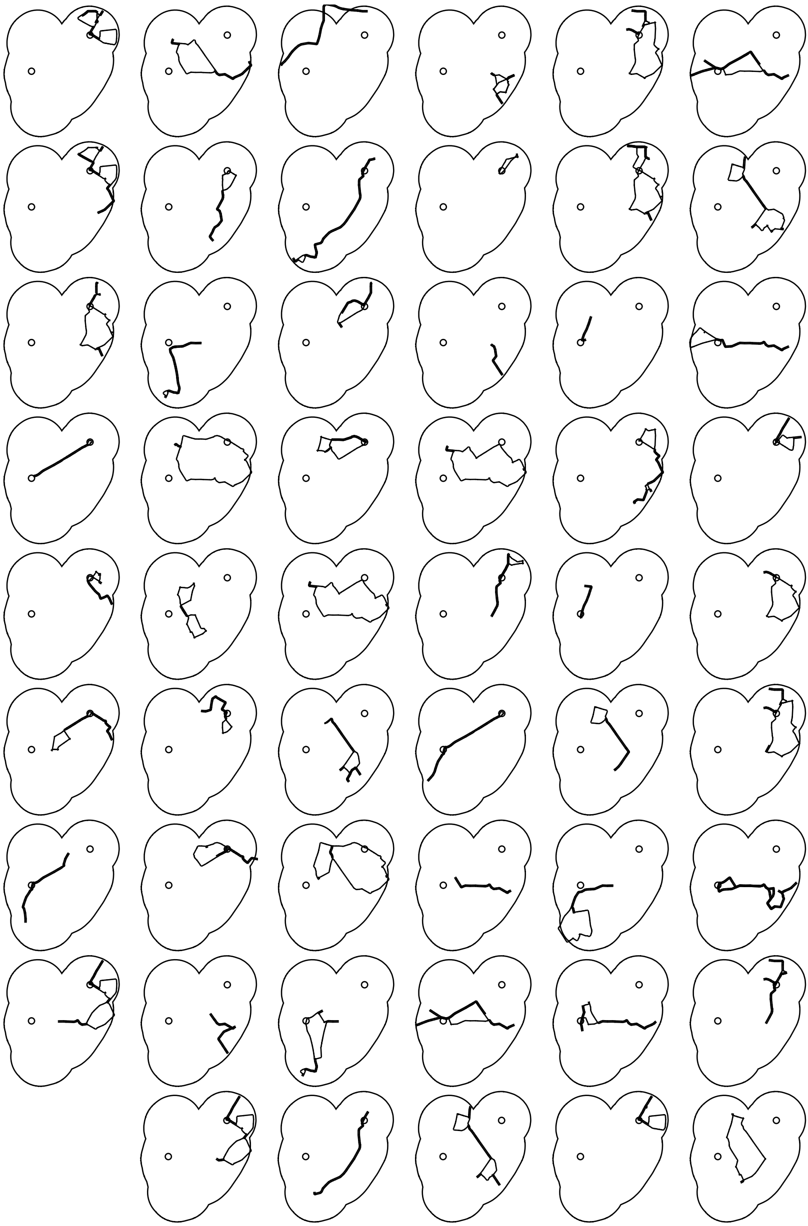


Figure D.18: Resulting *routes* of the *Area* setup — Run 7

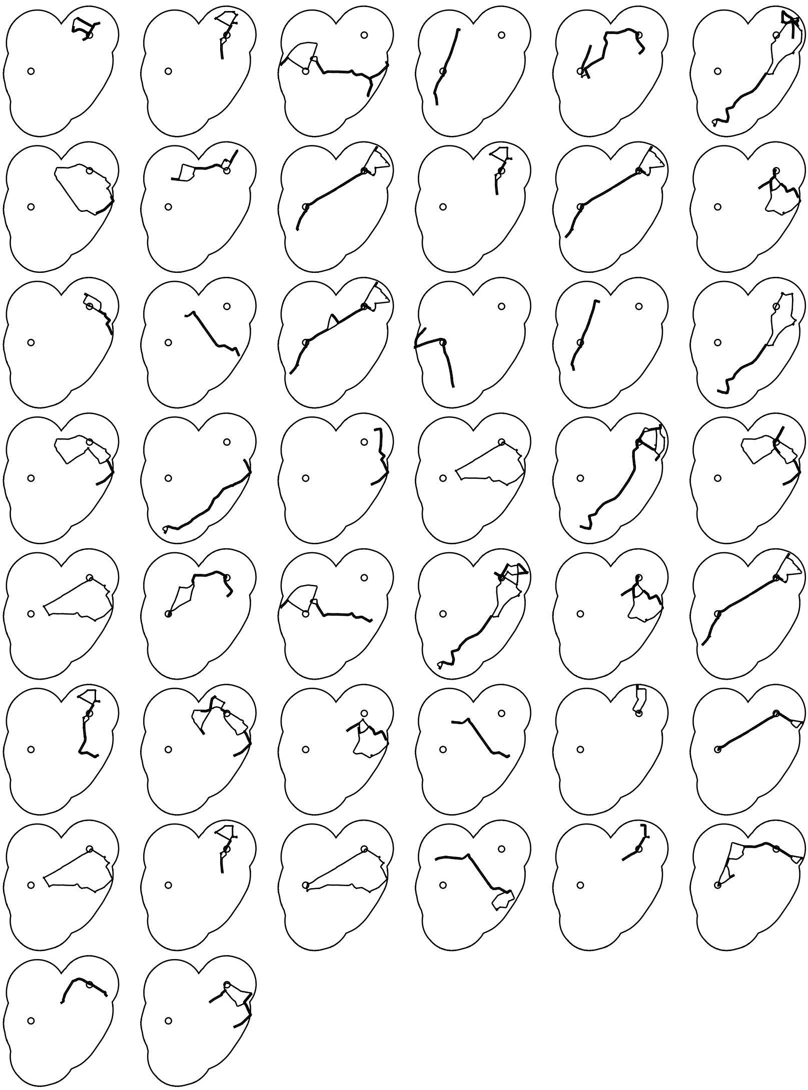
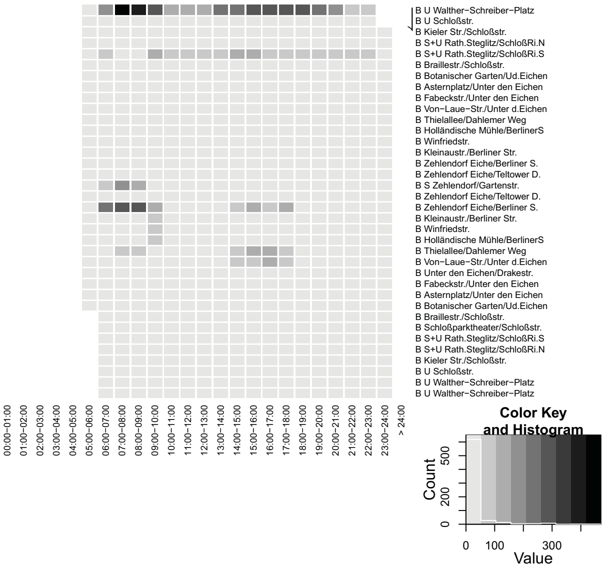
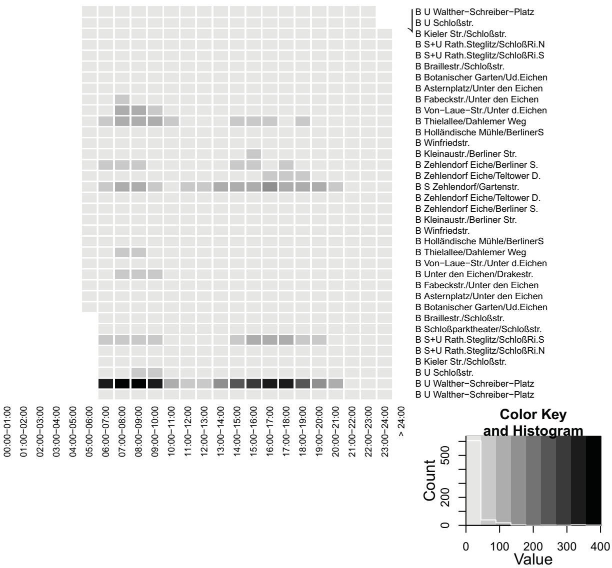


Figure D.19: Resulting *routes* of the *Area* setup — Run 8

Figure D.20: Resulting *routes* of the *Area* setup — Run 9

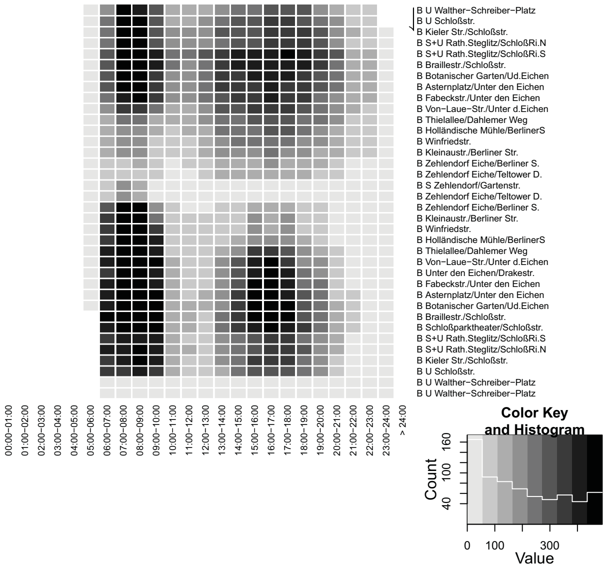


(a) Distribution of boarding passengers

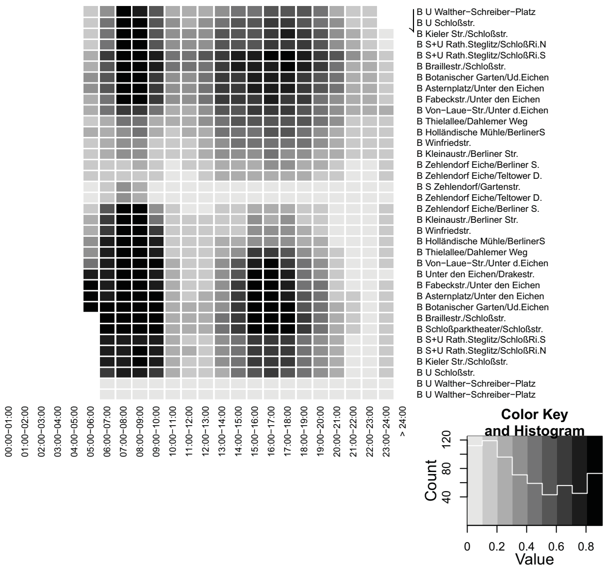


(b) Distribution of alighting passengers

Figure D.21: State-of-practice analysis of a minibus route connecting Steglitz and Zehlendorf

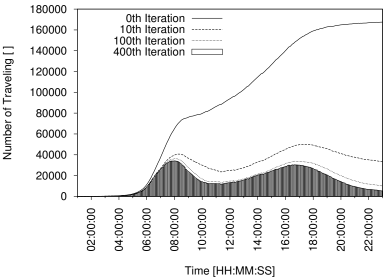


(c) Distribution of served passengers

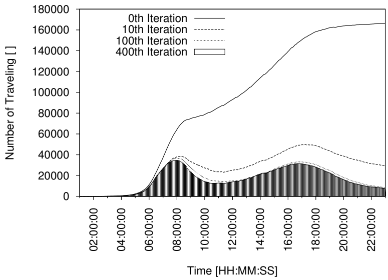


(d) Distribution of the passenger load factor

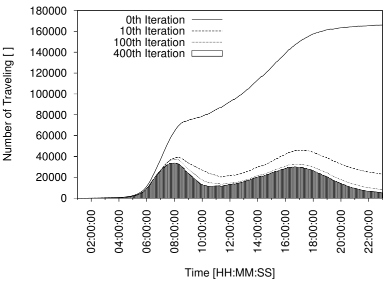
Figure D.21: State-of-practice analysis of a minibus route connecting Steglitz and Zehlendorf (cont.)



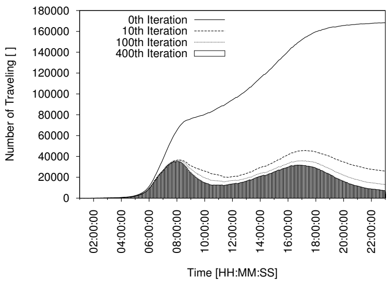
(a) Run 2



(b) Run 3

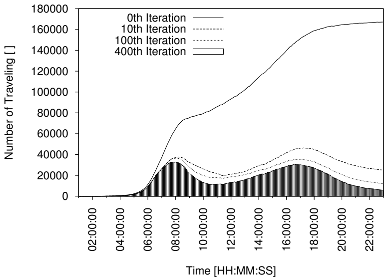


(c) Run 4

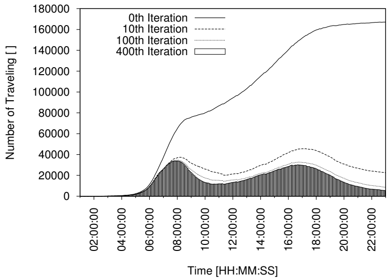


(d) Run 5

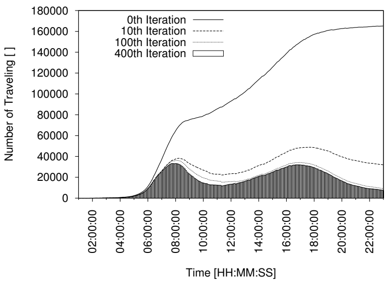
Figure D.22: Histograms of traveling public transport users – Runs 2 to 9 of the *Area* setup



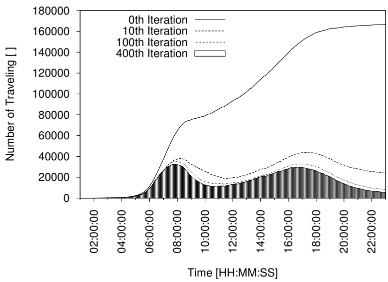
(e) Run 6



(f) Run 7



(g) Run 8



(h) Run 9

Figure D.22: Histograms of traveling public transport users – Runs 2 to 9 of the *Area* setup (cont.)

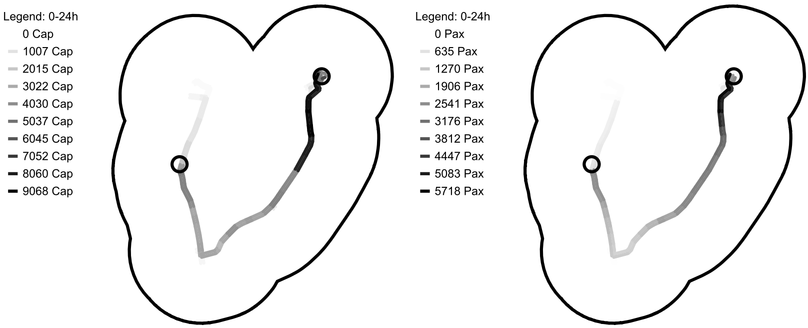
APPENDIX E

Adding a speed limit to the minibus

This chapter provides the results of the Berlin case study with a reduced speed of the minibus. As discussed in section 7.3, the direct non-stop minibus connections between the mayor houses of Steglitz and Zehlendorf are a direct result of the underlying road network. The minibus does only respect the speed limit encoded in the network. Contrarily, other modes of public transit are limited by the time tabling of their transit schedule. Thus, the minibus provides a faster trip than the formal buses of BVG and, moreover, a faster trip than the S-Bahn services offered on the same corridor.

If the minibus model is used to mimic formal bus systems, the transport planner may want to reduce the overall speed of the minibus. In order to test for the reactions of the model, a speed limit of 6 m/s is introduced. This roughly represents the average speed of BVG's buses within the scenario area as encoded in the transit schedule. An ensemble run is performed for both, the *Corridor* setup and the *Area* setup.

The resulting provided capacity and the number of served passengers for the *Corridor* setup are shown in Figure E.1. When compared to Figure 7.7 on page 125, the direct non-stop connections are removed completely. There is no more competition on the corridor between the two mayor houses.



(a) Average provided capacity per street section of all ten runs

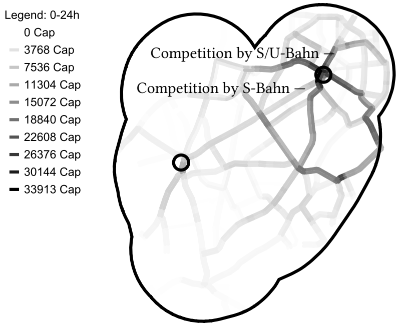
(b) Average number of passengers served per street section of all ten runs

Figure E.1: Evolved minibus network with a speed limit for the minibus of 6 m/s — *Corridor* setup

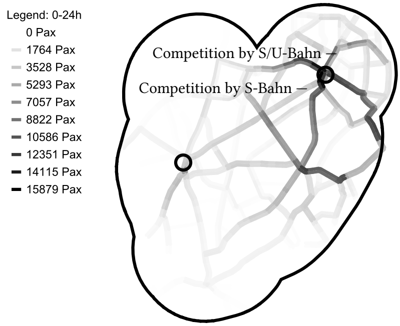
Moreover, the formal bus lines of BVG that are still present in the *Corridor* setup can successfully compete the minibus. As a result, the minibus focuses on serving passengers that cannot be served by the other transit offerings. The maximum capacity of the minibus is reduced to approximately the same amount as the original bus line 285 provided. However, the minibus preserves its ability to adapt its capacity to the demand.

For the *Area* setup, the comparison of the results shown in Figure E.2 and Figure 7.11a on page 130 indicate that the overall provided capacity is reduced, too. In particular, services running in parallel to rail services are reduced to a level of providing trips only to local customers. That is, trips going from the mayor house of Steglitz to the mayor house of Zehlendorf now use the S-Bahn services while passengers with a destination in-between still use the minibus. The same situation can be observed along the commercial district of Schloßstrasse north of the mayor house of Steglitz. There, passengers transfer early to train services when leaving the scenario area. Overall, the pattern of served passengers resembles more closer the situation of the *Reference* as shown in Figure 7.12b on page 131.

In conclusion, adding a speed limit for the minibus reduces the competitive advantage of the minibus. The minibus is forced to focus its services on the secondary network typically reserved to bus services. The direct competition can be prevented. Consequently, this brings the evolving networks closer the existing networks of the *Reference*.



(a) Average provided capacity per street section of all ten runs



(b) Average number of passengers served per street section of all ten runs

Figure E.2: Evolved minibus network with a speed limit for the minibus of 6 m/s — *Area* setup

Glossary

agent An agent represents a synthetic person within a multi-agent simulation. In this thesis, the term refers to passengers of public transport services only. 30

asymmetric congestion game Term used in game theory. Players/participants of the game have different strategies, i.e. different source-destination pairs. 6

bajaj Motorized version of a cycle rickshaw in Jakarta, Indonesia, named after its Indian manufacturer Bajaj Auto. 16

becak Type of human-powered cycle rickshaw known from Jakarta, Indonesia. 16

bemo Type of share taxi known from Jakarta, Indonesia. 16

BRT Bus Rapid Transit. Form of fixed line, high-capacity, high-frequency bus service often with dedicated bus lane. 97

ensemble run Set of runs with the same configuration except for the initialization of the random number generator (random seed). 70, 98, 107, 130, 190

genetic algorithm Algorithm that adopts the process of the natural selection. The individuals' rate of reproduction is linked to their fitness. Non-successful individuals die out.. 27, 30

iteration Cycle of operator replanning, passenger replanning and mobility simulation normally representing one day. 31

line Set of routes that are managed by one minibus operator. 28

minibus service Type of paratransit consisting of minibuses. Such a service is often called a "jitney" service. 21

paratransit Alternative mode of public transport. See Appendix A for further definitions. 9

paratransit operator Offers paratransit services with one or several vehicles. In this thesis, the term paratransit operator refers to minibuses only. 12, 21, 25

paratransit vehicle Vehicle used for paratransit services ranging from pedicabs to full-sized buses. 14

pax Abbreviation for passenger. 14

route Minibus service defined by the sequence of stops served, the time of the first and the last departure, and the number of minibuses put into service. 28, 49

route association Organization of a group of drivers with common interests, e.g. same service area. 12, 25

route profile Term used in public transport planning. Refers to the sequence of transit stops of a transit route. 3

run MATSim related term used to refer to the complete series of steps needed for simulation starting with the input data and finishing with the post analysis of the results, see Figure 4.1 for an overview. Normally, more than one iteration is included. 44

symmetric congestion game Term used in game theory. All players/participants of the game have the same set of strategies. 6

time profile Term used in public transport planning. Refers to the time needed to travel along a route profile. 3