# A PARATRANSIT-INSPIRED EVOLUTIONARY PROCESS FOR PUBLIC TRANSIT NETWORK DESIGN

Andreas Neumann (corresponding author)
Berlin Institute of Technology
Transport Systems Planning and Transport Telematics
Salzufer 17-19
10587 Berlin
Germany
Telephone: +49 30 314 78784
FAX: +49 30 314 26269
neumann@vsp.tu-berlin.de
http://www.vsp.tu-berlin.de

Kai Nagel
Berlin Institute of Technology
Transport Systems Planning and Transport Telematics
Salzufer 17-19
10587 Berlin
Germany
Telephone: +49 30 314 23308
FAX: +49 30 314 26269
nagel@vsp.tu-berlin.de
http://www.vsp.tu-berlin.de

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## Abstract

Public transport companies should run profitable transit lines and demand oriented services. This paper presents an evolutionary model for the design of demand responsive routes and transport networks. The approach adopts the survival of the fittest principle from competitive developing world paratransit systems with respect to vehicles, market actor characteristics, route patterns and route functions. The model is integrated into a microscopic multi-agent simulation framework, and successfully applied to a naive and a complex scenario. The scenarios include the interaction of paratransit services with conventional public transport. With limited resources paratransit services compete and cooperate with each other to find sustainable routes, which compete or complement existing public transport lines. Besides providing a starting point for paratransit modeling of a region, the approach can also be used to identify areas with insufficient supply of public transport.

# INTRODUCTION

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.

A lot of research has been done in the field of transit line optimization. Mohring (*1*) optimized headways and stop spacing of urban mass transportation services, without modifying the route. As the vehicle size influences the operating costs Jansson (*2*) proposed a model to optimize service frequency and bus size. Jara-Diaz and Gschwender (*3*) reviewed the evolution of microeconomic models for the analysis of public transport services with parametric demand and added the disutility of crowding. Short-turn strategies for bus corridors were studied by Delle Site and Filippi (*4*), and more recently by Cortés et al. (*5*), who, in addition, added deadheading to the problem. Urban bus corridors were further optimized by adding limited-stop services with high-frequency unscheduled services (*6*), and by the choice of fare collection systems (*7*).

Besides optimizing a single transit line, network design optimization has been studied. A summary of network design approaches with focus on bus networks was provided by Ceder and Wilson (*8*). Baaj and Mahmassani (*9*) proposed a hybrid route generation algorithm to generate a transit network meeting the demand of a given OD-matrix. Kocur and Hendrickson (*10*) studied the role of a supervising controller optimizing the network density, e.g. the distance between parallel bus routes, fares, and the frequency of service on a route. With focus on feeder services, the optimal feeder bus network to access a rail line was investigated by Kuah and Perl (*11*) and more general for cyclical demand by Chang and Schonfeld (*12*). Later, Chien and Schonfeld (*13*) looked into supplier and user cost minimization by a "joint optimization of a rail transit line and its feeder bus system". Jara-Diaz and Gschwender (*14*) compared corridor lines to direct lines.

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. Cortés (*15*) 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 demand of corridors is known, whereas the zones are optimized in real time with uncertain demand (*16*). Fernandez et al. (*17*) 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. (*18*) added traffic congestion and an adaptive predictive control to the dynamic pickup and delivery problem. Other approaches solving the dynamic pick-up and delivery problem were using genetic algorithms and fuzzy clustering (*19*), particle swarm optimization (*20*), and Benders decomposition, branch and bound strategy (*21*).

The present paper will follow Saez et al. and Cortés et al. in the application of bio-inspired algorithms. But rather than solving one system-wide instance, the present paper 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. *22*), but rather related to evolutionary game theory (e.g. *23*). A common topic in such investigations is under which circumstances cooperative structures can emerge despite the competition (e.g. *24*). The structure of the competition will be inspired by paratransit systems. The approach is useful both for the analysis of paratransit systems, and as a tool to generate alternatives for fixed line operators.

Thus, the present paper will look at transit *system optimization* through a co-evolutionary algorithm of transit *line optimization*. Synthetic transit lines increase or decrease their service frequencies by adding or removing vehicles, depending on each individual line's *fitness*. When no vehicle is left for a line, the line *dies out*, and is recreated as a new line between two randomly selected locations, and with a single vehicle.

The structure of this paper is as follows: the next section will describe the characteristics and underlying principles of paratransit systems. The second part will first define the proposed heuristic approach to solve the transit line route searching problem and then apply its implementation to two scenarios. The paper concludes with an outlook for the approach and possible applications.

## PARATRANSIT

### Definition and scope

The term paratransit has two meanings when referring to transport. One describes a kind of transport specially fitted to the needs of elderly or physically handicapped people. This paper, however, deals with the second meaning which is public transport ranging from taxis up to bus lines. In most cases, this is a user-demand-oriented mode of transport used in cities of the developing world. Although paratransit shares some underlying principles, it can be distinguished from demand responsive transit (DRT) systems by the way organization takes place. DRT systems heavily rely on a supervising level (controller) which allocates vehicles to individual trips or collective rides (e.g. *15, 16, 17*). Paratransit lacks a supervising control level, but nevertheless is not completely unorganized. According to Cervero (*25*) 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 (*25*, p. 18) is a third side

c) 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. Basically, it brings together those willing-to-provide and those willing-to-pay as every marketplace does. With transit drivers seeking for profit and customers searching for a cheap ride, the marketplace comes up with market-determined fares.

Concerning the demand side, paratransit serves all kind of passengers. This includes high-class educated people and students, middle-income households, middle-class customers (even car owners) as well as lower income classes, especially in cities of India and Africa. The service offered depends on the social class served. Different classes use a different level-of-service.

The supply side mainly consists of drivers and vehicle owners. There are further players more or less connected to the supply side like car mechanics and pressure groups. These will not be discussed in this paper, since they are not considered as a part of the supply side from a traffic engineering point of view. This paper focuses on the description of paratransit characteristics from the drivers' side.

In his study about informal transport in the developing world Cervero (*25*, p. 13) mentions a common core distinction among informal services: 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.

The focus of this paper lies on vehicles, market actor characteristics and route choice. A more comprehensive summary featuring case studies and additional background information on congestion impacts, motivation and total revenue of paratransit drivers can be found in Cervero (*25*) or more recently in Cervero and Golub (*26*).

## 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 paper is derived from (*25*, p. 15) and shown in Table 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 paper concentrates on class II and class III vehicles filling the gap between conventional buses and compact vehicles.

**TABLE 1 Summary of classes of paratransit vehicles that operate informally (*25*, p. 15)**

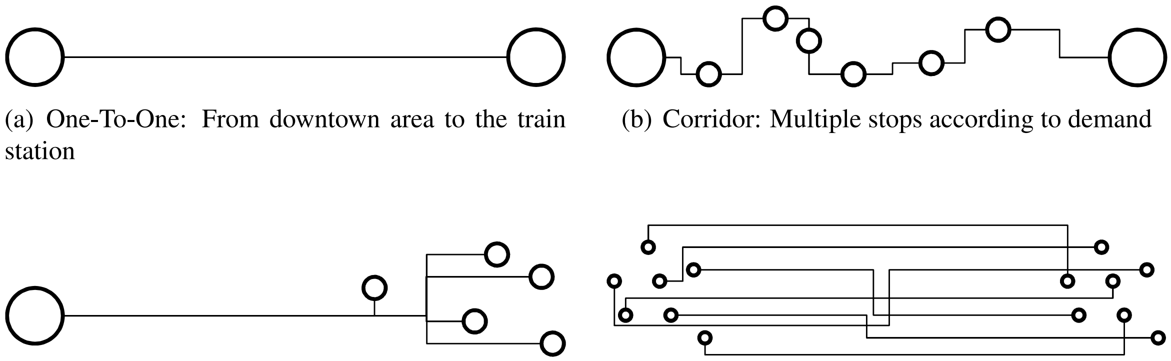
| | CLASS | Routes | Schedules | Capacity | Service Niche | Service Coverage |
|---|---|---|---|---|---|---|
| **I** | **Conventional Bus** | Fixed | Fixed | 25–60 Persons | Line–Haul | Region/Subregion |
| **II** | **Minibus, Jitney** | Fixed | Semi–Fixed | 12–24 Persons | Mixed | Subregion |
| **III**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

The number of passengers served varies from region to region. Numbers of carried passengers per day and vehicle vary from 60 to 520 in the case of Bangkok's minibuses (*25*, p. 27). Interviews with people from Rio de Janeiro indicate 12-15 passengers per trip and van. Examples from Eastern Mediterranean and Egypt 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.

## Market actor characteristics

Paratransit drivers do not match the characteristics of one single player. There are all kinds of types starting from one-driver-companies like single car owners and franchises, up to cooperatives with hundreds of members. For the purposes of this paper, only cooperatives are considered more closely.

Cooperatives, also known as route associations, consist of paratransit drivers, and are founded in order to fend off renegades and pirate drivers from the cooperative's service area. Although, in most cases, protection from open competition is the main objective, there may be other objectives. Such objectives include the enforcement of minimum standards, facility sharing, or



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

(b) Corridor: Multiple stops according to demand

(c) One-To-Few: Feeder and distributor to the marketplace

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

**FIGURE 1 Some examples of different route patterns**

joint negotiation with the administrative or political sector.

## Route choice

Regardless of the kind of market actor, the driver has to adapt to the demand. The driver does so by providing a service in a certain area or by plying along a corridor. Route choice can be categorized by a) the route pattern and b) the route function.

**Route pattern** Since route patterns heavily depend on the local market, there are as many different types as there are markets in the world. Some of the most common are shown in Figure 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 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 the 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. 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.

**Route function** 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 (*25*, 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.

**Total revenue**

A driver will adapt his route whenever demand changes. This decision is based on profit maximization by optimizing the income, cutting down expenses or by increasing 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 cooperative, or can be negotiated with the driver. Fare calculation may rely on the driver's intuition and can be based 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.

**Summary of paratransit systems**

Paratransit systems can be categorized by route pattern and function, by organization of drivers, kind of stops, and fare type. To summarize, most case studies obtained by personal communication and presented by Cervero (*25*) indicate that paratransit services are mainly organized as cooperatives 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. Hence, the approach presented in this paper will be based on those most common characteristics.

# PROPOSED MODEL

The proposed model enhances the multi-agent simulation MATSim (*27*).

## General

As described above, many paratransit services serve a corridor by plying a fixed route. For the proposed model, it is assumed that each route can be seen as a paratransit *line* operated by one cooperative. At the beginning, each cooperative starts with one *line* determined by two randomly picked links and two shortest paths connecting both links with each other. The resulting circular *route* is operated from 0:00 to 24:00 by one vehicle. Stops are located at every intersection, thus allowing boarding and alighting near any node of the network. A *line* serves every stop that it passes. Paratransit vehicles ply the same streets as buses and private cars. All types of vehicles interact in the way that congestion affects every type of vehicle, and paratransit and buses can be caught in a traffic jam as the private car user does.

## Demand

Demand is based on a synthetic population. Each agent of the population follows a plan, carrying out several activities. Activities are connected by legs. Each leg has a mode of transportation. The current simulation offers the modes walk, bike, car and public transport. The simulation features an integrated model in the way that an agent can have different legs in its plan, each using a different mode of transportation. In the approach used here, an agent using public transport can use paratransit services as well. Paratransit services are transparently integrated into the public transit schedule, implying that the model assumes that paratransit cooperatives announce their schedule beforehand. As route search is based on the schedule, trips using formal public transit in combination with paratransit can be found, allowing for multiple transfers. Although a paratransit vehicle may not be on time, the general frequency of the service is registered (see discussion of some aspects below).

## Paratransit modes of operation

The model allows for different modes of operation. Transit and paratransit vehicles 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. Paratransit vehicles can overtake each other and other buses at stops. A vehicle fully loaded will not try to pick-up additional passengers and instead proceed as fast as possible to the next stop determined by one of the passenger's desire to alight. A vehicle with empty seats left will ask the waiting agents at each stop it passes by for their destination. If the vehicle serves that stop, it will pick up the agent, otherwise not.

## Scoring of the paratransit cooperatives

Scoring takes place at the end of the iteration. For each passenger of a vehicle the cooperative is granted a lump sum, e.g. a positive score. For each kilometer a vehicle travels the cooperative gets a penalty, e.g. a negative score. Scores are summed up for a day (iteration). Profitable *lines* end up with a positive score, non-profitable *lines* with a negative score. The sum of all *lines* is transfered to the cooperative and forms the budget for the next iteration.

### Optimization process

Optimization takes place at the beginning of an iteration. Since a paratransit *line* is operated by one cooperative, each cooperative tries to optimize its own *line*. There is no explicit coordination or cooperation between the cooperatives, except for the fact that an agent using paratransit can transfer to a different paratransit *line*. Different cooperatives together can thus form a hub if this emerges from the optimization process, but otherwise are engaged in head-to-head competition.

At the beginning of each optimization step, a cooperative may have to compensate for a imbalanced budget by selling vehicles. For each vehicle sold, a lump sum is added to the budget. If no vehicles are left, the cooperative is shut down and another one is initialized with one vehicle for free.

If the current *line* operated has a positive score for the cooperative, the cooperative tries to optimize that *line* further. This can be done by altering:

a) The vehicle fleet. A cooperative can buy new vehicles from the budget for a lump sum. The lump sum for buying a vehicle is the same as for selling one. If the cooperative has insufficient funds, it can save the budget for the next iteration. More vehicles directly translate into higher frequencies.

b) The time of operation. A cooperative can change the time of the first or the last planned departure. The first departure can, for example, be set to 6 o'clock instead of the initial 0 o'clock. This can compensate for slack periods minimizing the expenses of empty vehicles circulating.

   First, the modification is tested with a second *line*, which operates the same *route* with one single test vehicle for free. After scoring, a score per vehicle is calculated.

   – If this score is higher than the one of the main *line*, the modification will be applied to the main *line*, i.e. the time of operation is changed.
   – If the score is lower, the modification is not applied.

   In both cases the test *line* is terminated and the vehicle dropped.

### Discussion of some aspects

The route planning by the passenger is similar to a schedule-based transit assignment. That is, paratransit is included in the passenger's route plan by the assumption that there will be a certain paratransit vehicle at a certain stop at a certain time. Especially with the mode of operation of type c) above – drivers ignoring the timing of their schedule and driving as fast as possible – the vehicle may be far away from its schedule. However, for typical paratransit services running at high frequencies, this is not a serious issue since the passenger will just take the first approaching vehicle heading to the desired destination. If, however, the *line* is run at a low frequency and the passenger has to wait for a long time, the route will achieve a low score for the passenger, and the passenger will turn to more attractive options acquired earlier due to the MATSim choice model.

### Possible enhancements of the model

The proposed model can be further developed by a series of optimization strategies. First, a new stop at the beginning or the end of the existing *route* can be added. The new stop must not form a loop or u-turn and should be in the general direction of the existing *route*'s corridor. Second, the *route* can be shortened by removing stops at the end of the *line* with no demand at all. A *line* can also be split if demand concentrates on two independent segments of the *route*. Effectively, this forms a cooperative within a cooperative thus allowing for subsidiary companies. Third, a franchise system can be introduced that prevents from two cooperatives running the very same *line*.

Further enhancements adopt mechanisms from real-world paratransit examples. For example, there are minor detours. Instead of only picking-up agents with a destination served by the predefined *route*, the paratransit driver can consider to incorporate a small detour. The vehicle 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 picked-up. Otherwise, the vehicle will proceed as planned.

Another form of adapting the predefined *route* is adding short turning. If a driver can make more profit in the opposite direction, he will make a u-turn going the opposite direction. The 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 (*28*). 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.

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 departure in order to avoid bunching. This allows for more passengers to aggregate along the route. The cooperative 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 and is already implemented in MATSim (*29*).

Finally, the model should offer full mode choice. The current implementation already allows agents to change mode, e.g. from car to public transport and paratransit respectively. However, this solution lacks a scoring function for the agent, which incorporates the monetary expenses related with paratransit. The model can then be incorporated to a real world scenario like the Berlin scenario available at VSP TU Berlin (*30*).

## APPLICATION

The proposed paratransit approach is tested with two scenarios. Both use the same multi-modal network, shown in Figure 2(a). It contains 16 nodes connected by 48 car links, each with a length of 1200 meters and a capacity of 2000 vehicles per hour. Each car link can be referred to by taking its start and end node's name, e.g. the link from node 14 to node 13 is called 1413, the corresponding back link 1314 respectively. 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 and a speed-limit set to 100 m/s. Capacity is set to infinity. Since the links A to D loop, the actual coordinate of the agents located on those links is identical with the one of the nearby node, e.g. node 14 for demand of link A. The paratransit vehicles used in this paper have a capacity of 11 seats allowing to carry 10 passengers and the driver. Since they ply on the car links, they are subject to the restrictions of these links. The vehicles stop at the end of each link they pass. This allows for transfers at the node, since every incoming link is a possible paratransit stop. For each person boarding, the vehicle is delayed by 2 seconds, for each person alighting, the vehicle is delayed by 1 second.

Furthermore, there is one train line circulating from node 1 via node 2 to node 3 and back to node 1, marked with a dashed line in Figure 2(a). The transit schedule allows for one round trip in about 15 minutes and the train stops at each stop for at least 15 seconds. The first train starts at 5 o'clock and then every 5 minutes until the last one departs at 13 o'clock. 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.

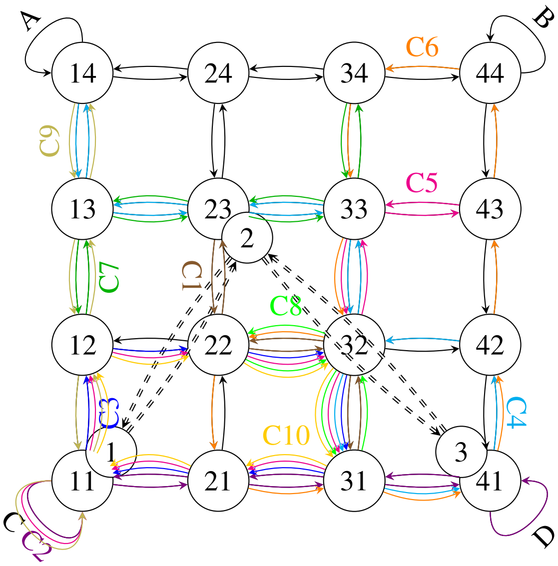
In each scenario, ten separate cooperatives C1 to C10 are allowed to operate paratransit lines in addition to the train. It is expected that not every cooperative will run profitable, since demand may not be sufficient. All scenarios run 10000 iterations with the same configuration, except for the demand. Traveller agents are only allowed to change their route, but must not change the transport mode. This allows to change to different paratransit lines, to the train, or to walk directly in case this is the least cost path. Agents determine the least cost path with regards to walking time, e.g. to and from stops, in-vehicle travel time, transfer time, waiting time, and line switch cost. Additional monetary costs like fares are not included in this paper. The cooperatives pay 0.30 per vehicle and kilometer traveled and gain 0.50 per passenger kilometer. This allows to run a profitable business with only one customer, but on the other hand, the cooperative has to compensate for slack periods as well. The price of a vehicle is set to 1000, regardless whether bought or sold.

**Scenario A-B+C-D**

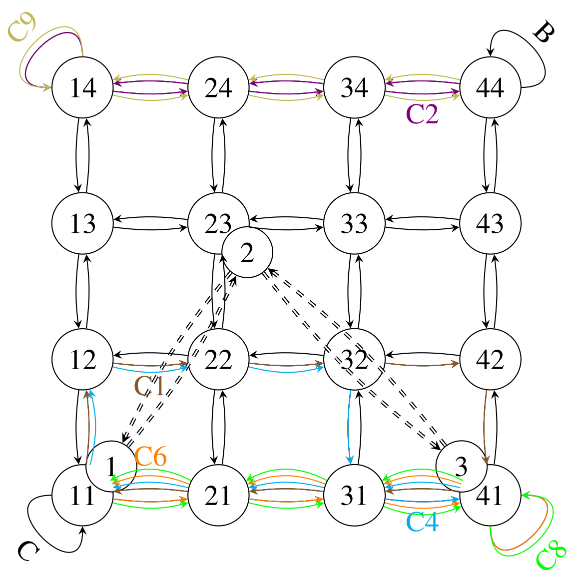
The first scenario features a demand of 1000 trips from A to B, 1000 trips from B to A, 1000 trips from C to D and 1000 trips from D to C. The traveler agents' departure time is uniformly distributed between 6 and 10 o'clock. It is expected that the connection A-B is served by paratransit only, whereas most agents on C-D will take the train.

At the first iteration, the cooperatives start with a randomly generated transit *line* and one vehicle. Recall that the *line*'s *route* is constructed as shortest path between two randomly selected points. This set-up clearly does not fit the demand. Figure 2(a) illustrates the *routes* of all co-operatives. The terminus of each *route* is labeled with the cooperative's name. Only six out of ten cooperatives have a suitable *line* in the first iteration. Cooperative C1 serves 244 passengers, C4 541, C5 233, C6 425, C7 838 and C9 437. C1, C2, C3 and C8 do not serve any passengers. 333 agents transfer twice, 681 agents have to change once and 2113 agents reach their destination without any transfers. 873 synthetic travelers walk directly. Although some agents manage to find a route without transfers, those agents have to compensate by long access and egress walking trips to the stops. The majority of the agents (1756) departing from link C and D take the train, but 244 opt for line C2. For them, it is faster to go by paratransit than to wait for the next train. No agent gets stuck en route, i.e. all agents reach their destination before midnight. The average travel time of all agents is 48min 25s. The agents score $+40.0$ on average.

At iteration 10000, six out of ten cooperatives survive with a profitable *line*. Figure 2(b) illustrates the *routes* found and features results for the number of trips served, the number of vehicles in operation, the operation time and the iteration in which the final *route* was found. Concerning demand running from A to B, C2 and C9 ply the very same corridor with different termini. From the agents point of view, this does not influence route choice, since both termini are located offside. All agents departing A will use the stop at the end of link A and leave at 3444. In return, agents departing from B will enter at 3444 and leave at 2414. So both connections have the




(a) Multi-modal network with one transit line (dashed line) - All initial paratransit routes of iteration 0 are colored. Remaining black links are not served by any of the cooperatives.




| | Trips | Veh | Time | Iter |
|---|---|---|---|---|
| C1 | 90 | 1 | 00:00-24:00 | 10000 |
| C2 | 880 | 14 | 02:17–10:40 | 2996 |
| C3 | – | – | – | – |
| C4 | 429 | 8 | 04:33-16:49 | 588 |
| C5 | – | – | – | – |
| C6 | 287 | 3 | 00:00–12:20 | 1168 |
| C7 | – | – | – | – |
| C8 | 898 | 13 | 03:03–16:06 | 253 |
| C9 | 1120 | 11 | 00:00–16:59 | 5756 |
| C10 | – | – | – | – |

(b) Iteration 10000 - Routes with demand only

**FIGURE 2 Resulting routes of scenario A-B+C-D**

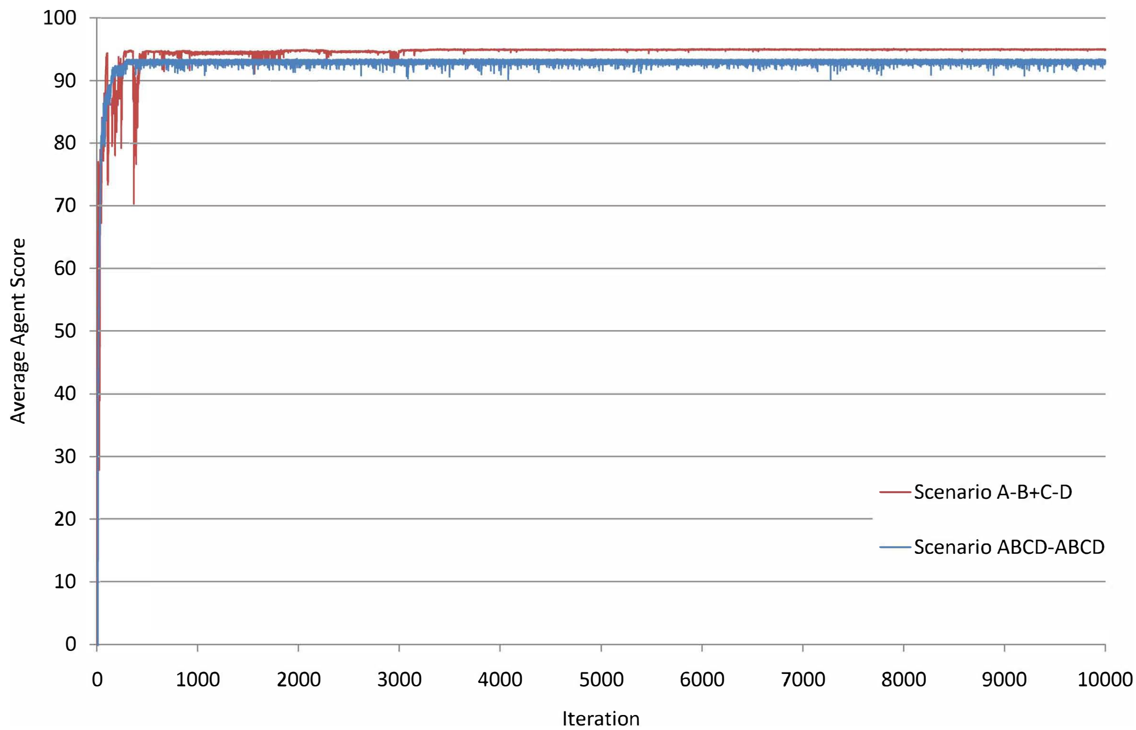



**FIGURE 3 Average agent score of each scenario**

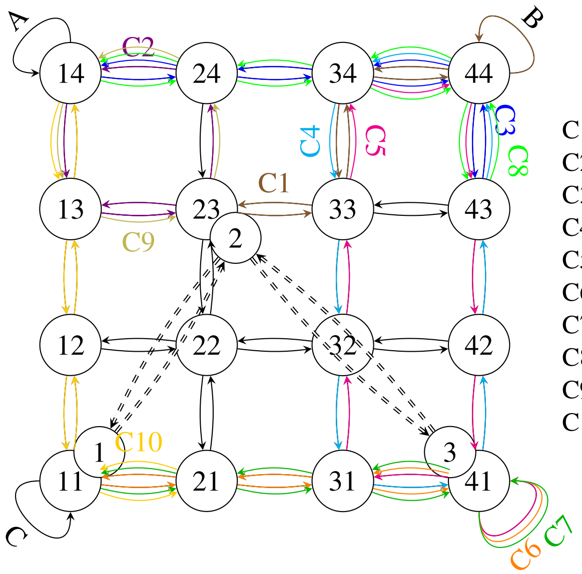
same travel time. Consequently, C2 and C9 serve a similar share of trips.

Analyzing the relation C-D and D-C respectively, C6 and C8 are engaged in direct competition as C2 and C9 are. This time, both have the same *route* length, but again this doesn't influence the agent's route choice. In addition, C1 started to compete in iteration 10000 by pirating 90 passengers going from D to C, but due to a detour on the way back could not run profitable and thus will be thrown out of business at the next iteration. C4 runs a profitable *line* from C to D because of first limiting the operation time, minimizing expenses, and second by having the same destination link 3141 as C6 and C8 have. Agents departing at C can not tell the difference and thus are effectively lured away from shorter routes. Since the stops are located at the links' end right next to the nodes, the *routes* found can be considered as virtually optimal *routes* for the given demand. Due to high supply caused by competition, only 296 agents take the train. All 4000 agents use a connection without transfers. Nobody walks directly. The average travel time drops to 3min 48s. On average, the agents score $+94.8$, with no agent getting stuck.

It should be noted, that the final paratransit network is found as early as iteration 5756. Succeeding iterations only further optimize the fleet management of the *lines*. Before the ultimately found solution, different solutions led to similar scores. According to Figure 3 the agent score for scenario A-B+C-D does not drop below 90 after iteration 500.

### Scenario ABCD-ABCD

The second scenario features a demand of 1000 trips in each combination of ABCD resulting in a total of 12000 trips. Again, the traveler agents' departure time is uniformly distributed between 6 and 10 o'clock. It is expected that some cooperatives will function as feeders to other lines.




| | Trips | Veh | Time | Iter |
|---|---|---|---|---|
| C1 | 1650 | 11 | 02:26–24:00 | 111 |
| C2 | 836 | 5 | 00:19–22:37 | 263 |
| C3 | 1373 | 11 | 00:00–17:46 | 257 |
| C4 | 1407 | 38 | 00:00–10:24 | 6 |
| C5 | 1145 | 37 | 06:04–09:43 | 6 |
| C6 | 575 | 3 | 00:29–21:31 | 101 |
| C7 | 1259 | 10 | 00:00–24:00 | 39 |
| C8 | 726 | 5 | 02:40–22:24 | 339 |
| C9 | 1034 | 6 | 03:22–19:50 | 83 |
| C10 | 2101 | 11 | 00:00-20:34 | 13 |

**FIGURE 4 Resulting routes of scenario ABCD-ABCD. Iteration 10000 - Routes with demand only**

Again, the first iteration starts with the same initial *routes*, because of the same random seed used. This time, the increased demand from each "corner" to every other allows all cooperatives to operate, but C1 and C8, see Figure 2(a) for *routes*. C2 is carrying 438 passengers, C3 19, C4 1496, C5 489, C6 2119, C7 1428, C9 3748 and C10 22. 1090 agents walk directly, 3178 agents get stuck. 4734 agents do not need to transfer, 2893 agents transfered once and 105 transfered twice. The average travel time of the completed trips is 3h 58min 42s. The agents score -181.8 on average.

In iteration 10000, all cooperatives find a profitable route, see Figure 4. Most relations are served by more than one cooperative with identical *routes*. This is the case at the relation A-B, with C3 and C8 plying the very same *route* and at the relation C-D, where C6 and C7 share the same *route*. A similar situation can be found looking at C4 and its counterpart C5, both connecting B to D. C4 is going counterclockwise, whereas C5 is going clockwise. C10 serves the relation A-C alone. C1, C2 and C9 function as feeder from A and B, respectively, to the train at node 2. C2 and C9 share the same *route*, but the terminus.

3967 agents take the train. From A to B 920 agents take the feeder and transfer to the train. The way back 950 agents opt for that connection. From B to C it is 936 agents using feeder and train in combination and from C to B 669. The relations A-C, A-B and B-D are served entirely by paratransit. As in the first scenario, the relation C-D faces a severe competition by paratransit *lines* resulting in a high frequency service. Consequently, only 190 agents going from C to D take the train. From D to C, 302 agents take the train. The rest takes C6 or C7. C10 is used by all agents going from A to B and vice versa. All agents going from A to B or B to A take C3 or C8. Analyzing traffic patterns of the relation B-D, one finds that agents going from D to B completely use C4, whereas from B to D demand splits to 927 agents taking C5 and 73 taking C4. Agents taking C4 walk or take C1 to node 33 and transfer to C4. C2 and C9 only serve agents going from

A to D or vice versa. No agent gets stuck or walks directly. The average trip duration is 4min 38s and the agents score $+93.1$ on average.

The solution that prevailed does not feature any paratransit *lines* going diagonally, e.g. from A to D. There is a clear distinction between *lines* at the edges and feeders to the train.

## DISCUSSION

Overall, it was thus demonstrated that the approach outlined in this paper is able to generate plausible transit lines in illustrative scenarios. As discussed earlier, the model does not claim to predict or reconstruct real-world paratransit systems. Yet it does, we would claim, generate paratransit-like lines with their most important characteristics such as finding market niches and operating demand-oriented under severe competition, and in consequence paratransit-like systems. The number of iterations – 10000 – is a lot, but still feasible for, say, cities with less than a million inhabitants. In addition, earlier iterations may provide sufficient solutions.

The approach can thus be used to generate a starting point for the modeling and simulation of a city or region with paratransit lines. This statement holds in particular also if not all aspects of those lines are known. Since, as discussed, the evolutionary algorithm is flexible with respect to additional constraints, it is possible to add the information that is known as constraints and let the algorithm evolve from there. The resulting paratransit structure can then be used to investigate aspects of strategic, operational, or regulatory changes.

Another important application, however, may be in the optimization of lines for a fixed line operator. These operators often can say which lines are in need of optimization. Here, one could, in the simulation, convert some of these lines to “paratransit lines” in the sense of the present paper, run a number of iterations, and eventually investigate if the resulting lines make sense from the analyst’s point of view. Once more, an advantage of the evolutionary approach is that it is usually straightforward to include additional constraints or complexities, such as driver rest rules, certain stops that have to be served, etc. Such issues will be investigated in future work.

## CONCLUSION AND OUTLOOK

The proposed paratransit model integrates into the existing multi-agent simulation framework MATSim. The agents of the synthetic population adapt to the supply provided by conventional public transport lines and paratransit services. The paratransit services optimize their routes according to the demand of the synthetic population. The resulting services both are profitable and fit the market restrictions. The heuristic paratransit approach allows to find new sustainable transit routes for conventional public transport. In addition, the approach can be used to identify areas without or with insufficient supply of public transport. Transport companies can then tap the full potential.

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