A PARATRANSIT-INSPIRED EVOLUTIONARY PROCESS FOR PUBLIC TRANSIT NETWORK DESIGN

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Abstract

Public transport companies should run sustainable 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 pickup 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 co-evolution and evolutionary game theory (e.g. *23, 24, 25, 26*). A common topic in such investigations is under which circumstances cooperative structures can emerge despite the competition (e.g. *27*). 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 mainly 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 (*28*) 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 (*28*, 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 operators seeking profit and customers searching for a cheap ride, the marketplace comes up with market-determined fares.

The supply side mainly consists of drivers and vehicle owners. There are further players 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 operators' side.

In his study about informal transport in the developing world Cervero (*28*, 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 (*28*) or more recently in Cervero and Golub (*29*).

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 (*28*, 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 (*28*, 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 (*28*, 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.

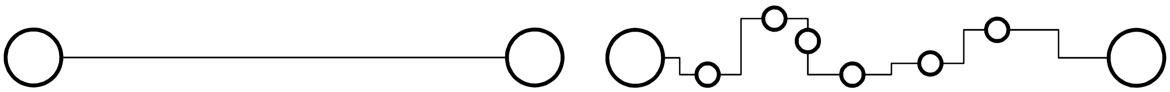
Market actor characteristics

There are many kinds of paratransit operators, 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 joint negotiation with the administrative or political sector.

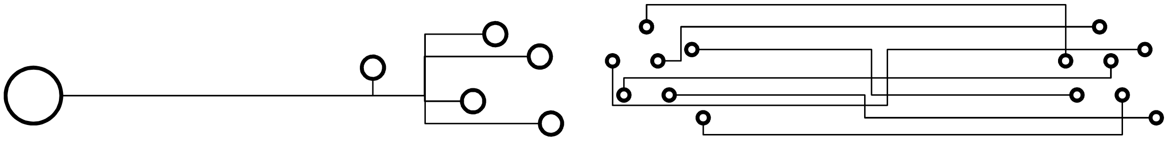
Route choice

Regardless of the type of paratransit operator there is, the operator has to adapt to the demand. The operator does so by providing a service in a certain area or by plying along a corridor. Route



(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

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 (*28*, 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

Most 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 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. Most case studies obtained by personal communication and presented by Cervero (*28*) 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. The approach presented in this paper 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. This paper will use the term "minibus service", and refer to the operator as a "paratransit operator" with the understanding that jitney/minibus service is one out of many possible paratransit services.

PROPOSED MODEL

The proposed model enhances the multi-agent simulation MATSim (*30*).

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 (operator). At the beginning, each operator 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 (minibus). Minibuses are assumed to run without breaks during their time of operation; it is assumed that some kind of crew scheduling makes this possible. 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. Minibuses 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 minibuses 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 as formal services. Paratransit services are transparently integrated into the public transit schedule, implying that the model assumes that operators 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 minibus may not be on time, the general frequency of the service is registered (see discussion of some aspects below).

The current default version of the MATSim public transit passenger router (*31, 32*) minimizes travel time (including walk), with an additional penalty for a line switch which is equivalent to an additional 60s of travel time. Fare does not play a role in that version of the router. See (*33*) for experiments with more realistic routing.

Normally, MATSim involves learning iterations on the side of the passengers. In order to save computing time, this is not done for the results presented later; instead, it is assumed that passengers' plans simply correspond to what the transit router computes. Still, the execution of passengers' plans is scored, in order to test for relaxation of the system (Fig. 3). Since the scoring function is not used for anything else besides this, the precise mathematical form is omitted to not distract from the main focus of the paper.

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. Minibuses can overtake each other and other buses at stops. A minibus 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 passengers' desire to alight. A minibus with empty seats left will ask the waiting agents at each stop it passes by for their destination. If the minibus serves that stop, it will pick up the agent, otherwise not.

Scoring of the paratransit operators

Scoring takes place at the end of the day (iteration). For each passenger of a minibus the operator is granted a lump sum, e.g. a positive score. For each kilometer a minibus travels the operator gets a penalty, e.g. a negative score. Scores are summed up for a iteration. Profitable *lines* end up with a positive score, non-profitable *lines* with a negative score.

Optimization process

Optimization takes place at the beginning of an iteration. Since a paratransit *line* is operated by one operator, each operator tries to optimize its own *line*. There is no explicit coordination or cooperation between the operators, except for the fact that an agent using paratransit can transfer to a different paratransit *line*. Different operators 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, an operator may have to compensate for a imbalanced budget by selling minibuses. For each minibus sold, a lump sum is added to the budget. If no minibuses are left, the operator is shut down and another one is initialized with one minibus for free.

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

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

b) The time of operation. An operator 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 minibuses circulating.

   First, the time 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 that 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 minibus at a certain stop at a certain time. Especially with the mode of operation of type c) above – 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 paratransit 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.

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 an operator within an operator thus allowing for subsidiary companies. Third, a franchise system can be introduced that prevents from two operators 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 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 picked-up. Otherwise, the minibus will proceed as planned.

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 (*34*). 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 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 and is already implemented in MATSim (*35*).

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 (*36*).

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 passengers located on those links is identical with the one of the nearby node, e.g. node 14 for demand of link A. The minibuses 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 minibuses 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 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 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. On the connection from C to D, the train is about 20% faster than the minibus.

Conversely, minibuses tend to run much 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.

In each scenario, ten separate operators C1 to C10 are allowed to operate paratransit lines, in addition to the train. It is expected that not every operator will run profitable, since demand may not be sufficient. All scenarios run 10000 iterations with the same configuration, except for the demand. Passengers 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. Passengers 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 operators pay 0.30 per minibus 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 operator has to compensate for slack periods as well. The price of a minibus is set to 1000, regardless whether bought or sold.

Scenario A–B/C–D

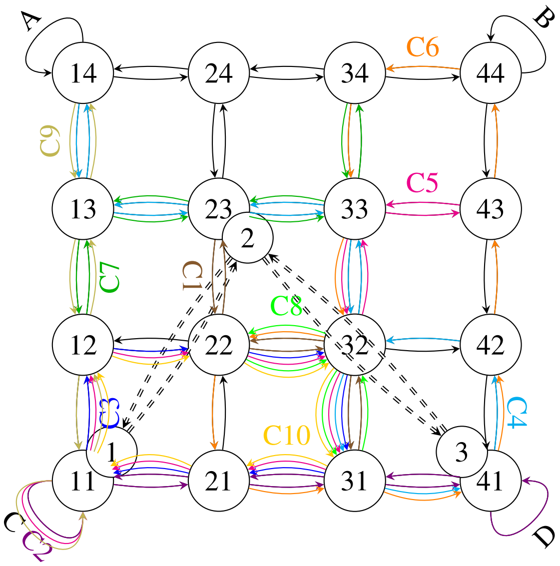
The first scenario features a demand of 1000 trips from A to B, 1000 trips from B to A, 1000 trips from C to D and 1000 trips from D to C. The passengers' departure time is uniformly distributed between 6 and 10 o'clock. It is expected that the connection A-B is served by minibuses only, whereas most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

At the first iteration, the operators start with a randomly generated transit *line* and one minibus. 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 operators. One of the two randomly selected points becomes the terminus of the line/route; it is labeled with the operator's name. Only six out of ten operators have a *line* that carries passengers in the first iteration: Operator 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 passengers transfer twice, 681 passengers have to change once and 2113 passengers reach their destination without any transfers. 873 synthetic travelers walk directly. Although some passengers manage to find a route without transfers, those passengers have to compensate by long walking trips. The majority of the passengers (1756) departing from link C and D take the train, but 244 opt for line C2. For them, it is faster to go by minibus than to wait for the next train. No passenger gets stuck en route, i.e. all passengers reach their destination before midnight. The average travel time of all passengers is 48min 25s. The passengers score $+40.0$ on average.

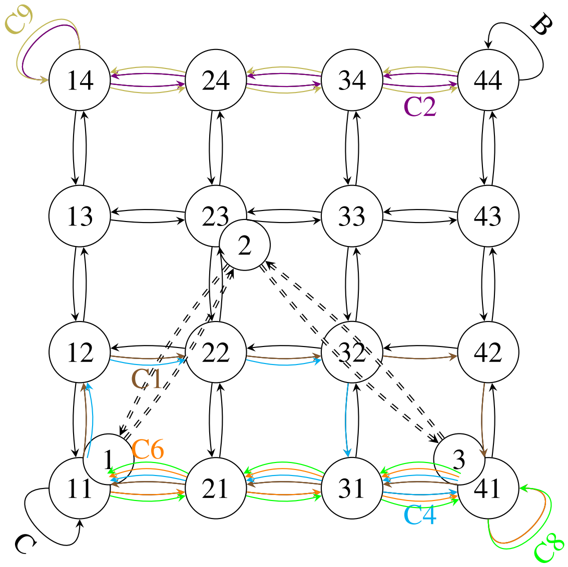
At iteration 10000, six out of ten operators survive with a profitable *line*. Figure 2(b) illustrates their *routes*, and provides details concerning the number of trips, the number of vehicles in operation, the operation time, and the iteration in which the final *route* was found.

Concerning demand between A and B, C2 and C9 ply the same corridor with different termini. From the passengers' point of view, the locations of the termini do not influence route choice since they do not interrupt the routes. The loop links A and B are very short (much shorter than drawn), so there is little difference both to passengers and to operators if they are included or not.

Analyzing the relation between C and D, C6 and C8 are engaged in direct competition. C4 runs a profitable *line* from C to D despite the detour because of first limiting the operation time, and second by having the same destination link 3141 as C6 and C8 have. Passengers departing near C



(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 operators.



	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

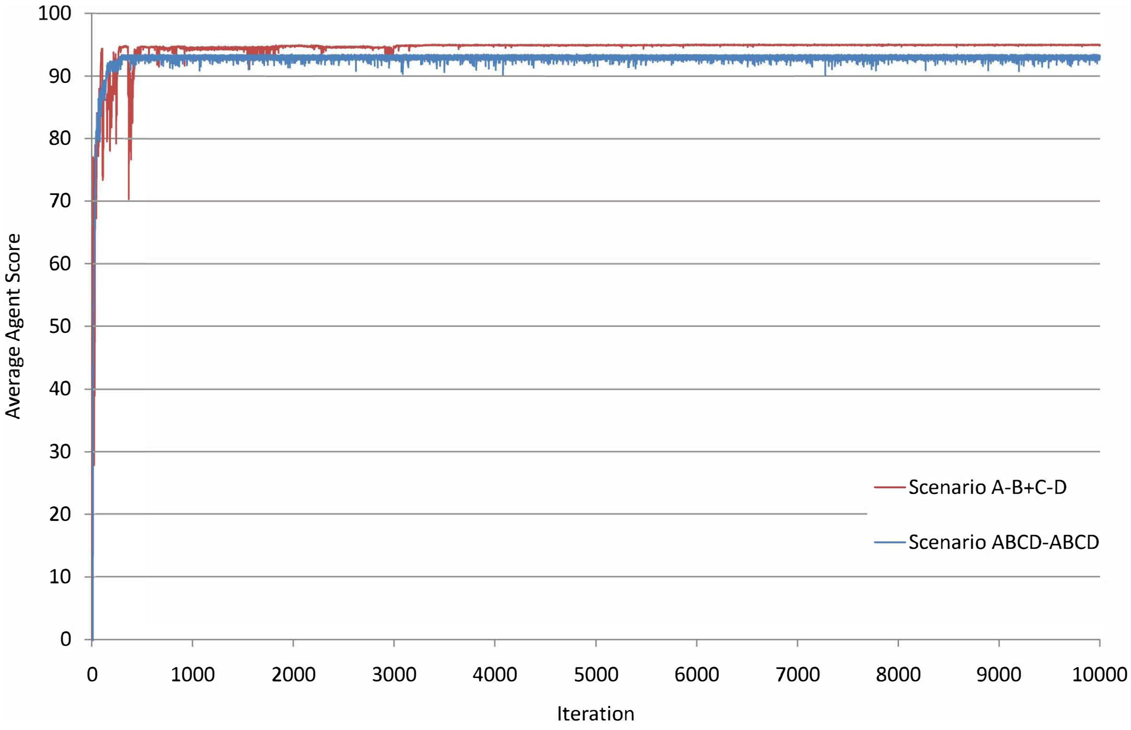


FIGURE 3 Average passenger score of each scenario

never *plan* to use C4 because of its longer journey, but they end up *using* C4 because its minibuses serve the desired destination, and passengers do not check the operator/line when boarding. C1 came up in iteration 10000, but it does not run profitably and thus will be thrown out of business at the next iteration.

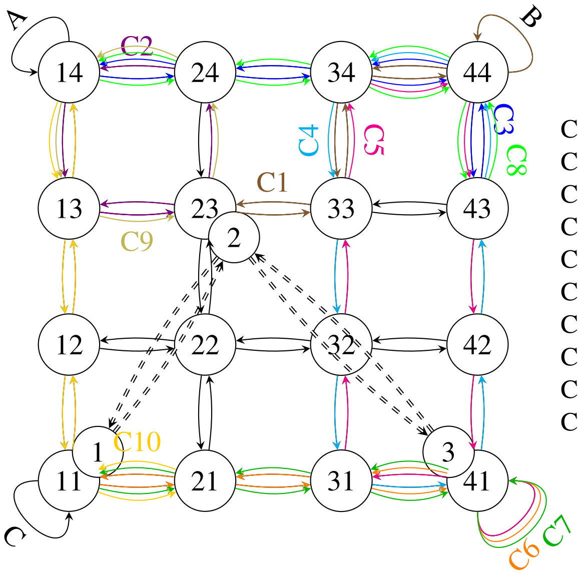
Overall, the *routes* found can be considered as close to optimal for the given demand. Due to high supply caused by competition, only 296 passengers take the train. All 4000 passengers use a connection without transfers. Nobody walks directly. The average travel time drops to 3min 48s. On average, the passengers score $+94.8$, with no passenger getting stuck.

The final minibus network is found as early as iteration 5756. Succeeding iterations only further optimize the fleet management of the *lines*. Previous solutions led to similar scores: According to Figure 3 the passenger 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 12’000 trips. Again, the passengers’ departure time is uniformly distributed between 6 and 10 o’clock. It is expected that some operators will function as feeders to other lines.

Again, the first iteration starts with the same initial *routes*, because of the same random seed. This time, the increased demand from each “corner” to every other allows all operators to operate profitably, except for 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 passengers walk directly, 3178 passengers get stuck. 4734 passengers do not need to transfer, 2893 passengers transfer



	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

once and 105 transfer twice. The average travel time of the completed trips is 3h 58min 42s. The passengers score -181.8 on average.

In iteration 10000, all operators find a profitable route, see Figure 4. Table 2 provides details about how the different demands are satisfied. The maybe most interesting result is that the diagonal demands A–D and B–C are served by a combination of minibus feeder lines plus train, while no diagonal minibus line develops. In contrast, C–D remains predominantly served by minibuses also in this scenario. No passenger gets stuck or walks directly. The average trip duration is 4min 38s and the passengers score $+93.1$ on average.

TABLE 2 Different OD relations and how they are satisfied (scenario ABCD/ABCD)

Relation	Served by Operator	Nr. of Passengers	
		to	back
A–B	C3, C8	1000	1000
C–D	C6, C7	810	698
	train	190	302
B–D	(walk or C1) + C4, C4	73	1000
	C5	927	0
A–C	C10	1000	1000
A–D (diag)	(C2 or C9) + train	920	950
	other	80	50
B–C (diag)	C1 + train	936	669
	other	64	331

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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