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Procedia Computer Science 280 (2026) 985–992

Procedia Computer Science

www.elsevier.com/locate/procedia

The 15th International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTrans 2026)
April 14-16, 2026, Istanbul, Türkiye

Exploring line-based flexible microtransit in agent-based simulations: Implementation and demonstration

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Abstract

Flexible line-based microtransit offers a middle ground between fixed-route transit and fully demand-responsive services, yet its evaluation within large-scale agent-based frameworks remains limited. This paper extends MATSim's demand-responsive transport (DRT) module to support line-based flexible services with compulsory stops, schedule-based slack, and optional demand-driven deviations. The concept is implemented and demonstrated in a realistic MATSim scenario of Kelheim, Germany, comparing it to standard DRT under different fleet sizes and stop densities. Results show that a single flexible-line vehicle can serve daily demand with considerably higher system efficiency of up to 22 % above comparable pure DRT systems, though with longer waiting and in-vehicle times. The implementation enables systematic assessment of semi-flexible transit designs within multimodal, activity-based simulations.

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Peer review under the responsibility of the scientific committee of the Program Chairs

Keywords: demand adpative systems; on-demand transport; multi-agent transport simulation; ridepooling; flexible line service; microtransit; semi-on-demand

1. Introduction

Flexible line-services have emerged as a promising way to reconcile two persistent tensions in public transport planning: providing acceptable service in low-density or peripheral areas while keeping operating costs and vehicle-kilometers under control. Conventional fixed-route services often run empty or must reduce frequency and coverage, whereas purely on-demand services offer high quality at substantially higher cost and with additional empty mileage. Vansteenwegen et al. [20] frame this as a continuum ranging from fixed routes to fully flexible dial-a-ride, highlighting the trade-off between user and operator generalised costs.

Within this continuum, semi-flexible or demand-adaptive systems (DAS, [10]) preserve key structural elements of bus lines (routes, schedules, compulsory stops) while allowing controlled deviations to better serve sparse or irregular

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demand. Errico et al. [2] provide a unifying framework and classify design decisions across strategic, tactical, and operational levels, noting that most studies rely on stylised models or single-line analyses under restrictive assumptions. Their survey points to the potential of semi-flexible services to outperform both fixed-route and purely on-demand systems in low- to medium-demand settings, but also underscores the need for tools that evaluate such designs in realistic urban networks.

Recent work has moved toward more operational analyses. Ng and Mahmassani [15], Ng et al. [14] develop autonomous minibus services with semi-on-demand (AMSoD) routes, showing through analytical results and simulations that hybrid operation can reduce both passenger and system costs. Fielbaum et al. [3] propose a line-based integration of on-demand ridepooling, demonstrating in Santiago and Berlin that small flexible fleets operating alongside buses can reduce walking and waiting times and even yield Pareto improvements under automation. These studies collectively show that line-based hybrids are promising beyond stylised settings.

However, most semi-flexible and semi-on-demand concepts are still examined either in bespoke simulators or analytical frameworks that treat demand and congestion exogenously. Large-scale agent-based platforms such as MATSim provide a rich environment to study how flexible microtransit interacts with multimodal networks and daily activity patterns, yet MATSim's existing DRT contrib focuses on generic on-demand services. There remains limited work implementing reusable, line-based semi-flexible microtransit, such as semi-on-demand feeders or hybrid routes, within MATSim's multimodal framework, and thus limited capacity for systematic exploration of design parameters, operational regimes, and equity impacts.

This paper addresses that gap by (i) specifying a flexible microtransit service concept compatible with existing MATSim scenarios, (ii) implementing it as an extension of MATSim's DRT module, including dispatching logic, schedule generation, and control parameters for line-based flexibility, and (iii) demonstrating the implementation in a realistic MATSim scenario, assessing impacts on access, waiting, and in-vehicle times as well as vehicle mileage and system efficiency.

2. Methodology

The flexible transit implementation is added to the multi-agent transport simulation framework MATSim [4]. The framework is open-source and written in Java and offers a comprehensive ecosystem for modeling various transportation systems, including private cars, public transport, and demand-responsive transport / microtransit. Each microscopic agent follows a daily schedule or plan that consists of activities and legs. During the simulation, agents experience how well their current plan performs, obtaining positive scores for performing activities and negative scores for traveling. The mesoscopic, spatial-queue-based simulation runs in iterations such that between the iterations, agents have a chance to adjust their plan by using various re-planning strategies such as route choice or mode choice to adapt to experienced travel conditions. Eventually, the simulation converges to a stochastic user equilibrium, in which agents may not improve their score any further by individually adjusting their plan.

Simulating typical fixed-line public transport is a core feature of MATSim [16], and typically requires a definition of transit vehicles, stop facilities, and a schedule consisting of lines and routes that connect individual stops with a given timetable. An efficient router has been implemented by Rieser et al. [17], allowing agents to route their planned trips during the replanning phase.
The simulation of on-demand transport is provided by MATSim's DRT extension [12], which has been applied and extended numerous times [5]. In principle, the extension requires a definition of a vehicle fleet and, optionally, a set of stop locations for pickups and dropoffs. The stops may be defined in the same format that is used for defining stops to be used in fixed line public transport. During the simulation, the optimizer tries to find an insertion for each request of an agent that chooses to travel by DRT, minimizing cost (usually: vehicle travel time) by adhering to request constraints (usually: maximum wait time and maximum detour). Extensions exist for electric fleets, prebooking and operational aspects such as facilities and driver shifts.

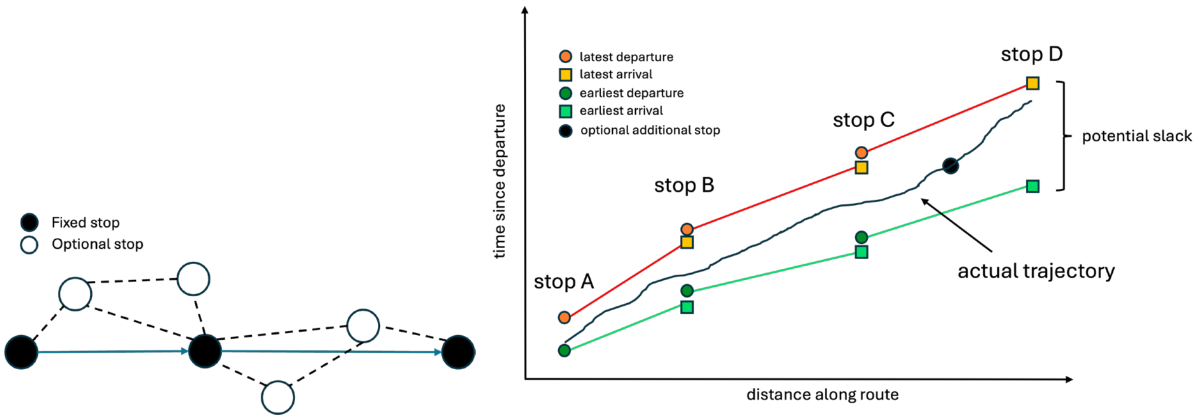
In the present work, both the public transport feature as well as the DRT extension are brought together to simulate flexible line services. The base idea is that MATSim's transit schedule format is used to define a skeleton transit route with a sequence of fixed stops, including their arrival and departure offsets. In addition, optional stops between compulsory stops that are not part of the fixed route but may be served if they adhere to schedule constraints may be defined (see figure 1a). Compulsory stops in the schedule are served on every departure. Requests for optional stops are accepted only if they can be inserted between their associated pair of compulsory stops without violating the schedule-defined slack corridor. If not, the request is not inserted into the current departure and is instead deferred to a subsequent cycle (or gets rejected depending on setup). The constraints are defined by the arrival and departure offset of each stop and specify the latest arrival (arrival offset) and latest departure (departure offset) at each stop. Together, these two constraints form the upper trajectory bound as seen in figure 1b (in red). The earliest arrival in the current implementation is based on the shortest possible network route at the time of departure. The earliest departure can either equal the earliest arrival or may be delayed by either defining a minimum stop duration or a fixed offset from the route's departure time. If the minimum stop duration is zero and no earliest departure offset is defined, the vehicle will still serve the stop with a zero-length stop duration (pass-through) unless a booked trip gets added to the stop. The earliest arrivals and departures form the lower bound of the line service trajectory, shown in green in figure 1b. The difference between lower and upper bound for each stop defines the vehicle slack at each stop which may either be used to extend the stop duration by adding additional requests or by serving additional stops along the way if a booking requires it. As the slack corridor may widen along a route, setting an earliest departure time at certain stops may help to maintain a more balanced headway along the route. In addition, it may be used to synchronize stops with external schedules, such as for intermodal connections at train stations. As the constraints are already defined by the schedule, the request related constraints are relaxed. In MATSim's standard DRT case, insertions of requests into vehicle schedules need to comply with certain constraints to be feasible, among which typically are maximum wait time, max travel time and maximum detour time. For the flexible line service, only the maximum wait time is kept (and set to rather high values depending on the mean headway of the service). In addition, the so-called 'pickup-delay' (i.e., how much more is a pickup allowed to be delayed after committing to a valid insertion) should be used in combination with a high maximum wait time. This way, an insertion further into the future can be found; however, the time communicated to the passenger will not be delayed too much longer. When a request is accepted, MATSim assigns and communicates a planned pickup time based on the current insertion into the vehicle schedule. This pickup time may be updated by subsequent re-optimizations, but only within the configured pickup-delay limit, ensuring that passengers are not repeatedly postponed beyond the initially communicated commitment. Because the vehicle must remain within the corridor defined by schedule offsets, detour and travel-time constraints are implicitly bounded and thus removed. A simple flow chart of the simulation logic is shown in figure 2.

The implementation thus allows for various forms of flexibility. For one, the network route between stops is dynamic and updated on the fly, which allows the vehicle to react to current traffic conditions such as congestion or road blockages. In addition, the stop or dwell duration may vary depending on actual demand. Lastly, the actual sequence of stops re-acts to the demand, underlining the on-demand aspect of the service. An additional form of flexibility is introduced through the way the line is operated. Since the concept is targeted at future autonomous services, the scheduling is implemented fully dynamic in that at a certain - configurable - offset before the start of a line departure an idle DRT vehicle is dynamically assigned to the flexible route service to service a given number of (chained) departures. This means that the service can also be defined in a hybrid setting. For example, during some hours of the day, all vehicles operate in a fully on-demand DRT setting, and during other hours, some vehicles are dynamically drawn out of the on-demand mode to serve a given number of flexible line departures.

3. Scenario

The scenario is based on the publicly available Kelheim (a town in Bavaria, Germany) MATSim scenario [11], which has been used to study various (autonomous) on-demand services [18, 19], including the on-demand Kexi service, which has been discontinued in the city in 2025. The scenario includes a network as well as a plans file that represents demand for DRT, totaling 158 requests for one day. In addition, a stop network for DRT services is provided.

For the setup of the flexible transit showcase, a simple circle line was defined, with an anti-clockwise route with six fixed stops, starting and ending at the 'Stadtplatz' (see figure 3). The stops were selected as they represent demand



(a) (b)

Fig. 1: Illustrative definition of slack time corridors along a route (a) and illustration of fixed insertion order of optional stops between fixed stops (b).

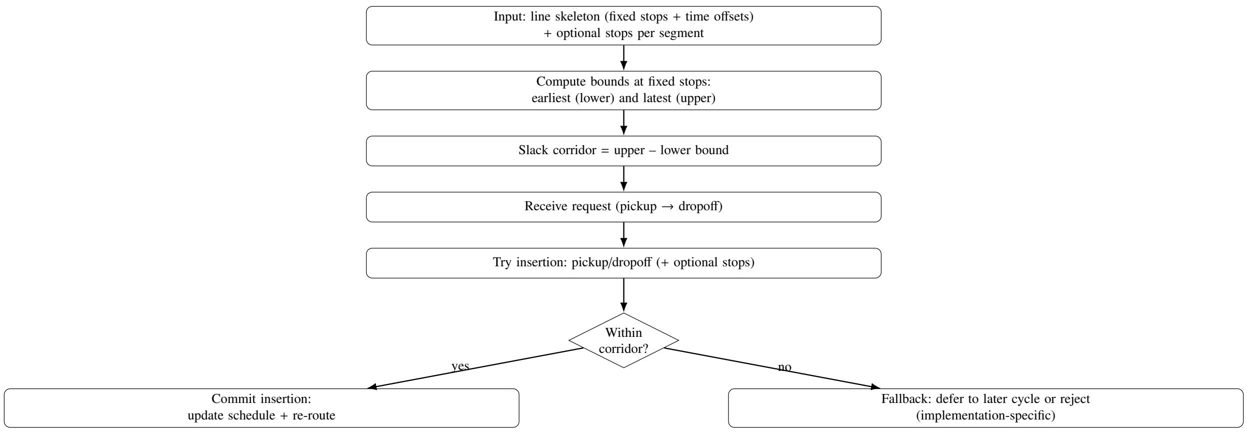


Fig. 2: Overview of the flexible line service logic: schedule-based slack corridor definition and feasibility-checked insertion of optional stops during operation.

hotspots that have a high probability for trip starting or ending there. Multiple additional optional stops were placed at other demand centers. It should be noted here that the stop density is somewhere in between typical on-demand settings and traditional fixed line transit lines. As explained above, the optional stops may only be inserted between two fixed reference stops. The transit schedule defines the mentioned route and schedules departures every 35 to 40 minutes (depending on actual route) from Stadtplatz. The departures are 'chained' after each other, meaning that the cycles form a closed loop, allowing passengers to remain seated between cycles. The first departure starts at 6 a.m. and the last departure is at 11:30 p.m. Requests that cannot be served within the slack of the current cycle are deferred to subsequent departures.

For comparison, a standard DRT service is compared to the flexible line service, once with one vehicle and once with two to serve the same demand using the same stops freely on-demand. The maximum waiting time is set to 30 minutes, which reflects a more rural setup. The detour factor is set to 30 %, meaning that the insertion should not introduce detours above that threshold when compared to the shortest possible direct route on the network. However, the constraints are used as soft constraints, meaning that requests will not be rejected if constraints are exceeded, but will receive a penalty in the insertion cost calculation, driving the optimizer towards avoiding insertions that violate the constraints. The standard DRT service also uses the default rebalancing settings in MATSim [1]. Both fleet sizes

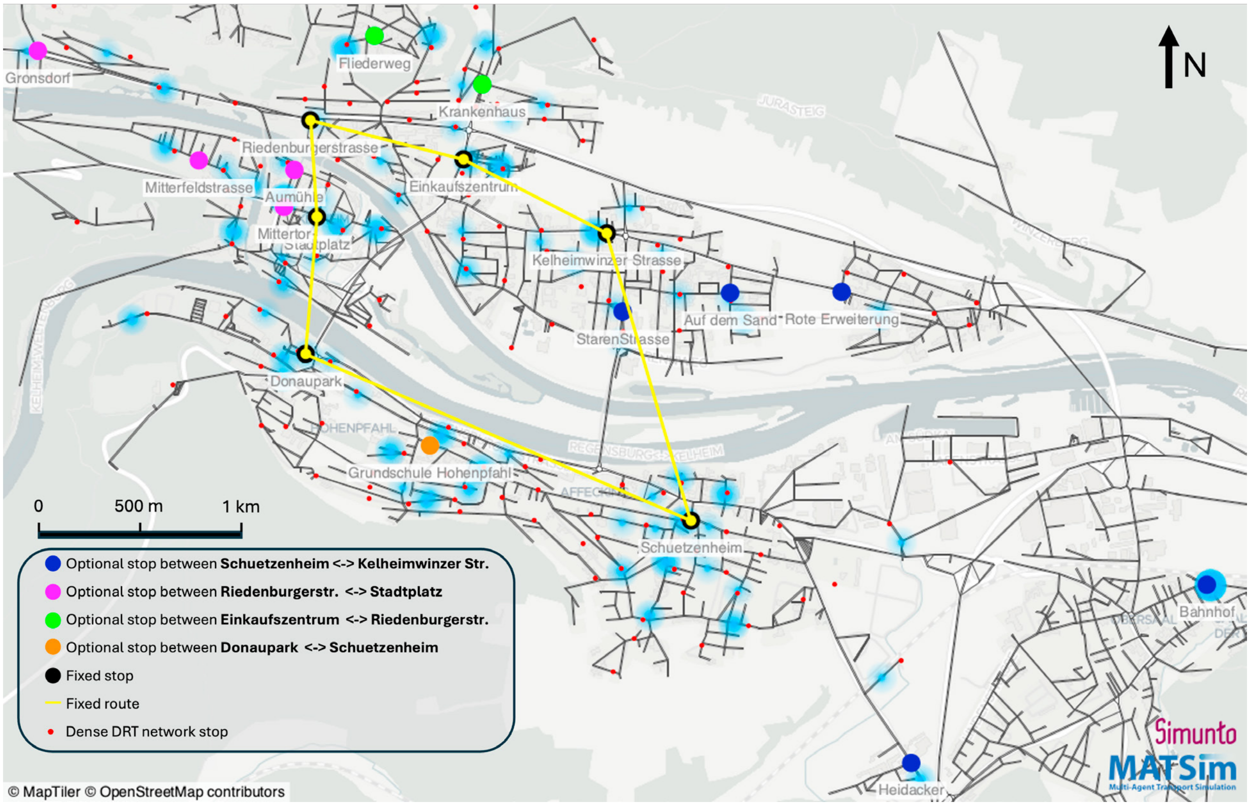


Fig. 3: The Kelheim scenario and the defined circle route (yellow line). The stops that are not part of the route are potential optional stops. Each group of optional stops with the same color may only be inserted between the same fixed stops (in any order). For example, the stops 'Fliederweg' and 'Krankenhaus' may only inserted between the fixed stops 'Einkaufszentrum' and 'Riedenburgerstrasse'. The light blue circles represent origin activities of the 158 requests in the scenario. The smaller red show the stops used for the dense DRT stop network scenario.

are simulated with the denser DRT stop network from the open scenario and with the coarser network used in the flexible line service.

The vehicles in all scenarios have ten seats. The scenario is meant as an illustrative showcase of the implementation. Vehicle charging and real-world traffic speeds are ignored for now. The scenario does not include fixed-route public transport and all trips in the experiment are served by DRT / flexible-line variants based on the fixed and given demand introduced above. To isolate operational effects, we keep demand fixed and do not allow mode switching in response to experienced utility. The scenarios will be compared across a set of indicators, among which are the mean, median and maximum wait time, mean in-vehicle travel time, kilometers driven and the system efficiency as defined by Lehnert et al. [8], which takes the sum of kilometers booked (i.e., direct network distance between origin and destination of all requests) divided by the sum of vehicle kilometers driven, indicating how efficiently the demand was served.

4. Results

The simulation results are summarized in table 1. It can be seen that the pure DRT scenarios struggle to serve the demand well with only one vehicle, as the wait times are exaggerated. With two vehicles, the DRT scenarios offer an attractive service from the customer's perspective, with very low waiting times and low in-vehicle travel times. Unsurprisingly, it becomes apparent that the demand becomes harder to serve for denser stop networks, as passengers are less bundled in space and larger detours become necessary. For the flex circle line, the demand can be served with one vehicle albeit with higher waiting times for the customers, that may still be acceptable for a rural town. The

Table 1: Selected indicators across the defined scenarios.

Scenario	Vehicles	Mean wait time [mm:ss]	Median wait wait time [mm:ss]	Max wait time [mm:ss]	Mean in-vehicle time [mm:ss]	Vehicle kilometers [km]	System efficiency	Mean access/ egress [m]
DRT reduced stops	1	36:04	36:19	88:12	06:34	590	0.82	265
DRT reduced stops	2	4:54	4:29	16:06	5:06	611	0.78	265
DRT dense stops	1	138:04	149:48	230:28	07:11	665	0.75	66
DRT dense stops	2	6:01	4:50	23:31	5:06	705	0.71	66
Flex circle line	1	11:02	09:06	35:27	15:13	483	1	265

in-vehicle travel times are considerably higher for the flex service, as the forced cycle route may introduce a lot of detour for the individual passenger. the vehicle kilometers traveled, and, thus, the system efficiency is highest for the flexible line service with a system efficiency of 1, which is around 22 % more efficient than the most efficient DRT scenario presented here. This is a comparatively high value for small on-demand services and means that the service does not introduce more vehicle kilometers than if every agent would have driven with private car instead (alone). The reduced stop network introduced for the line service seems to lead to acceptable access and egress distances that are still very attractive when compared to public transport thresholds found in the literature [21]. However, the dense stop network in the respective DRT scenarios naturally leads to even more attractive access/egress distances.

Figure 4 confirms the correct implementation of the line service in the simulation. It shows the slack corridor along the stops of the route (similar to figure 1b) and the actual trajectories of all departures of the circle line during the simulation. It can be seen that all actual trajectories stay within the corridor. Also, some trajectories indicate rather short cycles (i.e. near the earliest arrival/departure line in green). In contrast, some trajectories are closer to the latest arrival/departure line in red, indicating that multiple optional stops have been added to the route in this circle. As can be seen from the y-axis, the shortest possible cycle could end after around 600 s or 10 minutes. The longest cycles, however, take up to around 38 minutes (arriving 200 s late to the first stop 'Stadtplatz' at a 30 min departure offset). The flexible line service trades off higher in-vehicle times against considerably improved fleet efficiency, allowing one vehicle to serve all requests, a task likely requiring two vehicles in a pure DRT system. Similar to traditional fixed line transit, the flexible transit line decouples vehicle mileage from demand to a certain degree. The fixed part of the route is always served, regardless of the actual demand. It is therefore a non-trivial task to best design the fixed and optional parts of the route.

5. Outlook and Conclusions

The present study showcases an implementation of a flexible line service which may be seen as a hybrid between traditional fixed-line and contemporary on-demand services, and is particularly relevant in the context of future autonomous operations. Autonomous technology can be seen as a key prerequisite for offering such dynamically scheduled services at scale, since it enables flexible vehicle assignment and schedule adjustments without relying on fixed driver duties, which strongly constrain today's ridepooling operations [22]. The implementation re-uses a lot of MATSim's existing data structures such as the transit schedule which may allow using a schedule based router for the flexible line service in the future. The scenario presented here is not necessarily fully optimized for the flexible line service yet and was used primarily for demonstrating the new functionality. In particular, the definition of the route and optional stops was not based on a consistent methodology. Finding the best setup for introducing such a service should be investigated in future studies, ideally by developing a robust methodology allowing reproducible appraisals of whether certain demand should be served by fixed line, flexible line or DRT services - or a mix between them. For example, a service could mix on-demand vehicles with a 'core' flexible line, with vehicles being in different operation modes. Also, the operation mode could shift throughout the day from DRT to flexible line service and vice versa. In more comprehensive scenarios, the earliest departure feature explained above may be used to synchronize departure times with, e.g., regional train arrivals. The optimization of service setups could benefit from MATSim's iterative setups, similar to the optimization of minibus routes [9]. Generic simulated annealing approaches for iterative optimization have been added recently [6]. A big limitation of the current study is the assumption of fixed demand. Given the lower service quality, it is expected that demand for the service drops which could lead to a reduction of service efficiency. Future studies should incorporate the demand feedback of such services. Given that passengers still

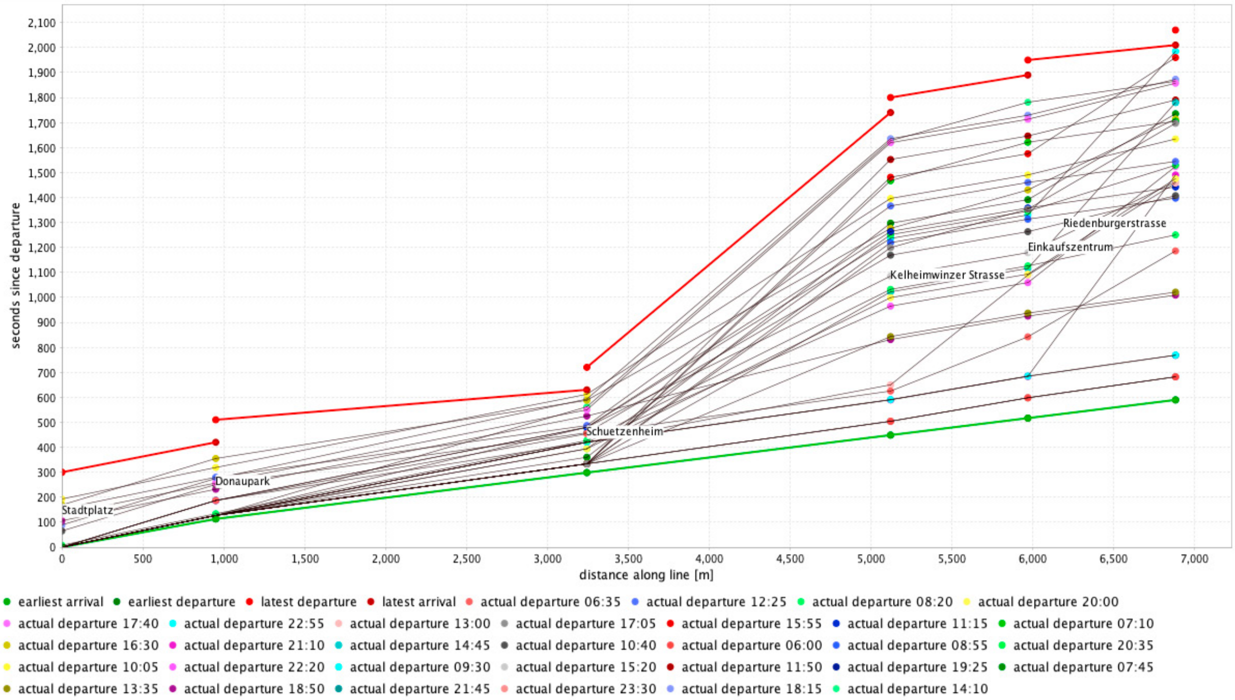


Fig. 4: Actual trajectories of individual departures of the flexible line service within the corridor defined by latest arrival and departure offsets of each fixed stop. It can be seen that some cycles are close to the shortest possible cycle duration, whereas most departures require at least some of the slack for serving optional stops.

need to book their ride in advance (which they can do from their current activity location) the increase in waiting time may not have a dramatic impact on service acceptance, as long as the initially communicated pickup time is not delayed too much. Concepts like these probably should be modeled using the prebooking feature by default [5].
An interesting further development will be the introduction of dynamic stop selection in MATSim. Whereas in reality many services also optimize the access/egress stop for a given request, MATSim pre-computes and fixes the access/egress stop before the simulation. However, especially in this setup, it might be the case that an optional stop may not fit into a current cycle of a flexible line route but another nearby fixed stop could be an alternative as well, meaning that the customer should be asked to walk to another stop instead. Scenarios with multiple flexible lines could also benefit from so-called 'intra-modal transfers' (i.e., changing from one vehicle to another) which usually are not viable in pure DRT settings [13]. The initial findings presented here suggest that there might very well be scenarios in which such flexible line services can be realistic alternatives to traditional public transport or pure DRT services, especially from an operator or public policy point of view, as the system efficiency may reduce vehicle mileage and fewer expensive vehicles may be required. Compared to fixed-line public transport, the increased flexibility could also improve accessibility for people with disabilities, who could benefit greatly from flexible stops that reduce access/egress distances [7]. To improve predictability of cycle times, the optional stops could also only be made available to passengers with mobility impairments. On the other hand, the optional stops could also be served in exchange for a premium paid by the passenger to increase financial stustainability. The implementation will be made available in the MATSim open source project shortly, to allow for further developments and applications.

Acknowledgements

This research was funded by the German Federal Ministry of Transport by decision of the German Bundestag within the project Integration von autonomen Fahrzeugen in Mobilitätsanwendungen - ALIKE 45AVF3B021. We want to thank Clara Konoplanski, Tilmann Schlenther and Sebastian Hörl for the discussions around the work presented here.

Conflict of Interests

We acknowledge our employment at the ridepooling operator MOIA.

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