Autonomous Mobility-on-Demand providing Superior Public Transportation in Rural Areas

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Abstract

Public transport lines have historically played an important role as economic lifelines of rural areas and form an important part of rural accessibility in many countries. The emergence of the autonomous vehicles will introduce a new form of transportation in which autonomous robotic taxis transport passengers in an on-demand fashion. In this work, we analyze if rural public transport lines with low utilization can be replaced with autonomous mobility-on-demand systems. More specifically, we compare the existing public transportation infrastructure to a hypothetical autonomous mobility-on-demand system both in terms of cost and service level. We perform our analysis using an agent based simulation approach in which unit capacity robotic taxis are operated in a street network taking into account congestion effects and state-of-the-art operational (dispatching and rebalancing) policies. We apply our analysis to the case of rural train lines in Switzerland that operate at low utilization and cost coverage. We show that a unit-capacity mobility-on-demand service could reduce journey times and operational cost at the same time. Furthermore, we demonstrate the influence of factors such as the length of the public transport line and conclude that with higher utilization and increasing line length, the train is getting more competitive.

Keywords: autonomous mobility, mobility-on-demand, taxi, rural transportation, train substitution, fleet control, agent-based simulation

1. Introduction

In rural regions the population density is by definition low and the distances to the cities and their services are large. To ensure the economic and social connection to the surrounding cities and within the area access to a suitable mobility system is key. In rural regions the preferred mode of transportation

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is the privately owned car [1]. Cars are the ideal means of transport to serve
the diverse travel demand patterns in a rural region as they are highly flexible.
Nevertheless, in many rural regions schedule and line based public transporta-
tion (PT) ensures that people without access to a car can travel. Such groups
are for example children which go to school in the next village, elderly people
which are not able to drive anymore or people which can not or do not want
to afford a private car. Due to the low population density in rural regions PT
differs substantially from the one in cities. The frequency of a PT line (e.g.
bus or train) is normally relatively low in a rural environment. Not only the
low frequency but as well the long journey time (compared to private cars) is
a drawback of public transport in rural regions. Also, for a PT line operator
an urban environment is more attractive than a rural area as it is often more
profitable to run a service in a densely populated region. There, the vehicles
have to drive large distances while only carrying a few customers. Thus, rural
PT lines are under a constant economic pressure and PT line operators often
search for more cost efficient services to ensure access to mobility. For example,
existing train lines have been substituted with bus lines [2] or bus lines with
dial-a-bus services [3].

Not only the PT line operators are changing their services. The mobility
sector in general faces some large changes in the near future. Two of the most
discussed novelties are the shifts in the taxi business and the automation of
vehicles.

The digital transformation enables taxi companies to improve their fleet
management: Their vehicles can be positioned much more efficient with the
help of intelligent control strategies and customers are assigned to taxis more
efficiently. This increases the interactivity of taxis in terms of wait times and
costs. Companies like Uber, Lyft or Grab are rapidly growing and advancing
the taxi business model. Throughout this publication, this taxi model is called
"conventional mobility-on-demand" (CMoD).

The other very rapidly progressing transformation is the automation of vehi-
cles. Over the last years it advanced to a point where self driving cars are tested
on streets around the globe [4, 5]. It can be assumed that vehicle automation
will further proceed and will have a high impact on mobility. If vehicles could
drive fully autonomously a larger part of the population would have access to
mobility. For example it would be possible for kids or old people without a
driving license to use a car on their own. Additionally, autonomous vehicles
would increase safety [6], reduce emissions [7, 8] or reduce the need for parking
spaces in cities [9].

Autonomous Mobility-on-Demand (AMoD) integrates vehicle automation
into a taxi service model. This combination is seen by many as the future of
mobility [10]. AMoD will enable a more affordable mobility while offering a
high spatial and temporal flexibility of the service. The costs are assumed to
be lower compared to CMoD, mainly because no wages for the drivers have
to be paid. High flexibility can be guaranteed as the AMoD service can serve
a customer from any location to the desired destination at any time. As the
travel demand pattern itself is not balanced an AMoD system requires the fleet
to rebalance. This is a rebalancing of unused cars to meet future anticipated demand. Without rebalancing, the system becomes unbalanced and the service level of AMoD decreases. Therefore such a fleet of autonomous taxis needs an intelligent fleet control strategy, the so called “dispatching strategy”.

Within this publication all the taxi services are called mobility-on-demand (MoD). This includes all services which allow independent rebalancing of the vehicles when they are not serving a customer (i.e. both CMoD and AMoD).

Driven by the low cost efficiency of rural mobility, this publication analyzes the influence of the emerging MoD services on rural PT lines. More specifically it analyzes if an existing rural PT line can be replaced by a MoD service. This work only focuses on PT lines with special characteristics which are illustrated in Figure 1. The PT line operates between the two cities A and B. The villages between the two stations A and B are served by the PT line and it connects them to the transit PT network which operates between larger cities. This includes as well a direct connection between A and B. The PT line is the only PT possibility in the rural region and no connection perpendicular to the PT line exists. One could imagine such a PT line in a valley without any possibility to cross the hills by PT. For the new MoD service it is assumed that a customer is served directly from his origin $O$ to the final destination $D$. The taxis are single-use and thus no pooling is considered.

To answer the question if replacing an existing PT line with MoD is feasible three steps are taken in this publication. First it is analyzed how many vehicles are needed to guarantee at least the same service level which the PT line provides today. Second, the influence of the dispatching strategy is studied. As a third research question it is analyzed how competitive an AMoD or CMoD fleet is in terms of operational costs compared to today’s PT line.
2. Related Work

In the following three aspects of ongoing research are presented. First the current situation of rural Demand-responsive transportation (DRT) systems and real world examples of such services in combination with public transportation are presented. Then a case study is introduced where an alternative solution for a planned public transportation line in New York City is evaluated. In the third part the current state of research on AMoD in terms of theoretical and simulation approaches is presented.

For the United States of America it is estimated that currently around 1500 rural DRT systems are in place [11]. A DRT is defined to be a service which differs from schedule and line based operating schemes in the sense that it “responds in some manner or form to individualized requests or demand” [11].

[3] presents an overview of the different mobility services in rural Scotland where many dial-a-bus services are running. A majority operates in a specific area where either no public transport was present before or an existing bus line was replaced. Often these services are operated by local taxi companies and financially supported by the government. For most of the services a ride has to be booked a day in advance. Some of the buses run based on a fixed line others are fully flexible and can pick up a customer at any location.

In Switzerland the national public transport company PostAuto offers around 20 dial-a-ride services in rural regions [12] which connect the area to the rest of the public transport system. The minibuses have to be booked up to an hour in advance and the service is schedule and line based. In some regions the dial-a-ride services could be upgraded to a regular public transport line as it was very successful.

In the Netherlands NS Zonetaxi [13] connects local taxi services to the national rail network. It solves the last mile problem with single-use taxis with a simple zone based pricing scheme. A taxi can be booked in advance via a national online platform. Other demand driven taxi and minibus services can be found in Europe in France (TaxiTub) or Germany (Anruf Sammel Taxi (AST)). Here many of the services pick up the customers at designated stops when they book the service in advance.

To summarize, it is observed that currently in many places very diverse transportation services are present in rural areas. This shows that demand driven services are a feasible solution if the local conditions allow for it. Most of the services have to be booked well in advance and often the pick up is at designated stations. Still, the private car remains by far the dominant transportation mode in a rural region, where DRT is only a niche product.

An alternative transport solution for the projected light rail line in New York city was evaluated in [14]. It was investigated if the travel demand could be served with a fleet of shared autonomous vehicles (SAV). The authors propose a line and station based service which is operated demand driven with SAVs with a capacity of 12 people. The event based simulation models the demand with a stochastic process and is free from influences from the environment (e.g. congestion). It was shown that the 39 light train vehicles could be replaced with
150 SAV to serve the customers with the same travel time. If the number of vehicles would be increased to 450 vehicles the same average wait time as the light rail service could be achieved which would reduce the travel time by 39%. The costs of such a service was not considered. It is concluded that SAVs can be a viable alternative to traditional line based systems and further studies are encouraged.

In [15] a detailed study examines the feasibility of ride pooling in a rural area as an alternative for conventional public transport. The main focus lies hereby on autonomous vehicles and its influence with scenarios until 2030. It finds that "ride pooling with autonomous vehicles in rural areas replacing classic public transport can be economically feasible" [15]. A vehicle could serve around 40 passengers per day and would travel between 108.000 km and 150.000 km per day.

AMoD as a future form of mobility is subject to ongoing research. On the one hand in multiple studies the impact of a mobility on demand fleet was simulated for different cities. On the other hand the control perspective of AMoD lead to the development of different fleet dispatching policies which were derived analytically and tested in simulations.

A first guideline to scale a fleet of autonomous single-use vehicles was presented in [16]. It concluded that the travel demand of Singapore can be met with approximately one third of today’s number of vehicles. Another early agent based simulation was carried out by [17] for Austin, Texas. It was found that the intra urban (car) trips could be served with a replacement rate of one autonomous vehicle per 9.3 conventional vehicles. This would generate an 8% increase of traffic.

Further studies which consider a replacement of privately owned cars with robotic taxis were carried out for the Cities of Berlin [18], Lisbon [19] and New Jersey [20]. The first was using the simulation framework MATSim (Multi Agent Transport Simulation) [21]. It was found that a replacement of the 1.1 million private cars today would require around 100’000 autonomous taxis. The second one pointed out that the mileage per vehicle rises from 30 to 250 km per day and that the carbon emissions can be reduced by nearly 40%. The third analyzes the ride sharing potential of an autonomous taxi system. It recognizes a high ride sharing potential especially during peak times and for trips starting on ending at train stations.

Concerning the dispatching strategies, in [22] it was shown that the optimal equilibrium rebalancing policy for the time-invariant case can be found by solving a linear program. [23] analyzed different fleet control strategies and shows that both the strategy as well as the demand profile influence the fleet performance.

[24] compared different AMoD fleet control algorithms for the City of Zurich with the MATSim extension AMoDeus [25]. The authors stressed the point that the right fleet control strategy not only reduces wait times but also gives a fleet operator an economic advantage. The methods used for the publication at hand extends the just mentioned work and will use the same code base.

In summary it can be stated that for AMoD different tools exist to analyze
the fleet behavior in an urban environment and out from high level perspective. Yet, in a rural environment no research was carried out for specific cases. Nevertheless, in rural regions multiple existing DRT services indicate that MoD might also be a possible solution for transportation in rural regions. Additionally, SAVs were already evaluated as an alternative solutions for line based transportation systems. The combination of these three topics leads to the research questions which are presented in the next section.

3. Simulation Methods

As introduced above in Section 1 this publication wants to answer three main questions concerning the case when an existing rural PT line is replaced with a MoD service:

1. What is the MoD fleet size $N$ required to serve the demand for mobility at a comparable or improved service level than the PT line does today?
2. How does the control strategy of the fleet influence the performance in terms of fleet size and wait time?
3. How does such a replacement change the operational costs? What is the difference between CMoD and AMoD?

To compare the two services some assumptions are made. For the PT line it is assumed that a line and schedule based service is in place. Furthermore, the PT line is the dominant public transport service in the region. For the MoD service it is assumed that the vehicles are only used by one person at time.

To answer the questions above an agent based modeling approach is used to simulate the fleet behavior and the existing PT line operation. First, in Section 3.1 the general simulation methods are presented. These can be adopted to all public transport lines which have the above characteristics. The simulation methods are explained by presenting the required input data, the simulation strategy as well as the resulting output values. This method uses a fixed MoD fleet as an input parameter. It is further shown how an appropriate fleet size $N$ is found and which fleet control strategies are used (Section 3.2). The presented methods are then applied to four specific case scenario. In Section 4 the four case scenarios are introduced and for each specific characteristics are pointed out. Because all scenarios are located in Switzerland the cost parameters presented below reflect the local conditions there. Nevertheless, with other cost parameters the presented methods can also be used outside of Switzerland.

3.1. Simulation Approach

Figure 2 shows the general approach used in this publication to analyze a replacement of an existing PT line with MoD. Based on the input data two simulations are carried out. One simulation is done for the MoD service. It evaluates the service level and cost for a given MoD fleet, a street network and the travel demand. The goal of the second simulation is to model the existing PT service. The current cost and service levels are evaluated based on the demand and the PT line properties. In the following the input data, the two simulation tools and output data are discussed in more detail.
3.1.1. Inputs

The following input data is fed into the simulation tools:

- **PT line attributes** are required to simulate the PT journeys and to evaluate the costs of the PT line. The following attributes of a PT line are used:
  - Line length $l$ from end to end ($A$ to $B$ in Figure 1).
  - The location of the PT stations along the line.
  - A schedule of the PT line which includes the drive times between stations as well as the number of PT vehicles per day $N_{\text{day}}$.

- The **taxi fleet** contains information about the vehicles and organization of the MoD service. The two most important parameters in this work are the number of vehicles $N$ (fleet size) and the dispatching strategy. These two values will be varied to find an optimal fleet setting for a given scenario. How the fleet size is determined is discussed below in Section 3.2. There as well the dispatchers used are presented. Other than the fleet size and the dispatcher, it should be mentioned again that the taxis are used by one person at the time. Furthermore it is assumed that the dispatching strategies function equally for AMoD and CMoD.

- The **travel demand** contains information about the journeys of the passengers on the existing PT line. For each journey the origin $O$ and destination $D$ (Figure 1) as well as the departure time is required. It is assumed that all the journeys which are served by the PT line today will remain the same (same $O$, $D$ and departure time) if the new MoD service is in place. The only thing which changes is the mode of transport. For this work the travel demand was extracted from a dataset which contains travel information for a much larger area than the region around the PT line. How the travel demand for a single PT line is extracted can be found in the Appendix A.1.

- The **street network** is an abstract representation of the real streets in the region around the PT line. It contains links which connect nodes with each other. Every link has a free speed and a length associated with it. Furthermore, some other attributes can be added such as the traffic flow.
capacity or the number of lanes. For the four case studies Open Street Map (OSM) data \cite{26} is used and further calibrated with Google Maps Distance Matrix API data \cite{27}.  

3.1.2. Simulation Models  
The input data is used in the two simulations to calculate the service level and the cost of both the existing PT line and the new MoD service.  

- The MoD Simulation is carried out in this work with AMoDeus which was used before in \cite{24}. AMoDeus is an extension of the agent based transport simulation framework MATSim \cite{21}. It simulates the activities of agents over one day. To proceed from one activity to the next the agents are moved with a specific mode of transport on the street network. AMoDeus adds an additional mode for MoD to the standard MATSim modes. Even though MATSim offers the possibility to let agents choose their mode of transport based on a cost function which includes for example the traffic situation, this work only considers the network simulation. When simulating the taxi fleet with AMoDeus the wait time $t_w$ (from submission of the request for a taxi to pick up) as well as the in-vehicle time $t_v$ (from pick up to drop off) of each journey are evaluated. The sum of the two values is then the journey time $t_j = t_w + t_v$. Other insights gained from the simulation are for example the distances driven per vehicle or request or the ratio between occupied and available taxis. Another important measure is the distance ratio which puts the distance driven with a customer in relation to the total driven distance.  

To calculate the operational cost of the fleet the model of \cite{28} is used. It contains very detailed cost parameters for rural regions and is calibrated for a setting in Switzerland. To use the cost parameters it is assumed that the fleet is operating only with midsize and non electric vehicles. This leads to the two cost functions for AMoD and CMoD with the parameters shown in Table 1. A more detailed view on the costs parameters can be found in the Appendix A.2. The costs per trip for AMoD are related to cleaning. For CMoD the cleaning costs are included in the costs per year as presented in \cite{28}.  

\begin{table}[h]  
\centering  
\begin{tabular}{l|c|c} 
\hline & AMoD [CHF] & CMoD [CHF] \\
\hline Costs per Vehicle and Year ($C_v$) & 12945 & 16090 \\
Costs per km ($C_{km}$) & 0.225 & 0.218 \\
Costs per Trip ($C_{trip}$) & 0.375 & 0 \\
Costs per Hour ($C_{hour}$) & 0 & 35 \\
\hline  
\end{tabular}  
\caption{Cost parameters for the AMoD and CMoD service. All values are adapted from \cite{28}. The parameters lead together with Equation [1] to the two cost functions for AMoD and CMoD. Detailed values in Appendix A.2}  
\end{table}  

The total yearly fleet costs $C_{fleet,year}$ are then calculated as shown in
Equation 1

\[ C_{\text{fleet,year}} = C_v \cdot N_v + C_{\text{km}} \cdot d_{\text{total}} + C_{\text{trip}} \cdot N_{\text{trips}} + C_{\text{hour}} \cdot t_{\text{working}} \]  

where \( N_v \) is the number of vehicles, \( d_{\text{total}} \) is the total driven distance by the fleet in one year, \( N_{\text{trips}} \) is the number of trips per year and \( t_{\text{working}} \) are the working hours by all drivers in a year. These yearly values are extrapolated from the simulations for one day as the data contains trips on an average day.

The average cost per vehicle kilometer \( CV_{\text{km}} \) can then be calculated with Equation 2

\[ CV_{\text{km}} = \frac{C_{\text{fleet,year}}}{d_{\text{total}}} \]  

and because all the taxis are used by one person at the time the total cost per passenger kilometer \( CP_{\text{km}} \) is

\[ CP_{\text{km}} = \frac{C_{\text{fleet,year}}}{d_{\text{customer}}} \]  

where \( d_{\text{customer}} \) is the total distance driven with customer.

- The PT model is used to retain a realistic comparison of the MoD service to today’s situation with PT. For this a PT journey is modeled with the following three legs which is the underlying procedure in [29]: (1) accessing a PT station, (2) driving with the PT to another station and finally (3) accessing the journey destination. The two stations are found by searching for the closest station to the origin and the closest station to the destination of the journey. For the access legs (1) and (3) it is assumed that the person would walk with an average velocity of 1.34 m/s [30]. The distance above 2 km is assumed to be covered by bicycle (or another PT) with an average velocity of 5 m/s [31]. The duration with the PT (2) is given by the PT schedule of the input data. This calculation covers the most important characteristics of a PT journey. Furthermore, it can be assumed to be conservative as it does not include any wait time at the station. This implies that a person would orient his or her daily plan according to the PT schedule and be capable of arriving exactly at the departure time at the station. To be sure the PT journey times are in the right order of magnitude each PT ride is compared to the result for a public transit ride in the Google Maps Distance API [27]. It could be shown that the presented model leads to a slightly lower journey time than the Google data would indicate (Figure 5). Hence, the model is a conservative approach when the MoD journey times are compared with the PT journey times.

The operational costs of a PT line are calculated with Equation 4

\[ C_{\text{pt,year}} = CV_{\text{km,pt}} \cdot l \cdot N_{\text{day}} \cdot 365 \]  

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where \( l \) is the length of the PT line, \( N_{day} \) the number of PT Vehicles per day on this line and \( CV_{km,pt} \) the average vehicle cost per km of the public transport service. For this work a value of 15 CHF/km \([32]\) is used for \( CV_{km,pt} \). This value contains all running costs such as the wages, vehicles, cleaning costs or overhead. Additionally it includes parts of the infrastructure costs associated with the railway and stations. Equation 4 neglects the different frequencies on workdays and weekends.

### 3.1.3 Outputs

The two services PT and MoD both have a certain service level and an associated cost.

- The main **MoD service level** measure is the journey time. It shows how long the whole trip takes from the time when a person calls a taxi to the point when he or she is dropped of at the destination. The journey time is especially important to compare MoD with PT.

  For MoD another important measure is the pure wait time for a taxi. When an customer calls a taxi he or she does not want to wait for hours until the taxi arrives. This would heavily reduce the reliability of such a service (e.g. connections to transit trains in the next city). In the used scenarios the peak hours occur from 6 to 8:30 am and from 4 to 6:30 pm which was found to be the highest demand and congestion time. During peak hours approximately 50% of the requests are raised. Thus in this work the mean wait time during peak hours is limited to five minutes. With this assumption it is guaranteed that firstly the wait times in off peak times are significantly below five minutes and secondly the maximal wait times can be bound to a acceptable range as it will be shown in Section 3.2.2.

  Thus the service level of the MoD service is a combination of the wait time and the journey time.

- The **MoD fleet cost** function was already presented in the MoD simulation model in Section 3.1.2 (Equation 1). Dependent on the fleet type (CMoD or AMoD) the cost function differs with the largest difference that the CMoD contains wages for drivers while the AMoD service does not.

- For the **PT service level** the journey time as outlined above is used. It contains the in-vehicle time and the time it takes to access the next station both at the origin and at the destination. Wait times at the PT station are neglected.

- The **PT cost** include the operational costs of the PT line. These are not dependent on the taxi fleet as they are a function of today’s PT operation costs only. Even the travel demand does not directly influence the operational costs as the number of PT vehicles is seen as a constant size in this publication.
3.2. Evaluation of Fleet Properties

The workflow shown above in Figure 2 includes inputs, the two simulation tools and the outputs. Until now the fleet was introduced as a given property. Nevertheless, in this publication the main focus is to vary the fleet properties to achieve a well performing MoD service in terms of the two outputs service level and cost.

The two properties of the MoD fleet which will be varied are the fleet size \( N \) and the dispatching strategy. It will be analyzed how the change in these parameters influences the MoD service. In this Section first the five dispatching strategies are introduced. So far only a few studies were conducted where different fleet control algorithms were compared with each other. In the second part it will be presented how an optimal fleet size is evaluated and what effects it has on the wait and journey times.

3.2.1. Dispatching Strategies

A dispatching strategy (dispatcher) has two major parts: the actual dispatcher and the rebalancing policy. The first defines which taxi will pick up which customer and assigns the requests to the vehicles. The latter relocates vehicles in the network to bring the system into balance and with that the pickup distances can be reduced. Within this work five different dispatching strategies were used. The first four are dispatchers which are already implemented in AMoDeus. The fifth is a heuristic approach which was developed to take the special PT line characteristics into account. While the first two dispatching algorithms only assign requests to available vehicle the other three dispatchers also include rebalancing.

1. The **demand supply balancing dispatcher** [33] compares the number of available vehicles with the number of unmatched requests at every dispatching step. If there are more available vehicles than requests for each request the closest vehicle is assigned. If the number of unassigned requests is larger than the number of available vehicles, each vehicle is sent to its closest request. This assignment is not optimized globally as it only iterates over the requests (or vehicles) once. This dispatching algorithm is binding which means that a vehicle can not be assigned to another request until it drops off the customer.

2. The **global bipartite matching dispatcher** (also called Hungarian Algorithm) solves a bipartite matching problem between the open requests and the available vehicles at every dispatching time step. This includes vehicles on a pick up drive which means that a prior assignment can be broken if a new request situation requires it. As a distance measure the routed distance throughout the road network is used.

3. The **feed forward fluidic dispatcher** was first introduced in [22] and a publicly available implementation is presented in [25]. A flow model is used to model the customers and the vehicles. The optimal rebalancing solution is found by solving a linear program based on historical data for
the arrival rates of customers and the origin and destination distribution. The program minimizes the number of vehicles rebalancing in the system.

4. The **adaptive real time dispatcher** was presented as well in \[22\] and the used implementation is presented in \[25\]. It solves a similar rebalancing problem as the feed forward fluidic dispatcher. Nevertheless it does not require a priori information for the arrival rates and the travel demand. It repetitively solves the optimization based on the current requests in a certain time horizon.

5. The **PT line dispatcher** is introduced here as a heuristic approach to tackle the special demand situation along a rural PT line. It uses the knowledge that during the morning rush hours people are traveling mostly from the rural regions to the larger cities at the end of the PT line (and vice versa in the evening peak hour). The global bipartite matching dispatcher was extended with a rebalancing strategy which is only in place during these peak times. If in the morning the fraction of idling vehicles outside of the train area (Figure A.8) accounts for more than $\alpha$ of all idling vehicles then the dispatcher sends as many vehicles into the train area until the fraction drops below $\alpha$. The destination of the rebalancing vehicles are the PT stations with a probability proportional to the passenger numbers at each station per day. In the evening the same procedure takes place in the opposite direction. Outside of the peak hours no rebalancing mechanism is in place. $\alpha$ is a tuning parameter for the dispatcher and is chosen in this work to be 0.3.

### 3.2.2. Optimal Fleet Size

For this work it is important that MoD improves (or at least preserve) the current service level. Only in a second step it will be analyzed how this affects the costs. As defined above the service level for MoD consists of the wait and journey time. Hence, a certain threshold for the wait time is defined which should not be exceeded. This threshold is chosen to be the above mentioned mean peak wait time with a value of 5 min. To find the number of vehicles that meet the specification a series of different MoD fleet sizes $N$ is simulated. After the evaluation of the appropriate fleet size the day profile of the wait time is analyzed for this fleet size. Furthermore the journey time will be compared to the PT values to make sure this fleet size is as well results in a higher service level.

An example of the wait times for different fleet sizes can be seen in Figure 3. As expected the wait time decreases with a higher $N$. In this example the mean peak wait time decreases below 5 min if the fleet is operating with a bit more than 50 vehicles. Therefore, in this case $N$ would be chosen to be 50 vehicles. A 20% decrease of the fleet size to 40 vehicles still leads to a mean peak waiting time under 8 min. This shows that the results in this region are stable and small changes in the number of vehicle do not influence the results substantially. With $N = 50$ the simulated 95% quantile of the wait time is at 12 min. Most of these requests occur around 7:30 am or 6:00 pm. During the peak times approximately 50% of all requests are submitted. It can be seen that
with a fleet size of 50 vehicles the (overall) mean wait time and the off peak wait time are at 4 min and 2.5 min respectively in this example.

The different mean wait times are a well suited measures for the sizing of the fleet size. Nevertheless it is important to check that the distribution over the day stays within an acceptable boundary. For the case of 50 vehicles Figure 4 shows the waiting times over the day. In this plot the lines identify the wait time of all the requests not yet picked up and how long the customer are waiting at this specific time. In this example there are only rarely more than 20 people waiting for a vehicle. Thus, a single customer who has not been picked up can strongly influence the 95% percent quantile. Again, the largest waiting times occur around the morning and evening rush hours. for this example it can be seen that the mean wait time hardly ever exceeds 10 min. Only for some minutes before 6 pm the mean wait time peaks at 25 min and the maximal value observed for the 95% quantile is 60 min. During off peak hours the wait times remain at a low level (i.e. below 4 min (mean) and 10 min (95% quantile)).

The maximum value of 60 min wait time for one requests looks quite high at first glance. The reason why such a high value is possible is because the dispatching algorithm used does only take the distance into account when assigning requests to vehicles. Thus, it occurs that some requests at the border of the scenario are not assigned for a long time as there are always closer requests for a vehicle. This could be solved easily for example with a strategy which takes the current wait time of the customers into account.

As mentioned above the wait time is not the only criteria for the MoD service level. The journey time is another important measure and other than the wait
Figure 4: Example for the wait time distribution over one day. Here for 50 vehicles in the Homburgertal scenario with the global bipartite matching dispatcher. The peak value for the 95% quantile around 18:00 which is cut off is 60 min.

Figure 5: Comparison of the PT (access time to the station plus in-vehicle time) and MoD (wait time plus in-vehicle time) journey times for an example scenario. Here the Homburgertal scenario with 50 vehicles and the global bipartite matching dispatcher was used.
time it can be compared to the existing PT line service level. Figure 5 shows the cumulative distributions of the journey times for both the PT line and the MoD service. The values taken are from the above example with a fleet size of 50 vehicles. It shows that the journey times are in general smaller for a MoD service than the journey times with the PT (on average 7 min faster). The reason for this is that the door to door transport of the MoD fleet eliminates the access time to a PT station. This access time accounts for close to 65% of the average journey time with PT. Hence, only if the start and end of the trip are close to a station the journey time with PT is shorter than with MoD. That is the reason why only 17 percent of the journeys will last longer with the MoD than with the PT in this example. And only for three percent of requests more than five minutes additional journey time have to be accepted if the PT is substituted with an MoD service.

Summarizing it can be stated that a fleet size for which the mean peak wait time of 5 min is not exceeded seems very practical. Such a fleet size keeps not only the average but as well the wait times during the day in an acceptable size. Furthermore it gives the MoD service a higher planning reliability. The resulting journey times with such a fleet size indicate that a MoD service will improve the service level compared to an existing PT line. The few exceptions are journeys that start and end near PT stations and that take place during peak times.

4. Four Case Scenarios

A replacement of various train lines is currently under discussion in Switzerland. To bring a new perspective into that debate and to analyze some of the advantages and disadvantages of a mobility-on-demand system in a rural region the following four train lines have been selected to be analyzed within this work (Figure 6). In addition the framework allows to quickly create and simulate new scenarios within Switzerland. As basis for this work the IVT baseline scenario [34] is used as travel demand and for the line properties data from the Swiss federal railway (SBB) was used (schedule from [35] and stations from [36]).

4.1. Homburgertal

One train line which had a lot of attention in the past years is the S9 (also called “Läufelfingerli”) between Sissach and Olten through the Homburgertal. It is a 18 km long train line with 6 stops in small villages all of which have a population below 2000 people. On this line a single train is operating with a frequency of one train per hour and it travels 22 min from end to end. The SBB data about passenger frequencies ([38]) at the stations indicates that 1000 people are using this line on a regular week day. Most of them travel either to Olten or Sissach or take a connecting train from there onward to larger cities such as Basel, Zürich or Bern. Between Olten and Sissach exists a second train line through a parallel valley with a longer tunnel. This line is the main connection for Intercity trains between the two towns. In November 2017, the population clearly rejected the plans to replace the train line with a bus service.
4.2. Thunersee

The regional train line between Interlaken and Spiez at the south cost of the lake of Thun (Thunersee) mainly serves the two villages Leissigen and Därligen with a total of 1500 inhabitants. There is a direct train between Interlaken to Spiez every half hour. Nevertheless, these trains do not stop in Leissigen and Därligen. For that another hourly connection operates on the 18 km long route. Exactly this connection was decided to be replaced with a bus service by the parliament of Bern in 2017 [39]. A detailed study [40] pointed out that on an average day only 416 people are transported from and to the two stations. Most of them want to travel to Spiez or from there on further to the larger cities Thun or Bern. Another large user group are the children who have to go to school in Interlaken.

4.3. Boncourt

Close to the border of France and Switzerland the 10.5 km long train line between Boncourt and Porrentruy serves 590 people on an average week day. The train running this service is not only operating between the two towns but starts in Delemont and ends in Boncourt. Therefore within this scenario a reduction of the operating area to the line between Delemont and Porrentruy is considered. The part between Porrentruy and Boncourt is served once an hour and takes around 15 min.
The connection to the close French city Delle is at the moment only possible with a bus service but it is planned to reopen the train line again. This is mainly due to the connection to the French high speed rail network which would start in Belfort. Therefore it can be assumed that this region will face some changes of the train service supply in the near future. Thus it is interesting to consider as well the possibility of mobility-on-demand service.

4.4. Tösstal

The S26 through the Tösstal in the east part of the canton of Zürich connects the city of Winterthur with Rüti over a distance of 41 km. Especially from Winterthur to Winterthur Seen the trains are very well used. Therefore only the rural part of the line between Winterthur Seen and Rüti ZH is considered within the analysis. On this part of the line the S26 is the only train which uses the track. Every hour one train serves all 14 stations along the valley. Additionally, one train per hour runs between Winterthur Seen and Bauma to give this part of the line a connection towards Winterthur with a frequency of 30 min. 8500 people are using the train line per day.

5. Results and Discussion

This section presents the simulation results in two steps: First, the influence of the dispatching strategies on the two simulation outputs service level and operational costs is presented for an example scenario. In the second part the results of the four case scenarios will be compared (Section 5.2).

5.1. Influence of Dispatching Strategies

Within this section the influences of the dispatching strategy on the following three fleet performance measures are presented: First on the wait time, second on the driven distance by the MoD fleet and third on the annual MoD fleet costs.

Figure 7a shows a comparison of resulting peak wait times for the five dispatching algorithms (Section 3.2.1) for different fleet sizes. The dispatchers differ in the mean peak wait time up to 3 min for the same number of vehicles. Within the region of interest between 35 to 60 vehicles the demand supply balancing dispatcher results in the largest wait times. The adaptive real time policy and the global bipartite matching dispatcher have slightly smaller wait times. They would require around 51 vehicles to serve the requests with an average peak wait time of 5 min. The feed forward fluidic policy solves the task with only 48 vehicles. It is the best performing dispatching algorithm which was tested from the literature (in terms of wait time). Nevertheless, the new algorithm specially developed for the PT line substitution can serve the demand even faster and only requires 47 vehicles for 5 min mean peak wait time. The PT line dispatcher can serve the customers with the shortest wait time over the whole range of vehicles presented in Figure 7a.
(a) Mean peak wait time as function of the number of vehicles and the chosen dispatching algorithm.

(b) Annual AMoD fleet costs as a function of the accepted mean peak wait time for the five dispatchers.

Figure 7: Influence of dispatching algorithms on the mean peak wait time (wait time in the period from 6 to 8:30 am and from 4 to 6:30 pm). Results for the Homburgertal scenario.

The reduction of the wait time comes with an additional cost: The total driven distance of the fleet increases when rebalancing is in place. To compare the dispatchers a comparison of the different distances for the five dispatchers can be found in Table 2. All the distances are evaluated at a fleet size of 50 vehicles. All of the dispatchers have similar distance with customer driven. This makes sense as they all serve the same demands. The small differences are caused by numerical errors. The first two dispatchers do not use any rebalancing which is why they have no rebalancing distance. The global bipartite matching dispatcher results in the shortest driven distance in total which makes sense as it optimizes the assignments globally. A low total distance is favorable because the fleet costs scale proportionally to it (Equation 1). For the pick up distance the PT line and the feed forward fluidic dispatchers clearly outperform the other dispatchers in this scenario. This finding is consistent with the results for the wait times in Figure 7a as the wait time directly relates to the pick up distance. The further away from a customer an available vehicle is located the more distance it has to cover and the longer the customer has to wait.

<table>
<thead>
<tr>
<th>Distances [km] per day</th>
<th>Demand Supply Balancing</th>
<th>Global Bipartite Matching</th>
<th>Adaptive Real Time</th>
<th>Feed Forward Fluidic</th>
<th>PT Line</th>
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</thead>
<tbody>
<tr>
<td>Total</td>
<td>11286</td>
<td>10955</td>
<td>13715</td>
<td>11806</td>
<td>11658</td>
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<tr>
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<td>9363</td>
<td>9366</td>
<td>9367</td>
<td>9362</td>
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<td>1578</td>
<td>1751</td>
<td>1408</td>
<td>1427</td>
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<tr>
<td>Rebalancing</td>
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<td>14</td>
<td>2598</td>
<td>1031</td>
<td>869</td>
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</tbody>
</table>

Table 2: Driven distances per day for different dispatching strategies for the example scenario with 50 vehicles.

The third important influence of the dispatching strategy is on the fleet
costs. This influence is a combination of the results for the wait times and the driven distances when inserted into Equation 1. Figure 7b indicates that the global bipartite matching and the PT line dispatchers perform best in terms of fleet cost. Additionally the feed forward fluidic policy generates not much more costs. While the global bipartite matching dispatcher can reduce the costs by holding the total distance low the other two algorithms have an advantage because they are able to reduce the wait time without a big increase of the total mileage. For a five minute mean peak wait time the total annual fleet costs are in the range from 1.6 to 2.0 Mio CHF for the example scenario.

It could be shown that the heuristic PT Line dispatcher can reduce the number of required vehicles compared to the current AMoDeus dispatchers. The heuristic approach makes an assumption about the future demand which is not done in the other strategies. As the results indicate that this can significantly reduce the cost and number of required vehicles, further analysis in this field should be carried out in the future. Not only in the line scenarios used in this publication but as well in more general problems one sees a large potential for a higher fleet efficiency when choosing an appropriate fleet control strategy.

5.2. Comparison of Four Case Scenarios

In this section the simulation results of the four presented scenarios in Section 4 are shown. Table 3 gives an overview over the most important results of each scenario. In the first part the general line properties are listed and the second part covers the simulation results.

The number of vehicles \( N_v \) required to guarantee a maximum of 5 min peak wait time differs a lot across the train lines. The fleet size varies from 16 (Thunersee) to 825 (Tössstal) vehicles. When one puts this number into relation to the number of passengers (share ratio) one gets the average number of customers per vehicle and day. It is around 26 in the Boncourt and the Thunersee scenario, a bit lower at 21.3 for the Homburgertal and by far the smallest value can be found in the Tössstal where only 10.1 customers are served on average by the same vehicle. This can be explained by the larger distance and the longer in-vehicle times for one request in the Tössstal scenario (and partly in the Homburgertal scenario). Hence, a vehicle has to spend more time to serve one customer and thus it can not serve as many per day.

A closer look at the daily vehicle performance shows that the vehicles in the Boncourt and Thunersee scenarios are driving around 290 km per day and in the Homburgertal and Tössstal 253 km respectively 171 km are driven. Of these distances only a fraction is covered with a customer which is expressed by the distance ratio. It is found that the values lie between 73 and 81 percent with the highest value in the Homburgertal scenario. This shows that the vehicles in the smaller scenarios can be used more intensively than in a larger case.

For the financial side it is found that the AMoD service can reduce the operational cost compared to today’s train costs. For the Homburgertal to 45% of today’s costs, Thunersee to 17% and Boncourt to 37%. In the Tössstal on the other hand the costs would nearly double with an autonomous mobility-on-demand service. A service with conventional taxis might only be economically
## General Line Properties:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Homburgertal</th>
<th>Thunersee</th>
<th>Tösstal</th>
<th>Boncourt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Line Length [km]</td>
<td>18.2</td>
<td>18.1</td>
<td>41.4</td>
<td>10.5</td>
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<td>21</td>
<td>57</td>
<td>15</td>
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<tr>
<td>Passengers per Day R</td>
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<td>416</td>
<td>8300</td>
<td>590</td>
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<tr>
<td>Stations</td>
<td>8</td>
<td>5</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Stations in Train Area</td>
<td>5</td>
<td>2</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Trains per Day N_{day}</td>
<td>38</td>
<td>38</td>
<td>54*</td>
<td>42</td>
</tr>
<tr>
<td>Passengers per Train km [1/km]</td>
<td>1.42</td>
<td>0.55</td>
<td>3.69</td>
<td>1.33</td>
</tr>
</tbody>
</table>

### Results:

- **Fleet Size N for Peak Wait Time under 5 min**: 47, 16, 825, 22
- **Share Ratio R/N**: 21.3, 26.0, 10.1, 26.8
- **Mean Peak Wait Time [s]**: 293, 259, 291, 287
- **Mean Wait Time [s]**: 233, 219, 222, 210
- **Avg. Drive Distance [km]**: 9.36, 8.64, 12.41, 8.22
- **Avg. In-Vehicle Time [s]**: 871, 654, 1133, 673
- **Avg. Daily Vehicle Distance [km]**: 253.1, 290.0, 170.9, 289.1
- **Avg. Vehicle Velocity [m/s]**: 10.37, 12.67, 10.78, 11.77
- **Distance Ratio [%]**: 80.4, 77.5, 73.1, 76.3
- **Train Costs [MCHF]**: 3.78, 3.77, 12.2, 2.41
- **Annual Fleet Cost AMoD [MCHF]**: 1.72, 0.65, 23.3, 0.89
- **Annual Fleet Cost CMoD [MCHF]**: 6.54, 2.17, 79.6, 3.14
- **Avg. Journey Time PT [min]**: 24.8, 25.2, 30.5, 26.0
- **Avg. Journey Time MoD [min]**: 18.4, 14.5, 22.6, 14.7

*Including trains from Winterthur to Bauma proportional to the covered distance.*

Table 3: Comparison of the results for the four scenarios described in Section 4. The PT line dispatcher (Section 3.2.1) and a minimal fleet size to achieve a 5 minutes mean peak wait time were used. The distance ratio is the fraction of the total fleet distance which is driven with a customer.
efficient in the Thunersee scenario. For the high costs in the Tösstal scenario three influences should be mentioned here. The high number of passengers (not only in absolute numbers but as well relative to the number of train km) requires a large fleet size which is expensive. Furthermore, the in-vehicle times in this scenario are substantially longer which again requires more vehicles. Ultimately the longer trip distance directly translates to higher costs for the fleet operator.

In the following paragraphs the findings are analyzed and evaluated for each case scenario separately. The Homburgertal scenario was found to be very interesting for a substitution of the train line with AMoD. It has rail tracks that are exclusively used by the S9 and there exists only one other bus line as public transport in this valley. For further discussion on this train line it should be taken into account what happens with to bus line (from Sissach to Wittinsburg). One possibility could be to serve these customers as well with the AMoD service as this would only require a larger fleet size but would further decrease the cost for PT in this region.

In the Thunersee scenario the costs presented for AMoD are very low compared the train costs. This is only possible because the customers who travel (every two hours) directly from Spiez to Interlaken with the train line are neglected. When these customers have to be served additionally then the AMoD service would not make sense. Another possibility would be to use an additional train for these customers as it is suggested in [10]. This would increase the costs for the new (AMoD) service although they could be held below the current train costs. As the number of passengers is very low in this scenario even a replacement of the train service with CMoD might be a possibility. To make a clearer statement about the economic effects one should further investigate on both cost structures (for the current train and a possible CMoD). Additionally, this region seems very interesting for sharing as a lot of similar demand patterns occur.

In the Tösstal scenario it was found that a replacement of the train line with AMoD is not realistic. The large fleet size would generate high costs and at the same time increase the congestion on the streets. It is furthermore a complex region with a lot of connections to bus lines along the train line. It would therefore require more investigation on how this integration with other public transport can be achieved.

In the Boncourt scenario it was found that a substitution with AMoD is possible at lower costs. Here, the connection to the close French City Delle should be considered if further discussion is going on.

Over all, it can be summarized that in specific situations AMoD can replace rural train lines at a higher service level and lower costs. CMoD normally is much more expensive than the current PT lines. Nevertheless, in some cases (e.g. Thunersee) it has the potential to serve as a pilot experiment to test the dispatching algorithms in a real world environment. Compared to MoD, the rail (and PT in general) becomes more efficient if longer distances with more passengers have to be covered. Hence, if one wants to find potential PT lines to be replaced by MoD the average trip distance should be short and the number of customers small.
6. Conclusion and Outlook

In this paper it was analyzed if the replacement of existing rural PT lines with an autonomous mobility-on-demand service is feasible in terms of service level and operational cost. Given the demand for mobility of today's public transport, the fleet behavior of MoD was simulated with an agent based approach using the MATSim extension AMoDeus. It was shown that such a service can operate at lower cost and with a higher service level. This holds especially for shorter lines with less demand. In such cases a substitution of the low profitable regional PT line can be an interesting alternative. For longer PT lines and for a higher demand examples were found where a replacement can not improve the current situation.

Furthermore, it was shown that the dispatching strategy clearly influences service level and the costs of the fleet. With a heuristic dispatcher it was possible to control the fleet more efficiently compared to the current dispatching strategies. Hence, it can be assumed that there exists still potential to improve the dispatching strategies when making assumptions about future demand.

For future work different aspects should be considered to improve the presented work. Especially within a valley where most of the trips are in the same direction and often end or start at similar places (e.g. train station or schools) sharing is assumed to be possible with only a small service level reduction. If sharing is considered heterogeneous vehicle sizes in the fleet should be analyzed. Another important factor which should not be neglected in future work is the change in travel demand if the new MoD service is in place. In this publication the assumption was made that the demand of today will remain the same in the future. But as MoD has a higher service level it is likely possible that as well more people would want to use such a service. Until the technical progress allows autonomous taxis to operate on a large scale MoD might be tested with conventional taxis. This can be more expensive than the PT service but the PT operator could gain very valuable knowledge about the future mobility system.

Appendix A. Appendix

Appendix A.1. Scenario Reduction to PT line

Often the required travel demand as input data for the simulation is not existing for a PT line. In this work a method was developed how the travel demand can be extracted from mobility data for a much larger region than the area of interest. Such data is often available from surveys of the population about their daily mobility behavior (e.g. for the United States of America or for the United Kingdom). To have a computationally affordable and for the local region representative and meaningful scenario the size of the large mobility data has to be reduced. Thus in the following paragraphs the used method is explained.

For a PT line from A to B it can be assumed that this line serves a specific area which is called "train area" (Figure A.8). The demand for public transport in this area is mainly met by the PT line which should be replaced with MoD.
Figure A.8: The access area defines the region where the new MoD service operates and the train area from which locations passengers use the PT line. Dependent on the location of the Destination $D$ a trip is split into (2) or kept as it is (1).

From the large mobility data it is assumed that all trips with mode public transport which start or end in this region use the PT line of interest. For the new regional scenario all these trips will be taken into account.

This assumption neglects transit PT (i.e. a trip from A to B is not taken into account as A and B are not in the train area). As long as only regional PT lines are considered it can be assumed that significantly faster connections from A to B are available. A passenger who wants to travel from A to B would thus prefer such a connection over the regional PT line.

A and B are generally not in the train area because often A and B are stations which belong to a bigger city. There other public transport systems such as bus or tram lines exist. This services will be maintained when the PT line is replaced. If one would include such a station in the train area a lot of customers who use the bus or tram according to the travel data would have to be served by the MoD service in the future. As the new service is only a substitution of the PT line and not the bus and tram service in the cities this is not desirable.

It should be mentioned here that in certain cases it could definitively make sense to include one (or both) of the final stations A and B in the train area. For example, if station B is located in a small village at the end of a valley. If there exists no (or only little) local public transport then the PT line is the only possibility to make a trip with public transport. In this case it is desirable that a MoD taxi can transport a person from station B to station A and therefore station B should be included in the train area.

A second region is defined which completely encloses the PT line of interest: the "access area". It defines the places with access to the new MoD service (Figure A.8).

Requiring one activity to be in the train area leaves two possibilities for the other activity of the journey: It can either be inside or outside of the access area (Figure A.8). In the first case (from $O_1$ to $D_1$) the MoD can reach the second location and bring the customer directly to (or pick up from) this place.
Therefore only the mode of transport has to be changed for such a journey. The second case occurs when the destination has no access to the MoD service ($D_2$). Then it is assumed that the agent will travel with both the MoD and PT service. The agent will change between the two modes at a station. At which station the change will take place is dependent on the location of $D_2$. The one station (of A and B) which is faster to reach form $D_2$ by public transport is chosen. Such a journey of the travel data (form $O_2$ to $D_2$) is split into a MoD trip (from $O_2$ to A) and a public transport trip (form A to $D_2$). The same process is vice versa in place when the origin is outside of the access area and the destination is the train area.

After this filter process two last steps are conducted to make the regional scenario comparable to today’s train line usage. First, if a person would have to walk further to the two PT stations than going directly to the next activity this person is removed from the regional scenario. And secondly the remaining population is scaled to the number of passengers $R$ which use the PT line according to the information of the PT line operator. This is necessary as the travel data normally does not reflect the local circumstances as it was conducted for a larger area.

Appendix A.2. Cost Parameter

In Table A.4 the detailed cost parameters are listed. The total values ($C_v$, $C_{km}$, $C_{trip}$ and $C_{hour}$) were already presented in Table[1]. All values are adapted from [28] and then used with Equation[7].
Table A.4: Cost parameters for the AMoD and CMoD services. All values are adapted from [28].

<table>
<thead>
<tr>
<th></th>
<th>AMoD [CHF]</th>
<th>CMoD [CHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Insurance per year and vehicle</strong></td>
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<td>800</td>
</tr>
<tr>
<td><strong>Tax</strong></td>
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<tr>
<td><strong>Parking</strong></td>
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</tr>
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</table>

References


U. Weidmann, Transporttechnik der Fussgänger, Schriftenreihe/Institut für Verkehrsplanning, Transporttechnik, Strassen-und Eisenbahnbau 90.


