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Impact assessment of autonomous DRT systems

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Abstract

The market entrance of shared autonomous vehicles (SAV) may have disruptive effects on current transport systems and may lead to their total transformation. For many small and medium-sized cities, a full replacement of public transport services by these systems seems to be possible. For a transport system operator, such a system requires a bigger fleet of vehicles than before, however, vehicles are less expensive and fewer staff is needed for the actual operation. In this paper, we are using a simulation-based approach to evaluate the service quality and operating cost of a DRT system for the city of Cottbus (100 000 inhabitants), Germany. The simulation model used is based on an existing MATSim model of the region that depicts a typical work day. Results suggest, that the current public transport system may be replaced by a system of 300 to 400 DRT vehicles, depending on their operational mode. Compared to previous, schedule based public transport, passengers do not need to transfer, and their overall travel times may be reduced significantly. Results for the cost comparison are preliminary, but results suggest that an autonomous DRT system is not necessarily more expensive than the current public transport system.

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Keywords: Mobility as a Service; demand responsive transport; shared autonomous vehicles; MATSim; public transport

1. Introduction

The market entrance of shared autonomous vehicles (SAV) may have disruptive effects on current transport systems. Their effect on private vehicle possession and usage is widely discussed (Litman, 2017), but they may also lead to a total transformation of public transit systems. In large cities, systems of SAVs offering a Mobility as a Service (MaaS) system may replace feeder bus or tram lines with a more flexible system, whereas high-frequency mass transit systems are expected to operate roughly the same way as today. These pooled SAV services may be referred to as Demand Responsive Transport (DRT). In smaller cities without true mass transit systems, autonomous MaaS-DRT systems may replace current public transport systems. In European cities of up to 200 000 inhabitants, these often consist of bus and/or tram lines running in unattractive frequencies. In those communities, MaaS-DRT systems may provide a higher level of service, lower travel times and possibly lower operational costs (and thus, less subsidies)

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than conventional public transport. Additional congestion effects due to a higher number of vehicles are usually not of relevance, mainly because congestion in such cities is usually not significant. In this paper, we are using a simulation based approach to evaluate the service quality of a MaaS system for the city of Cottbus, Germany. This includes both a comparison of different operational forms of DRT and a comparison with the service quality and costs of conventional public transport.

In the remainder of the paper firstly an overview of similar research is provided. This is followed by the methodology used and a results section. The paper concludes with a warp-up and outlook on possible further research.

2. Related work

Demand responsive transport, as a form of ridesharing systems, where multiple passengers share a car or van, is nothing new. Jitney and shared taxi services were a popular means of transport in US cities at the turn of the 20th century, before they were widely banned from operating. However, in many countries, these services continue to operate and are often the pre-dominant form of public transport. In general, these services have a fixed route or all passengers share the same origin and destination (Neumann, 2014, ch. 2).

App-based dynamic transportation network companies (TNC), such as UBER and Lyft, have both introduced pooled services in larger metropolitan areas. Upon ordering, customers receive an estimated arrival time at their destination and a fixed fare quote. Depending on the likelhood of pooling passengers with each other, the offered fare is significantly lower than for non-pooled options(Uber, 2017; Lyft, 2017). Most TNCs argue, that their service aims at passengers that previously would have used their private car, however, recent studies suggest, that public transport usage declines due to growing TNC use. This is especially true for buses, where a six per cent decline was measured, but also for light rail services (Clewlow and Mishra, 2017). In Europe, TNCs only recently started pooling of services. Notably, public transport operators themselves are more often starting to roll out TNC-like services. Among the first cities to introduce such a system was Helsinki, though the start attempt failed (Shared-Use Mobility Center, 2016). In Germany, Berlin's public transport agency BVG intends to roll out a pooled service during 2018 (BVG, 2017). However, a careful study needs to be undertaken in order to determine whether these MaaS systems perform better than private cars in terms of vehicle mileage and environmental sustainability (Bischoff et al., 2018).

A switch to mostly automated vehicles will have disruptive effects on MaaS systems, as operators will be able to offer SAV services at a fraction of the current cost. This may lead to a drastic reduction of private vehicles in metropolitan areas (Bischoff and Maciejewski, 2016; Kaddoura et al., 2018; Moreno et al., 2018). Recent cost assumptions conclude that SAV operators may offer their fleet services for prices around $0.40 - 0.60\frac{EUR}{km}$ (Bösch et al., 2018; Trommer et al., 2016) per car-sized vehicle.

According to Bösch et al. (2018), prices in this range will also lead to a decline in public transport usage, with an expected impact mostly on public transport lines outside densely populated areas. This finding leads to the question, if a replacement of classical, schedule based public transport with a DRT could be more user-friendly and even economical.

3. Methodology

In this paper, we use a simulation based approach to evaluate a possible DRT system. Simulations are based on an existing model and simulation software, which will be described in the following sections. Afterwards, the used evaluation methodology is introduced.

3.1. Simulation model of Cottbus

In this paper, a synthetic MATSim (Horni et al., 2016a) model of the city of Cottbus is used. Cottbus is a city of 100 000 inhabitants in the federal state of Brandenburg. It is situated roughly 110 km south of Berlin. The simulation model is based on work by Grether et al. (2011) and depicts a typical working day in the city. In the model, there are about 21 000 trips made by public transport within the city and its close surroundings. This number is slightly lower than the official data of the local public transport operator (Cottbusverkehr, 2016), mainly because the model's focus lies on work-related trips. The city's current public transport system consists of five tram lines and 13 regular city bus lines. The tram lines run in intervals of 15-20 minutes on weekdays, whereas the buses within the city run every 20 minutes to two hours. Services are limited during weekends (Cottbusverkehr, 2017). The long intervals in the current public transport cause high waiting times and a low flexibility when choosing the departure time. Additionally, some bus services operate only on request. The majority of these services are also depicted in the simulation model. Since the focus in this paper is the public transport demand, the original simulation model was reduced to only depict those agents using public transport, resulting in a synthetic population of 11 000 agents.[1] In the base case, all of them have at least one trip by public transit per day, whereas in the policy cases, these were replaced by various forms of demand responsive transport.

3.2. Simulation of Demand responsive transport

MATSim provides a set of extensions to simulate various MaaS systems (Maciejewski, 2016). These include taxi (Maciejewski and Bischoff, 2015), SAVs (Maciejewski et al., 2017) and DRT (Bischoff et al., 2017). In this paper, the DRT extension is used, which performs a centralized, on-the-fly assignment of vehicles to passengers as soon as a passenger requests to use the service. Usually, the request is assigned to the vehicle where the insertion of the request into the planned route will cause the lowest detour. However, this is subject to two constraints: Firstly, the overall travel time for any other passenger also traveling on the same vehicle needs to remain under a certain threshold t_r,

$$t_r = \alpha\, t^r_{direct} + \beta\,,$$

where t^r_{direct} denotes the direct ride time without detours and α and β are parameters to model the maximal time loss because of waiting, boarding and detours occurring due to the pick-up and drop-off of fellow passengers. Should this target service criterion not be met for the requesting passenger herself, she will still be transported, but her journey will take longer. Constraints are never violated for already scheduled passengers. Secondly, the expected boarding times for the awaiting customers and the new one need to remain within a defined time frame t^{wait}. This ensures that customers do not have to wait too long. The DRT module supports both a door-to-door dispatch of customers as well as a stop-based scheme, where agents need to walk to and from a nearby stop. Upon reaching the stop, the vehicle is called. Should start and destination stops be the same, the agent will walk all the way. In this paper, both modes are investigated.

3.3. Service parameter assumptions

For the simulation runs, we set the desired waiting time restriction t^{wait} to 10 minutes, so that the introduction of DRT can bring a significant advantage compared to the current public transport system which has long waiting times when changing or requires planning an exact departure time depending on the bus or tram departure due to the long intervals described above. For the detour parameters, a value of $\alpha = 1.5$ and $\beta = 10min$ was set. These parameters seem to provide a reasonable combination of detour and travel times and are derived from previous work (Bischoff et al., 2017). Furthermore, a stop time of 60 seconds per stop for boarding and alighting of passengers is assumed, independent of the number of passengers boarding and alighting. Idle vehicles are re-balanced in regular intervals according to the estimated demand of the previous MATSim iteration. To achieve this, two iterations with a constant demand were run per scenario. The re-balancing algorithm is based on the minimum-cost flow problem.

For the stop-based scenarios, a total of 400 stops were created in the network. Their locations are mostly along major roads, but also within densely-populated residential areas. For the placement of these stops, a K-Means clustering algorithm was used (Hastie et al., 2009, 509ff.). Every activity became one data point with the corresponding location. This means that sometimes many data points have the same location, if there are many activities happening here, such as, e.g., in shopping centers. An initial set of 400 centroids was chosen at random and the algorithm ran for 100 iterations.[2] With the result, most locations in the city are within 500 m of a stop. as the overview of the resulting

[1] In terms of MATSim terminology, "pure transit walks" from the original scenario were converted to walk. This means that persons who would have liked to use public transit, but could not find an appropriate connection with the conventional public transit, were excluded from MaaS as well. Including them would result in more demand, but presumably also higher costs, since this demand presumably is outside the operating times or operating areas of the existing conventional public transit.

[2] The open-source Java package can be found under `https://github.com/pierredavidbelanger/ekmeans`

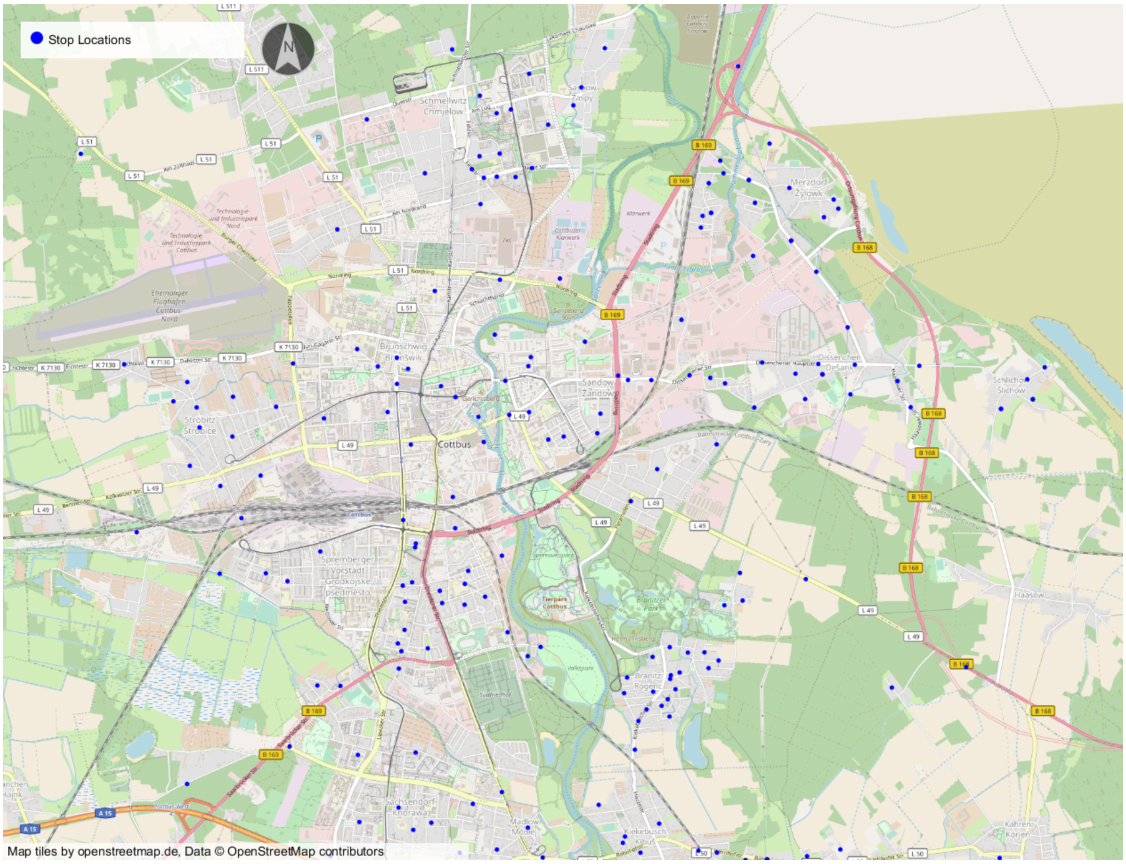

Fig. 1. Locations of DRT stops in the network

stop locations in figure 3.3 demonstrates. The average walking distance to a stop is 240 m, whereas in the base case scenario, the average walking distance is 585m to reach a transit stop.

Simulations for both the door-to-door and the stop-based scheme are run with a varying fleet size between 200 and 600 vehicles. A capacity of eight passengers per vehicle is assumed. For further analysis, only those simulation runs are evaluated where a certain service rate is reached and the fleet utilization is sufficient.

3.4. *Quality of service and economic assessment*

To assess the quality of these services, a set of service criteria need to be defined. On the passengers side, these include the waiting times for vehicles and total travel times. In order to find a wide acceptance, the service needs to be as reliable as schedule based public transport. This mainly means that the rate of trips where the target service criteria are met, needs to be high. Thus, only simulation runs with a compliance rate of than 95 per cent or more are evaluated.

On the operators side, the required fleet size and the vehicle kilometers traveled determine the overall operational cost. For the cost model, the assumptions of Bösch et al. (2018) are used, who assume a cost of 0.56 CHF (or roughly 0.50 EUR) per vehicle kilometer for pooled SAV operations. While these values are originating from Switzerland and thus might be slightly higher than what could be assumed for Germany, they take into account the operational and capital cost of SAVs in the most comprehensive way. Estimating the cost of current public transport operations is somewhat more difficult for the city of Cottbus, due to their mixed operations that both include urban and regional bus lines as well as tram lines. However, for a similarly sized city in Germany, a cost parameter of 2.38 $\frac{EUR}{km}$ was used for buses (Killat, 2014), so this value is used in this paper for all types of vehicles, while being aware that it is only a rough estimate.

Table 1. Simulation results for different fleet sizes and modes

Scheme	vehicles	Mean walk time [min]	Mean wait time [min]	Mean IVTT [min]	mean trip time [min]	target service rate [%]
door to door	300	0:00	9:58	20:47	30:45	93%
door to door	400	0:00	6:45	20:46	27:31	98%
door to door	500	0:00	6:32	20:30	27:02	100%
door to door	550	0:00	6:25	20:30	26:55	100%
stop based	250	9:36	12:23	20:29	42:07	92%
stop based	300	9:36	7:24	19:59	36:59	96%
stop based	400	9:36	6:40	19:48	36:15	99%
stop based	500	9:36	6:29	19:47	35:53	100%
Base case		23:13	11:31	15:33	50:17	

4. Results

Results suggest that travel times for DRT services are in all cases below the current public transport travel times.

4.1. Fleet size determination

Based on the service criteria defined under section 3.4, a minimum of 400 vehicles are required to offer a high quality service in a door-to-door operational scheme. In this case, the average trip time, composed of waiting time and in vehicle travel time (IVTT), is 27:31 minutes. If a stop-based system is used, the number of vehicles may be reduced to 300. In this case, however, additional walking times will result in an average travel time of 36:59 min. A complete overview of all simulation runs can be found in table 1.

4.2. Travel Times

In the base case scenario, the travel time consists of roughly 23 minutes of walking time, eleven minutes of waiting time (both at the origin and transfer stops) and 15 minutes of actual in vehicle travel. In the DRT cases, waiting times are lower, whereas in vehicle travel times are somewhat higher. In the stop-based simulation, also the access and egress walking times from stops are considerably lower than in the base case. While the average waiting times are similar in both cases, they are not spread evenly over the city, as figure 4.2 reveals. Especially in door to door mode, these are often considerably higher in less central areas.

4.3. Fleet utilization

While the demand in both simulation runs is the same, the door to door based system still transports slightly more rides than the stop-based system, where some agents walk if their access and egress stop are the same. This results in 21 346 daily requests being served in the door to door mode versus 21 292 requests in the stop-based mode. Consequently, and due to more detours, the daily vehicle kilometers traveled (VKT) are somewhat higher in the door to door scenario, resulting in a higher number of vehicles required (cf. to table 2). The average passenger kilometers per day (PKT) are roughly similar in both cases. The mean occupancy rate is, however, higher in the stop-based scenario. This in an indicator for a more efficient pooling of passengers, but may also mean that detours are longer. Detailed vehicle occupancy can be found in figure 4.3. In the stop based base, vehicles are, relative to the fleet size, more utilized, with no vehicles being idle during peak times.

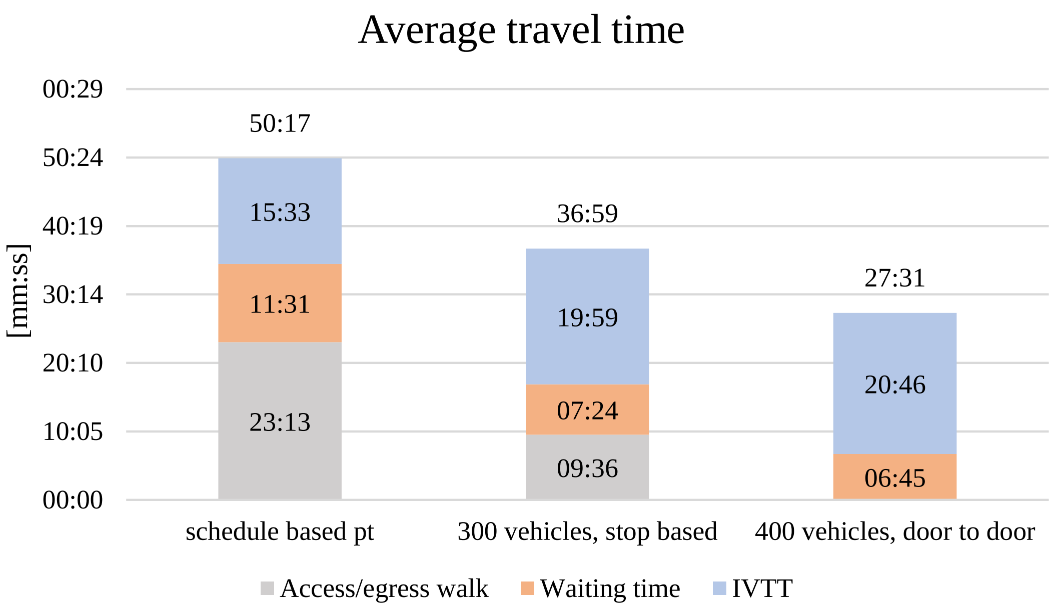

Fig. 2. Travel times in base case and DRT scenarios

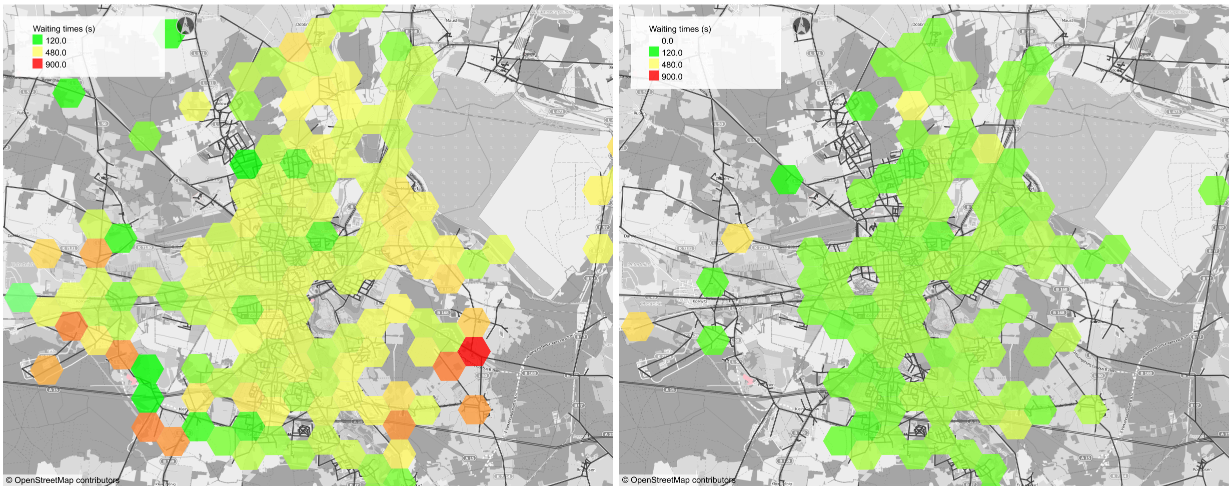

Fig. 3. Spatial distribution of average waiting times (in seconds) in door to door (400 vehicles, left) and stop based (300 vehicles, right) mode

4.4. *Cost assessment*

According to the assumptions in section 3.4, the daily operational cost of the stop-based system is 30 191 EUR, whereas for the door to door system, 32 653 EUR will be required, assuming driverless operations, i.e. no costs for drivers. The schedule based transport is currently serving roughly 5.5 million kilometers annually. This breaks down to roughly 18 000 km per work day. This would translate into operational costs of 42 840 EUR for the current system, including costs for drivers. Under these circumstances, both DRT systems using driverless eight-seat vans are likely to operate cheaper than the current schedule based public transport system with drivers. However, the cost calculation has some limitations, as the model has a clear focus on depicting peak and commuting traffic. Therefore, the operational

Table 2. Vehicle utilization in stop-based and door to door modes

Scheme	vehicles	Daily VKT [km]	Daily PKT [pkm]	Mean occupancy	Daily Empty Distance [km]	trips served
door to door	400	65 306	259 036	3.97	7 329	21 346
stop based	300	60 381	260 582	4.31	6 227	21 292

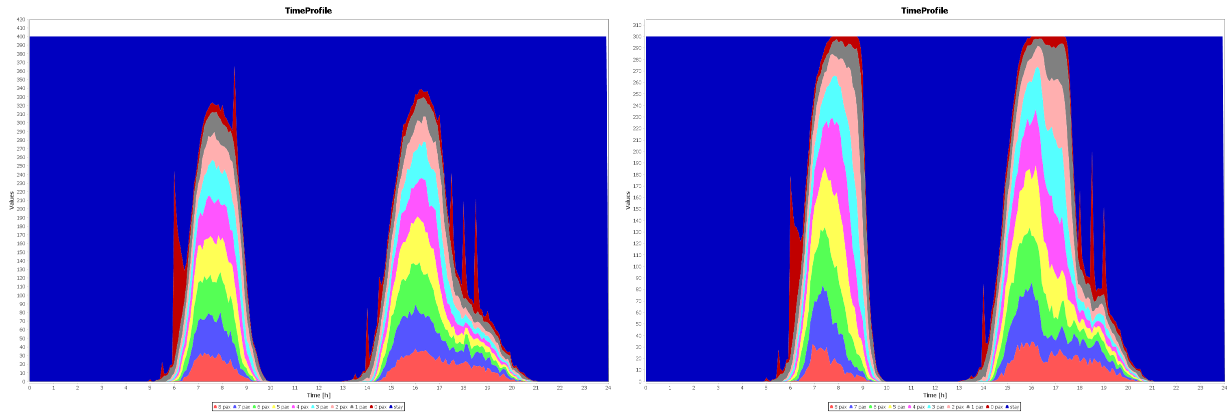

Fig. 4. Fleet occupancy in the door to door case (400 vehicles, left) and stop-based case (300 vehicles, right).

costs of the DRT service might in fact be somewhat higher. Still, self driving DRT systems are likely to be competitive with current schedule based transport with drivers.

5. Conclusion

A full automation of vehicles will have disruptive effects on public transport operations, as MaaS providers may start competing against them. In this paper we were able to show the possible impact of a fully automated DRT system in Cottbus, Germany using a simulation based approach. The results suggest that a DRT system that relies on stops will result in lower travel times and lower operating costs than classic, schedule based public transport. A switch to a door to door system will further reduce ride times for customers, but could still be cheaper to operate than classical public transport, despite the higher number of vehicles required. The results of the current paper leave some room for discussion. On the operative side, more variations than just stop-based and door to door should be evaluated. For example, to achieve an increased comfort and lower ride times, the usage of stops could be limited to peak hours and a door to door system could be operated at other times of the day, when vehicle utilization is lower. This should go hand in hand with an analysis of possible revenues. The current modeling approach assumes that a switch to a DRT system will leave the users of other modes than public transport as they are. However, it is likely that an attractive DRT system will also attract car users as well as cyclists and pedestrians. Further studies should thus take mode choice into consideration. The current, iteration based simulation approach in principal allows for this, however the required mode choice parameters for driver-less MaaS services are hard to estimate and need yet to be found.

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