What to do in the Meantime

A Service Coverage Analysis for Parked Autonomous Vehicles

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Abstract. Fully autonomously driving vehicles are expected to be a widely available technology in the near future. Privately owned cars, which remain parked for the majority of their lifetime, may therefore be capable of driving independently during their usual long parking periods (e.g. their owners working hours). Our analysis aims to focus on the potential of a privately owned shared car concept as transition period between the present usages of privately owned cars towards a transportation paradigm of privately owned shared autonomous vehicles. We propose two methods in the field of reachability analysis to evaluate the impact of such vehicles during parking periods. Our proposed methods are applied to a dataset of parking times of users of a telematics service provider in the Munich area (Germany). We show the impact of time and location dependent effects on the analyzed service coverage, such as business week rush hours or cover age divergence between urban and suburban regions.

Keywords: Reachability Analysis, Autonomous Driving, Network Theory

1 Introduction

Bates and Leibling (2012) estimate that about 4% of a car's lifetime is used for driving, leaving 96% left for parking. Parking usually occurs in regular intervals and during similar time spans, e.g., parking at home or at work. Recent advances in autonomous driving, however, lead to an increasing availability of almost self-driving cars to the public. Compared to their non-autonomous counterparts, autonomous vehicles promise to offer advantages like greater comfort and increased security for their users. The widely used SAE Automated Driving Standard J3016[3] classifies the autonomy of vehicles on a scale from 0 (*no automation*) to 5 (*full automation*). Current autonomous vehicles range between level 1 and 2, with level 1 referring to driver assistance systems such as adaptive cruise control and level 2 referring to partial automation like the current Tesla autopilot. With autonomous driving becoming more ubiquitous, we now try to show how fully autonomous vehicles (level 5) can be put to use instead of parking. We argue that there will be a transition phase between the current one-car-per-person paradigm (at least) and commercial on demand autonomous car services, soon. Privately owned Shared Autonomous Vehicles (SAV) allow their owners to offer it during parking periods

[3] https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic

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to be used by others. Assuming users with the willingness to do so, the resulting fleet of available cars might transport passengers to their desired destination while assuring its return in time when the owner needs it (e.g., driving home from work). Such future SAV-fleets do not require the introduction of any additional vehicles to offer a medium range transportation service as opposed to a commercial car sharing service. In addition to the initial cost, especially in cities, our considerations also prevent the loss of parking space. After an overview over related work in the field of fully autonomous fleet behavior and related implementation (sec. 2), we discuss the background in Section 3. We then present our methods in Section 4 and apply them in sec. 5. Reproducibility is provided in Section 6. We then conclude in Section 7 and point out directions for future work.

2 Related Work

With the upcoming vision of autonomous transport services, there are already several analyses in the field of service coverage, reachability analysis and demand to be found. Fagnant and Kockelman (2018), besides others, studied the behavior of shared autonomous vehicle (SAV) fleets on model simulations in the city of Austin, Texas and evaluated the replacement rate (how many units are needed) of such SAV.
Boesch, Ciari, and Axhausen (2016) modeled a similar demand analysis for the region of greater Zurich. Both settled in terms of how many regular cars can be replaced by SAVs. Their findings, however, depend on the spatio-temporal resolution at which their models operate. While our work tries to find answers in a similar field of application (coverage area and reachability of a SAV service), our setting can be seen the other way round (given real world journeys, what else could have been done in idle times). Please note that while our analysis is based on shortest path searches, we rely on a real-world dataset to determine idle times.
Studies in further spatio-contexts exist: Bischoff and Maciejewski (2016) considered the replacement of private cars with fleets up to 250,000 vehicles. As we aim for a smooth transition of present to future transport models, we assume the first generation of SAVs to be privately owned vehicles that can also be shared while parking.
Kolcsár and Szilassi (2018) utilize isochrone maps to assess accessibility of urban green spaces by combining multiple individual isochrones into a combined accessibility zone. It is calculated by intersecting isochrone maps with each other, suggesting a linear sum union, though no detailed information regarding their methodology is provided. Ala-Hulkko et al. (2016) apply accessibility analysis in form of least-cost paths on a street network to determine accessibility of ecosystem services such as national parks. Their method is used to analyze spatial disparity between ecosystem service providers and beneficiaries (POIs) in contrast to the service coverage of parked cars we focused on. There are also calculations of actual costs of SAV fleets, which consider after-drop-off journeys like parking or refueling, in addition to the sole ride costs (W. Liu 2018, e.g.). We see our work in between the present and a possible near future, when such calculations are needed.

S. Liu and Zhu (2004) present an accessibility analysis tool for urban transportation planning that combines various travel modes (e.g., car, public transport, pedestrian), including arbitrary origin and destination points outside transportation networks. In

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contrast to our implementation, they do not consider network speed limits in their distance function (shortest-path algorithm).

Ford et al. (2015) developed an accessibility analysis tool similar to the work of S. Liu and Zhu (2004), to assess sustainable transport in the city of London. They used a combined cost model (e.g., vehicle operation cost, public transport fare prices) including a shortest-path travel distance on a transportation network as cost component.

Innerebner, Böhlen, and Gamper (2013) present a web-based, geospatial reachability analysis system (ISOGA), which uses isochrones in multimodal spatial networks. While the network type differs from ours, we utilize a comparable three-tier architecture (separated into: presentation, logic and data tier) with a focus on the definition and implementation of the logical tier.

The concept of space-time prisms and time geography, first introduces by Hägerstraand (1970), which was then described and researched by Miller (1991), Miller (2008), and Miller (2017), are related in concept but differ in details of their implementation. In many articles, Miller describes the application of accessibility analysis of people, means of transport and spatial locations in the context of advancing time.

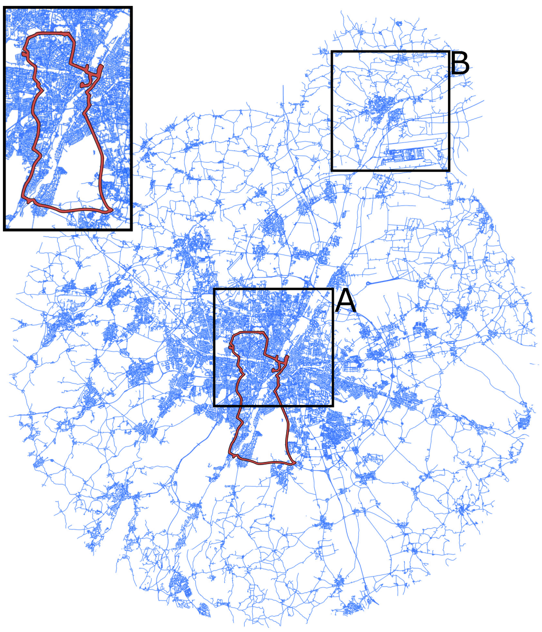

Fig. 1: Street network of Munich; Black boxes indicate the detailed analysis region; **A**: Munich Center, **B**: Freising Suburb. **Red Route**: Predefined route from city center to the suburbs along POIs.

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3 Background

Reachability can be defined as the set of reachable locations within a specified time budget. Analyzing service coverage of parking autonomous vehicles therefore, aims to provide information on the set of reachable locations during their parking duration.

Street Network: A street network is represented by a directed graph $G = (V, E, \phi)$ where a vertex $v \in V$ represents a street crossing or end-point. The street segment between two vertices is given by an edge $e \in E$. ϕ refers to an edge weight function (Barthelemy 2014) which we define as follows:

$$\begin{aligned} \phi &: E \rightarrow \mathbb{R}^+ \\ \phi(e) &= \frac{\text{length}(e)}{\text{max\_traversal\_speed}(e)} \end{aligned} \tag{1}$$

Function length(e) of an edge e is given in kilometers, max_traversal_speed(e) is given in kilometers per second. The traversal time $\phi(e)$ is therefore measured in seconds. An edge e connects two vertices by definition, so traversal along e is always possible. This implies that traversal_speed(e) > 0, $\forall e \in E$. The street network used in this work is a directed graph, continuous in time and discrete in space (edges have to be fully traversed), as defined in Gamper, Böhlen, and Innerebner (2012). It is important to note that the edge weight calculated by $\phi(e)$ denotes the fastest possible traversal. Neither congestion, traffic signals nor other sources of delay are considered in this approach.

Isochrones: Isochrones refer to the set of space points reachable within a given time budget from a given starting position (Bauer et al. 2008; Gamper, Böhlen, Cometti, et al. 2011; Marciuska and Gamper 2010).
Let P be the set of all space points, $o \in P$ an origin position, $t \in \mathbb{R}_0^+$ a time budget in seconds and $d(o, p)$ a distance function with $d : P \times P \rightarrow [0, \infty)$, returning the distance between o and p measured in seconds. An isochrone set is defined as follows:

$$Iso(o, t) := \{p \mid p \in P \land d(o, p) \leq t\} \tag{2}$$

Distance Function: We use a directed graph $G = (V, E, \phi)$ as the underlying data structure, therefore the distance between two vertices v_i, v_j is defined as the shortest-path between them. Dijkstra's shortest-path algorithm (Dijkstra 1959) is used determining the distances. An isochrone with origin vertex $o \in V$ and time budget $t \in \mathbb{R}_0^+$ on a street network G can therefore be defined as the set of all vertices $V_{iso} \subseteq V$ where the distance of the shortest path from o to $v_i \in V_{iso}$ is at most t:

$$Iso(o, t) = \{v \mid v \in V \land d(o, v) \leq t\} \tag{3}$$

4 Approach

We differentiate between individual and combined reachability to measure the possible impact of future SAV-fleets in the transition-phase to commercial on-demand SAV-services. This section introduces the methodology for analyzing reachability based

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on parked autonomous vehicles by extending the previously established concept of isochrones.

Individual Reachability Analysis: Isochrones represent all reachable points within a given time budget from a given starting vertex on a street network, which will be the parking position of a vehicle. Let C be a vehicle parking at location C_{loc} for C_{dur} seconds from starting time C_{start} to C_{end}. Further, let T be the function denoting the shortest-path travel time in seconds.

A point p is reachable by C if it is contained in the isochrone $Iso(C_{loc}, C_{dur})$. This concept of reachability however does not account for the travel time from p back to C_{loc}. Seamless reachability of a point p will therefore be defined as C being able to reach p and return to C_{loc} before or exactly at C_{end}. This means that C is guaranteed to have returned to C_{loc} before or at C_{end}, allowing the vehicle owner to seamlessly drive off without any waiting time. Seamless reachability can be formalized using the following constraint:

$$C_{start} + T(C_{loc}, p) + T(p, C_{loc}) \leq C_{end} \tag{4}$$

This allows to determine an upper bound for the round-trip travel time:

$$T(C_{loc}, p) + T(p, C_{loc}) \leq C_{dur} = C_{end} - C_{start} \tag{5}$$

Street networks are directed graphs, therefore the travel time $T(C_{loc}, p)$ may differ from $T(p, C_{loc})$. Each point p in an isochrone point set is associated with a travel time $T(o, p)$ as this information is necessary to decide whether or not p belongs to the isochrone. Due to the fact that isochrones utilize Dijkstra's algorithm to solve the shortest path problem, all possible travel times $T(C_{loc}, p),\ \forall p \in V$ within the specified time budget are calculated within one pass. The reverse travel time $T(p, C_{loc})$ is not included and needs to be calculated separately for each p.
To avoid computational overhead, we assume:

$$T(C_{loc}, p) = T(p, C_{loc}) + \varepsilon \tag{6}$$

$\varepsilon \in \mathbb{R}$ denotes the deviation in traversal between C_{loc} and p, which may occur if the shortest path from C_{loc} to p contains one-way streets or asymmetrical traversal speeds. This deviation ε is assumed to be sufficiently close to 0 and therefore considered to equal 0. Under this assumption, constraint 5 can now be simplified as follows:

$$T(C_{loc}, p) \overset{\varepsilon = 0}{=} T(p, C_{loc}) \leq \frac{C_{dur}}{2} \tag{7}$$

Vehicle owners may desire access to their vehicle some time before C_{end}, for example when leaving work early. Therefore, the isochrone definition may include a buffer time $\alpha \in \mathbb{R}$, measured in seconds. Using constraint 7, a seamless isochrone for a vehicle C will be denoted Iso_C and defined as:

$$Iso_C := Iso(C_{loc}, \frac{C_{dur}}{2} - \alpha) \tag{8}$$

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Combined Reachability Analysis: We now combine the previously presented methods and define two methods for analyzing the reachability of multiple vehicles. The first reachability analysis method provides information on vehicle availability along a route, the second method provides information on general service coverage.

Vehicle Availability along a Route: We aim to answer the question of how well a characteristic route is covered during a specified timespan.
Let $\mathbf{C}$ be a set of vehicles such that each vehicle $C \in \mathbf{C}$ is associated with a respective parking location C_{loc}, a start and end time C_{start}, C_{end} and the parking duration C_{dur}, which defines the time budget.

Furthermore, let R be a route starting at location p_0 and ending at location p_n. R may contain additional route points $p_1, ..., p_{n-1}$ traversed sequentially after p_0 and before p_n. Each route point p_i is assigned a dwell time $p_{i_{dwell}}$. After traveling to p_i, the specified dwell time passes before continuing traversal of the route.

A route segment $s_{i,i+1}$ with $0 \leq i < |P|$ is the shortest path between two route points $p_i, p_{i+1} \in P$, for $P = [p_0, ..., p_n]$.
The following availability analysis considers a single-segment setting: Any vehicle C transports a user along only one segment $s_{i,i+1}$ and will return to C_{loc} afterwards.
Let R_{start} be the start time of traversing the route. For each segment $s_{i,i+1}$ connecting route points p_i, p_{i+1}, the following two conditions needs to hold for vehicle C to seamlessly serve $s_{i,i+1}$:

$$\textbf{Condition 1:}\ T(C_{loc}, p_{i_{loc}}) + T(p_{i_{loc}}, p_{i+1_{loc}}) + T(p_{i+1_{loc}}, C_{loc}) \leq C_{dur}$$

$$\textbf{Condition 2:}\ R_{start} + \sum_{j=0}^{j<i} (T(p_j, p_{j+1}) + p_{j+1_{dwell}}) \geq C_{start}$$

Condition 1 ensures a sufficiently large time budget of C, condition 2 ensures that the available time window of C matches the desired traversal start time along $s_{i,i+1}$, given the route start time R_{start}. Each segment $s_{i,i+1}$ is associated with the number of vehicles satisfying both conditions and therefore being capable of seamlessly serving it. This allows evaluating the vehicle availability along the whole route.

Service Coverage at specific Date-Times: Additionally, we aim to answer the question of how well an area is covered by the service during a specified time-span.
The service coverage of the proposed hypothetical car sharing service is defined as the set of vertices $V^{sc} \subseteq V$ where each $v_i \in V^{sc}$ is associated with the number of vehicles $C^{sc} \subseteq \mathbf{C}$ seamlessly reaching v_i at a given date-time dt. V^{sc} therefore contains all vertices v_i such that $|C^{sc}|$ vehicles can reach v_i, pick up a user and at least drive back to the initial location within the time budget.
Modifying α (Equation 8) allows adding a buffer time, guaranteeing that any vehicle C counted in V^{sc} can travel at least α seconds without interfering with the time budget. To determine whether or not a vehicle C can seamlessly reach any vertex $v_i \in V$ at a given date-time dt, two conditions have to be satisfied:

$$\textbf{Condition 1:}\ v_i \in Iso_C$$

$$\textbf{Condition 2:}\ C_{start} + T(C, v_i) \leq dt \leq C_{end} - T(C, v_i)$$

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Condition 1 ensures general reachability, condition 2 ensures that the time-span during which C can reach v_i contains dt, meaning that v_i is seamlessly reachable by C at dt. The calculation of V^{sc} is described by the pseudo-code in Algorithm 1. Condition 1 is checked implicitly by looping only over all $v_i \in Iso_C$ at line 5. Condition 2 is checked by first calculating the earliest and latest possible arrival times v_{start} and v_{end} at v_i on line 7 and 8 and then only increment the vehicle count on v_i if line 9 satisfies Condition 2. The term v_{agg_cost} on lines 7 and 8 refers to the accumulated traversal time from C_{loc} to v.

Algorithm 1: Service Coverage

```
1  Function ServiceCoverage(C, dt):
       input: Set of vehicles C, date time dt
       returns: Set of vertices V^sc ⊆ V
2      begin
3          V^sc ⟵ ∅
4          for C ∈ C do
5              Iso_C ⟵ Iso(C_loc, C_dur/2 − α)
6              for v ∈ Iso_C do
7                  v_start ⟵ c_start + v_agg_cost
8                  v_end ⟵ c_end − v_agg_cost
9                  if v_start ≤ dt ≤ v_end then
10                     if v ∉ V^sc then
11                         V^sc[v] ⟵ 0
12                     V^sc[v] ⟵ V^sc[v] + 1
```

5 Evaluation

For evaluating our concept, we introduce the real-world dataset used for our analysis and then present the resulting service coverage of reused parked cars in the greater area of Munich, Germany.

Dataset: The dataset used for evaluation contains vehicle-parking coordinates in WSG 84, start and end date-time, as well as the implicit parking duration. Vehicle trajectories from origin-destination trips, supplied by a telematics service provider located in Munich, are used to generate the parking dataset. The provided trajectories have been chosen as a random sample from trips in a 30km radius around Munich and a 10km radius around Freising during the year 2018. Filtering was applied to reject vehicles with less than 10 present trips during that year. Vehicle parking entries are calculated as follows: For all vehicles, we consider all pairs of two chronologically consecutive trips T_1, T_2 from one vehicle, where T_1 ends at coordinate c_1 at time t_1, and T_2 starts at coordinate c_2 at time t_2. The vehicle is said to park during t_1 and t_2 at c_1 if distance$(c_1, c_2) < 500$m, as the provided trajectories are captured using GPS and are only accurate within 500m. Trajectory pairs with non-matching start-end-coordinates are rejected. Parking duration is calculated by $t_2 - t_1$. A representative sample is shown in Table 1.

Evaluation of Service Coverage: Three weekdays (Monday, Thursday, Saturday) are chosen for evaluation with the intention to cover both business week days and

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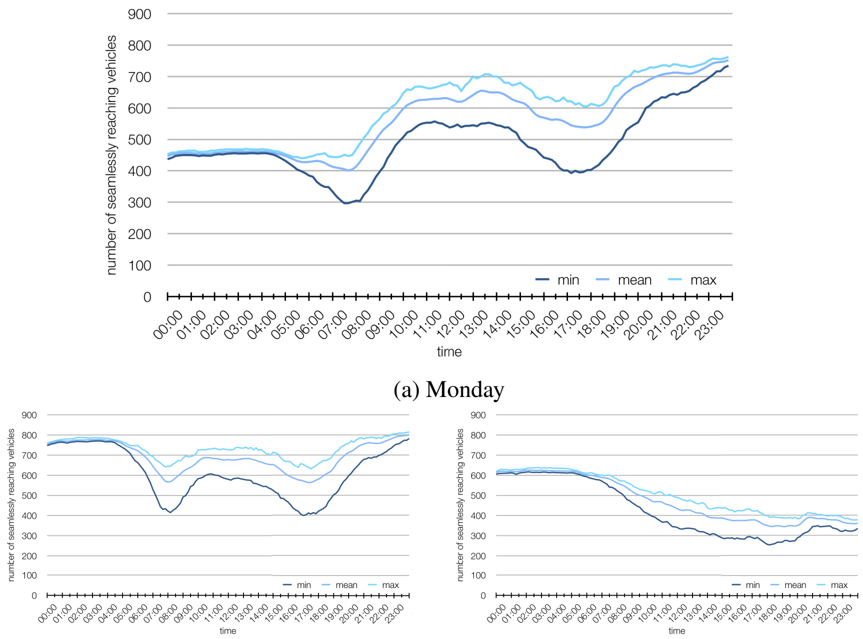
lat	lon	start.time	end.time	duration
48.1503	11.5951	1531815300	1531827000	11700
48.1513	11.5792	1527064941	1527079250	14309
48.2248	11.4399	1530635002	1530646695	11693

Table 1: Representative sample of vehicle parking dataset

weekend days, where vehicle availability is expected to differ (days start at 12 am and end at 12 am the day after). We compute the service coverage for 24 hours, split in discrete 10 minute bins which then results in 144 time steps (dt). For each dt, the corresponding vertex set V^{sc}_{dt} is calculated, where each vertex $v \in V^{sc}_{dt}$ is associated the number of vehicles seamlessly reaching it. The resulting chronologically ordered list of vertex sets is then used to analyze the change of reachability over time.

1339 unique vehicles were recorded during the evaluated days. On Monday 951 unique vehicles were recorded, on Thursday 1019 and on Saturday 806 vehicles.

Figure 2 shows an overview over all analyzed days by plotting the minimum, mean and maximum number of vehicles reaching all available vertices.



(a) Monday

(b) Thursday

(c) Saturday

Fig. 2: Overview of service coverage

Both weekdays (Fig. 2a & 2b) show a quite similar pattern. Vehicle availability starts at 450 to 750 vehicles, which then drops to a local minimum during morning rush hours (around 8 am). A second local minimum is reached during evening rush hour

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(around 5:30 pm). Availability rises and variances decrease rapidly after both rush hours (Fig. 2a). Both, morning and evening rush hour, show a similar effect by lowering the overall availability with a high variance. There is a recovery period between those hours on both days, so that a maximum in availability is reached not only at night times but also in the course of a usual weekday, from about 10 am to 4 pm. This observation, which seems astonishing at first, is mostly due the introduced bias of the observed user group. Nevertheless, this shows the huge potential that lies in parked cars. Figure 2c shows an overview for Saturday, which differs from both previously mentioned analyses. No peak times are visible, the overall availability is highest during early morning and falls off slowly during the day. The overall variance is lower compared to the weekdays. On Thursday 80% of those vehicles present at that day are actually usable. Saturday shows availability of just over 70% at best, decreasing towards the evening. On rush hours during weekday, these values drop to about a third (Monday: between 30% and 40%, Thursday: 40%). Worst-case scenarios are 30%, 40% and 30% in relative vehicle availability for Monday, Thursday and Saturday, respectively.

This overview analysis concludes that vehicle availability visibly changes during business week and weekend, being highest during the business week, especially during night, and lowest during weekend. Rush hour shows visible impacts during business week on both, availability and variability. Weekends are not affected by rush hour and show lower overall variability. High variability implies uneven spatial spread of available vehicles.

Further analysis of the service coverage will be conducted in the following, using rastered images. Two regions of the used street network are chosen: Munich, city center & the city of Freising (a Munich suburb; Fig. 1). Nine day times, starting at 4 am in regular 2 hour intervals are chosen for rasterization to provide a visual representation of service coverage change throughout the day. Please note that we also developed an interactive map with a finer temporal resolution of 144 steps in 24h. Figure 3 shows the rastered coverages for both of the regions for Thursday.

Both regions show similar coverage at 4 am (Fig. 3a & 3k) and 6 am (Fig. 3b & 3l) but start to visibly diverge at 8 am (Fig. 3c & 3m). The region around Freising shows visibly lower coverage, suggesting that more vehicles are available in and around the center of Munich, where coverage is higher. Service coverage at 4 pm and 6 pm show a similar divergence. The day times 10 am, 12 pm and 2 pm show similar coverage for both regions without visible change in between (Fig. 3d - 3f & Fig. 3n - 3p).

Service coverage at 8 pm is similar but slightly lower in Freising (Fig. 3i). Both regions show the effects of morning and evening rush hours, which is entailed by lower coverage. This observation is consistent with the availability minimum values seen in Fig. 2. The visible regional divergence in coverage during rush hour visualizes the effects of high variance and implies fewer available parking vehicles in and around Freising as compared to the center of Munich. Coverage rises after rush hour in both regions, suggesting that the coverage drop around rush hour may be caused by drivers commuting to and from workplace.

We omit the presentation of the detailed views for the other days (Monday & Saturday), as they show a similar pattern in accordance with Figure 2a. On Monday rush hours, availability of SAV-service diverges between Munich and Freising. Service coverage on Saturday is consistent with the overview shown in Figure 2c.

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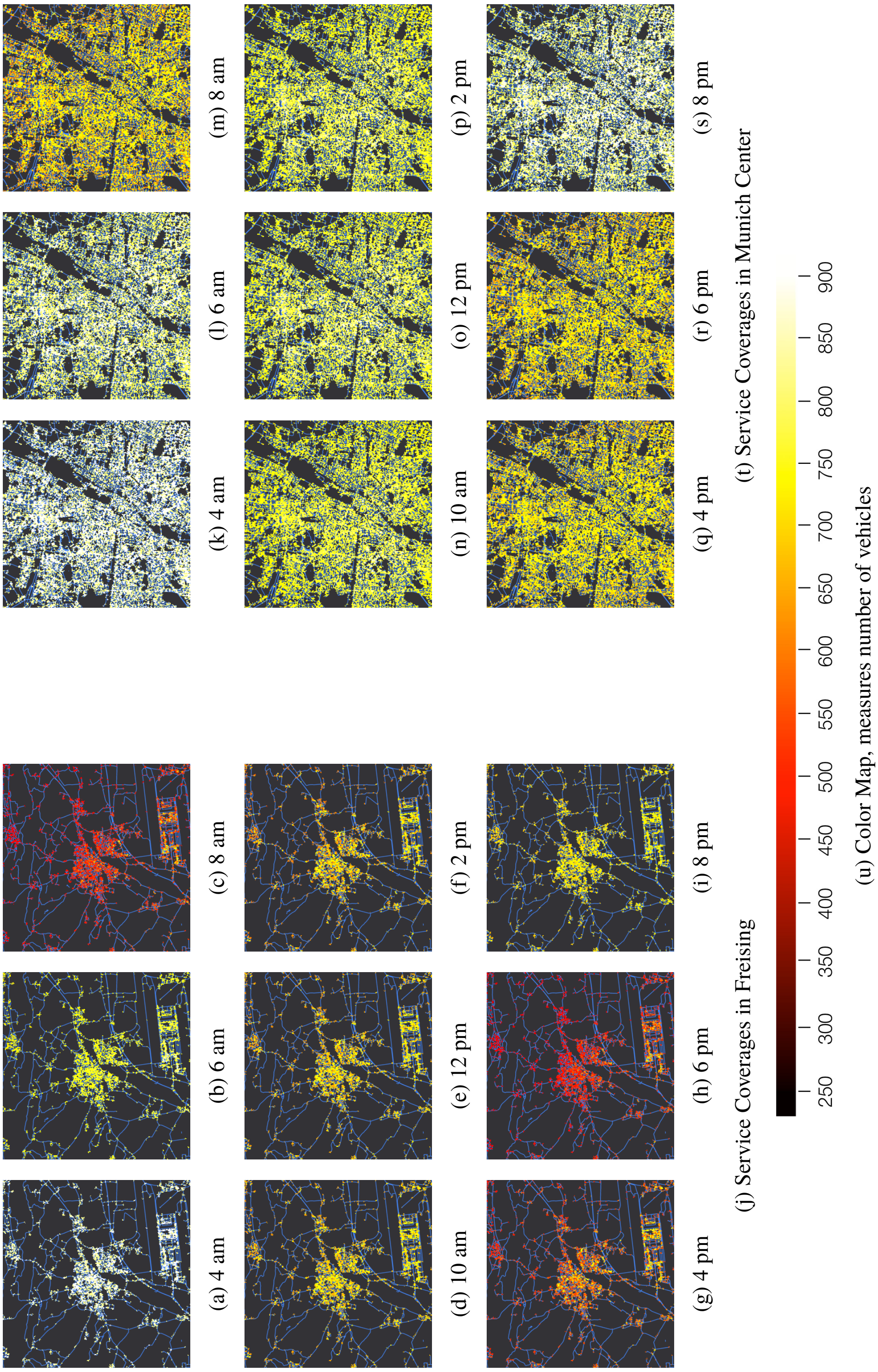

Fig. 3: Service coverages in the center of Munich and Freising suburb on Thursday. Background is darkened to enhance visibility of bright colors

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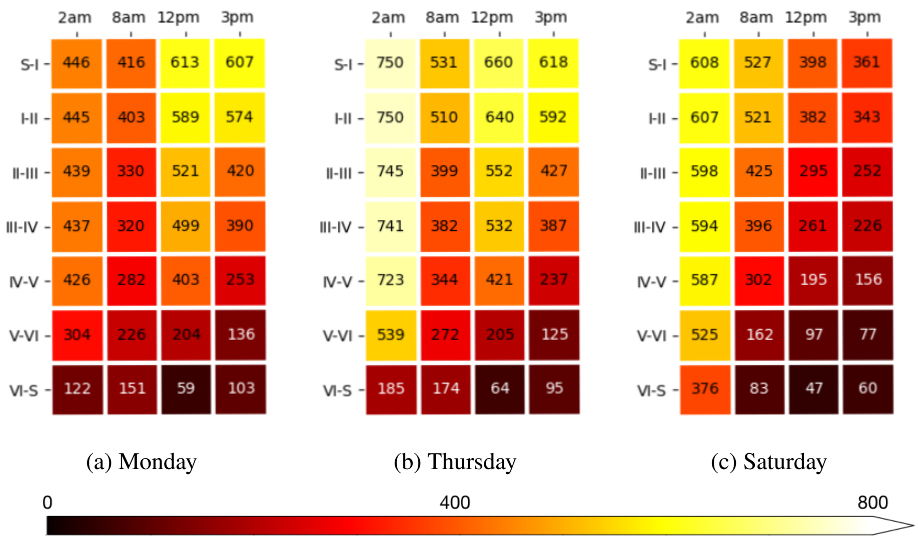
A continuous decrease in coverage is observable, while regional differences are less pronounced compared to weekdays. Freising showing a slightly lower coverage in general. Service coverage evaluation shows that vehicle availability depends not only on the temporal, but also on the spatial context (e.g., type of region). The fictive privately owned SAV-service is expected to be more consistently in and around the city of Munich, where more users can be served in general compared to the suburb Freising.

Vehicle Availability along a Route: In addition to the overall service coverage, we also want to evaluate the service availability along a route. We do this by calculating the reachability of every next stop along a predefined route as described before. To include possible temporal phenomenon, we do this for four different starting times at three different days (2 am, 8 am, 12 pm, 3 pm). The route was defined to cover famous touristic 'points-of-interest' in Munich as well as points outside the city center, aiming to model a plausible route via car sharing. The route is further chosen to be a round trip and is calculated to take a total of about 7 hours and 34 minutes, including dwell times. The analysis will be applied to the three dates used in the first evaluation section. Figure 4 shows an overview of the analysis results. Rows indicate the route segment, columns indicate the route start time. Cells contain the number of available vehicles. They are colored in accordance to the legend shown in Figure 4d to visualize low, medium and high vehicle availability.



(a) Monday (b) Thursday (c) Saturday

(d) Color Map, measures number of available vehicles

Fig. 4: Overview of vehicle availability along a route analysis. Cells show the number of vehicles available for serving a route segment at one day time

All three days show high vehicle availability during the first two route segments regardless of starting time, whereas the remaining segments show a drop in availability.

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One exception is observable in the 2 am column on Saturday in Figure 4c, where availability is continuously decreasing, but drops less harsh compared to other days and start times. Availability for route segments V-VI and VI-S on Monday shows low vehicle coverage on all start times except 2 am. Low coverage of route segment VI-S starting at 2 am shows the effect of overall service coverage drop during rush hours (ref. Fig. 4a). Departure from route point VI happens at around 9 am (7 hours offset) when starting the trip at 2 am. This departure time is affected by the rush hour induced coverage drop mentioned previously.

Thursday shows an increase in peak vehicle availability compared to Monday and Saturday, which is most pronounced on route segments I-II to III-IV. Vehicle availability on these segments with a route starting time of 2 am is visibly higher compared to both other days, visualized in the 2 am columns (Fig. 4b). This observed availability is consistent with the evaluated service coverage on Thursday shown in Figure 2b, which has shown broad and low-variance coverage during early morning. Route segment VI-S shows a similar drop in coverage, again due to the departure time being affected by the morning rush hour.

Saturday shows comparatively high vehicle availability along all segments when starting at 2 am, as segments V-VI and VI-S are not affected by the morning rush hour. The remaining route start times show a decline in availability, which is consistent with the decline in service coverage on Saturday shown in Figure 2c.

Service coverage is generally higher on shorter routes closer to the city center (up to 618 vehicles). Longer and more remote route segments are expected to be served worse in comparison. Route segments during the business week rush hour can be expected to be served worse (min. 47 vehicles), as well.

6 Data and Software Availability

All research data supporting this publication are available at OSF (doi.org/10.17605/OSF.IO/PWYJN, Illium et al. 2020). This repository additionally contains the computational workflow with instructions included in file README.md. This research uses OpenStreetMap[4] as a street data provider, which is licenced under the Open Data Commons Open Database Licence [5]. The analysis is performed using PostgreSQL [6] with the extensions PostGIS [7] and pgRouting [8].

[4]OpenStreetMap | https://www.openstreetmap.org

[5]ODbL | http://opendatacommons.org/licenses/odbl/1.0/

[6]PostgreSQL | https://www.postgresql.org

[7]PostGIS | https://postgis.net

[8]pgRouting | https://pgrouting.org

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7 Conclusion and Future Work

We aim to outline a scenario in which privately owned autonomous vehicles are able to provide transportation services for others. We propose two geographic reachability analysis methods based on a real-world trajectory dataset of a telematic service provider in the region of Munich, Germany (2018) (Illium et al. 2020). Our goal was to find an answer to our main question: In a transition between the traditional car ownership model and shared autonomous vehicle deployments, how would a service coverage look like?

Our first analysis provides information on general service coverage at a specified date time and offers both an overview of such a service area and insights into regional differences in vehicle availability. The service coverage evaluation shows a high impact of rush hours on suburban regions such as Freising near Munich (Figure 1 b) as compared to Munich City (Figure 1 a), which may be caused by drivers commuting to a work place in the city center. Service coverage during weekend was shown to be lower but more consistent due to the absence of the business week rush hour. Such a service may instead show an increase in free parking spots, entailed by an increase in traffic density outside rush hour.

The second analysis provides information on vehicle availability for concrete routes at a specified date time. Our evaluation shows that business week rush hours affect the service coverage and vehicle availability along routes. Evaluation of route based vehicle availability has shown that in a best-case scenario, about 40% to 50% ($\sim$ 400 vehicles) of the fleet is available near city center. Assuming each vehicle to hold 5 seats, 2000 passengers could theoretically be transported within Munich in this scenario. A limitation regarding our assumptions is the absence of traffic data, which will impact the service coverage especially during rush hour.

Future work may address the above-mentioned lack of traffic data to reduce the discrepancy between estimated and actual traversal times. In addition, further information regarding the vehicle characteristics (e.g., max. passengers, fuel / battery capacity or trunk / cargo volume) should be considered. Such information may be vital in a real world setting when users have specific intentions such as hauling or transportation. That being said, future analysis should also include refueling or recharging of each SAV, as owners do not want to find their cars on an empty battery, and the possibility to return the car exactly at the place where they left. With every additional parameter, such as those described above, our proposed analysis would allow a better view on a real world scenario. Another aspect to be addressed is the current "first come, first serve" approach of our system. It would be interesting to analyze the impact of an optimization of vehicle allocation to demand. Additional research regarding the willingness of vehicle owners to offer their parked vehicle for usage by the car sharing service may be advisable. A statistical model may be developed to consider potentially unusable vehicles in the case of vehicles temporarily 'locked' by the owner. Such a model may add information regarding the probability of available vehicles to actually be usable. Regarding the implementation, we further recommend the use of Isocontours by Baum et al. (2016) to decrease processing times in our analyses, especially for large vehicle fleet datasets. Finally, it would be interesting to learn, if the method described could also be used to define a demand for using the cars, i.e.: could a suggestion be made to use an available fleet car that makes another trip obsolete?

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