

Initial Analysis of Urban Air Mobility's Transport Performance in Sioux Falls

Raoul L. Rothfeld*

Bauhaus Luftfahrt e. V., Taufkirchen, Bavaria, 82024, Germany

Milos Balac†

ETH Zurich, Zurich, Canton of Zurich, 8093, Switzerland

Dr. Kay O. Ploetner‡

Bauhaus Luftfahrt e. V., Taufkirchen, Bavaria, 82024, Germany

Prof. Dr. Constantinos Antoniou§

Technical University of Munich, Munich, Bavaria, 80333, Germany

While numerous Personal Air Vehicle (PAV) and next-generation Vertical Take-off and Landing (VTOL) vehicle projects are being developed, the potential of their introduction within an urban environment has yet to be understood and applied. Thus, an Urban Air Mobility (UAM) extension for the transport simulation, MATSim, is being utilized on the test case of Sioux Falls. The results provide an outlook on the transport performance of UAM with varying parameters. Within the limitations of the current simulation, UAM access/egress and process times prove to be highly influential on passenger adoption.

Nomenclature

PAV = Personal Air Vehicle
UAM = Urban Air Mobility
VTOL = Vertical Take-off and Landing

I. Introduction

RECENT developments in electric propulsion and battery technology enable new areas of operation for air vehicles. Quieter operations and shorter mission ranges facilitate air vehicles' urban application. Increasing urbanization and population growth induce a rising transportation demand, thus, especially during peak-hours, a high willingness-to-pay for further time-efficient mobility alternatives is to be assumed. The recent concept of Urban Air Mobility (UAM), i.e. the utilization of next-generation Vertical Take-off and Landing (VTOL) vehicles or Personal Air Vehicle (PAV) in urban environments, could add additional transport supply into urban settings.

Current developments show a multitude of companies that advance the evolution of next-gen VTOL vehicles [1]. UAM, however, consists of more than the vehicles by themselves and requires an operational concept and infrastructure that allows for VTOL vehicle integration within existing urban transportation systems. The operational performance of a potential UAM implementation is to be analyzed using a self-developed extension [2] for the multi-agent transport simulation tool, MATSim [3], applied on an advancement of the prototype and research oriented MATSim scenario of Sioux Falls by Hörl [4].

*Research Associate, Economics and Transportation, Raoul.Rothfeld@bauhaus-luftfahrt.net

†Research Associate, Institute for Transport Planning and Systems (IVT), Milos.Balac@ivt.baug.ethz.ch

‡Team Lead, Economics and Transportation, Kay.Ploetner@bauhaus-luftfahrt.net

§Head, Chair of Transportation Systems Engineering, C.Antoniou@tum.de

II. Literature Review

Diverse aspects of UAM are currently being analyzed. UBER [5] published a White-paper in 2016 stating their take and view on UAM. Herein, urban air traffic management, noise, pollution, system reliability, and safety are being discussed. NASA published their strategy paper concerning regulatory steps in 2017 [6]. It is not yet clear, however, which business models will be dominant for UAM introduction and which ownership structures occur. Often, next-generation VTOL vehicles are regarded as parts of on-demand air mobility services with commercially-owned vehicles [7, 8]. The business model in this case would be rather similar to that of a car-sharing provider. In contrast, Nneji et al. [9] compare different concepts by distinguishing various ownership options (professional operator or self-operated) and operational models (centralized, decentralized, and self-owned ownership structures).

Additionally, VTOL projects demonstrate a broad spread in intended mission range, utilized technologies for generating VTOL capabilities, as well as other VTOL vehicle properties, such as cruise speed and passenger capacity as is being outlined by Shamiyeh et al. [1]. Cruise speeds, for example, range from 50 to 630 km/h for the listed VTOL vehicle, while passenger capacity ranges from one to six seats [1, p. 18]. While various VTOL vehicle concepts are being developed, no convergence towards a specific vehicle morphology can be identified, with some projects relying on rotor-based cruise and while others use wings for lift generation during cruise flight with additional propulsion or technologies to also allow for VTOL. While some projects, as listed by Shamiyeh et al. [1] have published some of their VTOL vehicle's performance claims, the claims have yet to be verified—either by VTOL demonstrations or by in-depth VTOL vehicle performance modeling. Modeling UAM, thus, also requires modeling and simulating variations in UAM vehicle parameters.

UAM integration approaches—into existing urban transportation systems—will also vary substantially depending on the potential need for VTOL infrastructure, as will the system's overall performance. Besides vehicle speed and capacity, UAM's system performance, also greatly depends on accessibility and, with that, on, for example, access times, access point distribution, and ease and speed of inter-modal transfer. In order to simulate the introduction of UAM into urban environments, an initial version of a UAM extension [2] for MATSim [3] has been developed.

In MATSim, a synthetic population is generated and represented by agents. Agents perform various activities during the day and, thus, generate transport demand. MATSim is based on an activity-based approach, which strongly focuses on people's behavior and the location of their activities. The utility of various activities and their respective dis-utility, e.g. for traveling to the location of a specific activity, is measured in a scoring function. Agents try to maximize their score by changing their travel behavior, their activity order, or the activities' starting times until an optimal allocation is reached, as described by Kai et al. [10]. MATSim has been used for a broad range of analyses, such as for the simulation of autonomous cars [11], policy evaluation [12], land-use analyses [13], and traffic signal analyses [14]. The most closely related to the application of MATSim for UAM, is an analysis of autonomous taxis by Hörl [15]. In order to assign a vehicle to an agent's travel request, they utilized the Dynamic Vehicle Routing Problem (DVRP) contribution by Maciejewski [16]. On this basis, the UAM extension [2] for MATSim has been developed and applied.

As a prototype use case, the city Sioux Falls is to be analyzed for its potential for UAM integration. Sioux Falls has been chosen as it is the default test-case for MATSim and widely used for demonstration in transport literature [4], providing, both, road and public transport networks, combined with “fully dynamic demand fitted with realistic socio-economic and demographic attributes”, according to Hörl [4].

Fig. 1 illustrates the study area to which the Sioux Falls MATSim scenario has been confined to by Hörl [4]. Besides the road network, the Sioux Falls scenario also provides a public transport network and schedule, realistic home and work facility locations [4, p. 15]. It is important to note that the Sioux Falls scenario is not “intended to be accurate and realistic with respect to the actual City of Sioux Falls” [4, p. 15]—yet, is intended as a test and prototyping scenario. As such, the synthetic population of the Sioux Falls scenario provides simplified daily plans for the virtual city's population, e.g. plans only consisting of commuting to and from work, without more complex day plans or agent's arriving in or leaving the study area via long-distance travel, e.g. via the airport. Still, the Sioux Falls scenario provides a suitable and computational manageable test bed for UAM integration.

This initial analysis of UAM integration in Sioux Falls will be performed under restricted options for integration and is intended to provide a basis for future, comparative studies. For example, it is currently assumed that UAM will first be realized by providing an on-demand travel model, rather than private operation or public, scheduled transport service models. Further, transport mode choice is simplified to rely solely on agent's value of time, disregarding personal preferences and, possibly, reservations towards an intra-city airborne transport mode. While first research towards travel preferences including UAM are currently being conducted (see [17] and [18, p. 2]), it has not yet been included in UAM simulation.

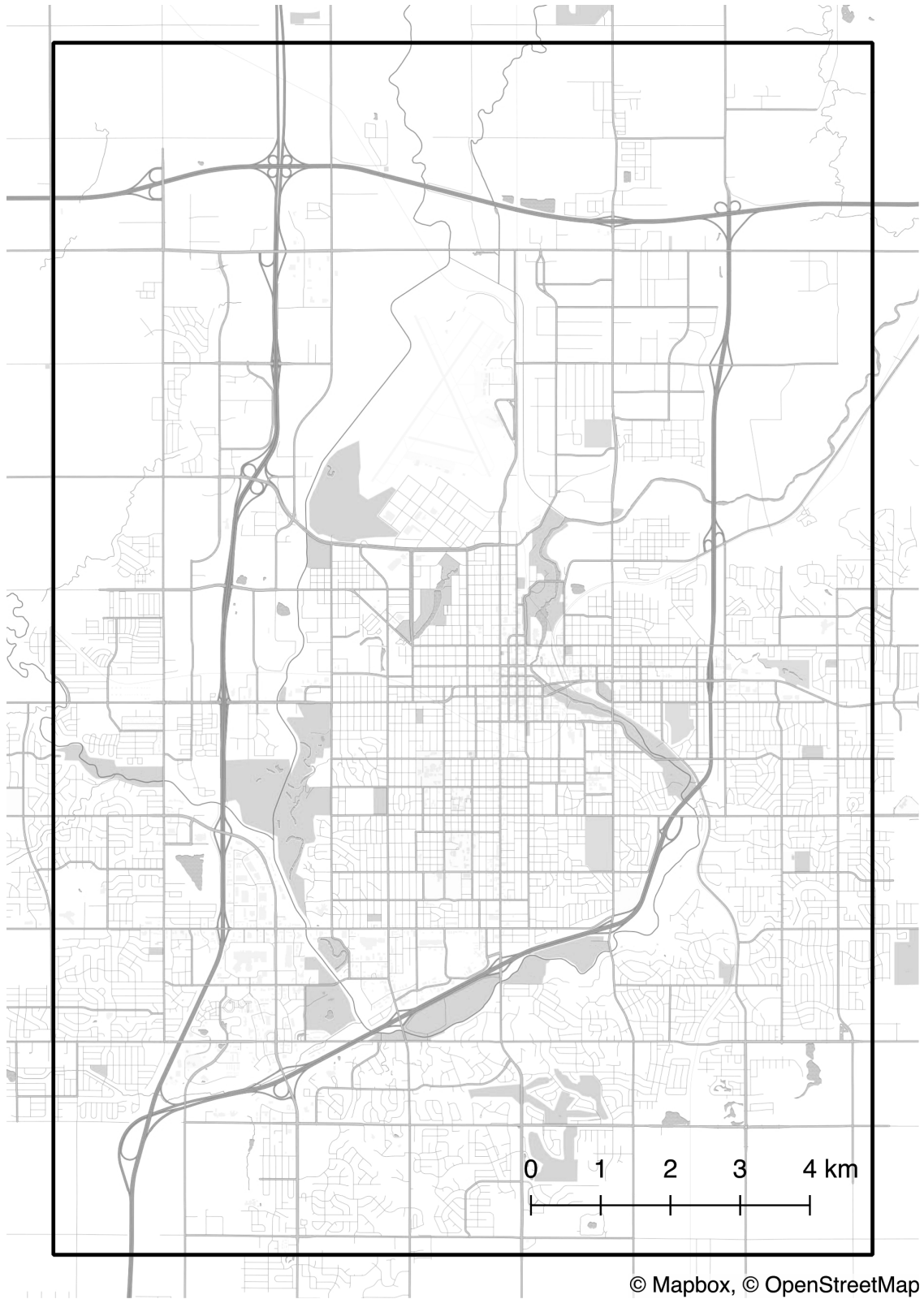


Fig. 1 Map of Sioux Falls MATSim scenario from Hörl [4, p. 16]

III. Methodology

The Sioux Falls MATSim scenario by Hörl [4] has been extended to enable UAM integration by adding UAM networks, UAM vehicles, and UAM configuration parameters—such as process times and available UAM station access/egress transport modes. A baseline scenario has been defined and serves as point of reference for subsequent scenarios with single parameter variations. For each subsequent scenario a single parameter, such as UAM vehicle cruising speed, has been changed without changing the remaining variables—*ceteris paribus*. The resulting multitude of scenarios have been simulated simultaneously on dedicated computational server in accordance to Horni and Nagel [19, p. 37].

A. Baseline Scenario

For the baseline scenario, a UAM network for Sioux Falls had to be established. It has to be noted that, as with the Sioux Falls MATSim scenario, this baseline scenario merely aims at being reasonable rather than realistic, as to allow for initial sensitivity analyses rather than provide recommendation on actual UAM realization. As there is no aerial network currently available for potential UAM networks in Sioux Falls, a potential one has been created by consulting Fadhil [20] and following his approach of identifying potential UAM infrastructure locations using geographic distributions and information. Further, Rodrigue et al. [21, pp. 180] has been consulted in setting up an initial UAM network for Sioux Falls.

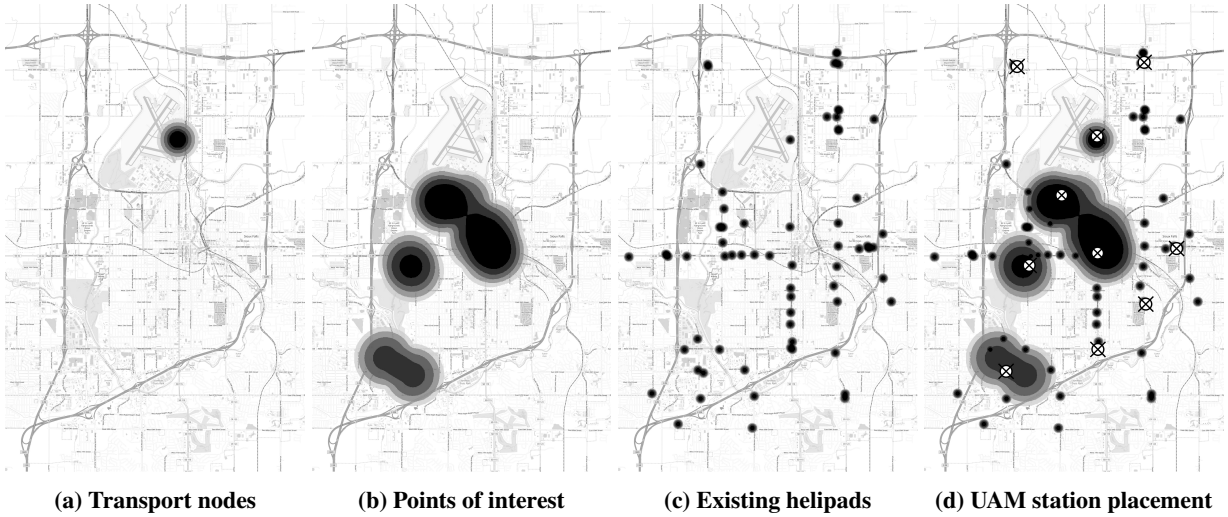


Fig. 2 Maps of Sioux Falls depicting the attractiveness for UAM Station placement based on different factors

Fig. 2 illustrates the various geographic information that has been utilized to place the initial UAM stations for the baseline scenario. Fig. 2a illustrates attractive positions for UAM stations based on existing large-scale transport infrastructure, retrieved via OpenStreetMap. In the case of Sioux Falls, Fig. 2a depicts the Sioux Falls Regional Airport as the sole large-scale transport infrastructure. Fig. 2b, on the other hand, illustrates the attractiveness for UAM stations based on local points of interest or common tourist destinations derived by gathering the locations of main tourist attractions from online tourist rating and information websites such as TripAdvisor. Fig. 2c depicts existing helipads within the study area, also retrieved via OpenStreetMap. Finally, Fig. 2d shows a combined map of Sioux Falls, with the previous three maps being superimposed and the chosen UAM stations marked as black-crossed, white-filled circles. For the initial baseline scenario, ten stations have been placed around transport nodes, points of interest, and existing helipads in order to achieve a potentially realistic UAM integration scenario. Fig. 3a shows the final placement of the UAM stations within the city of Sioux Falls.

For the baseline scenario, all UAM stations have been directly connected via aerial routes to each other station, resulting in the UAM network as depicted in Fig. 3b. Further, the aerial network is not capacity restricted. While throughput restrictions can be modeled, airspace capacity remains unlimited for this early investigation. Thus, vertical and horizontal separation of UAM vehicles have not been taken into account. The UAM network's flight level for cruise, however, is taken into account and has initially been set to 500 meters, after consulting minimum safe altitudes [22] for urban areas and adding a 50% additional safety buffer. UAM vehicles have to ascent to and descent from that flight level

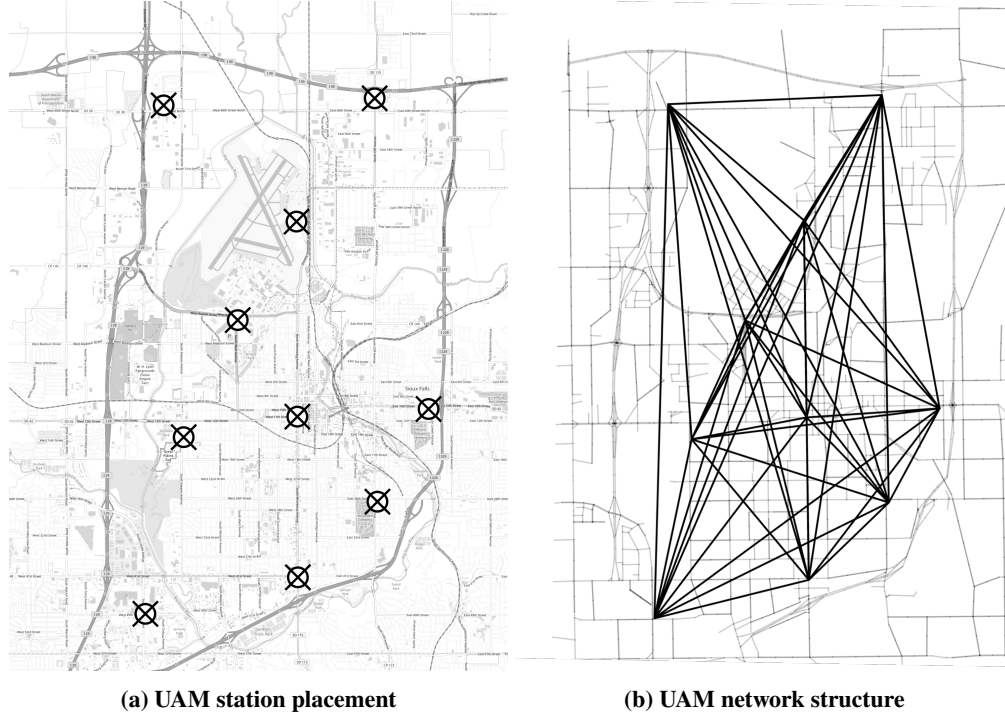


Fig. 3 Baseline scenario UAM station placement and network structure

for take-off and landing.

Further, for the baseline scenario, the UAM fleet consists of 100 UAM vehicles that have been evenly distributed across the ten, defined UAM stations at the start of the simulation. Thus, each station provides an initial vehicle pool of ten vehicles. Unfortunately, there is insufficient existent research for the provision of expected UAM fleet sizes, thus, the baseline scenario UAM fleet definition has been based solely on expert judgment. During simulation, the UAM vehicles are dynamically being distributed according to passenger requests. Thus, vacant UAM vehicles are being routed autonomously to a passenger approaching a UAM station which does not have a vacant UAM vehicle ready for the requesting passenger.

All scenarios, presented in this study, use homogeneous UAM fleets, i.e. use vehicles with the same attributes. These attributes, however, have been varied as well. Thus, for the baseline scenario, the UAM fleet consists of vehicles with a cruising speed of 150 km/h and vertical take-off and landing speed of 10 m/s. Again, due to little existing research, these speeds have been set based on expert judgment while consulting Shamiyeh et al. [1]. Additionally, parameters have been fixed for the baseline scenario, such as the price of using UAM with three times the car price that had been defined within the Sioux Falls MATSim scenario, maximum UAM station access/egress distance of 5 km, and total ground-based UAM process time of 2.5 minutes. The definition of ground-based UAM process time has intentionally been left vague as there is no consensus on which processes will be part of the pre-flight passenger operation. Thus, the ground-based UAM process time could potentially include processes such as elevator usage, security screening, and/or vehicle boarding. Finally, UAM access/egress options have been set to all available transport modes from the original Sioux Falls MATSim scenario, i.e. walking, driving, and using public transport.

B. Parameter Variations

After the baseline scenario had been defined, variation scenarios have been derived by selecting and alternating a single scenario parameter. The following parameters have been selected and alternated (baseline values added in parentheses):

- UAM vehicle cruising speed [km/h]: 50, (150), 250, 350, 450
- UAM vehicle VTOL speed [m/s]: 5, (10), 20
- Ground-based UAM process time [min]: 0.5, (2.5), 5, 10, 15, 20

- UAM vehicle passenger capacity [# of seats]: 1, (2), 4, 8, 12
- UAM fleet size [# of UAM vehicles]: 50, (100), 300
- UAM network [# of UAM stations]: 4, (10)

In its current implementation, variations of UAM vehicle VTOL speed can be equated with variations in UAM network flight levels. Thus, the above-listed VTOL speeds of 5, 10, and 20 m/s can be compared to equivalent flight level variations of 250, 500, and 1000 m. Further, it has to be noted that UAM passengers always had a pre-defined price that remains unchanged throughout these scenario variations and also remains the same in case of passenger pooling, i.e. multiple passengers using the same UAM vehicle simultaneously. While pricing structures in relation to passenger pooling is expected to have significant influence on UAM passenger adoption (c.f. [5]), the used UAM extension version does not currently provide the ability to differentiate pricing based on pooled flights. Additionally, passenger pooling is currently implemented to allow multiple passengers with identical origin and destination UAM stations to share their UAM vehicle—en-route drop-off or hop-on of additional passengers is not yet included.

IV. Results and Discussion

Each of the above-listed variations resulted in its own MATSim scenario and has completed its own simulation run, each with a multitude of iterations. In the following, each group of scenario, grouped by which parameter (e.g. cruise speed) had been changed in comparison to the baseline scenario, is presented separately.

A. UAM Baseline Results

The baseline scenario, and all subsequent variation scenarios, use the Sioux Falls MATSim scenario's population [4] and leaves it unchanged, which provides 84,110 agents. This synthetic population represents a 48% sample of Sioux Falls' current, actual population of 174,360 [23]. After the simulation, 3,693 out of the 84,110 agents used UAM for at least one trip during their simulated day, resulting in 6,179 UAM flights with 6,810 UAM passengers in total. The modal share of UAM yields 4%, whereas the majority of agent's still chose their car (74%), used public transport (18%), or decided to walk (5%) instead.

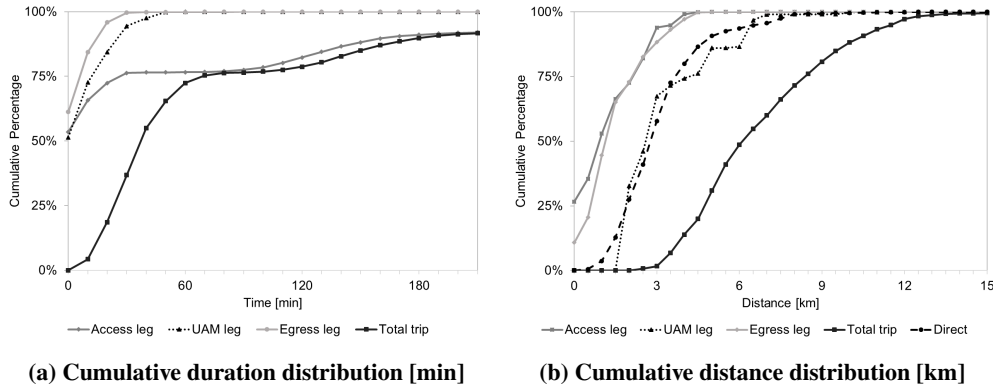


Fig. 4 Cumulative distributions of travel and flight times and distances of UAM-involving trips

Figures 4a and 4b illustrate the distribution of UAM flights in terms of times and distances, respectively. Figure 4a, for which all leg and trip duration have been clustered into 5 minute intervals, illustrates the cumulative distribution of times for:

- Access leg duration: Time duration between agent's departure of origin location until arrival at chosen departure UAM station.
- UAM leg duration: Time duration from entering the departure UAM station until leaving the destination UAM station, including all UAM processes, such as boarding or vehicle distribution to the waiting agent/passenger.
- Egress leg duration: Time duration between agent's departure of destination UAM station until arrival at final destination location.

- Total trip duration: Time duration between agent's departure of origin location until arrival at final destination location.

For access leg duration, 72% are below 30 minutes. However, a large share (28%) surpass the 30, 60, and even 270 minute mark for their UAM access leg. The average access leg duration yields $M=71$ ($SD=144$) minutes. An initial analysis shows that the, partly, very long access leg times all stem from the UAM station in the central business district of Sioux Falls and are access legs that use public transport exclusively. While, as mentioned, UAM station capacity is not limited, the common public transport network is. The high access times for some UAM passengers might be a result of public transport providing insufficient throughput for the high demand at that specific UAM station. The influence of long access legs carriers over to the total trip duration which averages $M=101$ ($SD=141$) minutes, where the majority (65%) of trips range between 0 and 60 minutes. For egress legs, 96% are below 30 minutes with an average egress duration of $M=10$ ($SD=9$) minutes. For UAM leg duration, which includes all required flight activities as well as, e.g., boarding, 51% are shorter than 10 minutes—though the minimum UAM leg duration is 8 minutes. All UAM legs are shorter than 60 minutes—averaging a UAM leg duration of $M=20$ ($SD=13$) minutes.

Figure 4b, for which all leg and trip distances have been clustered into 0.5 km intervals, illustrates the cumulative distribution of beeline distances, i.e. the length of a straight line between two points, for:

- Access leg distance: Beeline distance between agent's origin location and chosen departure UAM station.
- UAM leg distance: Beeline distance between origin and destination UAM stations.
- Egress leg distance: Beeline distance between agent's destination UAM station and final destination location.
- Total trip distance: Sum of beeline distances for an agent's access, UAM, and egress leg.
- Direct distance: Beeline distance between agent's origin location and final destination location.

For access leg distance, 66% are below 2 km, yielding an average access distance of $M=1.6$ ($SD=1.3$) km. The average UAM leg distance or flight distance resulted in $M=3.7$ ($SD=1.6$) km with flight distances ranging from 2.2 to 11.7 km. While most flights (76%) had a range of up to 5 km, it has to be noted that the flight distances heavily rely on the size of the study area and the distribution of UAM stations. A similar influence can be found for access and egress distances, as these are also dependent on the number and distribution of UAM stations throughout the study area. Correctly, do egress leg distance, which averages $M=1.9$ ($SD=1.1$) km, exceeds the 5 km mark—which has been set as the maximum search radius for suitable UAM stations for access and egress legs. The total trip distances average $M=7.2$ ($SD=2.5$) km with most trip lengths (55%) being less than 7 km. In many cases, the direct distance ($M=3.5$ km, $SD=1.6$ km) is actually shorter than the UAM leg/flight distance, which results on a detour factor for UAM-involving trips of $M=2.4$ ($SD=1.3$). It has to be noted, though, that this detour factor is based on beeline distances—for road usage, detour also exists between agents' origins and destinations based on the road or public transport network. An earlier investigation on road infrastructure in larger European cities found an average detour factor of 1.6 for driving and 2.1 for public transport [24, p. 11].

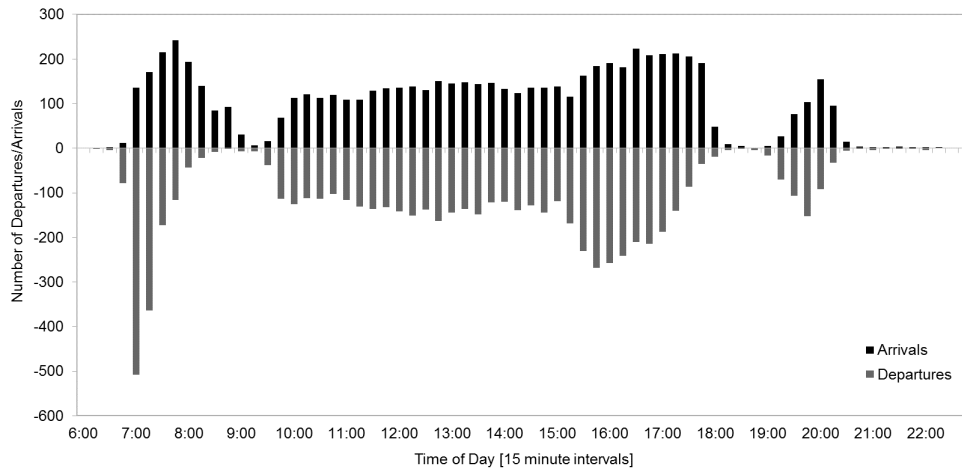


Fig. 5 Distribution of UAM departures and arrivals throughout the simulated day in 15 min intervals

Figure 5 illustrates the number of UAM vehicle departures and arrivals per 15 minute slots throughout the simulated day. The morning peak, between 06:45 and 08:30, shows a particular concentration of UAM departures and, subsequently, arrivals within a short period of time. During the busiest time interval from 07:00 to 07:15, 508 UAM vehicle depart the UAM stations, which—as of yet—are not restricted in their capacity. Medium transport demand can be observed throughout the day until the evening peak, between 15:00 and 18:30, results in an increase in UAM usage. Finally, a third peak for late-evening activities, between 18:30 and 22:00 concludes the simulated day.

Table 1 Percentages of passengers' access/egress mode choices for UAM-involving trips

Access and egress mode(s)	Passengers
PT–Car / Car–PT	57%
Walk–Car / Car–Walk	17%
Walk–PT / PT–Walk	13%
Car	9%
Walk	3%
PT	<1%

Table 1 shows the percentages of transport modes, chosen by UAM passengers, for UAM station access and egress. Most passengers combine the use of public transport with the usage of a car for either access or egress. It has to be noted though, that—currently—no penalty, i.e. disutility, is given for changing one's mode in combination with using UAM. Including the dislike of passengers for mode changes might affect the listed modal shares for access and egress, as most passengers (87%) chose to combine two different transport modes for UAM access and egress.

B. UAM Vehicle Cruising Speed Variation

Different scenarios have been simulated for the cruise speed alterations of 50, 250, 350, 450 km/h cruising speed, with 150 km/h being the cruise speed of all UAM vehicles in the baseline scenario. For a cruise speed of 50 km/h, the average UAM leg duration increased by 29% compared to the baseline scenario and yielded an average of $M=25$ ($SD=15$) minutes. Increasing the cruise speed to 250 km/h reduced the average UAM leg duration to $M=19$ ($SD=14$) minutes, a decrease of 5%. Further cruise speed increases resulted in an average of $M=18$ ($SD=13$) minutes and, thus, a 8% decrease for a cruise speed of 350 km/h. The average UAM leg duration decreases by 11% for cruise speeds of 450 km/h ($M=18$ km/h, $SD=13$ km/h). The effect of faster cruise speeds diminishes as the proportion cruise flight duration, which is part of the UAM leg duration, becomes smaller, while the UAM process times remain constant.

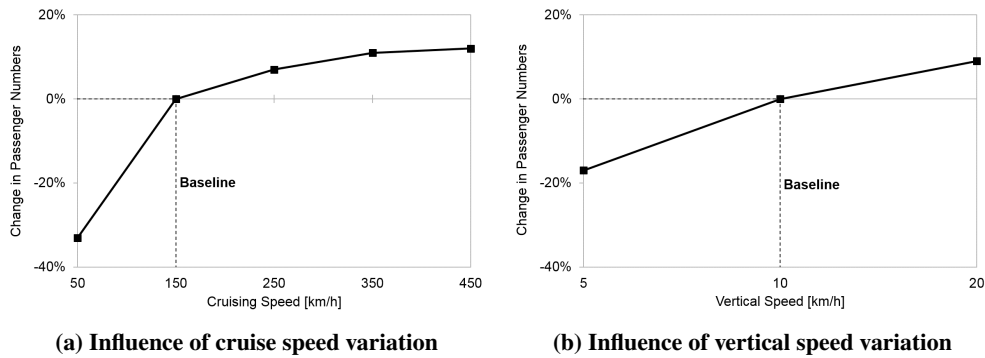


Fig. 6 Influence of UAM vehicle speed variations on passenger number compared to baseline

Figure 6a illustrates the effect of varying UAM vehicle cruise speeds on overall UAM passenger numbers compared to the passenger number of the baseline scenario. The 29% increase of average UAM leg duration with 50 km/h cruising speed results in a 33% decrease in passenger numbers, whereas the 11% increase in cruise speed (450 km/h) results in a 12% increase in passenger numbers.

C. UAM Vehicle VTOL Speed Variation

For vertical speed variations, two alternations have been simulated: 5 and 20 m/s vertical flight speed, with 10 m/s being the baseline scenario setting. The UAM leg duration, with 5 m/s vertical speed, increased by 14% to $M=23$ ($SD=13$) minutes and results in a 17% reduction in passenger numbers. For 20 m/s vertical speed, the average UAM leg duration decreases by 8% and averages $M=18$ ($SD=13$) minutes. The 8% reduction in UAM leg duration results in a 9% passenger number increase, as illustrated by Fig. 6b.

D. UAM Process Time Variation

For UAM process times, which encompasses the duration of an agent's arrival at a UAM station until take-off (and vice versa), five alternative scenarios have been simulated. Thus, this process might include elevator rides, buffer times, security processes, as well as boarding. The UAM process times have been simulated for 0.5, 5, 10, 15, and 20 minutes. The baseline scenario is defined with a 2.5 minute duration per UAM process, which occurs twice during each UAM-involving trip: once each at the origin and destination UAM stations.

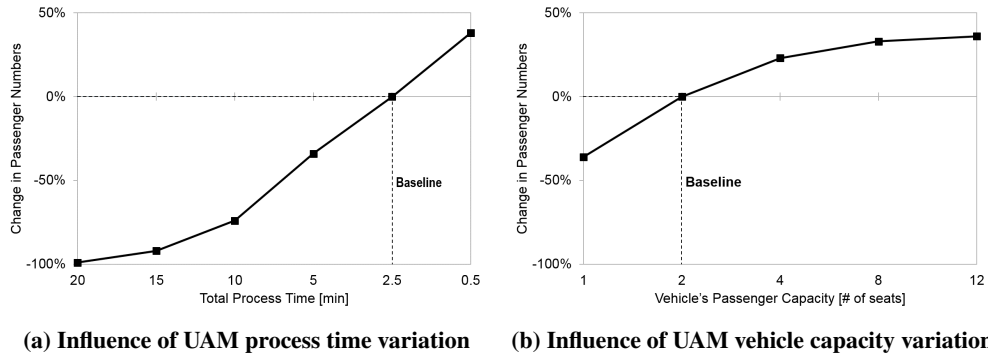


Fig. 7 Influence of UAM process time/vehicle capacity variations on passenger number compared to baseline

Figure 7a illustrates the effect of alternating UAM process times on overall UAM passenger numbers. Increasing the UAM process time to 20 minutes each, results in an average UAM leg trip duration of $M=45$ ($SD=3$) minutes (127% increase) and yields a 99% decrease in UAM passenger numbers. UAM process times of 15 minutes each, still yields a 92% decrease in passengers with average UAM leg duration of $M=36$ ($SD=5$) minutes (84% increase). UAM process times of 10 minutes still increase the average UAM leg duration by 56% ($M=31$ min, $SD=9$ min) and results in a 74% reduction in passenger numbers. Still, UAM process times of 5 minutes result in a 34% reduction in UAM passengers with an average UAM leg duration of $M=27$ ($SD=19$) minutes (38% increase). Finally, by cutting the UAM process time in half, i.e. setting UAM process times to 0.5 minutes each, the UAM passenger numbers increase by 38% with an average UAM leg duration of $M=12$ ($SD=10$) minutes (39% decrease).

It seems that UAM process times have a more severe effect on UAM adoption than UAM vehicle cruising or VTOL speeds. For an exemplary UAM trip of 15 km flight length, an increase of UAM process time from 2.5 to 5 minutes (100% increase) at each UAM station would have to be compensated by UAM vehicle cruising speeds of 900 km/h (500% increase) in order to maintain the UAM leg duration of 11 minutes. For UAM flight distances of less than 12 km, the time penalty of 5 minutes UAM process times could not be compensated by cruising speed at all. It is, thus, recommended for UAM stakeholders to focus on UAM process and access/egress times rather than purely on UAM vehicle speeds.

E. UAM Vehicle Passenger Capacity Variation

The baseline UAM vehicle capacity of two seats per UAM vehicle has been altered to one, four, eight, and twelve seats per vehicle in passenger capacity variation scenarios. For a UAM fleet with only one seat, the average UAM leg duration increased by 19% to $M=23$ ($SD=15$) minutes and resulted in a 36% decrease in overall passenger numbers. Even though agents do not have to wait for additional passengers to board their shared UAM vehicle, the average UAM leg duration increases with the reduction of passenger capacity as the transport performance of the remaining fleet has effectively been halved as no additional vehicle have been added as compensation. Thus, passengers had to wait longer than in the baseline scenario until their assigned UAM vehicle became available and reached the agent's departure UAM

station. Increasing the capacity from two to four passengers reduced the UAM leg duration by 19% ($M=16$ min, $SD=9$ min) and resulted in a 23% increase in overall UAM passenger numbers. Increasing the capacity even further, into the realms of flying mini-buses, to seat eight passengers led to a 33% increase in passenger numbers compared to the baseline scenario and a 22% reduction in UAM leg duration ($M=15$ min, $SD=8$ min). Finally, increasing the capacity to twelve seats increased the passenger numbers by 36% and decreased the average UAM leg duration by 23% ($M=15$ min, $SD=8$ min). Figure 7b illustrates the effects of varying the UAM vehicle passenger capacity on passenger numbers.

Table 2 Percentages of flights per number of passengers for each capacity scenario

Passengers	One-seater	Two-seater	Four-seater	Eight-seater	Twelve-seater
1	100.00%	89.79%	80.99%	78.57%	78.10%
2		10.21%	14.56%	13.92%	14.24%
3			3.58%	4.60%	4.44%
4			0.88%	1.81%	1.69%
5				0.76%	0.65%
6				0.29%	0.51%
7				0.04%	0.22%
8					0.06%
9					0.06%
10					0.01%
11					0.01%
12					

Table 2 displays the percentages of UAM flights by seat load factor, i.e. the number of passengers during a flight, for each of the before-mentioned capacity variation scenarios. It is important to note that these percentages are heavily dependent on the implementation and calibration of the simulated scenario and do not present a seat load factor forecast. However, regardless of UAM vehicle capacity, most flights transport sole passengers throughout all capacity variation scenarios: 78% to 90% are single-passenger flights, in cases where UAM vehicle offered at least two seats. With 14% to 15%, flights with two passengers are the second most common passenger constellation. Interestingly, in the passenger capacity scenarios of eight- and twelve-seater UAM vehicles, no flight ever made use of the complete vehicle passenger capacity.

The current pooling implementation, though, is rather simplistic in that passenger with identical origin and destination UAM station are being pooled if they wish to depart within a similar timeframe, i.e. during the access leg duration of the other passengers. Currently, all agents pay the same price for UAM transport, regardless of whether or not they have been in a shared vehicle. With the introduction of price differentiation and more elaborate pooling algorithms, one that—e.g.—allows for en-route drop-off and pick-up of additional passengers, these vehicle occupations are expected to change significantly.

F. UAM Vehicle Fleet Variation

While the baseline scenario provides a UAM vehicle fleet of 100 vehicles in total, two alterations have been simulated with 50 and 300 UAM vehicles. The reduction of the UAM fleet to 50 vehicles led to a 69% increase in UAM leg duration ($M=33$ min, $SD=40$ min) and a 61% reduction in passenger numbers, as agents had to wait an extended period of time for their assigned UAM vehicle. Increasing the fleet size, though, from 100 to 300 vehicles increased overall passenger numbers by 46% as UAM leg duration decreased by 43% ($M=11$ min, $SD=5$ min). It is, thus, evident that UAM vehicle availability and its effects on UAM trip duration has an impact on UAM adoption. Without UAM fleet cost, however, trade-offs analyses of fleet size versus fleet cost are not feasible at this early stage of UAM modeling.

G. UAM Network Structure Variation

As mentioned in Sec. IV.A, the number and placement of UAM infrastructure is elemental for UAM adoption and, subsequently, heavily influences the UAM passenger numbers. In order to illustrate the effect of network/placement changes, an alternate scenario with four UAM stations has been simulated. The resulting, different network structures

are displayed in Fig. 8. Additionally, Figures 8a and 8b indicate the aerial routes' usages by varying the line thickness of different routes. Bolder lines indicate more UAM flights within the simulated day.

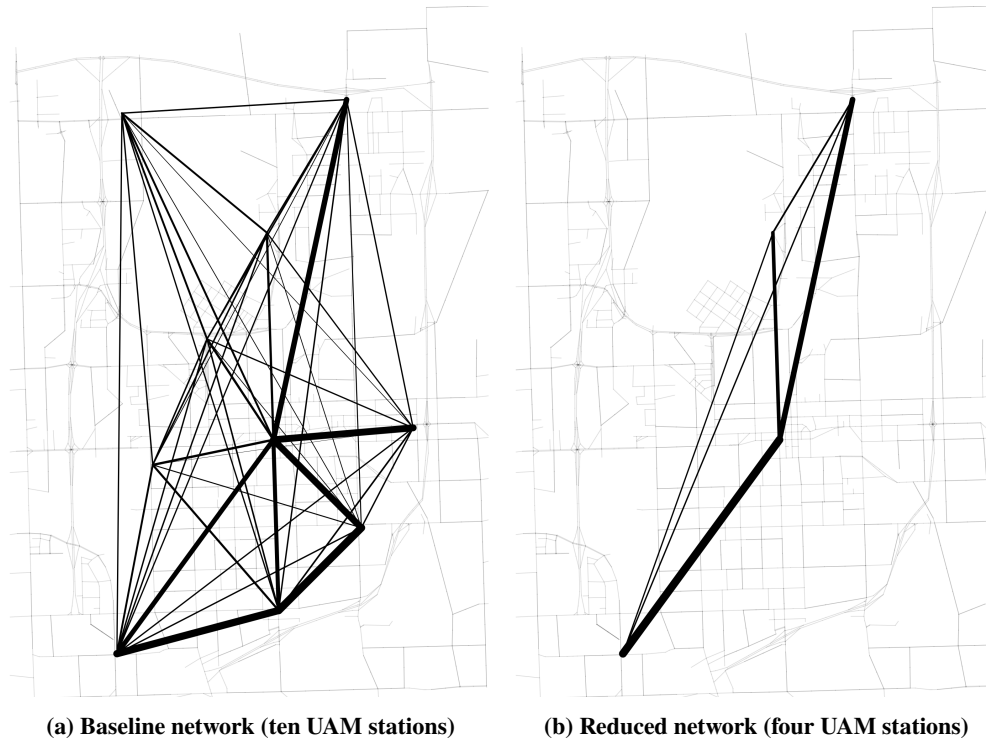


Fig. 8 Network usage (line thickness) comparison between baseline and reduced network

The reduction in number of UAM stations resulted in a 55% decrease in passenger numbers, as a large part of the simulated population remained outside the 5 km radius around each station for which UAM access/egress had been set to be feasible. Still, even without the 5 km radius limitation, the access and egress leg times would increase with the removal of UAM stations.

Future analyses with artificial grids of UAM stations could be used to identify areas with high UAM demand. Simulations could then be rerun with UAM stations placed within the identified high demand areas. This approach could be combined, in an iterative process, with the methodology presented by Fadhil [20] in order to optimize UAM infrastructure placement.

V. Conclusion

The presented results of the Sioux Falls use case for the MATSim UAM extension prototype gives first indications of the influence of UAM parameters on UAM transport performance and provides an initial basis for further UAM transport research. UAM adoption is strongly influenced by the potential travel time reduction perceived by potential passengers. The results show that UAM infrastructure and ground-based UAM processes have elemental influence on UAM leg trip duration and, thus, on passenger adoption. The industry's current focus on UAM vehicle capacity and speeds should be extended with UAM accessibility and short process times.

Future research in the field of potential transport performances of UAM should also implement UAM pricing differentiation and additional UAM vehicle parameters, such as maximum range and the requirement for charging/refueling. Lastly, future studies should be applied to study areas which aim to realistically represent the simulated population and city, as this Sioux Falls scenario remains a prototyping case.

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References

- [1] Shamiyeh, M., Bijewitz, J., and Hornung, M., “A Review of Recent Personal Air Vehicle Concepts,” Bucharest, Romania, 2017.
- [2] Rothfeld, R. L., Balac, M., Ploetner, K. O., and Antoniou, C., “Agent-Based Simulation of Urban Air Mobility,” *AIAA AVIATION, Modeling and Simulation for Unmanned and Personal Aerial Vehicle Operations*, Atlanta, 2018.
- [3] Horni, A., Nagel, K., and Axhausen, K. W., *The Multi-Agent Transport Simulation MATSim*, Ubiquity Press, 2016. doi: 10.5334/baw, URL <http://www.ubiquitypress.com/site/books/10.5334/baw/>.
- [4] Hörl, S., “Implementation of an Autonomous Taxi Service in a Multi-Modal Traffic Simulation Using MATSim,” , 2016. doi:10.13140/rg.2.1.2060.9523.
- [5] UBER, “Fast-Forwarding to a Future of On-Demand Urban Air Transportation,” , Oct. 2016.
- [6] Holmes, B. J., Parker, R. A., Stanley, D., McHugh, P., Garrow, L., Masson, P. M., and Olcott, J., “NASA Strategic Framework for On-Demand Air Mobility - A Report for NASA Headquarters Aeronautics Research Mission Directorate,” , Jan. 2017.
- [7] Reichenbach, M. I., “Personal Air Vehicles as a New Option for Commuting in Europe: Vision or Illusion?” *European Transport Conference 2013*, Karlsruhe Institute of Technology, Institute of Technology Assessment and System Analysis, 2013, p. 20.
- [8] Syed, N., Rye, M., Ade, M., Trani, A., Hinze, N., Swingle, H., Smith, J. C., Dollyhigh, S., and Marien, T., “ODM Commuter Aircraft Demand Estimation,” *17th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, Denver, 2017. doi:10.2514/6.2017-3082, URL <https://arc.aiaa.org/doi/10.2514/6.2017-3082>.
- [9] Nneji, V. C., Stimpson, A., Cummings, M. M., and Goodrich, K. H., “Exploring Concepts of Operations for On-Demand Passenger Air Transportation,” *17th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, Denver, 2017. doi:10.2514/6.2017-3085, URL <https://arc.aiaa.org/doi/10.2514/6.2017-3085>.
- [10] Kai, N., Kickhöfer, B., Horni, A., and Charypar, D., “Chapter 3: A Closer Look at Scoring,” *The Multi-Agent Transport Simulation MATSim*, edited by A. Horni, K. Nagel, and K. W. Axhausen, Ubiquity Press, 2016, pp. 23–33. doi:10.5334/baw, URL <http://www.ubiquitypress.com/site/books/10.5334/baw/>.
- [11] Boesch, P. M., and Ciari, F., “Agent-Based Simulation of Autonomous Cars,” *American Control Conference*, Chicago, 2015, pp. 2588–2592. doi:10.1109/ACC.2015.7171123, URL <http://ieeexplore.ieee.org/document/7171123/>.
- [12] Kickhöfer, B., Grether, D., and Nagel, K., “Income-Contingent User Preferences in Policy Evaluation: Application and Discussion Based on Multi-Agent Transport Simulations,” *Transportation*, Vol. 38, No. 6, 2011, pp. 849–870. doi:10.1007/s11116-011-9357-6, URL <http://link.springer.com/10.1007/s11116-011-9357-6>.
- [13] Ziemke, D., Nagel, K., and Moeckel, R., “Towards an Agent-Based, Integrated Land-Use Transport Modeling System,” *Procedia Computer Science*, Vol. 83, 2016, pp. 958–963. doi:10.1016/j.procs.2016.04.192, URL <http://linkinghub.elsevier.com/retrieve/pii/S1877050916302253>.
- [14] Grether, D. S., “Extension of a Multi-Agent Transport Simulation for Traffic Signal Control and Air Transport Systems,” Dissertation, Technischen Universität Berlin, Berlin, 2014.
- [15] Hörl, S., “Agent-Based Simulation of Autonomous Taxi Services with Dynamic Demand Responses,” *Procedia Computer Science*, Vol. 109, 2017, pp. 899–904. doi:10.1016/j.procs.2017.05.418, URL <http://linkinghub.elsevier.com/retrieve/pii/S1877050917310943>.
- [16] Maciejewski, M., “Chapter 23: Dynamic Transport Services,” *The Multi-Agent Transport Simulation MATSim*, edited by A. Horni, K. Nagel, and K. W. Axhausen, Ubiquity Press, 2016, pp. 145–152. doi:10.5334/baw, URL <http://www.ubiquitypress.com/site/books/10.5334/baw/>.
- [17] Fu, M., “Exploring Preferences for Transportation Modes in an Urban Air Mobility Environment - a Munich Case Study,” Master’s Thesis, Technical University of Munich, Munich, 2018.
- [18] Garrow, L. A., Ilbeigi, M., and Chen, Z., “Forecasting Demand for On Demand Mobility,” *17th AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, Denver, 2017. doi:10.2514/6.2017-3280, URL <https://arc.aiaa.org/doi/10.2514/6.2017-3280>.

- [19] Horni, A., and Nagel, K., “Chapter 4: More About Configuring MATSim,” *The Multi-Agent Transport Simulation MATSim*, edited by A. Horni, K. Nagel, and K. W. Axhausen, Ubiquity Press, 2016, pp. 35–44. doi:10.5334/baw, URL <http://www.ubiquitypress.com/site/books/10.5334/baw/>.
- [20] Fadhil, D. N., “A GIS-Based Analysis for Selecting Ground Infrastructure Locations for Urban Air Mobility,” Master’s Thesis, Technical University of Munich, Munich, 2018.
- [21] Rodrigue, J.-P., Comtois, C., and Slack, B., *The Geography of Transport Systems*, 4th ed., Routledge, 2017. doi:10.4324/9781315618159, URL <https://www.taylorfrancis.com/books/9781315618159>.
- [22] FAA, “Docket No. 18334, 54 FR 34294, Aug. 18, 1989, as Amended by Amdt. 91-311, 75 FR 5223, Feb. 1, 2010,” , Jan. 2012. URL <https://www.gpo.gov/fdsys/granule/CFR-2012-title14-vol2/CFR-2012-title14-vol2-sec91-119>.
- [23] U.S. Department of Commerce, “U.S. Census Bureau QuickFacts: Sioux Falls City, South Dakota; Brown County, South Dakota; UNITED STATES,” , 2016. URL <https://www.census.gov/quickfacts/fact/table/siouxfallscitysouthdakota,browncountysouthdakota,US/PST045216>.
- [24] Rothfeld, R., Straubinger, A., Paul, A., and Ploetner, K. O., “Analysis of European Airports’ Access and Egress Travel Times Using Google Maps,” *Air Transport Research Society World Conference*, Antwerp, 2017.