UAM-SUMO: Simulacra of Urban Air Mobility Using SUMO to Study Large-Scale Effects

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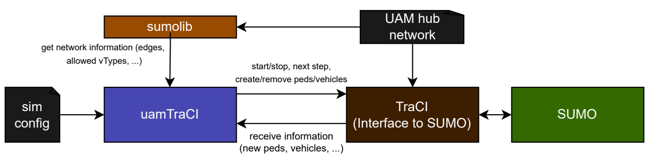

Fig. 1: High-level architecture of *UAM-SUMO*. *UAM-SUMO* adds the sim-config, uamTraCI, and the UAM hub network. First, a UAM hub network is created based on user-defined locations. Then, based on the sim-config, uamTraCI alters the simulated traffic and updates the main SUMO simulation.

***Abstract*—Urban Air Mobility (UAM) emerges as a potential solution to urban congestion. However, as it lacks integration with existing transportation systems, methods to study its impact are necessary. Traditional empirical approaches are insufficient to study large-scale effects in this not-yet-real context. We developed UAM-SUMO, an extension of the SUMO simulation platform, to simulate the impact of UAM on public transportation, particularly how air taxis affect traffic flow and mode choices. We detail the modifications to SUMO and the UAM operation parameters. We open-source our code at https://github.com/M-Colley/uam-sumo and present a proof-of-concept data collection and analysis for Ingolstadt, Germany.**

***Index Terms*—urban air mobility, SUMO, open source.**

I. Background and Summary

Residents of London, Paris, and Brussels endure more than 130 hours of traffic delays each year [1]. Automated Urban Air Mobility (UAM) is emerging as a potential solution to mitigate traffic congestion. The European Union Aviation Safety Agency (EASA) predicts that this new mode of transportation could become available within this decade [2]. Aligning with these forecasts, startups such as Lilium, Volocopter, and Ehang are planning to launch their services in select cities by 2030 [3, 4, 5]. Some projections suggest that by 2050, around 100,000 air taxis could be operational worldwide [6]. In addition to private companies, airspace concepts are also being developed by several national aviation agencies, including those of the US, EU, Germany, and the Netherlands [7].

UAM-SUMO explores the macroscopic effects of air taxis on traffic, focusing on how the introduction of air taxis leads to different traffic flows. If air taxis become a common form of urban transportation, their operation could affect overall traffic patterns by providing an alternative to ground transportation and potentially reducing congestion. However, integrating air taxis in existing traffic presents challenges, such as airspace management and ensuring safety for all users. The following sections provide background information on human behavior modeling, factors influencing mode choice, and previous human factors work for UAM.

a) Urban Air Mobility Modeling: Little previous work simulated UAM. Rothfeld et al. [8] present an extension for the simulation software MATSim that focuses on inter- and intra-urban air passenger transport using electric vertical take-off and landing (eVTOL) vehicles. This extension allows defining and simulating UAM infrastructure, vehicles, and operations within MATSim. Using the Munich MATSim scenario, researchers found the number and spatial distribution of UAM stations are crucial for UAM to offer travel time savings over cars [9]. [10] presented a simulation study using a proprietary simulator for Hamburg, Germany. It demonstrated that UAM could reduce travel time by 50% and route length by up to 16% compared to traditional taxicabs. Jiang et al. [11] evaluated simulators regarding their potential to study UAM effects, finding that "existing traffic simulators are inadequate for comprehensively representing UAM scenarios" [11, p. 20], showcasing the need for *UAM-SUMO*. Jiang et al. [12] also implemented some UAM features. However, currently, it is unclear what these are as they evaluated simulation speed.

II. Purpose

We employ the microscopic traffic simulation tool SUMO [13] to modify UAM attributes that affect the traffic network design. Microscopic traffic flow models focus on individual road users, capturing dynamic variables such as the position and speed of each air taxi and pedestrian. UAM-SUMO assesses macroscopic changes in traffic flow by varying factors in pedestrian decision-making, adjusting the percentages of air taxis and the number of hubs.

III. Characteristics

To run *UAM-SUMO*, first clone the repository. Afterward, install the required dependency specified in `requirements.txt`: rtree. To use cities other than those provided, download all necessary files (see https://sumo.dlr.de/docs/Networks/SUMO_Road_Networks.html) for a standard SUMO project and process them by adding UAM hubs (see Section IV-A). We highly encourage community involvement through comments, issues, or code contributions to the GitHub repository to foster collaboration and improve visibility [14].

IV. Code/Software

UAM-SUMO randomly replaces vehicles in the simulation with UAM customers and simulates them using UAM taxis as an alternative mobility option (see Figure 1). We alter the XML files which constitute the traffic definitions of SUMO. All changes in this program are made in copies of the original files to preserve the original network.

The proportion of vehicles that are replaced can be configured via the *uam_density* parameter. By replacing vehicles with UAM customers, we simulate the effects of choosing UAM instead of cars. The UAM taxis are unlike regular taxis, as they start all their trips from special UAM hubs, to which the pedestrians must arrive.

A. UAM Hub Creator

To simulate large-scale effects of UAM on traffic, a road network equipped with UAM hubs is required (see Figure 2). Our *UAM Hub Creator* converts any standard road network (i.e., `sumocfg` file) into a UAM network. It requires a standard road network and the desired UAM hub location coordinates (in x/y coordinates; choose manually from SUMO's graphical network editor `netedit` [15]). UAM hubs are then automatically created and connected. In addition, all the requirements for the simulation to work are added, and each UAM hub is connected to the nearest sidewalk to connect the UAM network to the standard road network.

To ensure the correct calculation of routes for UAM customers using the UAM taxi network, taxis are subsequently banned on all originally existing lanes of the network. Thus, a current limitation is that there are no standard taxis anymore.

SUMO's simulation of vehicles sometimes causes problems for vehicles taking extremely sharp turns ($\approx$ more than 145°). These could be created when connecting the ends (junctions) of the line-shaped UAM hubs with each other. To inhibit this, the UAM hubs are created perpendicular to the center of all coordinates. In most cases, this ensures that the angles between the UAM lane and the lanes connecting the hubs are as small as possible. For this, the center of all coordinates is calculated. For each UAM hub to be created, the two coordinates on the orthogonal line to the line between the center and the current UAM hub location, with a distance of half of the UAM hub's length, are calculated. Afterward, a junction is created on each of the orthogonal points.

For each of these junction pairs, the connecting lane is then created. These lanes prevent any access from regular vehicles by allowing only pedestrians and taxis to park on them.

The newly created network containing the bare lanes is then used to generate all `additionals` required for the UAM network. The following steps are executed for each lane. First, the ID of the closest lane allowing pedestrian access is required. `sumolib` [16] allows us to search for all edges in the network within a specified radius of a given location. To optimize runtime, the radius is initially small but increases with each failed attempt to find a suitable edge. Once the closest lane allowing pedestrian access is found, the UAM hub is created. We create it as a *lane* element and add the parking area for UAM taxis, using the *parking_area_length* and *uam_pa_capacity* (see Appendix). A bus stop is generated next to the parking area, allowing pedestrian access to the standard UAM network. To connect the standard road network (for pedestrians) with the UAM network, an `access` element, connecting the bus stop with the previously determined closest lane allowing pedestrian access, is added to the bus stop as a sub-element. Lastly, a `rerouter` element, enabling dynamic determination of the optimal parking area for the UAM taxis during the simulation, is generated.

In the next step, the individual UAM hubs are connected to create a working UAM transportation network, allowing direct travel of UAM taxis between them. First, the outgoing junction regarding the driving direction on the UAM lane is determined. Then, the incoming junction of all other individual UAM lanes is evaluated. The distance to our outgoing junction is calculated for each of those junctions. If the distance is lower than the configured *uam_hub_connection_radius* (see Appendix), a new edge connecting those two junctions is created. Afterward, two `connection` elements, allowing taxis to change from one edge to another edge, are generated. One connects the current UAM lane with the newly created edge, and the other connects the edge to the destination UAM lane. This process is then repeated for every other UAM lane. Lastly, the current network file is merged with the two required patch files using `netconvert` [17].

The final required element is the specification of a custom vehicle class for the UAM taxis, using the base taxi vehicle class as defined by SUMO with altered values and additional parameters. This enables us to add the UAM taxis using `TraCI` [18] at the start of the simulation. At this point, the *uam_taxi_length, -width, -height and -max_speed*, as well as the parameters controlling the parking space finding algorithm, are attached to the vehicle class. The parking space finding algorithm is necessary to re-distribute air taxis in the network. This new vehicle class is then added into a new `route` file, extending the base route file defined in the `sumocfg`.

After completing the above steps successfully, an update of the original `sumocfg` file is created. This newly created `sumocfg` file contains the UAM hubs at the specified locations and all other requirements for the UAM taxi simulation.

B. Urban Air Mobility

They also cannot access any part of the regular road network and act in a completely separate UAM network, connecting all UAM hubs in a straight line, to simulate them flying over the city. These customers do not use any other vehicles, as they first walk to the UAM network and, after their flight, walk the remainder of the way to their destination. Multimodal trips are currently not supported but can be added by altering the FINDINTERMODALROUTE method call in UAMTRACI.PY. This can be used to analyze the effects of UAM, such as on traffic congestion and travel times, on a large scale.

Before the simulation starts, all run options are processed, and a new folder for the generated output is created. Afterward, the `TraCI` [18] server is started using the processed options, and the UAM taxis are added to the simulation. For each UAM hub, a route to the respective UAM parking area and the UAM taxis is created. The number of taxis created per UAM hub depends on *uam_vehicles_per_hub* (see Appendix). Afterward, the route is added to every created air taxi so that they will start the simulation parked in their parking area.

The main simulation loop runs until either the preconfigured duration is reached or all vehicles and pedestrians have left the simulation. At the start of each step, the terminated vehicles of the previous step are determined, and newly added vehicles are adjusted. The simulation attempts to convert a newly added vehicle into a UAM customer based on the configured probability defined by *uam_density*. First, the vehicle's route's intended start and end points are determined. If pedestrians are not allowed on either of these points, for example, if the vehicle enters the simulation from a highway, we search for an alternative start or end point. To achieve this, we generate a list of edges in radius surrounding the respective point using `sumolib` [16] and sort them by distance. If none of the alternative edges in this radius allow pedestrian access for either the start or the end point, the vehicle conversion is aborted. Otherwise, we continue with the closest alternatives if a replacement is necessary. Using the start and end points, an intermodal route using walking and taxi as mobility options is generated. There are three possible outcomes to this situation. (1) No route was generated, indicating that it is impossible to reach the desired destination by walking and flying with a UAM taxi. Disconnected sidewalks and un-curated road networks can lead to this. (2) The generated route only contains a single walking stage, with the pedestrian walking from the start to the destination. Shorter routes, where using an air taxi, often used for traversing from one part of a city to another, are unnecessary, leading to this outcome. (3) A route with multiple stages, walking and flying as a customer in a UAM taxi, is returned. Regardless, a new pedestrian with the generated mobility stages is added, while the vehicle on which this route is based is removed from the simulation.

To keep track of all waiting UAM taxi customers, a dictionary maps the origin-destination edge combinations to a list of pedestrians who want to travel that route and their waiting time. This waiting time is incremented by the configured step_length (see Appendix) in each simulation step. The purpose of waiting time is to increase the efficiency of UAM taxis. Having no waiting time would lead to every single flight being a personal flight to the destination without any other passengers on board.

After increasing waiting times, we check if any pedestrian has made a new UAM taxi reservation in the current simulation step. For each new reservation, the following steps are performed. First, we check whether a similar reservation with identical origin and destination already exists in the reservation_dict. If so, the pedestrian who made the reservation is added to this entry. Otherwise, a new entry with the pedestrian and a waiting time of 0 is created.

Whenever either the waiting time exceeds the group_finding_time (see Appendix), or the number of pedestrians with the same origin and destination exceeds the uam_vehicle_capacity (see Appendix), a UAM taxi will be dispatched. First, the best available taxi is selected. This is preferably a taxi that is currently parked in the UAM parking lot of the origin UAM hub. Otherwise the next available taxi will be selected. This taxi is then ordered to pick up all waiting customers for the given route and transport them to their destination. After successfully dropping off the customers, the taxi automatically searches for the best available parking space and waits there for further orders. Parking is defined by the `uamHubConfig` (see Appendix). It includes a combination of taxi_abs_free_space_weight, taxi_distance_to_weight, taxi_time_to_weight, and taxi_rel_free_space_weight. The reservation_dict entry is removed when the pickup is issued.

Before the next simulation step starts, the UAM taxis are colored for better visibility in the GUI. Depending on whether a taxi is idle, on its way to pick up a customer, or delivering a pedestrian to his destination, the taxi is colored differently to differentiate between idle and occupied states. A list of vehicles present in the current simulation step is also stored to find newly added vehicles in the next step.

C. Simulated Urban Air Mobility Factors

Adjustable factors in UAM are diverse and directly impact traffic (e.g., *uam_taxi_person_capacity* defines how many pedestrians fit into a single air taxi). The appendix describes each factor with the default value.

D. Measurements/Logging

In addition to SUMO's standard output (see [19]), we generate two additional CSV files: one for UAM customer data and another for UAM taxis. These files contain the relevant parameters (see Appendix), such as `uam_density` and `group_finding_time`, plus the following for each entry: a timestamp, the current simulation step, the scenario name, the entity ID, and its current location.

An entry is added to the UAM pedestrian log file when a vehicle is converted to a UAM customer, a pedestrian makes a taxi reservation, enters or exits a vehicle, or leaves the simulation. In addition, the pedestrian's route start and destination coordinates are recorded, along with the vehicle

ID if the pedestrian is on board. The pedestrian's `state` is also logged, reflecting their next intent. The state `noRoute` is logged if no valid route is found, and `onlyWalking` if walking is faster than UAM. If the pedestrian becomes a UAM customer, the state `walking` is logged at the start of a walking stage, and `flying` at the start of a flying stage. Upon termination, the state `terminated` is recorded.

A log entry is created for each taxi in the simulation at each step. Similar to the pedestrian log, the current `state` of the UAM taxi is noted. Possible states include `idle` (parked or en route to parking), `onRoute` (heading to pick up a customer), and `active` (currently delivering passengers). When a taxi is `active`, the number of passengers (`pedCount`) and their IDs (`pedIDs`) are also logged.

V. Usage Notes

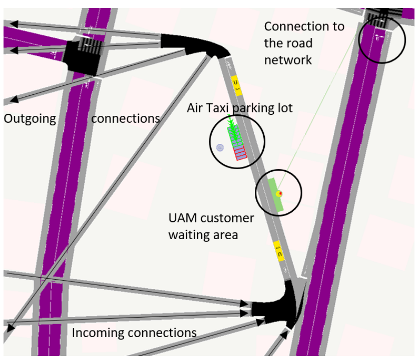

Fig. 2: A UAM hub. The hub is created at the specified position with a parking lot and a waiting area. Then, the hub is connected to all other hubs. Finally, a connection to the standard road network is created to allow pedestrian access.

Although SUMO supports integrating OpenStreetMap (OSM) data for simulating road networks, this often requires fine-tuning to correct errors. Therefore, we offer pre-curated scenarios from previous work in Ingolstadt, Wildau, Monaco, and Bologna. Additionally, simulations for Manhattan and London are available, with the latter generated and adapted using SUMO's OSMWebWizard.

Air taxis as drones represent one manifestation of robots and are, thus, relevant to the HRI community (e.g., see [20]).

VI. Evaluation

As we are interested in the large-scale effects of air taxis on traffic, we simulated Ingolstadt, Germany, as proof of concept. Due to time constraints, we chose a step size of 0.05 for converting vehicles to air taxi trips with a maximum of 0.3. For the number of UAM hubs, we chose 2, 3, and 5 based on exploratory locations, resulting in $6*3 = 18$ logs per city. Due to the data size, we make the data available upon request. We provide an initial overview of results for Ingolstadt, Germany, due to its realistically modeled traffic (taken from [21]). We provide a `Julia` script, which can be expanded for initial analysis. As we focus on providing the code, this analysis is not exhaustive, and we refrain from providing the results.

VII. Envisioned Usage Scenarios and Use Cases

Air taxis are one specific robot manifestation and are, thus, directly relevant to the HRI community (e.g., see drones [22]).

UAMs could become a viable alternative to current transportation options, but it is still unclear how the market will evolve and whether UAMs can effectively solve mobility challenges. To make informed decisions, policymakers and (potential) UAM stakeholders need ways to simulate different rollout scenarios, fleet configurations, and adoption models, to assess how UAMs could change travel behavior. *UAM-SUMO* allows to explore different design alternatives likely to influence the effectiveness, efficiency, and acceptance of UAM. Such design options include hub placement, air taxi capacity, pricing, pick-up strategies, and multimodal transportation integration. *UAM-SUMO* can be used to predict how these will affect travel times, energy consumption, reduced road traffic and overall carbon emissions, and improved ground traffic flow. By simulating these scenarios, *UAM-SUMO* provides policymakers with insights that can support government investment and policy decisions.

VIII. Discussion and Future Work

We introduced *UAM-SUMO*, an open-source enhancement to the SUMO simulation platform that enables the large-scale simulation of UAM and its impact on existing transportation systems. Our initial simulations in Ingolstadt, Germany, demonstrate the feasibility of integrating air taxis into microscopic traffic models to assess their influence on traffic flows and mode choices. Our implementation provides a foundational tool for researchers and policymakers to explore the potential implications of UAM integration.

For future work, we aim to refine *UAM-SUMO* by incorporating more sophisticated models of user behavior based on previous empirical work (e.g., [23, 24, 25, 26]) and decision-making processes related to transportation mode selection. We plan to extend our simulations to additional cities with diverse urban layouts to evaluate the generalizability of our findings. Furthermore, we envision integrating other emerging mobility concepts, such as micromobility options and interactions with autonomous ground vehicles, to simulate a more comprehensive urban mobility ecosystem. By enhancing the simulation's capabilities and incorporating advanced data analytics, we will provide deeper insights into the sustainable and efficient integration of UAM into future urban transportation.

IX. License & Maintenance

The code is accessible on GitHub under the MIT license, encouraging easy use, modification, and broad community involvement. Maintenance includes monitoring and prompt updates to ensure compatibility with the latest SUMO versions while supporting backward compatibility with the previous major version. Community contributions (bug fixes to new features) are welcome and will undergo review.

Acknowledgment

We thank the SUMO developers for their support. Scenarios are available under this link.

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