SAFE UAS LANDINGS AT ROAD TRAFFIC INTERSECTIONS

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Abstract

Since future air traffic will fly over densely populated urban areas, meeting stringent safety requirements becomes essential. In addition to appropriate capacity planning and actual collision avoidance, emergency procedures require particular attention. The probability of harming third parties in urban areas is given. Our study proposes an initial approach to demonstrate how an actively managed ground transportation system can be used as an intermodal safety network for urban air traffic. This includes the integration of road traffic intersections into flight planning and operations, as landing zones (blocked for ground traffic) in emergency cases. Based on tests on a simplified road network, a suitable intersection structure in Munich (Upper Bavaria, Germany) was identified and used to apply the proposed concept. Our findings indicate that optimizing intersection selection can mitigate negative impacts on ground traffic. The generic scenario resulted in an average speed reduction of less than 2% in the ground network and between 4–11% in the Munich-specific case. The intermodal safety network may serve as an indispensable component in the development of safe and efficient urban air mobility.

Keywords

urban air mobility; safety net; ground traffic management; landing sites

1. INTRODUCTION

In the dynamic landscape of Urban Air Mobility (UAM), ensuring safety in densely populated urban areas remains a key challenge. This study explores a novel strategy for establishing an intermodal safety network through dynamic ground traffic control. It investigates whether intersections can serve as emergency landing sites and how traffic management systems can ensure their safe use. The proposed system may rely on centralized coordination, vehicle-to-vehicle (V2V) communication, or interconnected traffic junctions equipped with sense-and-react capabilities.

The research has three objectives: identifying suitable intersections along flight paths, establishing air-to-ground communication protocols, and managing ground traffic during air taxi emergency landings. Feasibility is assessed using OpenStreetMap (OSM) data to model realistic urban scenarios for both air and ground traffic [1]. Safety improvements are measured by minimizing third-party involvement and integrating street networks as contingency landing sites. This multimodal approach is essential for future urban air operations and aligns with emerging safety standards [2]. In UAM, emergency landings must consider for urban infrastructure and traffic conditions [3]. Roads and intersections offer potential landing sites but are dynamically used throughout the day. Modern traffic management centers could facilitate such emergency landings by temporarily closing intersections, while ground-based support could enhance safety.

Intermodality optimizes travel by integrating different transport modes [4]. Unlike ground vehicles, which can stop during emergencies, airborne platforms must rapidly locate safe landing sites. Not all open spaces are suitable, but traffic-light controlled intersections could be repurposed for emergency use [5]. These systems already manage traffic dynamically [6], and extending them to support UAM could provide a safety net for flight operations. Selected intersections would be blocked only briefly during specific flight segments and reopened immediately after a fly-by. Continuous monitoring would help maintain road efficiency while meeting the safety demands of urban air travel.

1.1. State of the art

UAM is an emerging field focused on integrating of electric vertical take-off and landing (eVTOL) aircraft - such as air taxis - into existing urban transport systems, as outlined in relevant studies [7, 8]. Design studies for air taxi [9], its landing sites [10, 11], and operational concepts for managing urban air space [12] provide initial insights into what UAM could look like. Urban traffic management centers currently monitor and control traffic, where traffic lights utilize algorithms to respond to real-time traffic conditions, improving traffic flow and minimizing delays [13]. As UAM continues to evolve, one of the key challenges is optimizing these ground-based traffic management systems to also accommodate low-altitude air traffic, ensuring seamless integration with existing transport networks. Furthermore, operating in urban airspace pose a risk of harming uninvolved third parties in the event of an emergency. To mitigate this, it is crucial to establish a ground-based safety net that enables controlled emergency landings. Intelligent systems could support this by identifying suitable urban landing sites while actively coordinating ground traffic to ensure safe deployment.

1.2. Structure of the document

The document is structured as follows. After the introduction, a state of art was conducted. Section 2 introduces the urban safety net conceptualizing the urban landing sites. In Section 3 a generic use case is created to develop an optimization model. The objective of the optimization process is to identify an controlled emergency landing site that minimizes the impact on ground traffic. In Section 4 a realistic use case from Munich (Upper Bavaria, Germany) is derived, to provide a first demonstration of our emergency landing concept (intermodal safety net). The paper concludes with a discussion and outlook (Section 5).

2. URBAN LANDING SITES

The commercial use of air taxis includes transporting passengers or cargo between vertiports [14]. Based on UAM demand forecasts, vertiport planning considers flight routes both within the metropolitan area and to destinations outside of it, such as business parks or residential areas [15]. In residential areas, for example, the rooftops of shopping centers could serve as suitable locations for vertiports, while road junctions could be considered as potential sites for emergency landings [16]. UAM flight routes must be planned to allow emergency landings along the entire route wherever possible. Sufficient ground space must also be available to enable a safe emergency landing of the air taxi. A fundamental operational and technical requirement for safe communication and flight guidance in low-altitude urban environments is the presence of traffic light systems at key intersections, as these systems manage and control surrounding ground traffic. However, it should be noted that not every traffic light-controlled intersection that offers sufficient physical space for an air taxi is necessarily suitable for emergency landings. The characteristics of the surrounding near the traffic light-controlled intersection plays a critical role in determining suitability.

In residential areas of North American cities - such as the metropolitan regions of Houston, Dallas, San Francisco, and Los Angeles - it is common to find wooden utility poles that support power and communication lines, as well as traffic signals. These structures can pose significant obstacles for the air taxi (may not be visible to it) and must be considered during the selection of potential emergency landing sites. In residential areas of European cities - such as the metropolitan regions of Hamburg or Munich - ground transport infrastructure often includes tram lines operated by local public transport providers. These trams typically cross roadways (e.g., Munich - District Bogenhausen, "Cosimabad" stop[1]). At traffic-light controlled intersections, the presence of overhead power lines used for tram operations can pose a significant obstacle in the event of an emergency landing (see Fig. 1).

FIG 1. (left) Representation of the residential area in Munich-Bogenhausen. (right) A traffic light-controlled intersection with obstacles.

3. GENERIC USE CASE AND OPTIMIZATION MODEL

We model traffic dynamics and facilitate potential emergency landings by creating a simplified road network and air taxi trajectories using the simulation software AnyLogic (see Fig. 2). The simulated road network includes nine intersections equipped with traffic lights, each operating on a 15-second cycle of green and red phases. Ground vehicles enter the road network at the upper-left and exit at the lower-right corner. The simulation spans a total duration of one hour. Air taxis are assigned a cruising speed of 90 km/h, while each vehicle enters the road network at an initial speed of 30 km/h and can accelerate up to a maximum speed of 50 km/h (speed limit in built-up area). At each intersection, vehicles face a decision point with a 50% probability of either continuing straight or making a right turn onto the subsequent road. The blue line in Fig. 2 represents the predefined trajectory of the air taxi.

3.1. Optimization model

The objective of the optimization is to provide safe intermodal traffic management by temporarily closing appropriate intersections to vehicles (priority control) for a given flight segment. The effects of these short-term priority regulations are determined by the measured reduction in average speed.

Notations:

I	Set of all intersections
K_t	$\subseteq I$, set of candidate points within the range

Notations (cont.):

T	Set of the time frames for optimization
x_{it}	A binary decision variable, where $x_{i,t} = 1$ indicates that intersection i is closed for safety landing at time frame t, and $x_{i,t} = 0$ otherwise
C_{it}	The parameter representing the number of vehicles coming to intersection i during time frame t
S_{it}	Average speed of vehicles coming to intersection i during time frame t
M_{it}	Maximum number of vehicles stand before the intersection i during time t

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[1] https://www.google.com/maps/place/48.1534722,11.6295556

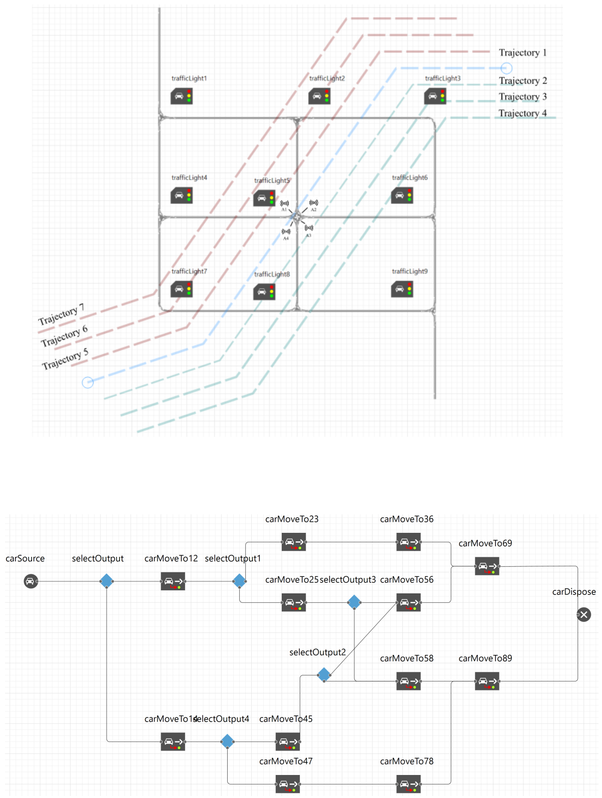

FIG 2. **(top) Simplified ground and air traffic network with seven different aircraft trajectories around a centered reference trajectory and nine controlled intersections. (below) Model of traffic logic for the traffic network (vehicles enter from the north, leaving at the south, same probability of driving straight ahead or turning east-/ southbound, no loops).**

Objective Function:

$$\min \frac{C_{it}}{S_{it}} \quad x_{it} \tag{1}$$

s.t

General constraints:

$$\sum_{i \in K} x_{it} \geq 1 \qquad \forall t \in T \tag{2}$$

$$C_{it}\, x_{it} \leq M_{it} \qquad \forall i \in I, t \in T \tag{3}$$

$$x_{it} \in \{0, 1\} \qquad \forall i \in I, t \in T \tag{4}$$

The formulated linear programming model aims to optimize the scheduling of intersection closures within a network of roads over discrete time frames to minimize the total expected delay experienced by vehicles. The decision variables, x_{it} are binary and represent whether intersection i is closed during time frame t ($x_{it} = 1$) or open ($x_{it} = 0$) for emergency landings. The objective function (1) aims at minimizing the total number of vehicles (delay time of the vehicles) arriving at the closed intersection. The delay is calculated by the first part of the objective function $\frac{C_{it}}{S_{it}}$ over all intersections, which means the more vehicles or slower speed at intersection i during time frame t can increase the delay time. Constraint (2) ensures that at least one intersection is closed during time frame t for emergency landing. Additionally, a specific set of candidate points K is introduced, representing the intersections within the range for emergency landing. The formulation ensures $x_{it} = 0$ for the intersections outside the candidate set, emphasizing that only intersections within the specified range are eligible for closure. Constraint (3) limits the total number of affected vehicles. This linear programming model offers a systematic approach to identifying the optimal intersection for emergency landing closure while considering the incoming traffic to minimize potential delays. The linear model is solved by Gurobi package 10.0 on a 24-kernel CPU with 32GB RAM (Windows 11).

3.2. Results

We investigated the effects of seven trajectories on the road network, as shown in Fig. 2, since trajectories can vary in both planning and real-time operation. The objective is to identify at least one intersection as a reserve site for potential emergency landings, as determined by the optimization model. The designated blocking time is set to 20 seconds, meaning that if a traffic light-controlled intersection is selected as a potential emergency landing site, it must be obstructed for at least this duration. In the event of an actual emergency landing, the intersection remains blocked for the entire event. Extending the red phase of traffic lights beyond their standard cycle is expected to cause delays in ground traffic, observed by a decreased average speed in the corresponding traffic scenario. Table 1 summarizes the results for the seven evaluated trajectories. The baseline scenario serves as a reference, considering the absence of air taxis. This scenario adheres to the standard cycle of traffic lights without any interruptions.

TAB 1. Average speed in the ground traffic system.

speed (%)							
Baseline (no air traffic)	Trajectory 1	 2	 3	 4	 5	 6	 7
100	99.2	98.2	99.2	99.8	99.0	99.4	99.6

The results show that the road network can serve as a safety mechanism for urban air traffic without causing a significant reduction in average vehicle speed (less than 2%). However, the current use case is a very generic proof-of-concept character.

4. MUNICH USE CASE

Integrating the developed optimization model into a more complex and realistic urban ground traffic scenario requires an evaluation of a specific city area with an appropriate amount of potential traffic-light controlled intersections. For this purpose, we selected the Maxvorstadt district in Munich, which is a legacy of the first planned urban expansion of Munich. Maxvorstadt covers an area of 4.3 square kilometers and is located in the northern part of Munich's city center. As of December 2023, the district had a population of 51,945 residents, which is moderately congested.

FIG 3. (left) Munich-Maxvorstadt: Traffic scenario was derived from local observations and assumptions about general traffic patterns. (right) Different flight trajectories.

With moderate traffic volumes typically observed between 8:00 a.m. and 8:00 p.m., enabling emergency landings while minimizing disruptions to ground traffic becomes a key objective. To support this, we identified eleven potential emergency landing sites within the Maxvorstadt district. These intersections were strategically selected based not only on their suitability for emergency landings but also on surrounding traffic flow and the physical space available to safely accommodate an air taxi landing.

Furthermore, to assess the impact of UAM operations on ground traffic, we analyzed seven distinct air taxi trajectories within the Maxvorstadt[2]. These trajectories, shown in Fig. 3 (left), represent variations in the offset from a main trajectory (denoted by blue line). The trajectories include three offsets to the left (designated as 1L, 2L, 3L in yellow) and three to the right (labeled as 1R, 2R, 3R in purple, see Fig. 3 (right)).

The results, summarized in Table 2, provide a more nuanced perspective compared to the generic use case discussed in the previous section. In particular, when the ground-based safety net is activated during operation along trajectory 2R, the average speed in the ground traffic system decreases by 11%. A similar but slightly smaller impact is observed for trajectory 3R, with a reduction of. For the remaining trajectories, the implementation of the proposed concept results in an average ground traffic speed reduction of approximately 4–6% compared to the baseline scenario.

TAB 2. Average speed in the ground traffic system.

	Baseline (no air traffic)	Trajectory 0	1L	2L	3L	1R	2R	3R
speed (%)	100	94	94	95	96	96	89	91

5. DISCUSSION AND OUTLOOK

For the implementation of UAM, the development and operation of a ground-based safety network for unexpected events and possible in-flight emergencies is a critical prerequisite. While many operational concepts focus on standard flight procedures, vertiport design, air taxi development, and the transport of passengers and cargo, this paper focuses on an intermodal safety concept that integrates both managed ground and air traffic. Through the active control of ground traffic and the coordinated management of air traffic (e.g., filing and coordination of flight plans), it becomes possible to temporarily block light-controlled intersections in emergency situations, thereby enabling safe landing opportunities for air taxis.

To demonstrate the proposed safety concept, we developed a simplified and structured road network with 3x3 traffic-light controlled intersections and formulated an optimization model. In this setup, intersections are evaluated as potential emergency landing sites through optimization to minimize interference between air and ground traffic. As the generic model already indicated minor effects on ground traffic - specifically, a reduction in average speed of less than 2% - the model was subsequently applied to a real-world scenario in the city of Munich. In this more realistic scenario, the impact on ground traffic became more pronounced, with average speed reductions ranging from 4% to 11%.

This study introduced an innovative concept for an intermodal safety network and demonstrated the impact of potential interactions with the ground traffic system. Future research will focus on developing comprehensive optimization models that incorporate both centralized and decentralized traffic management strategies. In particular, we would like to draw attention to trajectory optimization, considering the utilization of the ground (safety) network. Further efforts will explore technologies to improve aircraft positioning accuracy in complex urban environments (e.g., in the presence of obstacles) and on addressing uncertainties in the optimization process. These advancements aim to enable the seamless integration of UAM systems into urban environments while optimizing ground traffic flow and minimizing disruptions.

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