

Article

# Reinventing Mobility Paradigms: Flying Car Scenarios and Challenges for Urban Mobility

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**Abstract:** Flying vehicles are receiving more and more attention and are becoming an opportunity to start a new urban mobility paradigm. The most interesting feature of flying cars is the expected opportunity they could offer to reduce congestion, traffic jams and the loss of time to move between origin/destination pairs in urban contexts. In this perspective, urban air mobility might meet the concept of “sustainable mobility”, intended as the ideal model of a transport system that minimizes the environmental impacts by maximizing efficiency and travel speed. For transport engineering planning issues, further knowledge is required in this field to understand the effects that a possible urban air mobility system, including the ground traffic component, could have in terms of sustainable mobility in the above meaning. This paper contributes to this topic by providing an analysis of different urban flying car scenarios by using an agent-based approach with different traffic conditions. The preliminary results obtained on some test networks and focusing on travel cost effects suggest that the expected advantages the flying car will depend on trip origin/destination points, average distances travelled in the urban contexts and the location of transition nodes, which are introduced as interchange nodes between aerial and ground mode.

**Keywords:** urban air mobility (UAM); flying cars; traffic management; transportation network; software agents

## 1. Introduction

Sustainable mobility is one of the main key challenges that stakeholders and policy makers have to face in order to give people the opportunity to move freely, communicate and establish relationships without harming themselves or the environment in which they live. Because of recent technological advancements, bringing urban mobility into the third dimension—the airspace—is now considered a real chance towards sustainable mobility (see for example the EU funded initiative for next generation urban mobility [1]). In this perspective, flying vehicles (such as Personal Aerial Vehicles, PAV, and Passengers Unmanned Aerial Vehicle, PUAV) and Urban Air Mobility (UAM) are receiving increasing attention for the interesting opportunity they offer to move people within urban areas. In fact, air connections provided by flying vehicles are expected to reduce surface transport congestion, integrate logistic chains and, at the same time, reduce infrastructure maintenance costs. Potential benefits in terms of improved transport reliability would affect not only emergency services and freight delivery, but also individual trips, while a reduction in travel times would lead to a reduction in trip delay and improved quality of life, which are some of the facets of sustainable mobility.

From here on, “flying cars” are considered vehicles expected to move on both ground and air mode, so that transition between air and ground modes is possible. The potential benefits of using “flying

cars” in an urban context have caught the interest of scientists, engineers and companies, including, for instance, Uber [2] that is planning to start with aerial taxi services in the near future [3]. Following this trend and in the perspective of potentially feasible UAM scenarios, a growing number of flying vehicles are being developed or tested all over the world together with studies to understand which kind of features are more desirable for this type of vehicle [4–6]. At the same time, there is an increasing number of research programs dealing with the different aspects of this new form of urban mobility (see, for example, the *NASA Urban Air Mobility Grand Challenge Program* [7]; or the recent EC call *Towards sustainable air mobility* [8]). To simulate the effects of flying cars on urban mobility, the interactions occurring among flying and ground vehicles and with ground obstacles, as well as users’ criteria leading to aerial mode choices, should be considered. Some studies have started simulating UAM scenarios by considering how to safely manage air vehicle separations in high-dense traffic conditions with several scheduling horizons [9,10] and airspace integration concepts [11]. Free-flight conditions, where it is assumed that each vehicle is responsible for separations, have also been tested by using a computational guidance algorithm with collision avoidance capability [12]. Some other studies have used a MATSim [13] tool to simulate UAM transport performances with varying parameters (such as stations, access/egress, the number of vehicles, Vertical Take-off and Landing vehicle features) and by using the available Sioux Falls MATSim scenario [14,15]. Finally, a comparative analysis for three case studies have investigated potential operational constraints for UAM services depending on specific mission types or environments [16]. Most of the previous studies make use of software agent technologies (from hereafter simply agents) [17,18] as a tool to simulate UAM scenarios. Indeed, agents are autonomous, goal-oriented and time-persistent software entities that can be provided with different degrees of intelligence, learning, adaptive and pro-active capabilities [19], including social and self-organizing skills [20,21]. In most transportation studies, agents have been associated with different entities—such as travelers, vehicles, and signals—to interact in a complex way with other entities and to simulate multifaceted, intelligent behaviors (also adopting machine learning techniques) such as, for instance, human behaviors [22]. Agents have also been exploited for mesoscopic traffic simulations, combining micro and macro aspects [23,24], and macro simulations (e.g., [25,26]), although in this case their use appeared limited.

Implementing an air urban transportation system is complex because many technical, urban, legal and economic criticisms must still be solved. On one hand, the needs and features of urban air modes have neither been taken into account in the existing urban context (such as requirements for landing and take-off areas), nor in current rules (such as for safety, security and privacy issues related to the possibility for a flying car to pass over or near to buildings). On the other hand, the implications of a UAM transportation system, which results from the interactions between air and ground transport modes, are not yet fully understood.

Starting from the above overview, this study wants to explore the potential of air transport mobility in urban contexts in the “sustainable mobility” perspective and to answer to the question: “is this new mobility opportunity overcoming some of the main problems—congestion and increasing travel times—that are considered some of the “sustainable mobility” shadow variables?”. In fact, flying vehicles are considered (or offered on the market as) one of the options to reduce travel times to move between origin/destination pairs (then they would contribute to improve life quality). At the same time, they would reduce environmental impacts because of the expected decrease in ground vehicle congestion. This study will analyze from a quantitative point of view to what extent there is evidence for those improvements. Finally, the aim of the paper is neither to analyze flying vehicle technology in itself, nor to discuss socio-economic implications, potential for inclusion/exclusion, and so on, but to simulate the “system” in a holistic perspective where, potentially, different types of vehicles (ground and flying) could be used.

To address such issue, the status of the urban transportation network made by both ground and aerial links—where flying and ground vehicles can partially coexist—has been simulated, which is an important planning and management transport activity [27]. UAM scenarios, where flying cars are

used in cities in both flying and ground modalities, are explored by using agent-based simulations, the features of which have been designed by considering the main rules and standard behaviors that flying cars should have. Each agent represents a moving object—both flying and ground vehicles. Starting from the recent development of Connected Automated Vehicles (CAVs), and by considering flying cars as a further evolution of CAVs, the hypothesis here is that manned or unmanned flying cars have similar behaviors, because automation has been considered a standard feature of this type of vehicles. The simulation has been addressed to verify which kind of improvement flying cars could represent for urban mobility and whether flying cars could be a sustainable alternative to the current urban scenario. To this aim, a travel time index has been proposed and some test networks, at increasing size, have been designed for a baseline scenario—where only ground vehicles are allowed—and some alternative scenarios—where flying vehicles are allowed in both ground and flying modes. The choice to simulate test networks at increasing size has been made in order to avoid comparing real scenarios, in which the specificity of facilities and network structures may produce distortion effects. Then, the results will provide insights into the possible benefits of flying vehicles for explanatory test cases that are comparable among them and will serve as basis for further studies. Preliminary results, which focus only on travel cost effects, show that flying cars may represent an alternative solution to only ground scenarios depending on trip origin/destination points, average distances travelled in the urban contexts and the location of transition nodes, which are introduced as interchange nodes between aerial and ground mode.

The paper is organized as follows. In Section 2, the main features of flying cars and some likely expected scenarios are described. In Section 3, the proposed model is introduced, and, in Section 4, the results of some simulations are presented. Finally, in Section 5, the results are discussed and some conclusions are drawn.

## 2. Main Features of Flying Cars and Air Urban Mobility Cases

The main features of flying cars, which are still prototypes, are discussed shortly in Section 2.1 with respect to possible UAM expectations. It is worthwhile to note that the attention has been addressed mainly to the “flying features” of such vehicles, which represent the main difference as regards standard ground cars. Starting from this overview, in Section 2.2, three main cases are identified, which have been thought to be among the most representative ones for an urban air mobility.

### 2.1. Flying Car Main Features

Flying cars’ main features have been identified in: (i) architecture; (ii) range, endurance and speed; (iii) vertical position and main flight rules; (iv) take-off and landing requirements; (v) automation level; (vi) communication technologies.

As for architecture, current flying car prototypes have suitable sizes that allow them to also be used on road lanes or parked in available slots as standard cars. Compared to standard cars, their aerodynamic shapes improve performances during the flying stage and, at the same time, are conceived to be suitable for ground mode [28]. Currently, helicopter-like prototypes are more common than airplane-like ones, because of their capability to take off and land (almost) vertically, to hover and to fly forward, backward, and laterally with greater flexibility than airplane-like vehicles [29]. Furthermore, as they do not require long runways for take-off and landing, they are more suitable to be used in reduced spaces.

Range and endurance are, respectively, the maximum flight distance—measured on the ground—that can be travelled for a given amount of fuel/charge and the maximum flight time, still in relation to the available fuel/charge. Range and endurance are specific aerodynamic features roughly depending on [30]: (a) the vehicle weight, which may change during the journey for fuel-powered vehicles; (b) the specific fuel/battery charge consumption, which in turn depends on the kind of engine; (c) the engine power or the thrust; (d) the weather conditions. Depending on the required performances, range could be more important than endurance and vice versa. For example, range estimate is relevant

to move between origin and destination points. On the contrary, a good endurance is preferred for surveillance or security control tasks.

Speed performances refer to two drive conditions: (i) on the road and (ii) in-flight. The first value depends mainly on the “Rules of the road”, which may change among countries. The second value depends on aerodynamic features, such as combinations of maximum speed and the angle of attack (this latter is the angle between the airfoil chord, wing or blade, and the vector representing the relative motion between the object and the fluid through which it is moving), weight, load factor and the center of gravity, among others [31–33].

When flying, vertical separations are required to avoid collisions with other oncoming traffic. Height, altitude and flight level (see Figure 1) are generally used to identify the vertical position of flying objects. Height is the vertical distance of the object, measured from a specified datum, expressed in feet AGL (Above Ground Level). Altitude is the vertical distance of the object measured from the Mean Sea Level (MSL). Flight Level (FL) is a surface of constant atmosphere pressure and identifies the vertical distance of an object above the isobaric surface of 1013.25 hPa, which is the zero level.

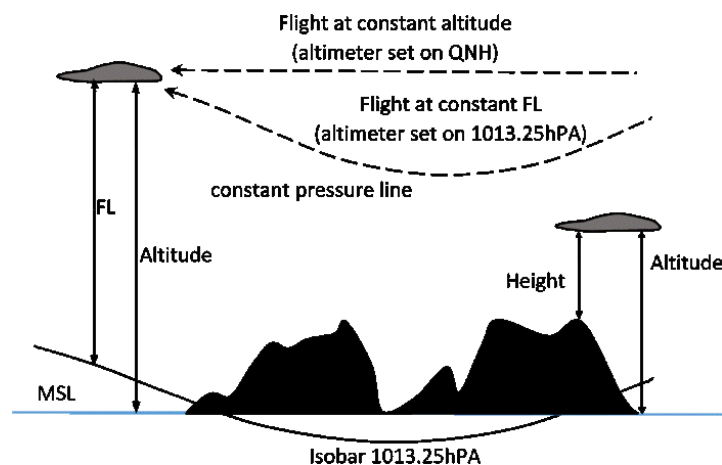


Figure 1. Identifying the vertical position of a flying object.

Two flying conditions are currently operating [34]: Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). VFR flights apply to Visual Meteorological Conditions (VMC) and are freely operated below 900 m (3000 ft) from the ground or water without any particular cruising altitude, although they are not allowed above FL200. IFR flights apply to Instrument Meteorological Conditions (IMC), defined as weather “below the minimums prescribed for flight under VFR”. Navigation is made by referring to on-board instruments rather than on visual references. For flying car scenarios, VFR conditions are expected to be realized at Very Low Level (VLL) airspace, usually defined as 0–500 ft AGL. In addition, below 7000 ft—which in principle could be an expected maximum vertical position for a flying car—it is possible to fly without cabin pressure plants.

As for take-off and landing, flying cars could require runways (Conventional Take-off and Landing, CTOL, procedure) or only short spaces for vertical operations (Vertical Take-off and Landing, VTOL, procedure). For CTOL vehicles, runways are necessary to run and gain enough speed to generate lift to go up. On the contrary, VTOL vehicles do not require long runways or do not require runways at all. VTOL features are particularly suitable for urban contexts, as they require reduced dedicated areas for taking off and landing.

Flying and ground cars may be fully automated, partially automated or flight assisted, depending on the on-board automated driving systems. For automated vehicles, flying drivers can take control at any time also depending on their reactions to automation devices [35,36]. “Automated” features differ from “autonomous” ones because these latter imply decision-making capabilities. An automated vehicle acts by following some automated mechanisms (e.g., forward-collision warnings and automatic

braking, also without driver intervention), but the driver may take control. Autonomous vehicles are fully automated, monitor what is happening around them, react on the basis of some kind of learning and are driverless.

Safe interactions between automated/autonomous vehicles require suitable communications between the various entities involved, the main purpose of which is to prevent dangerous situations, using appropriate communication protocols and standards, designed to support vehicle transmissions in different application scenarios. In this context, communications are commonly classified in: (i) vehicle-to-vehicle (V2V), consisting in wireless communication between neighboring vehicles [37,38] to realize 3D separations among vehicles and obstacles [39] also avoiding the effects of wake turbulence, which implies lift variations [40,41]; (ii) vehicle-to-infrastructure (V2I), linking vehicles to infrastructures—including ground obstacles such as buildings and electric cables, traffic lights and roundabout [42–44]; (iii) vehicle-to-everything (V2X), which includes V2V and V2I and also communication between vehicle and pedestrian (V2P), roadside (V2R) and device (V2D) [45,46] in order to create safe environments.

Communication architecture, reliable routing protocols and potential disconnection outside the coverage range of the ground infrastructure are crucial key factors for connected vehicles. Particularly for flying vehicles, some recent studies explored V2V and V2I communication networks such as Vehicular Ad hoc Networks (VANETs) [47] and Flying Ad hoc Networks (FANETs) [48,49], to improve traffic safety and prevent collision accidents. Some recent tests [50] also showed that conventional Air Traffic Control (ATC) approaches might be unfeasible for high urban traffic levels and complex urban environments.

## 2.2. Air Urban Mobility Scenario

In the following, the selected scenarios refer to situations in which flying cars are used also within cities and in both flying and ground modes. In the other cases (only inter-city and/or inter-region journeys, without ground and/or within-city circulation), they have the same role as current helicopters or private jets and are not relevant for the aims of this paper. Generally speaking, three main cases could be expected, namely:

- (A) Point-to-point services between origin/destination prefixed points, mainly flying mode (Figure 2);
- (B) Long/medium-distance trips, flying mode for the longer legs and ground mode within cities (Figure 3);
- (C) Short/medium-distance trips, also within cities, by combining flying and ground modes (Figure 4).

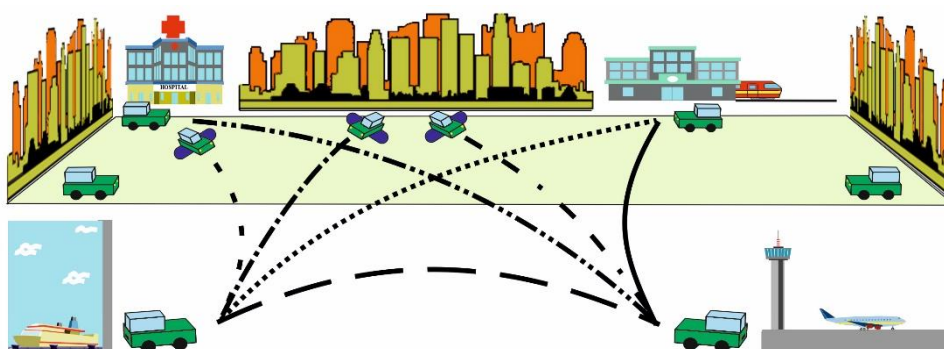


Figure 2. Case A: Point-to-point services between pre-fixed points.

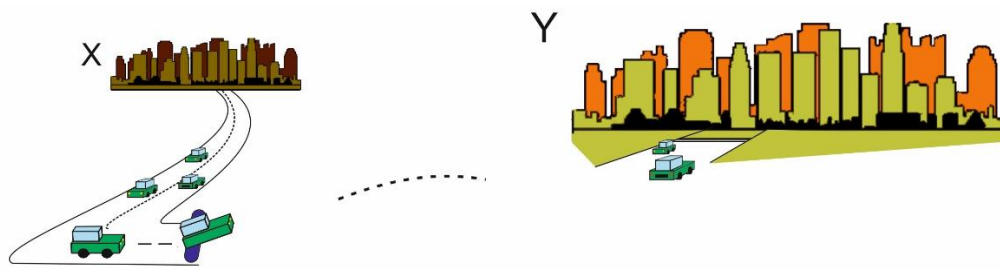


Figure 3. Case B: Long/medium-distance inter-city trips.

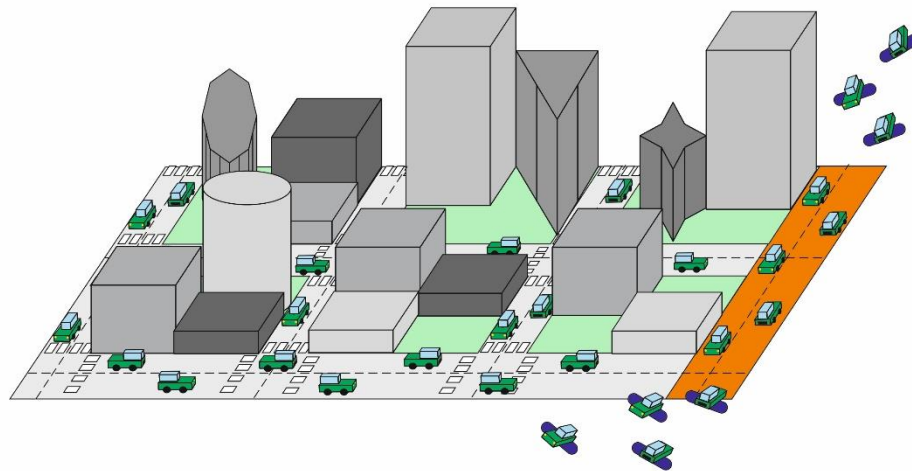


Figure 4. Case C: Short/medium-distance trips, flying and ground modes within cities.

#### Case A

Figure 2 represents transport services to/from relevant places (such as hospitals, ports, airports, other transport terminals) from/to suitable collecting areas (e.g., parking areas close to terminals or located into the city) by certified transport operators. Service is realized by a restricted number of circulating vehicles that follow planned routes. Landing and take-off activities are planned depending on authorized flight plans and occur only at approved areas, such as collecting areas in some suitable city zones or parking areas.

#### Case B

Figure 3 refers to long/medium-distance inter-city trips. External or dedicated roads lead to separated take-off/landing areas (CTOL or VTOL) where vehicles start/end the flying leg of the journey, which is also the longer one. If take-off/landing areas are within the urban area, there are proper flying-car terminals, from which suitable, separated routes lead to urban roads. Shorter distances within the city are covered by ground mode. Flying-mode and ground-mode operations are completely separated. Specifically, within cities, only the ground mode is allowed, apart from transport services provided, as in scenario A, if planned. Range and endurance for the flying leg should be suitably computed in order to plan a safe journey between inter-city origin/destination points.

#### Case C

Figure 4 shows a free-flight scenario—i.e., flying cars move both within cities and between city pairs. Again, the computation of range and endurance is relevant for a safe trip, both for the between-city and within-city legs. Within-city trips are allowed almost everywhere, although take-off/landing operations occur only at dedicated areas suitably linked to the main roads where only ground mode is allowed.

Case C has been selected for simulating UAM scenarios because it can include the main features of both cases A and B. In fact, on the one hand, case A is a particular configuration of case C, where only shared flying car services are authorized. On the other hand, case B is included in case C again as a particular case where flying cars can take-off and land only in specific areas, which are at city boundaries or in separated terminal areas.

### 3. The Model

The agent-based model proposed here wants to test some UAM scenarios for the selected case C, described in Section 2.2, in order to provide a preliminary assessment of the flying car potential in an urban context. In particular, only within-city trips have been simulated, which are the most interesting in the urban context. The comparison among scenarios is based on travel time, which is a preliminary, important indicator of how conveniently travelers can move between origin/destination pairs and indirectly of how sustainable flying car scenarios could be in the sense of easiness to move. The hypothesis here is that all the vehicles are electric, which is coherent with the current development of e-mobility, both in terms of new generation vehicles and facilities adopted within cities, i.e., fast charging power stations.

Based on the overall features of case C, three main types of interactions have been considered: (i) among flying cars; (ii) between flying cars and existing ground obstacles; (iii) among flying cars and ground cars.

As for interactions among flying cars, automation and supporting devices are considered to keep horizontal and vertical separations, right trajectory and altitude. In fact, it has to be expected that flying cars will have a high level of automation for keeping safe distances—in the all three dimensions—in line with similar expectations for the still-in-progress models of automated/autonomous cars. Data exchanged among vehicles include location, direction and speed, which are assumed to be processed by on-board devices in order to provide information useful to avoid collisions or wake turbulence effects. In addition, a control center has been included, which provides information to vehicles. Vertical position may vary with meteorological conditions, then it has been considered that flying cars are suitably equipped to identify and keep a safe vertical position during flight also according to meteorological conditions.

For the planned route between a trip origin/destination pair the minimum vertical position has been set suitably greater than the height of the highest building or ground obstacle. Without losing the general nature of the performed experiments, potential prescriptions preventing one from flying below a given height—apart from the minimum height due to building features—when operating over a built-up area or from flying at all over some particular zones (e.g., military areas, government buildings) have not been considered. In fact, the hypothesis has been made that safety and security issues have been solved, as it could be expected in a UAM scenario. It is worthwhile to note that it is not in the aim of this paper to focus on issues concerning rules and prescriptions for security reasons. Only technical issues and safety limits concerning minimum heights for avoiding obstacles have been considered.

Interactions between flying cars and existing ground obstacles are relevant during landing/take-off, which have been simulated only along prefixed, safe routes. Potential obstacles are mainly buildings—especially in high-density/high-populated cities where also variable building heights are expected—and electric cables/antennas—particularly for low-level flights during landing/take-off. Interactions among flying cars and ground cars occur during the transition from flying mode to ground mode, i.e., during landing/take-off, which is allowed within the city only at pre-fixed “transition areas”. Transition areas should be suitably located in the urban context—i.e., in order to both reduce interference with obstacles/ground traffic and minimize disturbances—and then have to be identified where the urban structure is sufficiently dispersed, also by considering the variability of the descent path—e.g., due to meteorological conditions. Reasonably, transition areas are located at no less than the  $d_{min}$  of each other (see below). Dedicated transition roads link transition areas to the ground

transport network. The number and location of transition areas and roads within the city should provide a suitable coverage of the city and, at the same time, assuring safe conditions for entering the ground traffic network.

To summarize, the following preliminary conditions have been set to perform the experiment:

1. Flying cars are suitably equipped to keep the right distances among them and between them and ground obstacles.
2. Flying mode is allowed over the city at a suitable minimum height, while landing and take-off have been allowed only at some prefixed transition areas and roads, which are connected to the ground network.
3. To move between specific origin/destination pairs, a combination of flying and ground mode can be adopted: flying mode allows moving quickly for the longer leg between transition nodes, while ground mode has to be used to reach the specific trip destination or to start from a given trip origin.

Starting from the above conditions, the agent-based model has been specified as follows:

1. Each vehicle  $i$  (in flying or ground mode) is associated with an agent  $A_i$  (from hereafter the terms agents and vehicle will be used in an interchangeable manner).
2. For each couple  $(A_i, A_j)$  of agents, the following conditions hold:
  - (a) In ground mode,  $\forall A_i$  following  $A_j$  along the ground axis  $x$ , the minimum distance  $d_{ij}$  between  $A_i$  and  $A_j$  is  $d_{ij} = t \cdot v_{gi} + s_{ib}$ , where  $t$  is the technical time for starting braking, assumed the same for all the  $A_i$  ( $t = 1$  sec);  $v_{gi}$  is the ground speed of  $A_i$ ;  $s_{ib}$  is the braking distance at a constant deceleration  $a_i$ , which has been assumed the same for all the  $A_i$ .
  - (b) In flying mode,  $\forall A_i$  flying over  $A_j$ , the vertical position along the  $z$  axis is  $h_i = d_0 + n \cdot s_z$ , where  $d_0$  is the minimum height allowed to overfly the urban area;  $s_z$  is the minimum vertical separation between  $A_i$  and  $A_j$ , which is the same for each couple of agents  $(A_i, A_j)$ ;  $n$  is the number of agents under  $A_i$  on the  $z$  axis.
  - (c) In flying mode,  $\forall A_i$  following  $A_j$  along the same horizontal route, the minimum distance between  $A_i$  and  $A_j$  is constant and equal to  $s_x$ .
  - (d)  $\forall A_i$  passing from ground to flying mode, the climbing occurs at the transition areas based on a booked and confirmed time-slot authorization; this time slot depends on the estimated arrival time at the transition area, which in turn depends on ground traffic conditions.
  - (e)  $\forall A_i$  passing from flying to ground mode, the descent occurs at the transition areas based on a booked and confirmed time-slot authorization; this time slot is estimated when leaving from the origin transition area according to the expected flying time between two transition areas.

Note that agents can use only one horizontal route, although at different heights, then at a first attempt no separations along  $z$  have been introduced.

3. Each  $A_i$  moves between a trip origin/destination ( $O/D$  from hereafter) pair by following a path that can be made by both ground and aerial links according to the conditions listed below:
  - (a)  $\forall A_i$  moving between an  $O/D$  pair, if the Euclidean distance between the  $O/D$  pair is less than  $d_{min}$  the trip will take place on ground mode only, otherwise a combination of ground and aerial links will be used;
  - (b) Each  $A_i$  that moves between an  $O/D$  pair will choose one path according to a minimum cost criterion;
  - (c) The minimum cost criterion corresponds to a minimum travel time, where the travel time on the generic ground link has been assumed as  $t(f) = l/v_g = l/(a - b \cdot f_g)$ , where  $f_g$  is the link ground traffic volume, which here corresponds to the number of agents that are on that link at a given time,  $v_g$  is the ground speed empirically computed for urban roads as  $(a - b \cdot f_g)$ ,  $a$  and  $b$  – empirically computed for averaged road features (such as width, obstacles,



secondary interferences, slope) – are respectively equal to 37.5 and  $8.5 \cdot 10^{-6}$  for  $v_g$  measured in  $Km/h$ ; for the aerial link, travel time is computed just depending on link length and allowed speed  $v$ ,  $t = l/v$ . The automated/autonomous features of flying vehicles may imply ground speed harmonization—then reduced speed variance—and better traffic conditions [51]. The previous travel time functions are coherent with the vehicle automation features, which in any case are expected to suit road features;

- (d) The hypothesis here is that flying cars are highly automated/autonomous; however, given that (i) it can be assumed that pilots can take control if needed, particularly on ground mode, (ii) human perception of speed and distance is not reliable at high speeds, mainly on flying mode, and (iii) short reaction times are required of a driver, to this aim, it is assumed that agents communicate also with a central monitoring UAM Agency and are autonomous in their choices to some extent. To minimize the risk of collision during a free-drive conditions, in addition, agents will communicate with the UAM Agency sending/receiving information about their position, those of other agents and obstacles as well as the state of the transportation network in terms of link travel cost at that time (see also below); all the  $A_i$  adopt the same take-off and landing procedures and, to avoid collisions with other agents, variations of speed and altitude are controlled by the Agency, which provides suitable information to the agents;
- (e) For the combined path, i.e., ground and aerial sections,  $A_i$  will start the trip only when it receives information by the Agency, in order to avoid congestion effects at the transition areas;
- (f) During the flying section,  $A_i$  will move only between a couple of transition areas by following the Euclidean route.

To compare some case C scenarios, the ratio between the total “flying ground” travel time and the total ground travel time for “only ground” mode to move between an  $O/D$  pair, over all the agents and  $O/D$  pairs, has been considered:

$$\mu = \frac{\sum_i T_{O/D,i}^{g+f}}{\sum_i T_{O/D,i}^g} \quad (1)$$

where:

- $\sum_i T_{O/D,i}^{g+f}$  is the travel time to move between the  $O/D$  pair in “ground + flying” mode on the path chosen by  $A_i$ ;
- $\sum_i T_{O/D,i}^g$  is the travel time to move between the  $O/D$  pair in “only ground” mode on the path chosen by  $A_i$ .

#### 4. Experiments

The experiments performed to simulate the UAM scenarios described in Section 3 are based on some test transport networks suitably built that, although simplified for clarity, represent a proper network structure. In particular, simulated test networks at increasing size have been considered in order to avoid comparing real scenarios at different sizes, because the specificity of facilities and network structures might produce distortion effects. Then, results will be comparable among the several networks. In the following, the transport test networks, the simulation characteristics and the obtained results are described.

##### 4.1. Transportation Test-Networks

The experiments have been carried out on simulated test transportation networks given that current urban contexts do not consider UAM needs at all, such as suitable safe take-off and landing spaces for flying cars inside the cities also according to flying rules in the urban context, which could vary within and among cities. Any of them can be defined at this time, also because they will depend on the adopted standards for commercial flying cars.

The test transportation networks have been set by adopting a modular approach, which is based on a suitable symmetric “module”. The designed module (depicted in Figure 5) is  $L \times L$ , there are 25 nodes and all links have the same capacity and the same length  $l = L/4$ . For simplicity, the figure reports just one link to simulate the two-way roads connecting each pair of nodes, although oriented links, as in this case, should explicitly consider the direction for each pair of nodes. As depicted in Figure 5, links are represented with a light blue continuous line, while the red links represent the virtual connection between demand points, i.e., trip origin/destination red nodes  $V$ , and transport supply (see for example [52]). Aerial take-off and landing activities can happen only at the transition node  $T$  (green circle in Figure 5) for each module. Take-off and landing operations are suitably separated at the transition node in order to keep two distinct traffic flows entering/exiting the transition node in ground mode for reaching the destination. Each  $A_i$  starts the trip from its origin node  $V_k$  and will reach the transition node  $T$  in ground mode. In flying mode,  $A_i$  will move only between transition nodes of the modules forming the transportation network and will, again, use the ground links to reach the destination  $V_l$ .

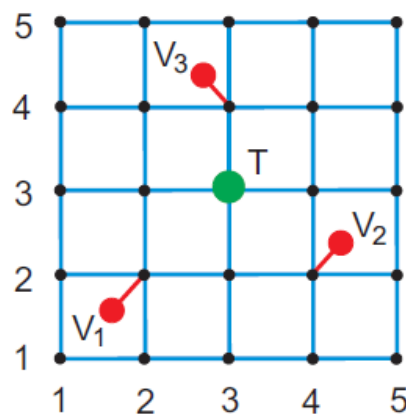


Figure 5. Baseline transportation network module.

It is worthwhile to note that the simplified topological symmetry and the hypothesis on link features do not influence the preliminary results, as the link features (such as travel times, capacity, length) may be changed even though the graph topological structure remains the same. For these first experiments, the simplified structure has been considered more suitable than a more complex one in terms of link features. In addition, it is not the aim of this work to explore the optimal location of the transition nodes and for this reason too the modular, symmetric structure of the test network has been considered.

#### 4.2. Simulation Characteristics

Three test networks having different sizes in terms of baseline modules, i.e.  $3 \times 3$ ,  $6 \times 6$  and  $9 \times 9$  modules with  $L = 1000$  m, have been considered for the experiments. The origin/destination trip demand (i.e., the set of agents moving between  $O/D$  pairs) has been generated starting from an average value of 300 vehic/h and variation coefficient  $c_v = 0.4$ . The  $O/D$  values have also been split for several time slices—each one of 5 min for 1 h of simulation—in a random way for each simulation. In more detail, each  $O/D$  value has been split in 12 sub-values such that their sum is equal to the generated  $O/D$  value.

As described in Section 3, in the UAM scenario, an agent is associated with each flying car. All the agents are assumed to have the same characteristics, which is not unrealistic because flying vehicles have been considered standardized and automated and to avoid collisions, agents, also assisted by the Agency (see Section 3, point d), are compelled to respect some constraints.

To perform the experiment, the minimum flight height has been set equal to 40 m, which comes from the hypothesis that the highest building in the given urban context is no more than 25 m and there

is a suitable distance of 15 m between the building roof and the lowest agent's height position, which has been considered proper to meet the minimum safety and security issues. Note that, setting different minimum height for skyscraper urban contexts could require some additional conditions on the initial hypothesis here made about uncongested aerial links, i.e. depending on the maximum allowed flight height. However, it is not in the aim of this study to explore these additional conditions. The ground speed follows the empirical relationship  $v = a - b \cdot f$  (see also note at point 3.c in Section 3). As the number of agents on a given link increases, such speed is modified accordingly, and the travel time is computed.

For aerial links, the cruise speed has been set in the range [80, 120] Km/h according to the aerial link length and height. As for potential waiting times to access the aerial links, the departing time from the transition node depends on the expected ground travel time to reach such node from the origin and the expected flying time to reach the destination transition node. In particular, the Agency will provide information about the current state of the transportation network to each  $A_i$  and, therefore, for each  $A_i$ :

- (i) The expected travel time to go from the origin to the destination node is computed, according to the real number of agents already using the transport links;
- (ii) If there are no other agents at the expected arrival travel time at both the departing and arrival transition node, then  $A_i$  moves on the network along the computed path to reach its destination;
- (iii) Otherwise,  $A_i$  will wait at the trip origin until a suitable free slot is ready.

This condition allows for avoiding:

- (i) Waiting times at the departing transition node, which could generate undesirable queues and ground traffic jams near the transition nodes;
- (ii) Unsuitable flying queues at the arrival transition node. The possible waiting time contributes to the total path travel time so that in some traffic conditions only-ground paths might be comparable to, or even better than, "ground + flying" paths, particularly for short distances.

Finally, when reaching the transition node for accessing the aerial link, for each  $A_i$ :

- (i) The travel time to reach the assigned height depends on the maximum acceleration ( $a_{i,g} = 2.5 \text{ m/sec}^2$  [53]) and the assigned speed (from 80 to 120 km/h according to the distance between transition nodes and the assigned height);
- (ii) The travel time to move along the aerial link depends on the assigned cruise speed;
- (iii) The travel time to arrive at the destination transition node depends on the allowed deceleration to land at a suitable speed compatible with the maximum allowed ground speed.

The path cost has been computed by using a minimum path search algorithm [54]. For the first UAM scenario ( $S_0$ ), a free-flow travel cost has been assumed for all the ground links, under the hypothesis of a baseline trip demand, split into 5-min time slices, that produces low-level link flows. To simulate further scenarios under several traffic levels, the trip demand has been increased by 15%, 30% and 45% compared to  $S_0$ . As demand increases, link traffic flows increase and then link travel costs increase. To consider such effects, each agent identifies its minimum cost path at a given time, corresponding to the traffic flow condition on the network at that time. As the agent moves on the links belonging to its path, each link cost function is updated to include the additional agent moving on it. The following agent will choose its minimum cost path according to these updated values.

In the agent model, after a trial-and-error procedure, the minimum distance of  $d_{min} = 1500 \text{ m}$  has been set as the one under which only the ground mode has been considered. In fact, the hypothesis of landing/take-off allowed only at given transition areas, which is reasonable and coherent with the previous hypothesis about the city structure, also means that there are few areas where transition is allowed. In addition, this is also coherent with safety requirements about intersection trajectories among flying vehicles that may occur at different heights during the transition from flying to ground and vice-versa.

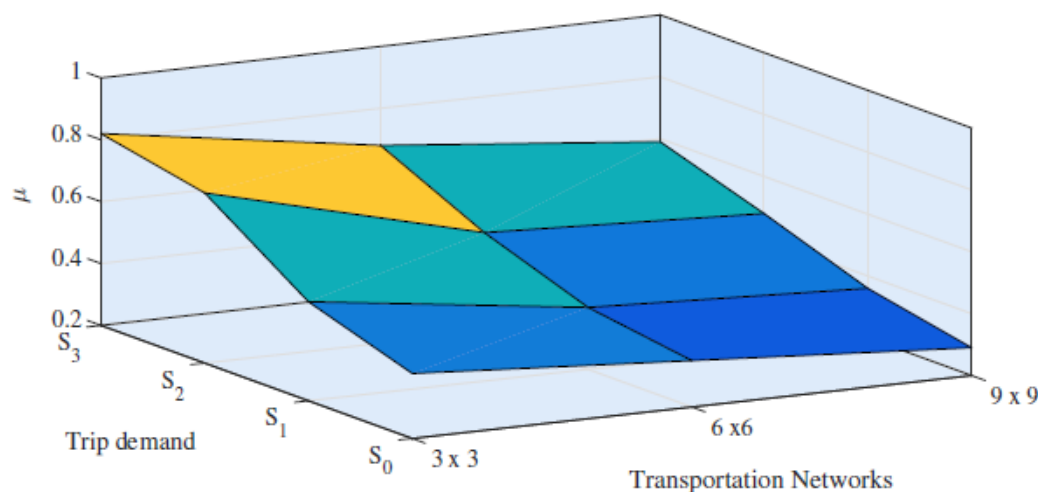
As for the flying mode, the aerial network has been considered virtually uncongested for each traffic condition, as agents may use lanes at several heights separated each other by  $s = 5$  m (see Section 3). Finally, in a reference scenario where no flying vehicles are allowed, the agent model described in Section 3 is limited to the ground part, the travel times do not include flying components and then  $\mu = 1$ .

#### 4.3. Results

For each of the considered transportation networks and  $O/D$  trip matrices, the agent-based simulations have been made and the value of  $\mu$  has been computed (see Table 1 and Figure 6).

**Table 1.** Simulation results.

|                            | 3 × 3 Modules<br>$\mu$ | Transportation Networks 6 ×<br>6 Modules<br>$\mu$ | 9 × 9 Modules<br>$\mu$ |
|----------------------------|------------------------|---|------------------------|
| $S_0$ (Baseline $O/D$ )    | 0.41                   | 0.35  | 0.29                   |
| $S_1$ (15% $O/D$ increase) | 0.52                   | 0.40  | 0.36                   |
| $S_2$ (30% $O/D$ increase) | 0.75                   | 0.52  | 0.48                   |
| $S_3$ (45% $O/D$ increase) | 0.82                   | 0.68  | 0.59                   |



**Figure 6.** Simulation results.

As Table 1 shows, an increase in the demand level generally produces an increase in the total travel times—measured by the value of  $\mu$ —for all the test transport networks. Generally speaking, the travel time increase is more relevant for the smallest network, where the aerial links are expected to be less used because of the smaller distances. When the network size increases (from  $3 \times 3$  to  $9 \times 9$  modules) and then the average distances increase, there is a gain in the total travel time because the longer leg of the trip will be travelled by using aerial links, the travel times of which are shorter than ground travel times. Generally, aerial links are convenient on the longer distances, while ground links must be used for the shorter leg of the trip to reach the specific destination from the transition node and vice versa. When the demand level is increasing, as in scenarios  $S_1$ ,  $S_2$  and  $S_3$ , the ground traffic flow component increases, then ground travel times increase too and travel-time savings reduce with respect to  $S_0$ .

## 5. Discussion and Conclusions

The agent model set to simulate the selected case C has provided a preliminary analysis for a possible large use of flying cars in UAM scenarios. As a general comment, the results obtained show that an increasing use of flying cars produces contrasting effects on the ground network depending on

the network size and the amount of demand. For the latter, an increase in trip demand level generally produces an increase in link traffic flows, which, in turn, produces an increase in travel costs according to a congested network approach. In these conditions, and as known from the literature referring to user equilibrium traffic flow assignment (see, for example, [52,55]), an agent's path choices will change depending on link travel times, thus producing a traffic flow distribution on the network. The particular feature of the network here is that some of the links, specifically aerial ones, have been considered uncongested—which at a first attempt may be considered reasonable because horizontal lanes at several vertical heights are possible—and then travel times on aerial links do not depend on traffic flows. At the same time, the use of such links is limited to transition nodes, in other words, although travel times on aerial links are generally more convenient because *i*) aerial link speed is greater than ground link speed and *ii*) link travel times do not depend on the amount of traffic on such links, to use them, the transition node must be reached by ground mode. Since the structure of cities has been considered as the current one, flying and ground modes co-exist because individual trip origins and destinations are reached only by ground accesses. As a consequence, not all the trips are suitable for flying legs. In fact, when ground traffic increases and then travel times generally increase, reaching transition nodes to use the aerial links is not necessarily more convenient than using an only ground path for the given *O/D* pair. In addition, in some traffic conditions, waiting times at the origin are possible, thus increasing the overall travel time.

Although limited to this first set of experiments and the hypothesized scenarios, however, two main preliminary comments about the use of individual flying cars in urban contexts can be carried out: *(i)* they are not necessarily more convenient and sustainable than current ground mobility when the demand level is increasing; *(ii)* the potential advantage is linked to the *O/D* pair distance, the location of transition nodes and demand level. It is worthwhile to note that an increasing level of trip demand may depend on population increase but also on increasing flying car share. In other words, some appealing properties—such as the opportunity to bypass ground congestion—could generate increasing purchases, thus increasing the use of flying cars in future scenarios, which, in turn, would produce an increase in network congestion.

Further research is required to better understand how UAM scenarios could be planned, which depends on still open questions linked to key features associated to the possible large use of flying cars, and how sustainable they could be in terms of life quality. A first important step is to set standards and safety/security regulations, both for those on board and those who are overflown. Current rules do not consider the possibility to fly over the city at low altitudes, except some specific, authorized flights. If flying cars are approved, such rules should be changed and adapted to new scenarios, by keeping safety and security conditions at high levels. The vehicle itself requires particular attention. As an object that moves in the air, it should be certified according to the International Civil Aviation Organization (ICAO) standards, which currently do not exist and should eventually be designed for this type of vehicle. Before entering the market, companies should approach regulator bodies (for example the European Authority for Aviation Safety in Europe) and agree with them on some vehicle requirements.

The future of flying vehicles will depend on policies and urban planning other than technical features. UAM scenarios require new rules and technologies to manage the “flyground” transport system as well as suitable Flying Control Systems, here simulated by the UAM Agency, that should deal with a great amount of data and ensure the safe and secure control of the system. On the other hand, the current urban structure of cities is unsuitable for flying vehicles in general and then the relevant question is whether flying cars will adapt to the current organization and driving rules or if we should imagine, starting from now, new management and organizational features for cities that will meet future flying car characteristics.

Finally, as for the agent model tested here, further advancements are expected by simulating the aerial congestion, the impacts due to waiting times for starting aerial trips under controlled conditions,

and the optimization of transition node location. Network design issues also deserve greater attention, particularly for the aerial component of the trip.

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