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# Competitiveness of on-demand air taxis regarding door-to-door travel time: A race through Europe

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ABSTRACT

We design and implement a door-to-door travel time estimation framework, which aims to analyze the potential competitiveness of on-demand air taxis in Europe when competing with existing transportation modes: car, railway and traditional air transportation. Our grid cell-based framework, opposed to previous studies, allows for fine-grained, high-resolution estimation of travel time lower-bounds between any points in the region of interest. Region-specific results on domination points and competition transitions of all modes are obtained and reported. Our work helps to understand the competitiveness of on-demand air taxis through the lens of door-to-door travel time estimation. keyword: On-demand air mobility; Competition range; Grid-based framework.

## 1. Introduction

As a result of increasing urbanization, and enforced by the large rise in population, traffic problems become more acute all over the world, particularly with the rise of so-called megacities (Kraas, 2007). These agglomerations of multi-million populations, e.g. London, Beijing, Sao Paolo, Sydney, and Mumbai, face a tremendous amount of transportation demands. The core problem is the same everywhere: Londoners loose an equivalent of 35 working days per year. The traffic chaos in Sao Paolo costs the Brazilian economy at least 30 billion dollars per year. The average commute time for Mumbai residents exceeds a staggering 90 min per day. Moreover, not only the pure waste of time/money should be considered, but also the effect of these stresses on the human body and the environment. Accordingly, given the wide extend of problems with traffic nowadays, it is clear that there is a need for a significant change. Solely increasing capacities of existing transport modes does not lead to the desired goals.

In urban traffic, with less than 500 km distance, the third spatial dimension (= altitude) is largely ignored so far. Traditional air transportation is considered as a valid option for longer distances only (Sun et al., 2017), particularly given the large amount of time required for boarding/de-boarding, security checks, and baggage claims. These additional factors increase the total door-to-door travel time significantly, compared to approx. 700 km/h speed in the air, depending on the distance traveled. Therefore, nowadays it is difficult for air transportation to compete with ground transportation, particularly, given the recent advancement in high-speed rail technology. For instance, now it is possible to travel from Berlin to Munich, a distance of around 650 km using the latest ICE (Inter-City Express) technology within 4 h. The exterior locations of Munich Airport, as well as, to-be-opened Berlin Brandenburg Airport,

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make it increasingly harder for scheduled aircraft to compete with the improved high-speed railway network.

Throughout the last decade, the third dimension, altitude, has risen as a promising solution for satisfying transportation demands on a shorter range. Accordingly, many companies have started to design prototypes, such as the Chinese eHang184, German Lilium, Kitty Hawk, Volocopter, Boeing-Aurora, and Airbus Vahana. On-demand, short–to–medium distance, personalized air vehicles (Schippl et al., 2013; Holmes, 2016) have the potential to radically improve urban and regional mobility, save time in peoples' daily commutes as well as on regional thin haul connections (Kreimeier et al., 2017). A network of small, electric or hybrid-electronic air taxis, which can take off and land at smaller areas, due to their limited size, is going to revolutionize the way we think about transportation. Conducting a conceptual study for the applicability and effectiveness of using on-demand air taxis is computational challenging, mainly due to the conflict of modeling a large urban area of up to 1000 km diameter and the desire to have a high-resolution model that can be used for accurate prediction of transportation mode usage, when introducing on-demand air taxi service.

At RWTH Aachen University in cooperation with the University of Applied Sciences Aachen a regional air taxi is developed, planned entry into service of the Silent Air Taxi is 2024. With four passengers, a range of 500 km can be reached in hybrid-electric mode, with two passengers onboard the range increases to 1200 km. Due to current regulations the vehicle is designed to initially carry a pilot. However, it is equipped with a high level of automation, such that in the medium term safety pilots on the ground will take over control of the fleet of Silent Air Taxis. The Silent Air Taxis have a short take-off and landing capability. Aiming for regional transport the capability for vertical take-off and landing is omitted due to efficiency considerations. Beyond 2030 in order to substantially decrease the door-to-door travel time the Silent Air Taxi will be qualified for take-off and landing on ground based landing systems (Binnebesel, 2013; Rohacs et al., 2014) of 150 m length. This enables the Silent Air Taxi to operate from roof tops of large buildings such as train stations or malls. A lifting body concept allows for a spacious cabin suitable for business travelers and senior passengers. The ducted fans together with an optimized sound quality will guarantee the possibility of 24/7 operation. Ticket prices will be similar to a first class train ride.

The purpose of this research is to design and implement a scalable simulation framework which can be used to assess the impact of on-demand air taxis, such as the Silent Air Taxi described above, on the existing transportation modes. This effort requires to solve several challenges, including data management, accurate modeling of multi-modal transportation infrastructure, and computation hurdles induced by the size of the region of interest. In this study, we develop a door-to-door travel time estimation framework, which is able to compute a lower bound for the travel time between any two points in the region of interest, taking into account four different transportation modes: car, aircraft, railway, and air taxi. Note that subway is not considered as a transportation mode in our current study, because our goal is to estimate travel time without congestion. Subway only has a significant advantage over car transportation in case of congestion/traffic jam. Since our study is concerned with minimum free-flow door-to-door travel time, we take car as a proxy for other public transportation modes, including subway, tram and bus.

We integrate multiple datasets which are available at planet-scale and show how they need to be adapted for estimating travel time boundaries. In detail, we combine transportation data modeled in Openstreetmap (OSM) with the publicly available Open Source Routing Machine (OSRM) and OpenAIP, a dataset on airspace restrictions. Moreover, for determining properties of the regions of interest, such as water/land-coverage and population density, we use the database Gridded Population of the World (GPW). Throughout the study, we model the transportation inside a region of interest by splitting the region into a number of grid cells, which allows for much more fine-grained analysis, compared to traditional inter-city models.

This paper is organized as follows. In Section 2, we introduce and discuss the relevant literature on air taxis. Section 3 describes the methodology for estimating the door-to-door travel time with different transportation modes at a large scale and with fine resolution. We report the results of an experimental evaluation on Europe in Section 4. The paper is concluded with Section 5.

## 2. Literature review

Several researchers have investigated the emerging business model of on-demand air mobility. Potential market size of thin-haul on-demand air mobility services in Germany was estimated (Kreimeier et al., 2017), with a comprehensive analysis of the entire German population and their linear spatial distances to feasible airfields. Economical assessment of on-demand air mobility with focus on the German market has been conducted (Kreimeier et al., 2016); the willingness-to-pay for the on-demand air mobility was determined, depending on several factors, such as travel speed, distance, convenience, spare time for non-transport related activities, and spontaneity to start a journey. Liu et al. (2017) provided an overview of recent research efforts on personal air vehicles, focusing on the US and Europe research activities. It was found that despite of the dramatic technology innovation, several challenges still remain in the ultimate application of personal air vehicles, especially safety, infrastructure availability and public acceptance.

A few studies analyzed the network topologies of on-demand air taxis. Bonnefoy (2005) evaluated the very light jet air taxi networks in the US, including demand modeling with the gravity model, trip generation based on Monte Carlo simulation, aircraft routing and pilot assignment, as well as unscheduled maintenance events. However, only scenario testing was performed because of lack of air taxi data. The impact of accepting different percentages of passenger-demanded trips and fleet size on the potential profitability of air taxi services was evaluated in Mane and Crossley (2007). A weighted network analysis tool to analyze the on-demand air mobility network was presented (Wawrzyniak et al., 2009), with real-world cargo aircraft movement data within the US central command area of responsibility in the year 2006.

On-demand air taxi service features door-to-door travel patterns, this also indicates more dynamic and complex operations. Moreover, non-revenue-generating trips (repositioning flights) should exist to meet the dynamic demand. Among on-demand aviation services, there are several types of programs: Fraction ownership, time-share, joint ownership and so on Yao et al. (2005). While fraction ownership allows different stakeholder to use aircraft resources for a fraction of time at different levels, it is gradually gaining more popularity. Yang et al. (2008) proposed a set partition model for the Fraction Management Company (FMC) to solve aircraft scheduling problem and verify it using a dataset with at most 76 nodes and 100 aircraft. He further extended the model (Yang et al., 2010) to consider uncertainty in demand and aircraft resources to obtain a robust scheduling. Experiments were carried out under different demand distribution over 100 city nodes. Van der Zwan et al. (2011) adopted the Yang's set partition model (Yang et al., 2008) and provided a detail description of aircraft routing problem for per-aircraft air taxi operator. Contrary to the column generation used in Yang et al. (2008), they used a K-shortest path alike algorithm to generate feasible routing pools for set partition. The instance included 225 airports over 72 h time horizon. Espinoza et al. (2008) presented an integer multi-commodity network flow model for on-demand air transportation service and solved large instances with over 300 aircraft and over 2,800 requests by parallel local search algorithm (Espinoza et al., 2008). Munari (2017) proposed a standard mixed-integer programming model for on-demand aircraft assignment problem, with multiple types of aircraft and a set of flight requests, and the objective function is to minimize the total costs with reposition flights. The problem instance was up to 102 flight requests, 52 airports, 30 aircraft, and 6 aircraft types, and CPLEX was used to solve this problem. Mane and Crossley (2012), on the other hand, tried to combine aircraft allocation and aircraft design together, in order to solve concurrent aircraft design and operations planning problems. The integer programming model entailed revenue generating trips, non-revenue-generating trips, and charter flights. It was tested through direct CPLEX implementation for an instance of 10 city nodes because of the complexity of the model formulation.

There are several operational challenges when implementing on-demand air transportation systems. With the case study of Log Angeles, (Vascik and Hansman, 2017a) identified key operational constraints facing hypothetical on-demand mobility aviation services, among which five are critical: Noise and public acceptance, accessibility of takeoff and landing areas, interaction with air traffic control, ground infrastructure, and flight density. The first three key operational constraints were further investigated in Vascik and Hansman (2017b) and potential mitigation approaches were discussed as well. Hsiao et al. (2014) developed an air passenger demand model for the cross-Taiwan-Strait markets, including demand generation and demand assignment. It was shown that GDP, investment, flight frequency, flight time, and ticket price have significant impacts on the demand; two markets (Taiwan-Shanghai and Taiwan-Guangdong) have higher potential for air taxi services. In order to ensure the best possible match between supply and demand for an air taxi company, (Farhoudi et al., 2010) used a system engineering design method together with a design-to-value requirement analysis to model the values. de Jong (2007) investigated the operational costs of air taxi operations and a dynamic programming approach was used to perform cost-effective and flexible optimization of the costs. A case study with ten airports, 38 routes, and 270 flight request per week was used to represent the air taxi network of Etirc Aviation (a company which operates personalized business flights in Europe and Russia). Lee et al. (2008) proposed a single provider air taxi service model, characterizing the week-to-week flow of passengers and aircraft. Two models were compared: discrete-event model and a flow model. It was shown that the flow model could be used for a pricing application. Because of the absence of data, hypothetical air taxi service scenarios were used.

Public acceptance of the personal air vehicles, especially unmanned air taxis, is a key question of their application in the real world. An opinion survey, with 400 individuals representing the general public and 135 individuals representing key stakeholder groups, was administrated to assess participants' knowledge, attitude, and practices about unmanned aircraft (Reddy and DeLaurentis, 2016). While it was found that the support or opposition to unmanned aircraft is conditional for most responders; women and respondents more than 36 years old from the general public, as well as pilots and employees from the airline industry, are less supportive of unmanned aircraft. Factors which influence the decision to fly on fully autonomous passenger airlines were investigated in Vance and Malik (2015). It was shown that the integrity characteristics of the airline is the most significant positive influence; while the life insurance liability guarantee is the most negative influence. In addition, with some adaptation on the age and profession demographics to match the US population, it was found that there are around 30%, who is willing to fly, is bounded with 95% probability.

## 3. Methodology: Door-to-door travel time estimation

In order to study the competitiveness of air taxis, we develop a door-to-door travel time estimation framework, which is able to compute a lower bound for the travel time between any two points in the region of interest. We integrate multiple datasets which are available at planet-scale and show how they need to be adapted for estimating travel time boundaries. In detail, we combine transportation data modeled in Openstreetmap (OSM) with the publicly available Open Source Routing Machine (OSRM) and Open AIP, a dataset on airspace restrictions. Moreover, for determining properties of the regions of interest, such as water/land-coverage and population density, we use the database Gridded Population of the World (GPW). In the following subsections, we describe how these datasets are combined into a general door-to-door travel time estimation framework, which is then used in Section 4 to assess the potential competitiveness of air taxis compared with traditional transportation modes, including car, aircraft, and railway.

### 3.1. Grid-based model

Throughout our study, we model the transportation inside a region of interest by splitting the region into a number of grid cells. Such a grid representation allows for much more fine-grained analysis, compared to traditional inter-city models. In Fig. 1, we visualize a part of Europe (see Section 4 for details about selected countries) as overlaid by a grid, highlighting grid cells with a population larger than the mean of all grid cells. Varying the number of grid cells makes it possible to trade estimation accuracy for computation feasibility. The latter is surprisingly complex, given that having $N*N$ grid cells, we are interesting in potentially $(N*N)^2$ travel time estimations. For a resolution of 200∗200, the setup used in our study, this yields approx. 1.6 billion grid cell pairs.

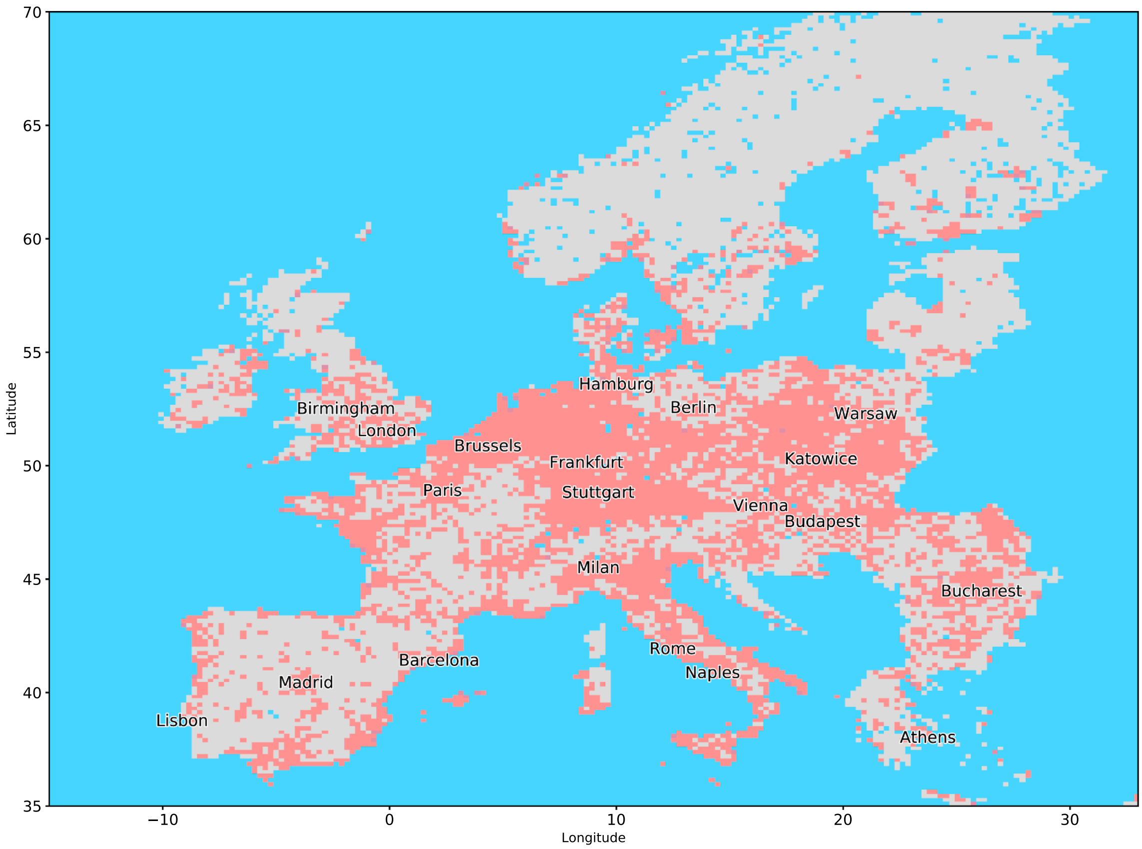


**Fig. 1.** A grid-based visualization of the 29 European countries (ISO-3 country codes): AUT, BEL, BGR, CHE, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GBR, GRC, HRV, HUN, IRL, ITA, LVA, LTU, LUX, MLT, NLD, NOR, POL, PRT, ROU, SVK, SVN, SWE, at a resolution of $200 * 200 = 40{,}000$ grid cells. Light-blue grid cells contain more than 50 percent water at the cell center coordinate. The pink cells have a population density above the mean of all 40,000 grid cells. All remaining cells are land cells with population density below or equal to the mean of population density. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

At such a scale of multiple million of travel time estimations, the usage of public routing systems becomes infeasible, given restrictions on the number of queries or fair use policies. In general, these routing services limit the number of (free) queries per hour; in order to enforce their fair use policies. Moreover, since we want to compare different transportation modes, one of which is not established yet, we aim to implement a fair and comparable door-to-door travel time estimation framework based on open data (see Fig. 2). This framework allows to make a prediction for the best-case travel time, e.g., free-flow time for using a car. For our study, the estimation of best-case travel times already poses many conceptual and computational challenges, which are solved below. Additional factors, for instance regarding congestion and delay, can be taken into account as future work, possibly extending our estimation framework.

### *3.2. Door-to-door travel estimation between two grid cells by car*

Since it is infeasible to use existing, web-based routing engines, such as those provided by Google or Bing, we develop our own framework for estimating travel times between any two points (= grid cell centers). For the travel time estimation with cars, we use Openstreetmap in combination with Open Source Routing Machine, which are briefly summarized below.

Openstreetmap (OSM) is a community-driven project which aims at creating an editable map of the whole world available for free use. According to recent studies, the data stored in OSM is largely complete, particularly for urban areas (Neis and Zielstra, 2014). Interestingly, the efforts of the OSM community on modeling transportation infrastructure have made it possible to use OSM as a reliable source for routing and network analysis: transportation modes throughout the world are being modeled, including physical layout of streets, speed limits, railway stations, etc. The project Open Source Routing Machine (OSRM) (Luxen and Vetter, 2011) has developed scalable implementations for routing vehicles with different speed profiles at continental scale based on OSM data. The implementations of algorithms are released as server application (see http://project-osrm.org/). OSRM achieves scalability by simplifying shortest path calculation with the use of so-called contraction hierarchies, which allows to take shortcuts during the answering of longer-distance queries.

For this study, we make a set of assumptions, which aim at making the car travel time estimation more realistic. The vehicle width

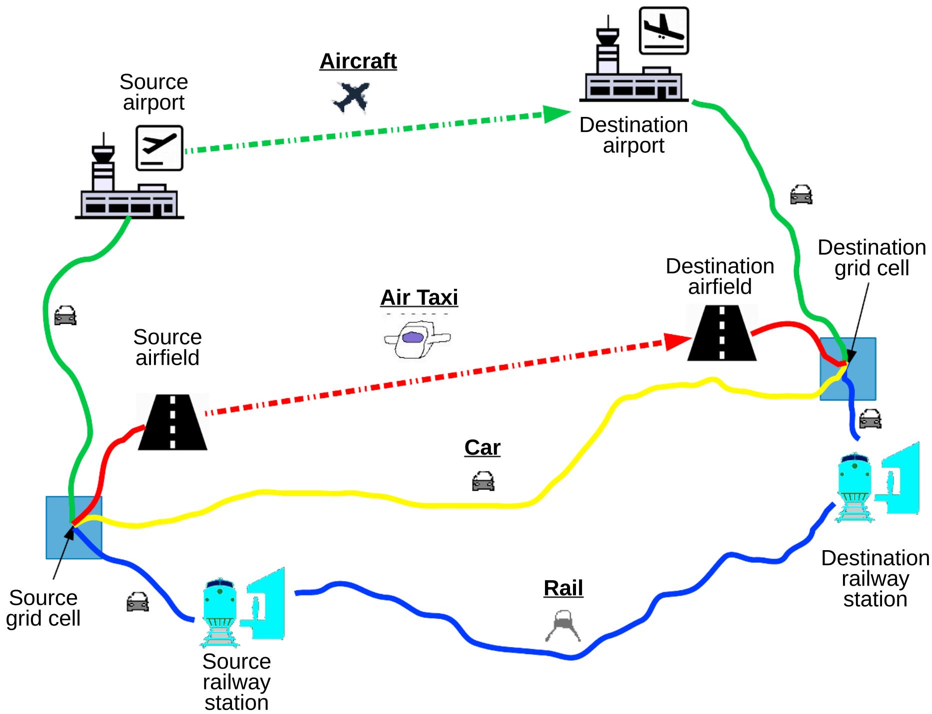


**Fig. 2.** Four different transportation modes considered in this study, for traveling from a source grid cell center (left) to a destination grid cell center (right).

is assumed to be 1.9 m and the height at most 2.5 m (which is important to consider when deciding whether narrow streets can be passed by a vehicle or not). The default speed on highways is assumed to be 90 km/h, unless the speed is explicitly annotated in OSM. Different speed constants are assumed for other non-annotated rural roads, depending on the road surface, i.e., rocky roads at 20 km/h and mud roads at 10 km/h. We have included turn restrictions as they are modeled in OSM; also we included the option for transporting cars by ferries from OSM-modeled car terminals (at a speed of 5 km/h) and transporting cars by shuttle trains on modeled routes (at a speed of 10 km/h). Note that these speeds are not the average realized velocities, they are the maximum speeds each segment of certain highways. In this case, average congestion is not included in the annotated speed, and thus, our framework provides a free-flow travel time between two points in the region of interest.

Furthermore, OSM distinguishes several types of roads, depending on their importance. The fraction of ways being annotated with maxspeed values is rather high for segments with high importance, e.g. motorway (two or more running lanes major divided highway, 87.9%), trunks (major roads which are not highways, 74.2%), primary (linking larger towns, 63.7%), and secondary (linking towns, 48.7%). For all non-annotated roads, OSRM has a mechanism to predict the maxspeed values based on road type and country, with pre-defined values. Overall, this makes the estimation of free-flow time rather accurate.

According to our own experiments with commercial travel direction services (particularly, Google Maps and Baidu Maps), the free-flow travel time estimation of these services coincides with the routing time from OSRM. It should be noted that, once congestion or other external events are taken into account, the travel time might increase. Our current study provides a lower bound estimation of door-to-door travel times in order to compare the potential competition range. Future studies could include congestion; but it would be very challenging to model these effects at a larger scale. To sum up, the door-to-door travel time between two grid cells $g_1$ and $g_2$ by car is estimated by: $T_{car} = T_{OSRM}$, where $T_{OSRM}$ is obtained from routing with OSRM over OSM data.

### 3.3. Door-to-door travel estimation between two grid cells by air taxi

We estimate the lower bound for the travel time by air taxi between two grid cells $g_1$ and $g_2$ as follows:

$$T_{airtaxi} = T_{access} + T_{boarding} + T_{flight} + T_{deboarding} + T_{egress} \tag{1}$$

We explain the components of the door-to-door travel time by air taxi $T_{airtaxi}$ below. First, we compute the access time $T_{access}$ by car from $g_1$ to a nearby airfield; we evaluate multiple airfields, see below. Next, we take into account a buffer time $T_{boarding}$ which stands for leaving the car, entering the airfield, and boarding the air taxi. In the initial operation phase of the silent air taxi, we assume that one pilot is on board and the pilot will assist or be in charge of the passenger boarding process. This is a pragmatic way for the case that the silent air taxi has one pilot on board. When the pilotless silent air taxi becomes a reality, we think the passengers would go through some fully automatic scanning machines prior to boarding the air taxi. Throughout this study, we set $T_{boarding} = 20$ min. $T_{flight}$ is the actual flight time between two airfields, one close to $g_1$ and another airfield close to $g_2$.

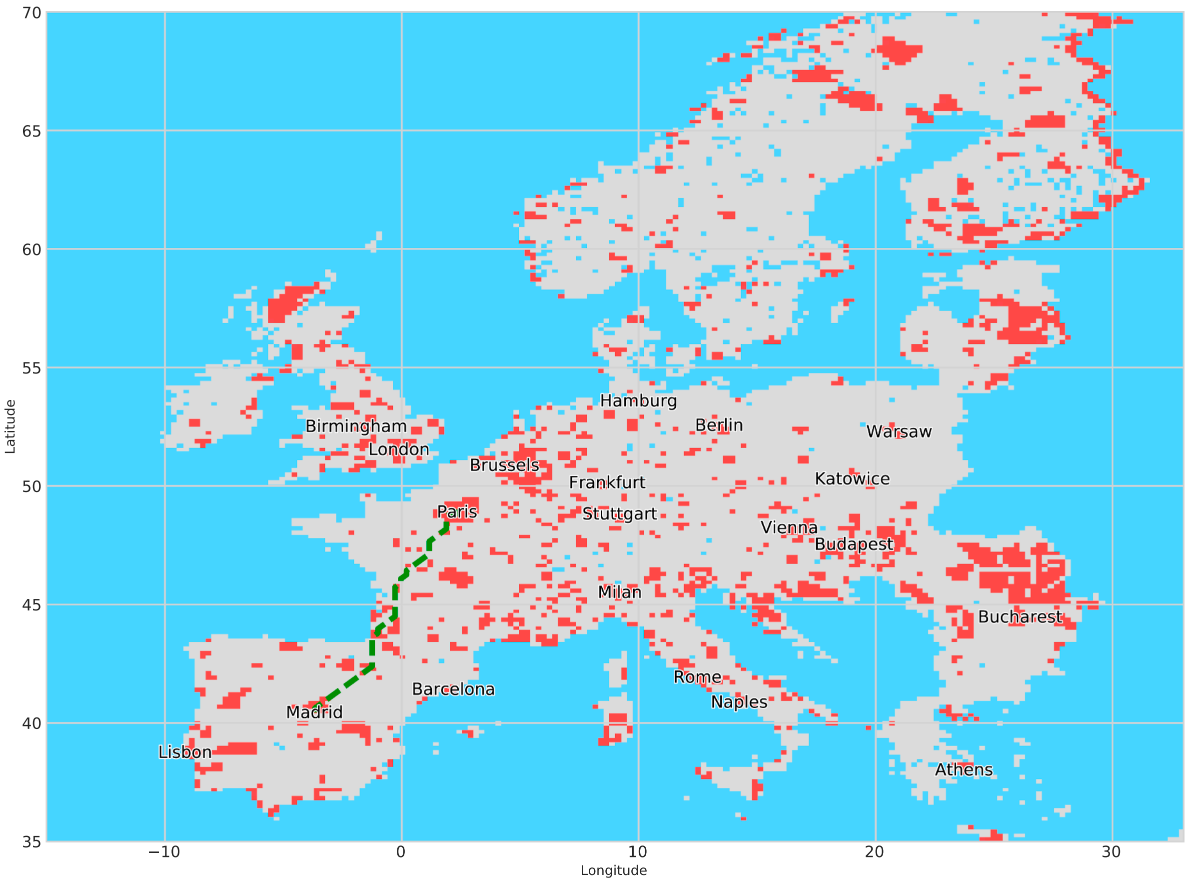


**Fig. 3.** A grid-based visualization of the airspace over Europe at flight level 100, as obtained by airspace descriptions from OpenAIP (http://openaip.net), at a resolution of 200 ∗ 200 = 40,000 grid cells. Light-blue grid cells contain more than 50 percent water at the cell center coordinate. Red cells visualize a grid cell with existing flight restrictions. All remaining cells are land cells. The green lines visualize the obtained air taxi trajectory from Paris to Madrid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Typically, air taxis cannot fly directly along the great circle between origin and destination, given that there exists many airspace restrictions at different flight levels. These restrictions protect important/sensitive infrastructure, e.g. military areas or nuclear power plants. Moreover, the area around airports is usually also restricted to aircraft that are either landing or departing from that airports. Since the area and type of restrictions largely depend on the country, we use a publicly available dataset, OpenAIP, a crowd-sourcing effort and has the goal to provide free, yet precise navigational data to the public. Data is grouped by country and contains information on all flight levels and provided in country-specific files in an XML-like format. We estimate the actual flight time by routing air taxis through non-restricted airspace along the shortest available route. At an average speed of 200 km/h at flight level 100, avoiding zones with flight restrictions as: prohibited, danger, and restricted. Fig. 3 shows an example for routing an air taxi from Paris to Madrid, using OpenAIP data.

The time $T_{deboarding}$ is set to 15 min, which includes passengers leaving the air taxi and passing through the airfield. Finally, $T_{egress}$ estimates the time driving from an airfield to the center of the destination grid cell by car. Both, $T_{access}$ and $T_{egress}$, are obtained by computing $T_{OSRM}$ as described in Section 3.2.

Regarding the choice of source and destination airfields, we use a simple selection strategy as follows: For each grid cell (source/destination), identify three closest airfields, in terms of driving time, and then compute $T_{airtaxi}$ for all 3∗3 combinations of source and destination airfields. Finally, take the minimum $T_{flight}$ from all nine combinations as an estimation for the shortest travel time by air taxi. The intuition of choosing three closest airfields is that, given we do not consider actual flight schedules, we wanted to cover a sufficient number of airports in each direction of a grid cell. Our own experiments showed that with three airfields, the choices become reasonable, i.e. avoiding to drive for an airport 100 km West, in order to fly to the East afterwards. Alternatively, one could also introduce a distance threshold.

The airfield information (location, offering scheduled flights or not), comes from an open airport database (http://ourairports.com). We have only selected airfields without scheduled services. The rationale is that air taxis are unlikely to use large airports such as Frankfurt (FRA) or Berlin-Tegel (TXL), simply because there is not enough capacity, especially departure/arrival slots. Regional airports without fixed schedules, on the other hand, are likely to welcome air taxi operators to use their airfields.

There are also other possibilities to improve the selection of airports, given that in some cases smaller regional airports with scheduled services also accommodate general aviation, such as private jets. Indeed, these smaller regional airports could also accommodate air taxis in the future because of their underutilized capacity. Unfortunately, we do not have capacity data for all airfields in Europe, therefore, the distinction by scheduled services was the most realistic and feasible option.

### 3.4. Door-to-door travel estimation between two grid cells by aircraft

Similarly to the door-to-door travel time estimation for air taxi, we estimate the travel time for aircraft between two grid cells $g_1$ and $g_2$, with some modifications explained below:

$$T_{aircraft} = T_{access} + T_{outbound} + T_{flight} + T_{inbound} + T_{egress} \tag{2}$$

$T_{access}$ and $T_{egress}$ are computed in the same way as for $T_{airtaxi}$. The difference here is regarding the choice of source and destination airport: For the routing of aircraft, we only use airports which have scheduled flights according to http://ourairports.com. Other airports (smaller ones, without scheduled flights) are discarded for routing aircraft. $T_{outbound}$ includes the process of check-in, departure passport control, security check, and boarding the aircraft; while $T_{inbound}$ includes the process of arrival passport control, customs inspection, and baggage delivery (if the passenger has any). We set $T_{outbound} = 75$ minutes and $T_{inbound} = 20$ minutes, given the more strict requirements on check-in, luggage handling and security checks, together with limited capacities, at large airports.

Finally, $T_{flight}$ is obtained by routing the aircraft through the airspace at flight level 300, instead of flight level 100; at an average speed of 600 km/h. In the current study, we only use airports which have scheduled flights for the aircraft routing; the actual networks offered by airlines are not included. This could be one further research direction to show the commercial viability of air taxi services in the absence of scheduled flights.

### 3.5. Door-to-door travel estimation between two grid cells by railway

The railway travel time is composed of the following elements:

$$T_{rail} = T_{access} + T_{boarding} + T_{train} + T_{deboarding} + T_{egress} \tag{3}$$

$T_{access}$ is the access time by car to a railway station, $T_{boarding}$ is the time spent at the railway station (15 min), $T_{train}$ is an estimation of the actual travel time by train, $T_{deboarding}$ is the time spent at the destination station (15 min), and $T_{egress}$ the time required from the destination station to the center of the destination grid cell by car. For estimating the train travel time, $T_{train}$, we use a recently published methodology based on Openstreetmap. We briefly summarize the procedures here, for details please refer to Wandelt et al. (2017).

1. **Data extraction**: Raw data from Openstreetmap pbf files are loaded into an intermediate data structure which allows us to fix inconsistencies in the mapping process, mainly concerning the normalization of node and link attributes, as well as their hierarchical propagation from relations to ways and nodes.
2. **Connecting the network**: Induced by mapping inaccuracies, the railway network as modeled in Openstreetmap is highly disconnected. This step addresses the problem by merging nodes (and thus components) efficiently, based on a filter-and-refine framework.
3. **Connecting stations to the network**: The Openstreetmap community often models railway stations as individual ways/relations not connected to the actual railway infrastructure. In this step, all such stations are connected to the railway network within a distance threshold of 500 m.
4. **Network simplification**: The network obtained by the previous steps is highly complex (having millions of nodes), where many nodes have a degree of two, i.e., exactly two neighbor nodes. We simplify the network significantly, while preserving the real distances and indications of maximum speed.

The result of the processes described above is a weighted network: Nodes represent stations; links describe the connection between these nodes and are annotated with temporal information, obtained by the maximum speed and spatial distance (see Fig. 4). We explain this concept further as follows: If an Openstreetmap way is annotated with a maximum speed of 250 km/h, and the way has a length of 700 m, then we annotate the link in the network with a travel time of $\frac{700 * 3600}{250 * 1000} = 10.08$ s. The resulting weighted network is used to estimate a lower bound of the travel time between any two railway stations in the network, by simply transforming them into shortest path computations between these stations.

Note that we use the available annotated maximum speed of the rail track (infrastructure) to estimate a lower bound for the travel time by train. If the maximum speed of a rail track is not available in the Openstreetmap, we use 100 km/h instead. We did not use average speed, we assume trains can travel at the maximum speed in the current study.

## 4. Results

In this section, we report the results of our study, by evaluating the potential competitiveness of air taxis regarding door-to-door travel time in Europe. For this purpose, we define the region over Europe as the area covered by the 29 countries listed in Table 1 (in the Appendix). We analyze this region of interest at a resolution of $200*200 = 40{,}000$ grid cells. At this resolution, a single grid cell is around $15*15$ square km at a latitude of 52 deg.

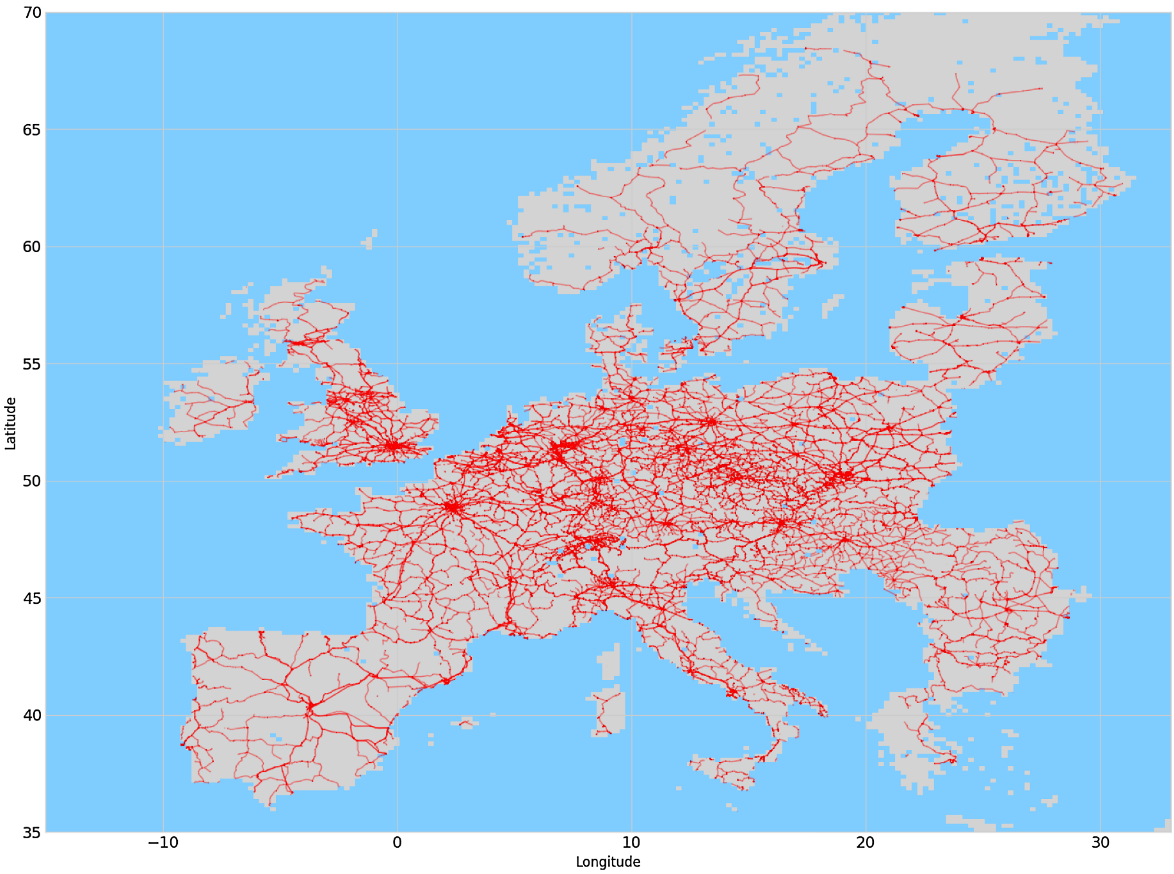


**Fig. 4.** Visualization of the railway network extracted from Openstreetmap.

### 4.1. *Competitiveness of air taxi from city-center regarding door-to-door travel time*

In the first part of our experimental evaluation, we analyze the competitiveness of air taxis against three established modes (car, aircraft, and railway) when travels start inside city centers. For this purpose, we first selected the 500 most-populated cities in Europe, visualized in Fig. 14 in the Appendix. According to their locations, these cities are representative for a large part of the European area in this study. Note that not all grid cells in three Nordic countries (Sweden, Finland, and Norway) are included, only the area covering top 500 most-populated cities is selected, since the populated cities are preferably located in the warmer, southern parts.

We first visualize the assessment methodology for a specific city as an example. Assume that we want to compare the competitiveness for all four transportation modes starting from the city center in Berlin (latitude: 52.5218, longitude: 13.4015). First, we identify the grid cell center closest to the given city center. Next, we estimate the travel time to all other grid cell centers belonging to one of the 29 countries in our study (approximately 14,906 out of 200∗200 = 40,000 grid cells). For each grid cell, we identify the fastest transportation mode regarding door-to-door travel time. The result is visualized in Fig. 5, with different colours for each transportation mode. As a general observation, the travel towards nearby grid cells is often fastest by car. With longer distances, the fastest transportation mode changes depending on the direction of travel: Staying inside Germany (i.e., west of the city center), the preferred mode is rail transportation; but when leaving towards the eastern part (Poland), air taxi has a clear advantage over the other transportation modes, which could be simply explained by the better railway structure/connectivity inside Germany, compared with the cross-domestic railway connections towards Poland. Once the distance to the destination grid cell is increased even further, traditional aircraft becomes the mode of choice, when considering the door-to-door travel time as the major decision driver.

We performed the operations described above for the top 500 populated cities in Europe; or, to be more precise, on the grid cells closest to these city centers. Fig. 6 visualizes the relative competitiveness of each mode for the top 20 cities with variable distances from the city center. One commonality among all curves, is that for short distances, car travel is dominating; while for longer distances aircraft is the fastest transportation mode. The main driver of deviation between the city charts is the transition between these two points and the degree of dominance for railway and air taxi, respectively. Exemplary, we compare the two cities of London and Warsaw. For London, the transportation between 100 km and 400 km is strongly dominated by railway. If one would like to enter this area with air taxi, one cannot gain a significant door-to-door travel time advantage. For Warsaw, on the other hand, air taxi does have a large potential to reduce travel times, compared to railway. This small example shows, that the decision on whether air taxi is

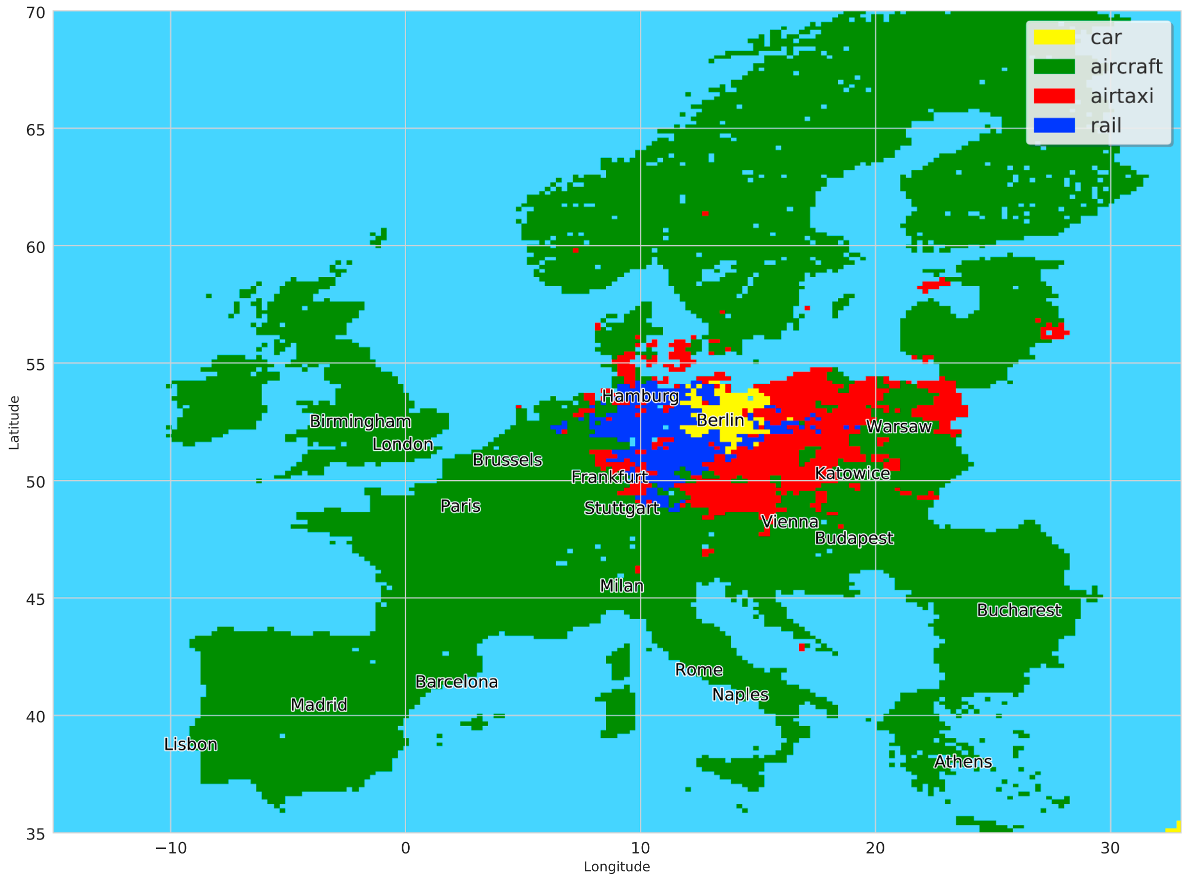


**Fig. 5.** Door-to-door travel time competitiveness of four transportation modes starting from the city center of Berlin (latitude: 52.5218, longitude: 13.4015).

a strong competitor, or not, largely depends on the region, with some extreme cases and many transitions in between.

In Fig. 7, we visualize the dominating competitor for each of the 20 cities. For this visualization, we split the curves on relative competitiveness at intervals of 20 km, and identify which mode is the most frequently used one. It can be seen that for most cities, we have either air taxi dominating or railway, but usually not both.

In order to understand how frequently railway and air taxi can coexist with each other, we compare the maximum relative competitiveness of both modes for all cities and the results are visualized in Fig. 8. There are two kinds of boxplots: the ones with purple colour on the left show the transition point where car is more competitive in terms of door-to-door travel time, comparing with other modes (aircraft, air taxi, and railway); the ones with green colour on the right show the transition point where aircraft is more competitive in terms of door-to-door travel time, comparing with other modes (car, air taxi, and railway). These two transition points are used to identify the potential competitive intervals between air taxi and railway, which are further analysed separately in Fig. 9.

It can be seen that the variation of domination distances inside a country is often smaller than for cities in different countries, which means that the distance threshold when people would shift from car to other modes (if only concerning shortest door-to-door travel time), depends more on the overall domestic infrastructure, than on a city-specific property. The overall median of all car-to-other-mode transitions is around 100 km. Notably, Finland, with large unpopulated area of coniferous taiga forests, has the highest median transition point for cars, which means that people use cars for much longer distances than, for instance, compared to Czech Republic, which has the smallest transition distance.

Given the two boundaries induced by car and aircraft, we proceed to analyze the competitiveness of air taxi with railway. The goal is to analyse for the top 500 cities which transportation mode is dominating (air taxi vs. railway) and also highlight the transition between both modes. In Fig. 9, we plot the maximum relative competitiveness of air taxi against railway, for each of the 500 cities in our study; and visualize the results with a 2D kernel density estimation. For the majority of cities, we observe a maximum competitiveness for air taxi of around 90–100%, which means that air taxi has at least a range in which they completely dominate the transportation (regarding shortest door-to-door travel time). Moreover, the dominance of air taxi has a direct influence on the competitiveness of railway. This result is less obvious than it sounds: We compare the maximum competitiveness of modes at wide, different ranges, i.e. the sum of all maximum competitiveness is not 100%. In summary, the major insight is that if a city has highly competitive mode for a specific distance, then the same mode is also competitive for other distance, i.e., there exists no cities where railway and air taxi would coexist for different destinations.

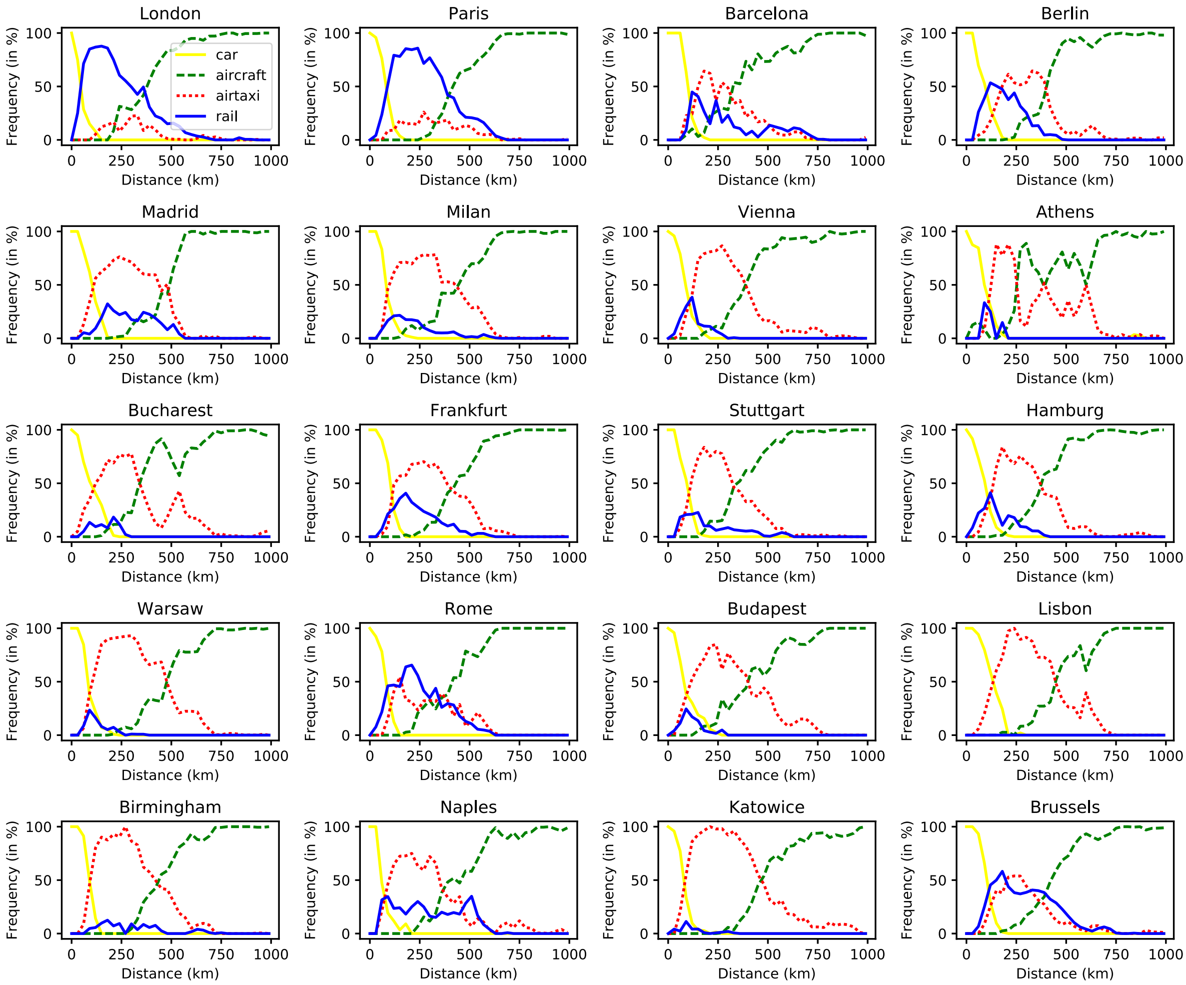


**Fig. 6.** Relative competitiveness for the top 20 cities in this study: The x-axis shows the distance in km; the y-axis represents the fraction of grid cell pairs with a given distance, where a certain transportation mode (car, aircraft, air taxi, or rail) is the fastest option. The curves are obtained by estimating the door-to-door travel time from the city center to all other grid cells. Distances are obtained by computing grid cell-center distances; the curve for mode *m* are obtained by computing the fraction of grid cells for a given distance where mode *m* is the fastest. We can observe that for London and Paris, rail is more competitive than air taxi.

In the next experiment, we aggregate the city-results at the country level, in order to see which countries are rather attractive for potential air taxi and which countries are better served by railway. The result is shown in Fig. 10. Surprisingly, for all countries, the majority of cities has a potential for air taxi to take a dominating lead for travel distances between 100 and 450 km. In fact, railway is only the dominating transportation option for the range of 100–120 km in Sweden, but does not occur in any other countries/distance ranges. This result confirms that air taxi has a bright future for bridging the existing transportation gap between car and aircraft, particularly on low-demand routes.

Fig. 11 reports the competition ranges of transportation modes induced by the top 100 cities in our study. It can be seen that car is the dominating transportation mode up to a range of around 80 km. Between 80 km and 130 km, there is a range of competition between car and air taxi, where air taxi is gradually replacing car as the fastest transportation mode, with increasing distance. In the same range, rail-based transportation reaches its peak, with a large confidence band up to 40%; the actual value largely depends on the grid cell pair at hand. The next interesting transition point is between 220 km and 340 km, where aircraft is replacing rail as the fastest transportation mode. The last transition, from air taxi to aircraft takes place at a range between 350 and 480 km. For longer distances, aircraft is usually the dominating transportation mode regarding door-to-door travel time.

### 4.2. Identifying grid cell pairs with large potential travel time improvements

In this experiment, we explore the improvement in travel times for grid cell pairs. The goal is to identify routes which have a large potential in reducing the travel time and also with reasonable high demands. Without the latter constraints, the obtained routes are mainly connecting islands to Mainland Europe. Therefore, we compute the demand between all grid cell pairs, as induced by the

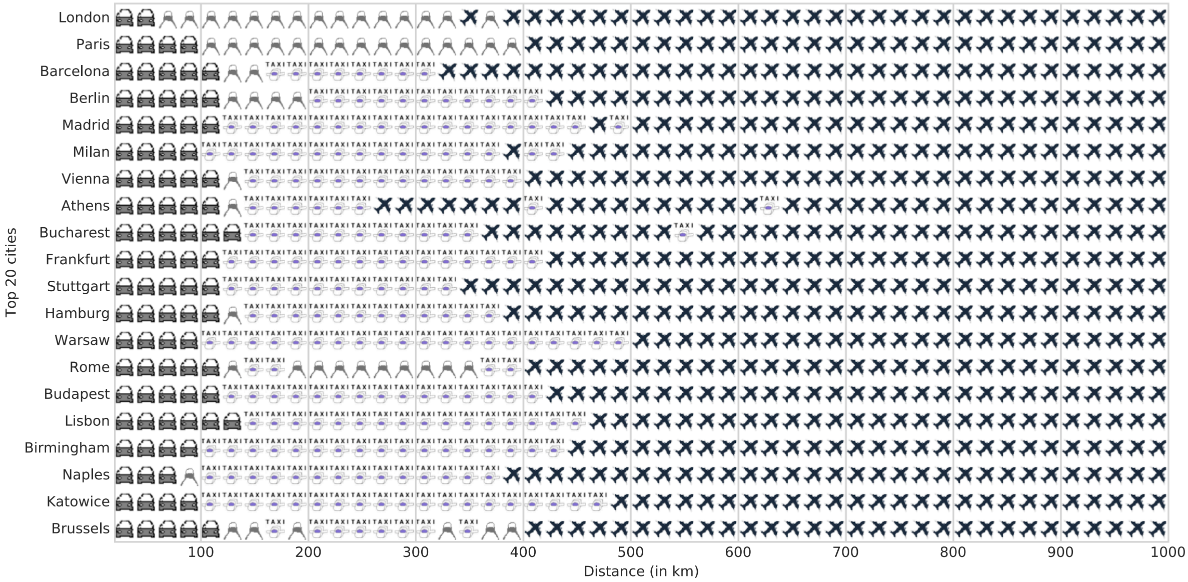


**Fig. 7.** Aggregated visualization of domination transition distances from car to air taxi/railway and from air taxi/railway to aircraft at the city level.

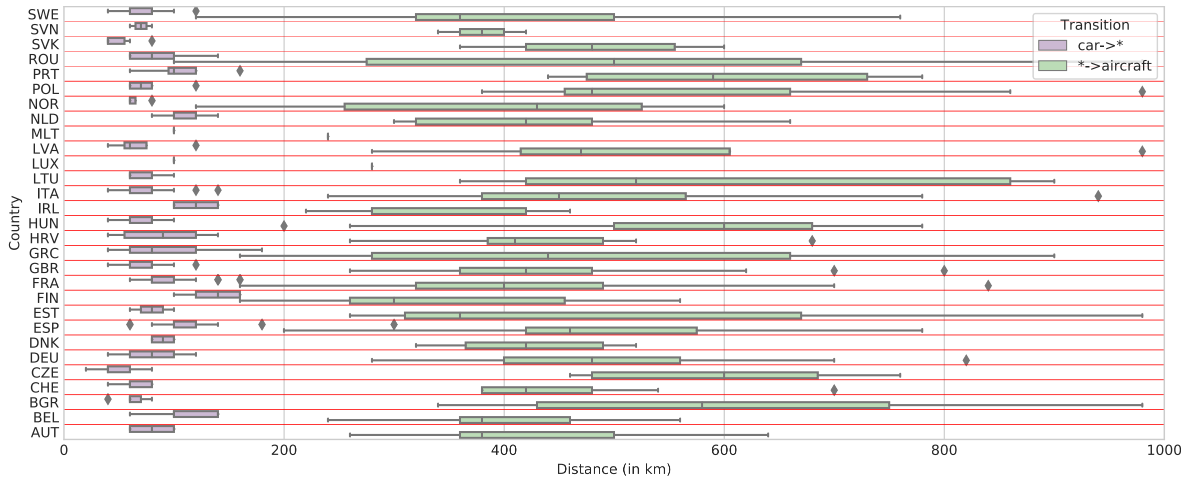


**Fig. 8.** Visualization of transition points for switching from car to other modes (left) and switching from other modes to aircraft (right). Each row represents two box plots for a country: The first (left) box plot visualizes the transition point from car domination to other modes and the second (right) box plot visualizes the transition point towards domination of aircraft. These two boundaries define the real competition area for air taxi and railway. Results for all 500 cities are grouped by country.

radiation model for mobility (Simini et al., 2012). The radiation model was proposed to predict mobility patterns and it only requires the information on the population distribution as input. Comparing with the classical gravity model, the radiation model is parameter-free and it can overcome several limitations of the gravity model, such as parameter fitting and analytic inconsistencies. The analytical formulation of the radiation model is (Simini et al., 2012):

$$<T_{ij}> = T_i \frac{m_i n_j}{(m_i + s_{ij})(m_i + n_j + s_{ij})} \tag{4}$$

where locations $i$ and $j$ have population $m_i$ and $n_j$ respectively, with distance $r_{ij}$ from each other; $s_{ij}$ is the total population in the circle of radius $r_{ij}$ centred at location $i$, but excluding the source and destination population; $T_i = \sum_{j \neq i} T_{ij}$ is the total number of commuters who start their journey from location $i$ ;$< T_{ij}>$ denotes the average flux from location $i$ to location $j$. Given the population of each grid cell from Gridded Population of the World (GPW), we compute the demand estimation $<T_{ij}>$ between each grid cell pair. Based on the estimated demand and the travel time reduction by using air taxi, we estimate the success of an on-demand air taxi service as follows:

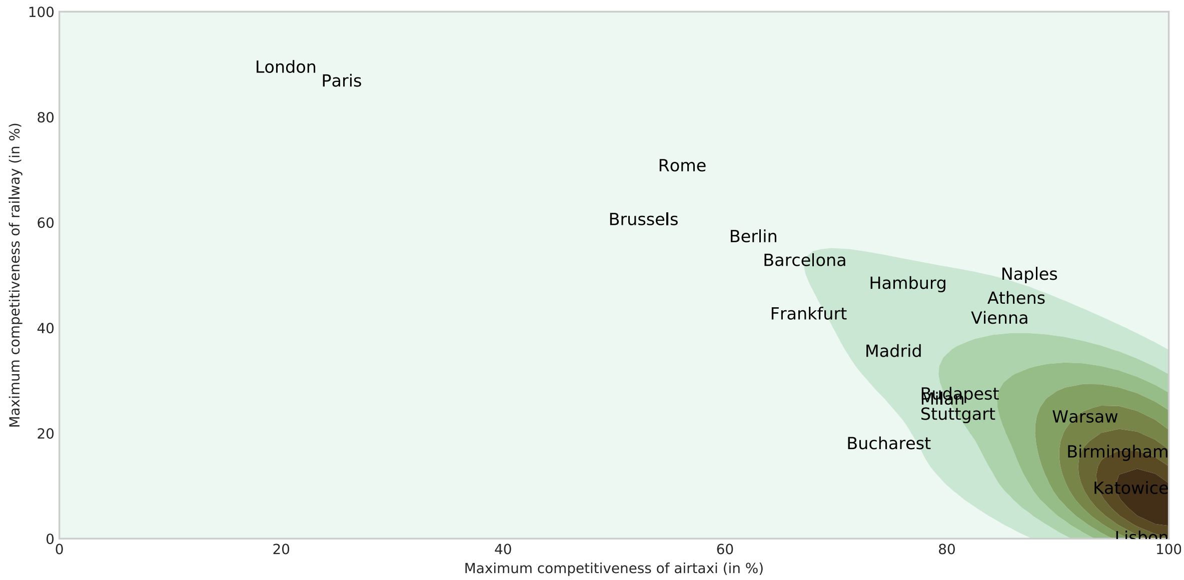


**Fig. 9.** Visualization of competitiveness between air taxi and railway as a 2D-kernel density estimation plot over 500 cities: Maximum competition frequency in percent of air taxi (x-axis) against railway (y-axis). Darker colour indicates a higher density. The locations of top 20 populated cities are highlighted with their names; the names for other data points are not shown for the sake of readability. Air taxi has a range of 100% domination only, if railway does not have domination range for a given city. This means that for cities well-connected to the rail networks, the entry of air taxi is unlikely to have significant, large competitiveness in terms of door-to-door travel time.

$$S = \frac{min(T_{car}, T_{aircraft}, T_{rail})}{T_{airtaxi}} * < T_{ij} > \tag{5}$$

First, an air taxi service is more likely to succeed, if it reduces the travel time between grid cell pairs significantly. Second, higher demands increase the likelihood of regular flight requests, and thus, the more likely there would be regular on-demand services in this region. The top 1000 links regarding criterion $S$ are reported in Fig. 12. When the demand is considered, we have many links with high potential inside Spain, Great Britain, and France, connecting major cities. Interestingly, the Western part of Germany together with Netherlands and Belgium, does not have links with high potential. The reasons are twofold. First, the railway infrastructure is rather well developed in these regions. Second, given the large agglomeration of high-demand grid cells, many travels take place inside the metropolitan areas, compared to traveling to outer parts.

### *4.3. Comparison between grid-cell based system and public routing system*

In order to verify and calibrate our results using grid-cell based system, we provide a parallel study with a selected smaller number of locations using the public routing system, where the query process for the public routing system is manageable and feasible. We provide insights on the correlation between travel times estimated by our door-to-door framework and those obtained by using Google Maps API.

Fig. 13 reports the correlation between our estimated travel time by car and train versus the times provided by Google Distance Matrix API. For these experiments, we have chosen 60 city pairs randomly from our dataset. For each request, we set the start time to 8:00 AM local time. We find that the car travel time by Google is usually slightly longer than those times obtained from open source routing machine. Regarding train travel time, our estimation based on openstreetmap is a lower bound for those obtained by Google. This can be explained by the fact that we perform routing on the infrastructure without actual schedules. It should be noted that a simple adjustment of travel times by factor is not recommended, given that some of the travel times are rather close to the real travel time from Google. Based on our analysis, these are cases which are directly connected by a single train without many stops in between.

## 5. Conclusions

On-demand air mobility is emerging to address the major challenges of urban and regional transportation, by exploring the third dimension (altitude) for transportation systems. In this study, we designed and implemented a door-to-door travel time estimation framework, which yields a lower bound for the travel time between any two grid cells in the region of interest. While the

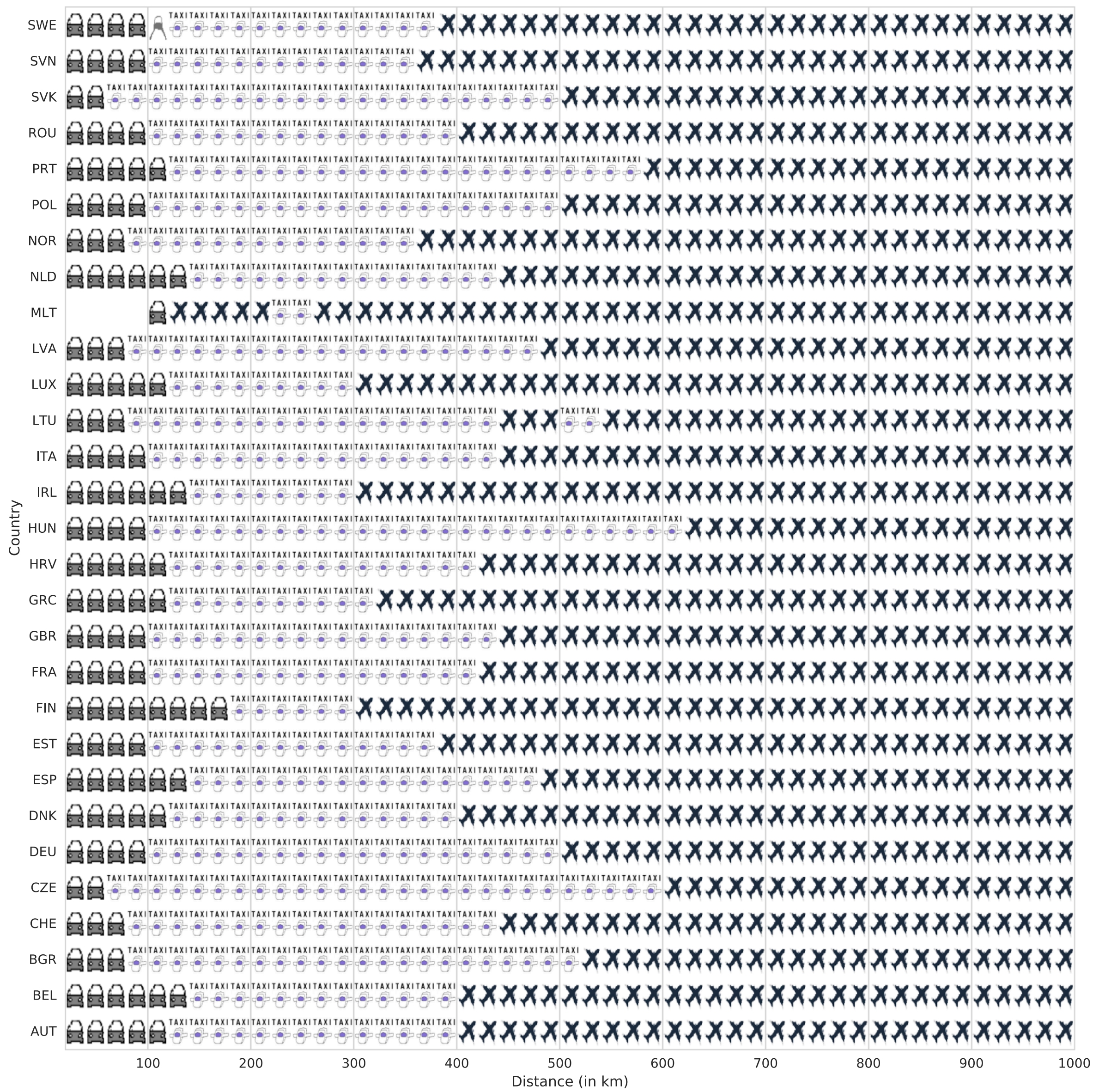


**Fig. 10.** Visualization of domination transition distances from car to air taxi/railway and from air taxi/railway to aircraft at the country level.

competitiveness among different transportation modes largely depends on the origin and destination of a trip, we find that the major competitor for air taxis are railway connections, since they provide short travel time at similar distances. Since our approach uses data available for regions throughout the world, it is able to predict the impact of introducing on-demand air taxi service all over the world in a consistent manner. The major analytical results are as follows:

1. Our results indicate a major operation range for air taxis between 80–130 km and 220–340 km, where air taxis are replacing cars (former) or aircraft are replacing air taxis (latter). Such an operation range should be considered for the design decision making when constructing air taxis for the region of Europe.
2. Within their operation range, air taxis mainly compete with railway service. In general, reliable and fast railway service between two cities makes it hard for air taxis to gain a competitive advantage in travel time. Accordingly, the interesting routes for air taxis are between regions without well-connected railway infrastructure.
3. The competitiveness of air taxi service largely depends on the region. Some cities are rather well connected by rail structure, e.g. Paris. Accordingly, competitiveness of air taxis in such regions is rather low (to only around 20% of the destinations).

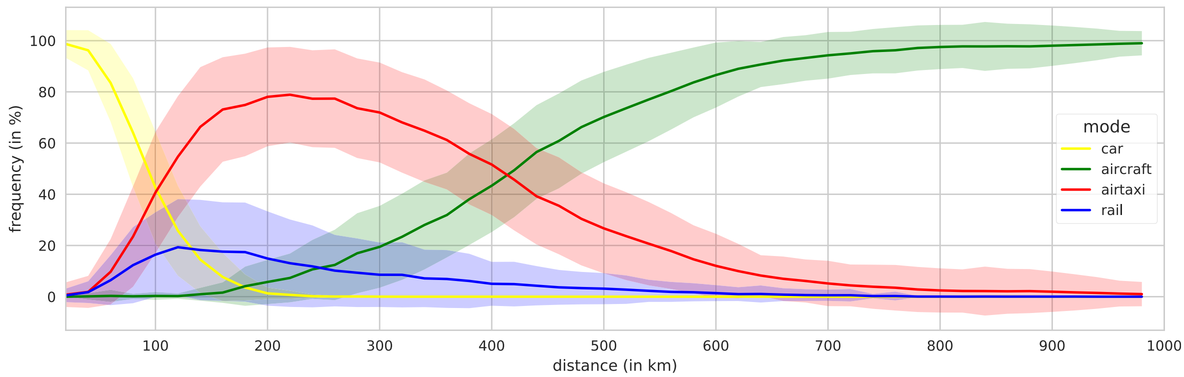


**Fig. 11.** Visualization of the aggregated relative competition frequency for the top 100 cities in our study, showing confidence bands with standard deviation. The transition from car to air taxi is around 100 km and the transition from air taxi to aircraft is around 420 km. We limit this chart to the 100 cities, since the bands become significantly wider for 500 cities.

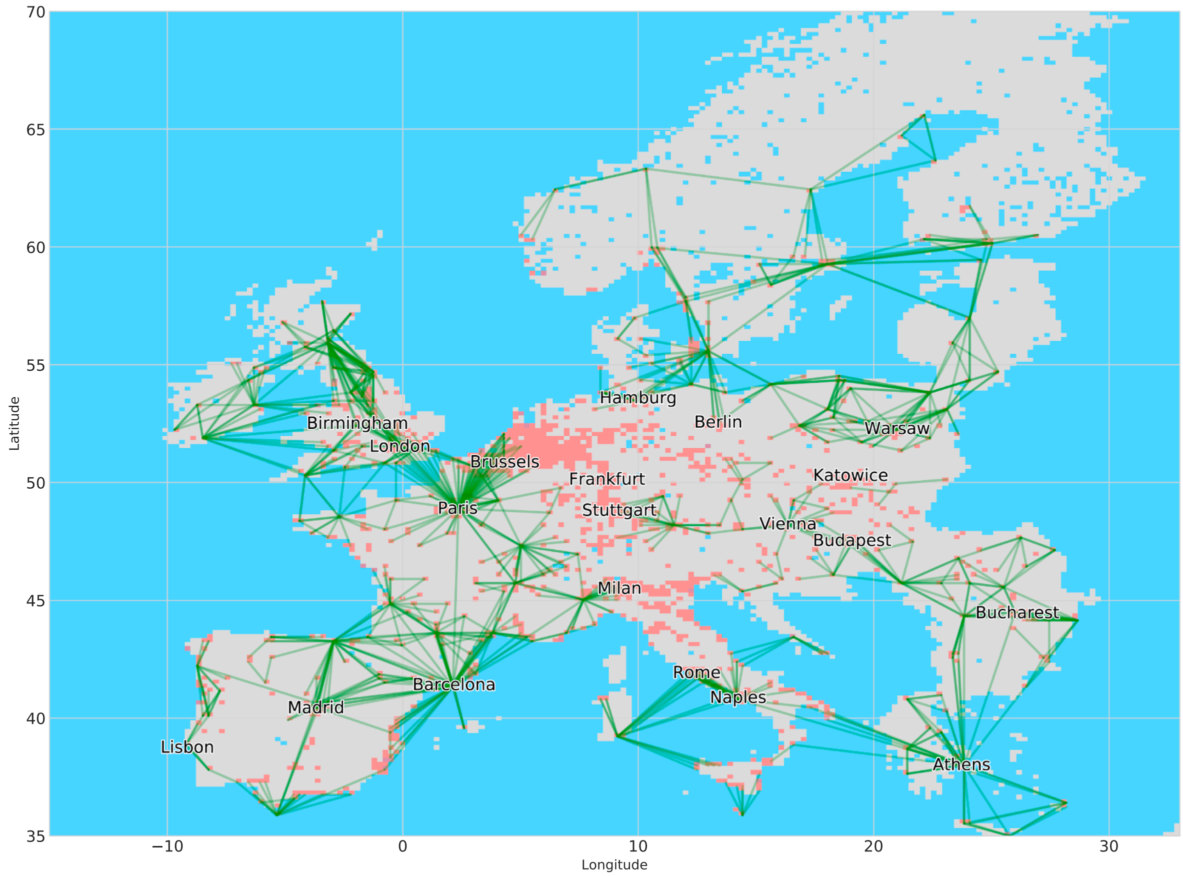


**Fig. 12.** Visualization of the top 1000 links when considering travel time reduction and travel demand between grid cell pairs in Europe. The red coloured grid cells indicate the population density of the grid cells is above the median values of all grid cells. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nevertheless, the majority of cities is not well connected to railway transportation or located at the periphery of the railway network, e.g. Madrid, Vienna, and Lisbon. In these latter cases, air taxis are highly competitive regarding travel time (to around 80% of the destinations). When deciding the locations of hubs, the overall connectivity of a city should be analysed beforehand.

4. The competitiveness of air taxis in a specific city does not depend on the distance to the destination alone. For instance, Berlin is

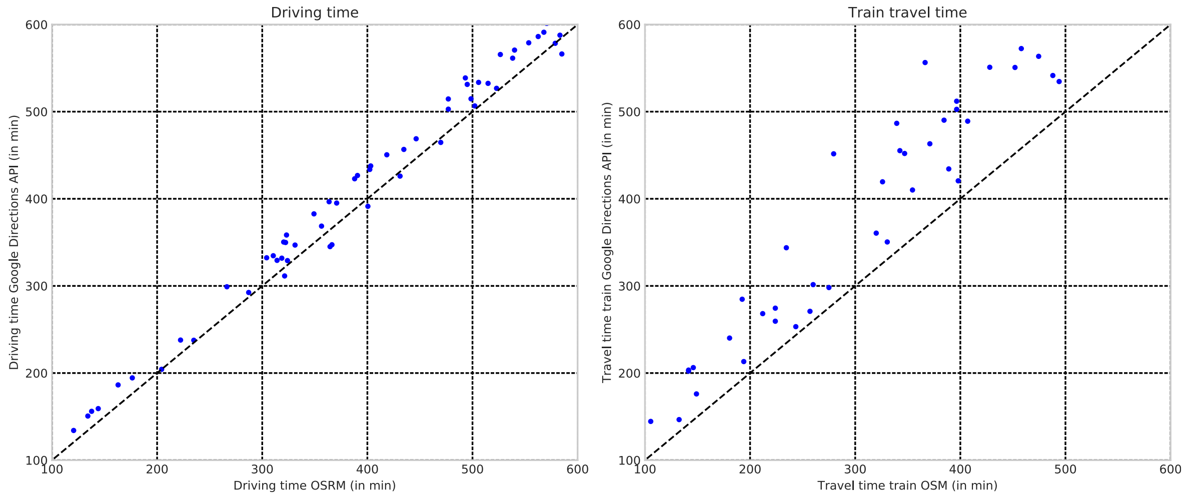


**Fig. 13.** Correlation between travel times estimated by our grid-cell based door-to-door framework and those obtained by using Google Maps API. The left sub-figure shows the driving time obtained by open source routing machine and Google; the right sub-figure shows the train travel time based on openstreetmap and Google.

very well connected to the remaining part of Germany by HSR service, particularly, with the introduction of HSR service to Munich. On the other hand, the connection towards the East, e.g. Poland, is rather limited and infrequent, which opens possibilities to use Berlin as an air taxi service hub towards Eastern Europe. Therefore, the decision of whether a city should be served by air taxis depends on direction and distance.

5. Grouping results at the country level, we find that all countries in Europe have a large potential to benefit from air taxi service up to 450 km. Accordingly, the introduction of air taxi service should be considered as an important step for the whole European community, and operators/legislation should pave ways for opening their arms for cross-country service.
6. Initial experiments for identifying interesting links for air taxi service shows that the largest potential is found at the periphery of Europe, with highly-populated cities as a kind of service hub. Interestingly, at the heart of Western Europe, covered by Belgium, Netherlands, and Germany, very few high-potential links are found. This can be explained by excellent connectivity of existing transportation modes in this region. Therefore, air taxis serving peripherical areas could help to reach ambitious door-to-door mobility goals of the European Commission.

In order to implement a feasible framework - in terms of required computational resources, we made a few simplifications below. We discuss these simplifications and a few limitations of our approach, which could lead to future work in this area:

1. For estimating the driving time between origin and destination, we compute the free-flow time, assuming that there is no congestion or other reasons for delay on the route. During commuting hours, with such an assumption, we might underestimate the real travel time. Therefore, we aim to derive a lower bound for door-to-door travel time. Future studies could model the impact of introducing an air taxi service by considering real or empirical congestion/detour factors. Obtaining such data at a high resolution for a large area is challenging.
2. Similarly, we employ a simplified routing strategy for aircraft, air taxi, and railway, again with the goal to derive a lower bound for door-to-door travel time. For air transportation, we already consider the restricted airspace. Future models could also consider the deviation of speed along the route, detour/delay factors between airports and actual schedules. For railway transportation, we assume that the train can follow any infrastructure route in the network, which might underestimate the travel time in some cases. Therefore, future studies could add information about actual rail schedules for the region of interest, in order to obtain more accurate travel times.
3. Naturally, the time of day influences whether two airports or railway stations are connected conveniently. In our current study, which is the first at such a large scale, we do not consider schedules. Scheduled air or rail travel come with the limitation that delay often occurs because there is only a limited number of available travel options as well as less flexibility. The average speed of rail transport is low due to a high number of stops and lack of direct services. In general, considering service schedules, the competitiveness of air taxis is likely increased further, given their on-demand character, depending on the number of available air taxis. Particularly, cities with infrequent service do have a higher desire and potential to benefit from introduction of air taxi services. Accordingly, future studies could further elaborate on the starting time of journeys and schedules of existing transportation modes.
4. The mode choice of passengers is more complex in practice, than only considering the travel time. In our current study, travel costs are not assessed, among other main drivers of modal choice by passengers. Getting data for these factors with a high resolution and at a large scale is very challenging. Future studies could extend our work with additional factors in order to derive more realistic mode choices.

5. As our analytical results showed, air taxi routes should be chosen carefully, depending on existing connectivity and travel demand. In fact, complementation of existing railway infrastructure with new air taxi service, is a challenging multi-modal network design/improvement problem. Future studies could formally define such novel network design problems with multi-modal interactions and develop efficient solution techniques (Sun et al., 2017)..
6. Our current study focuses on the potential impact of air taxi service on Europe. The situation in Europe is different than for other regions, e.g., regions with much stronger focus on HSR transportation (China) and regions with stronger focus on road/air transportation (US). Future studies could also look at the potential market of on-demand air taxis in North America as well as other regions of the world, especially those metropolitan areas such as New York City-Washington DC-Boston or Los Angeles-San Francisco-Seattle.

Despite these limitations, our work attempts to evaluate the possible impact of air taxis at a large spatial scale and with high level of detail. We hope that our work lays a foundation for understanding the competitiveness of on-demand air taxis through the lens of door-to-door travel time estimation.

## Acknowledgement

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## Appendix A

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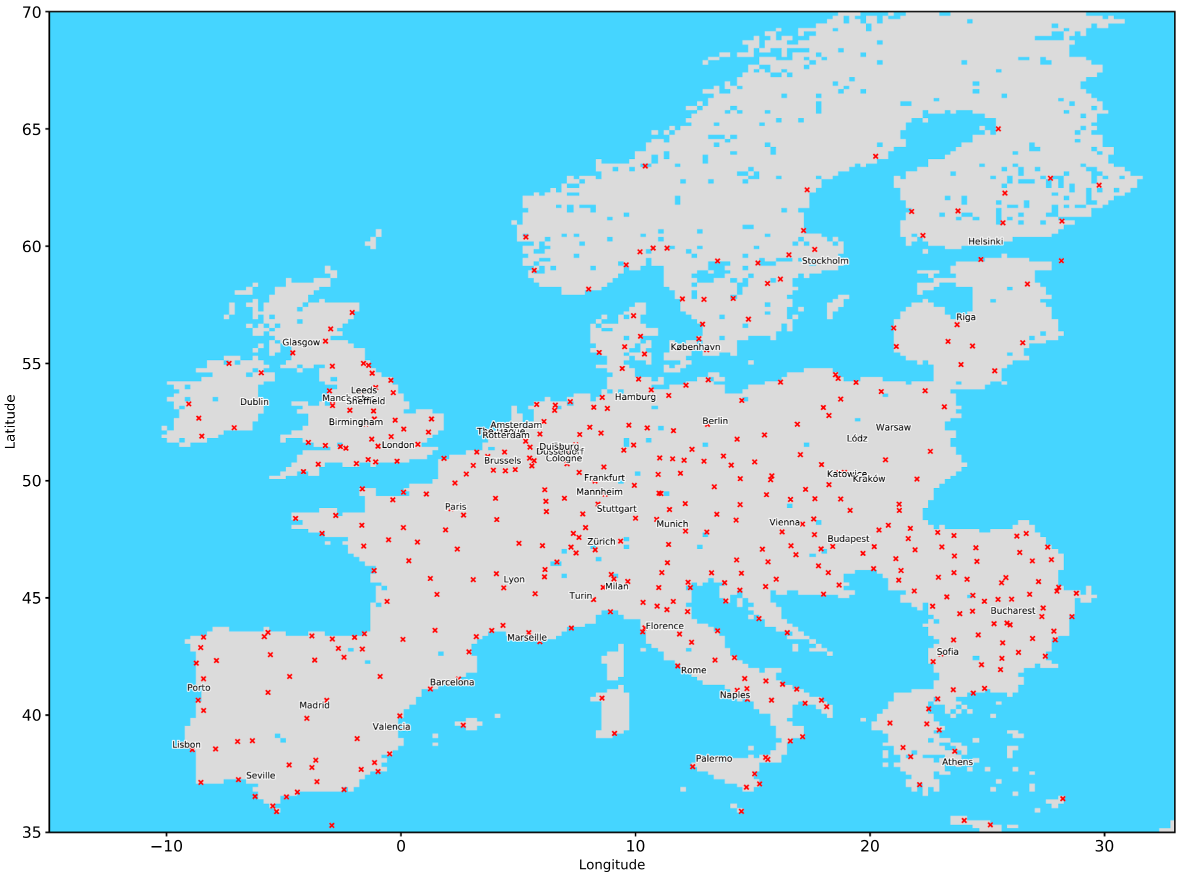


**Fig. 14.** Overview on the locations of the 500 cities selected for this study. Cities were selected according to the total population with largest population first. Top 50 largest cities are identified by name, the remaining 450 cities by a red cross. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
Overview of the 29 countries in this study, including the ISO3 code, population, the number of grid cells, and the number of cities for each country.

| ID | ISO3 | Name | Population | Number of grid cells | Number of cities |
|---|---|---|---|---|---|
| 1 | AUT | Austria | 8,192,880 | 232 | 8 |
| 2 | BEL | Belgium | 10,379,067 | 95 | 9 |
| 3 | BGR | Bulgaria | 7,385,367 | 287 | 15 |
| 4 | CHE | Switzerland | 7,523,934 | 105 | 9 |
| 5 | CZE | Czech Republic | 10,235,455 | 233 | 12 |
| 6 | DEU | Germany | 82,422,299 | 1076 | 57 |
| 7 | DNK | Denmark | 5,450,661 | 150 | 6 |
| 8 | ESP | Spain | 40,397,842 | 1257 | 46 |
| 9 | EST | Estonia | 1,324,333 | 160 | 3 |
| 10 | FIN | Finland | 5,231,372 | 1437 | 10 |
| 11 | FRA | France | 60,876,136 | 1530 | 51 |
| 12 | GBR | United Kingdom | 60,609,153 | 820 | 46 |
| 13 | GRC | Greece | 10,688,058 | 340 | 17 |
| 14 | HRV | Croatia | 4,494,749 | 164 | 8 |
| 15 | HUN | Hungary | 9,981,334 | 255 | 17 |
| 16 | IRL | Ireland | 4,062,235 | 227 | 5 |
| 17 | ITA | Italy | 58,133,509 | 795 | 52 |
| 18 | LTU | Lithuania | 3,585,906 | 217 | 5 |
| 19 | LUX | Luxembourg | 474,413 | 7 | 1 |
| 20 | LVA | Latvia | 2,274,735 | 225 | 4 |
| 21 | MLT | Malta | 400,214 | 2 | 1 |
| 22 | NLD | Netherlands | 16,491,461 | 113 | 13 |
| 23 | NOR | Norway | 4,610,820 | 1297 | 8 |
| 24 | POL | Poland | 38,536,869 | 960 | 24 |
| 25 | PRT | Portugal | 10,605,870 | 221 | 8 |
| 26 | ROU | Romania | 22,303,552 | 649 | 40 |
| 27 | SVK | Slovakia | 5,439,448 | 141 | 6 |
| 28 | SVN | Slovenia | 2,010,347 | 53 | 2 |
| 29 | SWE | Sweden | 9,016,596 | 1827 | 17 |

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