COMPETITIVENESS OF AIR TAXIS REGARDING DOOR-TO-DOOR TRAVEL TIME: A RACE THROUGH GERMANY

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Abstract

Door-to-door travel time within the European Union shall be reduced to less than four hours for 90 percent of all travelers, according to the goals of 'Flightpath 2050'. Point-to-point thin-haul connections provided by air taxis can help to achieve this goal, as analyzed by academia, and envisioned by start-ups like the German e.SAT or the Swiss Dufour.

To further examine the market potential for air taxis within Germany, a sophisticated transport model was set up comparing door-to-door travel times and cost for the established transport modes train, car, and CS-25 aircraft with a novel air taxi service capable of utilizing local CS-23 airfields. Moreover, important parameters for the success of air taxi services are analyzed in depth.

For the purpose of this study, a piloted 5-seater aircraft with a required take-off distance of less than 800 m was considered and a reasonable price range for business trips comparable to a first-class train service ticket was investigated. In addition to existing analyses, this study also uses real-world data for train services and actually serviced routes of CS-25 aircraft. A figure for the state-of-the-art traffic volume and trip distribution on district level in Germany was adapted from the Traffic Interconnection Forecast 2030 of the German Federal Ministry of Transport and Digital Infrastructure (BMVI). For these existing transport modes plus the proposed air taxi service, travel time and travel costs are calculated for each particular route using statistical models. Assuming a constant number of gross travelers on each route, the mode choices for each route are redistributed according to the value of travel time saved (VoTTS) and the according distribution of passengers' willingness to pay for time savings.

Results show that travel time on certain routes can be shortened by 50 percent resulting in an air taxi demand of at least 5000 air taxis overall. Market share, however, is strongly dependent on assumed price per kilometer. Hence, if industry can achieve a cost-level comparable to a first-class train ticket, a significant market share potential for air taxi services of 2.7 % of all business travel is forecasted by this study.

1. INTRODUCTION

In order to sustain Europe's leading industrial position and competitiveness, the European Commission developed a vision for the European air transport system and industry, to be achieved within the first half of this century. Environmental goals of 'Flightpath 2050' such as reductions in CO_2 (-75 %) and NO_X (-90 %) emissions as well as 65 % noise reduction led to the research and development of alternative powertrain solutions for aircraft [1]. The goals also include the aim for 90 % of door-to-door travel within Europe being completed within 4 hours, which calls for a more general change in the air transport system. By 2050, passenger and freight services should be more efficient and seamless, based on a resilient air transport system. This system must be closely integrated with alternative modes of transport and established connections to the rest of the globe as part of the interconnected global aviation system. To conveniently meet the growing demand for flexible point-to-point connections, air mobility will be the essential transport mode. Air mobility is regarded the fastest travel option to connect the regions of Europe but can – depending on the geography and available infrastructure – even remain the most time-efficient means of transport even for some medium-distance connections. [2] For Germany, the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) investigated the availability of high-speed infrastructure for automobile, long-distance rail and CS-25 air services. For each administrative district, the average time to access the corresponding infrastructure was determined, as shown in Figure 1.

Figure 1: Visualization of accessibility model results provided by BBSR [3], own figure, red indicates worse connection

Depending on the location of the administrative districts, the infrastructural accessibility of these three presented transport modes can be weak (highlighted by red color), in particular the availability of CS-25 airports for the majority of districts (very right map of Germany). Both individually

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and in combination, these three modes of transport show gaps in nationwide accessibility of high-speed infrastructure even in a densely populated and wealthy country such as Germany. On-demand air mobility (ODAM), on the other hand, is not only a capable addition to urban traffic, but it is also able to provide fast intercity connections [4]. By utilizing the existing CS-23 landing infrastructure, ODAM provides a dense coverage of access links to high-speed transportation through the 366 ODAM-feasible airfields in Germany. These airfields include more than 80 % of the German population within a radius of 20 km. [5], [6]

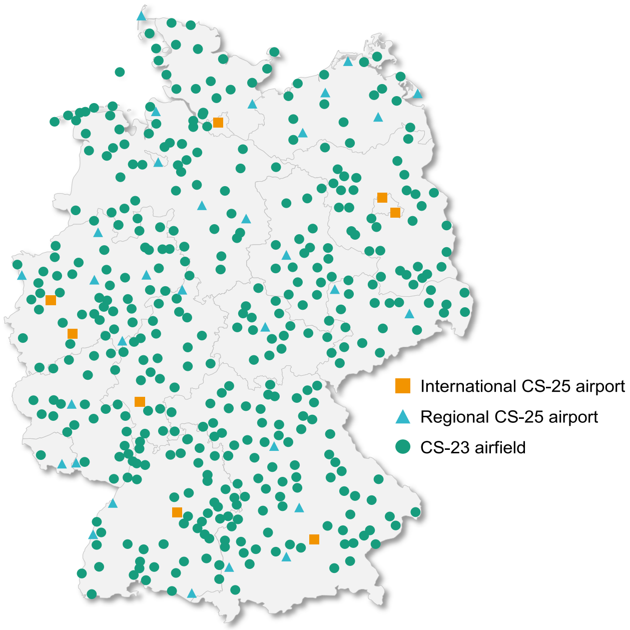

Figure 2: Airport and airfield infrastructure in Germany by type

Along with the aviation market growth and innovation culture leading to the advent of specialized business aircraft [2] and the current infrastructure, the demand for interregional ODAM is expected to increase as well with providers expected to enter the market as early as 2025, e.g. for business travel and commuting [4]. In the last few years, multiple academic institutions as well as enterprises and start-ups in the aviation sector have investigated the market potential for ODAM air-taxi services as an alternative transportation mode, like e.SAT, Dufour, Lilium, Rolls Royce or ELICA [7]-[11].

This paper investigates the application of ODAM aircraft in the German business-travel market. As start-ups focusing on ODAM services assume a price range comparable to a first-class train ticket, like e.SAT [7] or Dufour (0.64 €/km) [8], this study is analyzing the business-travel market due to a higher willingness to pay. It is presumed that ODAM services are provided by short-takeoff-and-landing (STOL) aircraft which – depending on the specifications – can directly access the CS-23 airfield infrastructure available in Germany. The objective of this paper is to assess the application potential for ODAM business-travel services within Germany by quantifying weaknesses in the currently available travel modes and evaluating the substitution by ODAM services from a holistic perspective. For this, travel time (TT) and travel costs (TC) are to be compared for three established business-travel transport modes and ODAM services. These are motorized vehicles, public transport using first-class long-haul rail services and CS-25 aircraft. Firstly, a literature review is performed to establish the current state of ODAM market potential assessment. Next, the methodology used to determine market behavior with the introduction of an additional mode of transportation will be laid out. This includes the discretization of the population into clusters, the simulation of individual transport modes as well as a way to predict distribution of travelers for certain routes among four modes of transport based on travel time and cost. At last, the results will be presented and discussed in comparison to existing findings.

2. LITERATURE REVIEW

A comprehensive market analysis requires both a foundation of traffic demand forecasting methods as well as a well-researched literature motivation to ensure the right focus. In the following, the general approach for macroscopic transport modeling will be presented as it serves as the basic structure for this study, followed by the key concept of traffic demand allocation. Thereafter, the current state of ODAM demand research will be presented to point out the research gap this study is looking to fill.

The holistic perspective and problem area defined in the objective of this paper can be allocated to transportation science, specifically transportation forecasting. Since the 1950s, a four-stage model is typically applied for this, first used in the Chicago Area Transport Study [12]. Until today, it is the standard approach for macroscopic traffic modeling and planning studies [13], [14] and is available e.g. in PTV Visum, a large-scale commercial solution developed by PTV Planung Transport Verkehr AG [15]. The four steps enclosed are briefly outlined below:

- **Trip generation**: The gross number of journeys within the objective area are quantified based on observations and socio-economic factors. In this case, all business-related travel in Germany, published by the German business-travel association VDR [16], is considered.
- **Trip distribution**: All journeys are distributed among origin-destination nodes of the objective area, estimating gross traveler demand per connection served. For this, the German population is discretized into a fixed number of clusters and a origin-destination matrix with relative travel demand is derived from the Traffic Interconnection Forecast 2030 [17].
- **Mode choice**: Per connection in the origin-destination-matrix, all transportation modes are ranked based on travel time and cost. A modal split is derived, depending on the traveler's respective willingness to pay and travel-time differences among the transportation modes.
- **Route assignment**: Based on the results, the individual elements of transport demand are distributed among the route alternatives of the real transport network. This step is not relevant to this investigation and will therefore not be considered.

This four-step approach enables the problem to be modeled in separate parts of which each is adaptable should new inputs arise.

Next to this foundational structure of transport modeling, a specific concept of the mode choice section to determie the modeled demand will be introduced here. The so-called value of travel time saved (VoTTS) is an important concept applied in transportation planning studies. It is used to assess the impact of travel time and travel costs on the individual choice of transport mode and can be utilized to quantify the modal split. VoTTS is defined as a traveler's individual willingness to pay to reduce travel time and is quantified as a trade-off between travel time and cost [18]. Depending on the reason of the journey and the financial situation of the traveler, the individual VoTTS may vary. Additionally, VoTTS have been found variable with the distance of the relation and the total travel time [19]. VoTTS is a popular approach for computing mode choices in transportation forecasting. Previous studies investigated the cost of delay, or the benefit of infrastructure investments, by evaluating the time benefit and using VoTTS to convert it into a monetary value [20], [21]. This method entails the disadvantage of reducing the mode-selection process to monetary variables only, presupposing a rational decision maker. In the business-travel context, however, VoTTS is reflected by the wage rate paid by the company [22], making the decisions for business travel more rational than private travel. As this paper focuses on business travel, the rationality of a VoTTS approach is acceptable. Both four-step transportation forecasting model and VoTTS concept are used for large-scale transportation planning purposes until today [23] and will be considered for the ODAM market potential approximations.

Several researchers investigated and quantified the emerging market potential of ODAM, which will be presented below. Different approaches have been applied; however, it will be shown that there is still research to be done in the domain of traffic demand forecasting for ODAM services.

Sun et. al. analyzed the transportation infrastructure in Europe for the four transport modes to be included in this study [24]. Based on the comparison of door-to-door travel times, the impact of ODAM air taxis was evaluated, and relations with minimum travel time for the novel air-taxi service were highlighted. This study pioneered the evaluation of the competitiveness of air taxis. However, the focus was only set on minimum travel times. A VoTTS influence among the different transportation modes was disregarded and accordingly a demand forecast was not provided. Also, this continental study limited the focus on connections between Europe's 100 biggest cities. This approach does not offer sufficiently dense modelling for ODAM, which shows high dependency on network density, transport mode availability and price-per-kilometer [25].

A denser origin-destination matrix is used by Kreimeier [23], with 412 nodes based on Germany's Nomenclature des unités territoriales statistiques NUTS-3 regions. A full-scale transportation planning model for Germany including ODAM services was designed, comprising the transportation modes car, CS-25 service and ODAM. Due to the high modeling effort and lack of data at the time, railway connections were not considered in the model. The logic to compute the mode choice of a set of gross travelers is based on a relation with VoTTS. Depending on the set model parameters, a market potential for up to 40,000 ODAM aircraft was computed, with high variability from the marginal costs per kilometer travelled. However, the proposed traveler allocation model which clusters passengers by their distances to points-of-interest, such as airports, has a high complexity and parameters as the resolution are therefore not easily adjusted. Also, the considered price-per-kilometer range for ODAM service is comparatively low (0.2-0.6 €/km).

Another study concerning market potential of thin-haul air mobility in Germany was conducted by Paproth et al. [26]. In addition to Kreimeier's set of transportation, trains and intercity bus connections were added. Through a origin-destination matrix based on Germany's 412 regions (NUTS-3) a ODAM modal share of 6 % was predicted for 2030. A set of 20 airports were identified as main hubs, through which 30 % of estimated trips are routed.

Lastly, Bauhaus Luftfahrt studied the integration of Urban Air Mobility (UAM) to complement existing public transport in a transport model [27] for the area of Bavaria in Germany. Socio-demographic factors were used to predict user behavior in 2030 in order to be able to assess a long-term application. A reference case resulted in 1 % market share for UAM, which would make it a fast and flexible complement to established modes of transportation. This study also found the price-sensitivity of the ODAM market share to be high, especially the sensitivity to distance dependent fares.

Research on this subject lacks a holistic transportation planning model for a market segment with high willingness to pay and a sophisticated geographic resolution. Hence, this study focusses on the higher paying business travel market in Germany, including all three current transport modes (individual motorized transport, CS-25 air travel and long-distance train) plus the novel ODAM air-taxi service. Therefore, a transportation forecasting model for business travel within Germany based on VoTTS is presented in the subsequent chapters of this paper, including all mentioned transport modes. This model will be used to estimate the volume of travel conducted by ODAM services upon market entry.

3. METHODOLOGY

3.1. Application of transportation forecast model

From the four-step transportation forecast model introduced above, the **first three steps** are applied to estimate the market potential for business-travel ODAM services in Germany. The aggregated business travel demand within Germany has been obtained from the VDR business travel report 2020 [16]. For the year 2019 a total of 195.4 million business related trips were calculated, increasing 3.1 % compared to the previous year. The authors acknowledge that these numbers originate from before the Covid-19 pandemic, which had severe impacts on mobility around the world. The impact on the transportation industry, of this pandemic so far and its future course, is still being investigated. Even if Europe's business travel market has already started recovering, the Global Business Travel Association estimates, it will take at least until 2025 to reach pre-pandemic levels [28].

The corresponding distribution to allocate these trips to connections of the origin-destination matrix, was derived from the Traffic Interconnection Forecast 2030 of the German Federal Ministry of Transport and Digital Infrastructure (BMVI) [17]. From this forecast, the distribution between the 412 urban and rural districts of Germany (NUTS-3 level) were adapted, focusing on those trips with more than 100 kilometers of distance (trip distribution). Any shorter connections were disregarded, because modal share results from Kreimeier and Sun [23], [24] showed low relevance of ODAM over these distances. This helps differentiate between regional and urban air mobility, as described by Stumpf [29]. The state-of-the-art selection of transport modes is available in the forecast as well and will be utilized hereafter to calibrate the VoTTS setup, a priori disregarding the ODAM option. The calibrated model will then be applied on the transportation planning approach including ODAM services to derive beneficial relations and the market potential (mode choice).

3.2. Discretization of population

To connect the geographic distribution of the population in Germany with the district based BMVI forecast, the population per district is discretized into centers of up to 100,000 inhabitants. This further ensures a better representation of a population center compared to centroids of the area of the same region. For this, a clustering algorithm is applied on Germany's 1-kilometer by 1-kilometer population grid as provided by [6]. A set of roughly equivalently weighted clusters was achieved, whose population-density based centroids serve as nodes in the targeted origin-destination matrix. The resulting distribution of the 1010 individual points is displayed in Figure 3. As mentioned before, only routes between clusters with more than 100 km will be considered for the transportation model.

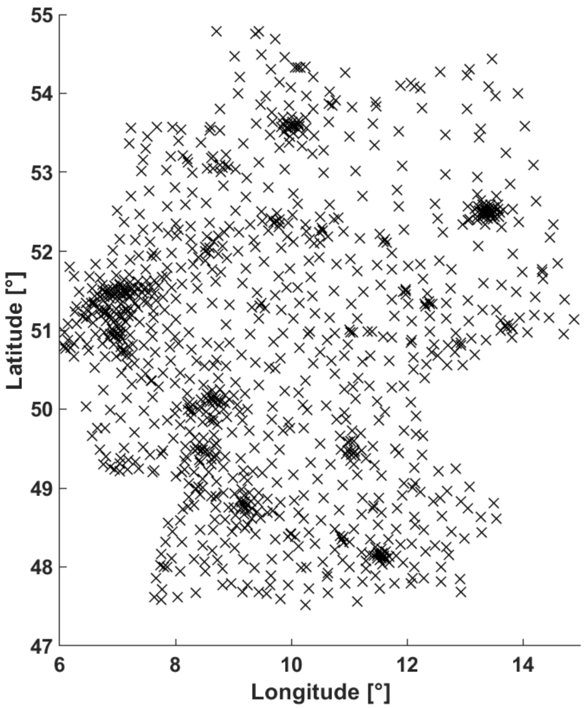

Figure 3: Result of clustering algorithm applied on the administrative districts of Germany

3.3. Simulation of transport modes

The four transport modes are modelled as follows, including the two output dimensions travel time (TT) and travel costs (TC). A comprehensive table of all transportation modeling parameters can be found in the appendix.

- **Motorized individual transport (MIT)**: Direct connection between the clusters qualifying as described above. A detour factor of 1.3 is applied to the spherical distance of the clusters [30] to compute the travel distance, and an average speed depending on this distance was assumed [31], from which the TT is computed. TC depend on the travel distance and assume a marginal price per kilometer driven of 35 ct/km [32].
- **CS-25 service**: From the 26 CS-25 airports in Germany, valid flight routes are derived from actual airline connections as offered for the summer flight plan 2019. The route is divided into three legs, respective access and egress routes by car/taxi (MIT) as well as the flight itself. The flight is modelled as a trapezoidal profile, assuming average vertical ascending and descending speeds during climb and descent. Given the spherical distance multiplied by an in-air detour factor of 1.06 as defined by Gollnick [33], the TC are estimated utilizing a marginal price per airborne kilometer. Access and egress segments, also called first and last mile, are modeled as a competition between personal car travel and taxi service, with respective parking fees, if applicable. At the destination, a rental car option is available instead of the personal vehicle. For both journey legs each, the minimal-cost option is selected, respectively. Total TT and TC are computed as a sum from these three legs of the route.
- **Long-distance train**: The third option includes the utilization of the Deutsche Bahn long-distance railway services. Utilizing the Deutsche Bahn application programming interface (API), actual TC and TT for a first-class long-distance rail connection were extracted for a booking process one day in advance. First and last mile legs were computed similar to CS-25 services, assuming a reduced parking fee at the inbound train station.
- **ODAM**: The interregional ODAM service was modelled for the 366 airfields in Germany feasible for ODAM transport, considering the infrastructure's runway length and the aircraft's required runway performance. Like the CS-25 service, the flight is modelled as a trapezoidal profile, assuming average vertical ascending and descending speeds during takeoff and landing. The first and last mile are modelled similar to the last two modes, assuming free parking at the airfields.

Distance: 412,83 km	**ODAM**	**CS-25**	**Car**	**Train**
Cost [€]	312	427	187	255
Duration [min]	220	297	418	389

TAB 1: Exemplary cost of transportation for a route from Aachen to Magdeburg

TAB 1 shows an exemplary calculation of TT and TC for all four modes of transportation. It illustrates clearly the tradeoff to be made by a traveler. Therefore, the model includes a distribution function of travelers' willingness to pay, represented by VoTTS. The TC and TT dimensions are the input parameters for the respective VoTTS per relation. Consecutively, the VoTTS are set up and utilized to determine mode choice for each route.

3.4. VoTTS model calibration

From a publication of the German Federal Statistical Office (Destatis), the distribution of the national household income is available based on a representative sample. Twelve income categories are differentiated. In accordance with Kreimeier [23], the VoTTS for Germany are estimated assuming an annual inflation of 1.5 %, resulting in the proposed VoTTS distribution curve presented in Figure 4.

The median VoTTS value (an amount half of business travelers will expense) is used as the calibration parameter for this model. This means, the VoTTS curve is shifted along the x-axis during calibration. The benchmark for configuring the model was the modal split of the Traffic Interconnection Forecast 2030 [17]. A version of the model excluding ODAM was adjusted to best match these results, to ensure traffic and traveler behavior was represented in a realistic way.

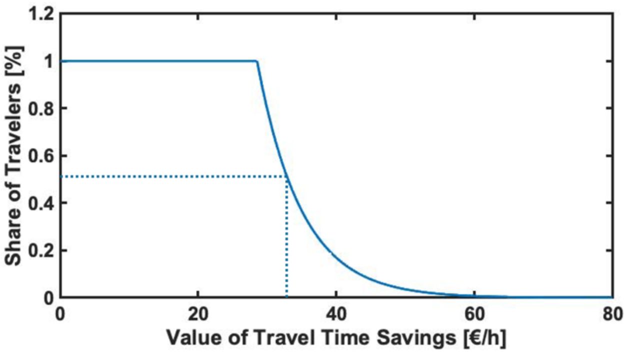

Figure 4: Assumed VoTTS distribution for business travel, adapted from Kreimeier [23]

The final parameter value has been determined to be 33 € per hour of travel time saved. A dependence on the distance is not implemented in this model. In addition, the model does not consider location sensitivity in the amount of VoTTS, so companies in each region have comparable business-travel expenditure preferences.

3.5. Mode choice

To determine the mode choice, the transportation model was implemented in MATLAB. For a specific route, the TT and TC are computed for all transportation modes. Starting from the perspective of the slowest travel mode, the differences in TC are divided by the savings in TT for each faster mode. The quotient represents the costs per hour to upgrade to the next fastest mode of transport. From the aforementioned distribution, the share of travelers willing to pay the respective cost are determined to result in a share of travelers for each mode of transportation.

The mode choice data per relation sum up to 1 or 100 percent. Should a transport mode provide the fastest and simultaneously the cheapest connection, it is supposed that all traffic flows via this transport mode. In the end, all routes and the respective means of transport are aggregated to a total value of the transport choice. This is done by weighting the individual routes according to the number of travelers from the Traffic Interconnection Forecast 2030 [17].

4. RESULTS

4.1. Derivation of market potential

Following, the results from the aforementioned transportation and mode choice model will be presented and compared to similar studies. First a simulation solely based on travel time is performed, by assuming infinite willingness to pay from all travelers. This enables a validation basis to compare to Sun's findings [24]. Thereafter, a full simulation, including VoTTS based mode choice is done and the overall transportation demand for ODAM will be calculated.

Considering solely the influence of TT for mode choice, the model computes similar results compared to Sun et. al. The overall mode choice values are as follows: ODAM (43.0 %), CS-25 (14.2 %), Car (8.5 %) and Train (34.3 %). For distances between 100 and 500 km, ODAM services dominate the other mode choices. For longer distances, CS-25 air travel becomes the fastest choice for most connections. The shortest distances are dominated by cars, although complemented by train, which only has a significant share of mode choice on distances less than 200 km. These findings can also be observed in Figure 5.

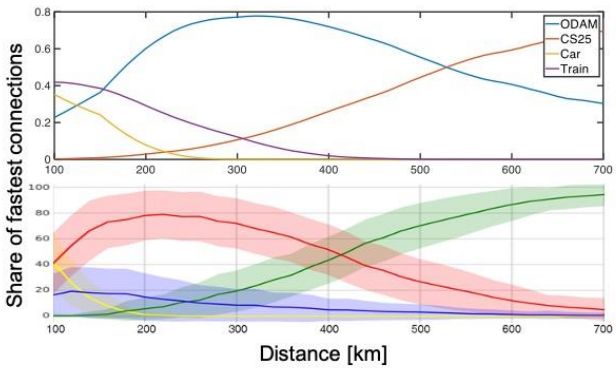

Figure 5: Modal-split results for fastest travel option, disregarding VoTTS influences, comparison with Sun et. al. (bottom) [24]

The calculations show a high level of conformity with the results of the reference model by Sun et. al. [24] regarding travel in Europe. Even if the modeled geography differs between both models, the level of conformity of both transport systems is considered sufficient. The developed model is therefore considered valid in the specification and parametrization of the four transport modes.

In the next step, the focus should be set on the presumption that the mode-choice decision for business traveling takes its financial perspective into account as well: Both TC and TT are considered simultaneously, as covered by the concept of VoTTS.

When including the respective costs per travel mode and the corresponding VoTTS, the overall mode choice is retrieved from the model. The shares are: ODAM (2.7 %), CS-25 (4.3 %), car (77.4 %) and train (15.6 %). The results of mode choice based on the trip length are illustrated in Figure 6.

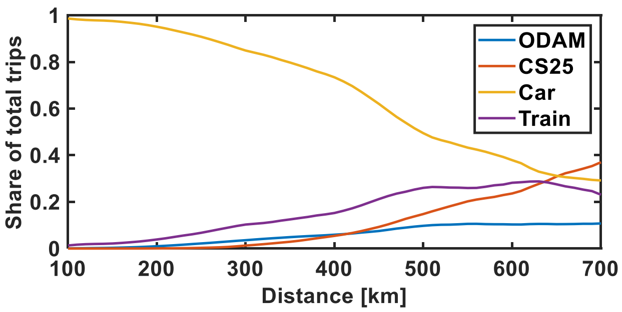

Figure 6: Modal-split results with VoTTS influence

The car receives the biggest increase in modal share compared to the purely speed-based evaluation before and expands its competitive range across all connection lengths. The advantage only fades at distances above 500 km. This is mostly due to relatively low cost and good accessibility, as no first or last mile connections are required. Trains show a preference shift to longer distances, compared to the purely speed based calculations before. A moderate speed advantage at lower distances is overcome by high cost, even for short trips, which put the train almost always at a disadvantage to the car. Both aircraft mode shares are largely decreased, however especially the competition of the car and ODAM at medium distances has a great impact here. Only at distances over 450 km can airborne modes of transportation reach relevant modal shares, which is to be expected due to the higher cost, which have to be justified by a bigger time difference. This greater difference in travel time especially shows at these higher distances. Comparing both CS-25 and ODAM at lower distances, the denser network of small airports for CS-23 aircraft and the decreased ground processing times result in CS-23 generally being more successful than CS-25 at shorter trips.

Finally, to derive a transportation output for the concerned modes, each trip's mode choice is multiplied with the corresponding distance travelled and aggregated by the weights determined from the VVP 2030. Together with the 195.4 million annual business trips within Germany [16], an accurate amount of passenger kilometers required by each mode of transportation can be calculated. ODAM hereby accounts for 4.51 billion passenger kilometers of transportation capacity. To put this figure into context with a market demand for ODAM aircraft, the approach by Kreimeier [23] is used. The transportation capacity is translated into a potential market demand for ODAM aircraft, based on the annual revenue passenger kilometers (RPK) an aircraft is able to deliver for an average load factor. For handling interregional business travel and commuting services, a four-PAX five-seater piloted aircraft is regarded suitable, and its market potential analyzed in detail. Assuming a yearly transport capacity of 850,000 RPK for the exemplary aircraft, a minimum of 5,300 ODAM aircraft operated at the same time is computed.

To showcase further dependencies of the ODAM share in greater detail, a sensitivity analysis was done and will be explained in the following.

4.2. Success factors for ODAM

While the mode choice of each mode of transportation already holds plenty of information, the sensitivity of the ODAM share to the variation of different parameters will also be evaluated. The identification of critical variables can provide enormous benefit to entities seeking to enter this highly dynamic market. The conducted evaluation included four parameters, namely runway performance of ODAM vehicles, specific costs per kilometer for both CS-25 and ODAM services, as well as ODAM flight speed.

Parameter	Modulation Interval	Difference in ODAM share (from 2.65 %)
Runway performance	600-900 [m]	+ 2.80 % / - 1.54 %
CS-25 cost per kilometer	0.05-0.55 [€/km]	- 1.95 % / + 0.08 %
ODAM cost per kilometer	0.55-0.75 [€/km]	+ 9.82 % / - 2.50 %
ODAM flight speed	250-350 [km/h]	- 0.67 % / + 1.36 %

TAB 2: Parameter modulation results

All these parameters have an influence on the ODAM market share, as can be seen in TAB 2. The runway performance shows relevant influence on the modal share of ODAM in both positive and negative directions. The price of CS-25 operations does not show a significant difference in ODAM share, if increased. However, if CS-25 flights become cheaper, the ODAM mode choice reduces. This must be taken into account, as the price of CS-25 flight for this model is at the higher end of the interval at 0.47 €/km [34].
The most relevant parameter proves to be the price per kilometer. While an increase in price reduces the ODAM share by 2.5 %, which is to be expected, a reduction in price results in an increase of almost 10 %. This highlights the importance of cheap transport offerings, as was already found by evaluation of the general mode choice data. These findings match the sensitivity of ODAM to price-per-kilometer as discussed earlier, however further investigation of this model is needed to clarify the extent of this effect.
Lastly, the flight speed of ODAM vehicles has a lower effect than runway performance but it is still relevant. Especially, since the results show a greater difference in mode choice for speed increases (+1.36 %) compared to decreases (-0.67 %). This is to be expected, because with

increasing speed, ODAM differentiates more strongly from high-speed trains, which increases its performance advantage in addition to the denser connection network. The resulting trade-off between performance for short runways and higher flight speed and economic operation for a lower price-per-kilometer needs to be solved in aircraft development.

4.3. Limitations

The results of this model and calculation were obtained under certain assumptions, whose influence on the ability to transfer results to reality shall be discussed subsequently.

First, this model is used to calculate the shift in transport capacity of the three conventional means of transport. The system is subject to a displacement effect by reallocating a share of the current transport capacity to the new mode introduced to the system, namely ODAM. A market growth effect – i.e., traffic additionally generated by the ODAM service, was not considered. This might lead to a slightly lower total transportation capacity forecast compared to reality. Additionally, it was assumed that each mode of transportation was capable of handling the demand it was allocated. Road and railway networks historically have to manage congestions and capacity issues, which were neglected in this simulation. The modal share of these transport modes might be overestimated in this regard.
Regarding each individual's mode choice, the decision-making process is reduced to rational factors of time, money and monetary value of time. Emotional or ideological aspects, such as aviophobia or environmental awareness, are disregarded during the mode-choice phase of modelling. The results of this are very complex to estimate, as many different preferences for or against certain modes of transportation may exist.

Another aspect that contributes to an over-evaluation of speed and thus demand is the lack of scheduled connections, especially for train and CS-25 services. These modes of transport are characterized by a regular frequency of operations throughout the day. In the proposed model, however, the simulation was conducted independently of time, hence resulting in equal time flexibility for each mode of transport. This puts ODAM and cars at a disadvantage, as the on-demand aspect does not result in the time benefits it is intended to in reality. Hence the ODAM and car modal share are probably underestimated in this regard.

The VoTTS model used to assess travelers' willingness to pay for reductions in travel time contains some assumptions and limitations as well. A more detailed investigation was conducted by ETH Zürich [19], which uncovered several dependencies of the value people attribute to their travel time savings. Results show that VoTTS not only depend on the individual's economic standing and professional direction, but also on trip properties such as distance travelled or mode of transportation. This might lead to a generally more diverse, but also truer to life representation of travelers' behavior. To set up this transportation model however, these factors were reduced to a rational approach solely using economic standing. To include a greater scope of VoTTS dependency would not only have been computationally more expensive, but also challenging to back up with a satisfying database. Further economic factors, as gross domestic product (GDP) distributions are also not considered separately. These factors are integrated into the Traffic Interconnection Forecast 2030 [17], which served as a basis for relative route weighting for this model. However, GDP was not part of the mode choice calculation, which it might influence. Certain routes might thus prefer more expensive or affordable transportation. The influence on the estimated overall ODAM demand is relatively small, however if market entry scenarios with route prioritization would be considered, GDP distributions should be introduced additionally.

Finally, the business trips considered are mere origin-destination trips with return trip. This means that there is only one destination for each connection, without consideration of multi-stage round trips or open jaw flights. However, given the business-travel context of the general modelling scope, this can be considered an acceptable approximation.

5. CONCLUSIONS

In summary, this paper evaluated the competitiveness of on-demand air travel in comparison to the three most important modes of business travel in Germany: car, train, and CS-25 flight. Based on a thorough literature review, a corresponding transportation model was constructed to enable a comprehensive estimation of mode choice data. Using the proven concept of four-step traffic estimation in combination with the value of travel time savings, methods of transport demand estimation were implemented to simulate market behavior for the entry of on-demand air travel. Calculations are based on a model that was calibrated on different traffic studies to ensure correct simulation of the already established means of transportation.

The developed method has successfully proven the ability to estimate mode choice shares for cars, ODAM, CS-25 and trains in a closed market scenario. While this was used to estimate the number of aircraft needed to fulfill this need, more data could be extracted for further investigation. Evaluating the different modal splits of different routes could provide insights into the specific regional features, that support certain transportation modes. In a market entry scenario, routes that are most relevant to ODAM success could be identified to be operated first.

From the presented transportation model results and the conducted sensitivity analysis, important requirements and specifications towards the aircraft design were derived. Overall, ODAM shows a relevant market potential of over 5,300 vehicles needed to meet the demand. Especially compared to train and CS-25 offerings, ODAM is able to utilize its higher network density, to allow for even shorter travel times. However, the car still turned out to be the dominant choice of most travelers, especially for shorter distances. This is mostly due to the low cost generated by car travel. Accordingly, the most vital ODAM parameter has been found to be the specific price per kilometer. This confirms findings of other studies investigating market entry of small aircraft with on-demand operation [23], [27]. These insights help to establish an on-demand aircraft transportation market, by ensuring a successful market position for ODAM aircraft towards established interregional business travel.

Lastly, with regard to the current Covid-19 pandemic, the given numbers for business travelers are expected to not be accurate for the near future and will likely turnout much lower within the next years. However, a transportation model like this one does still offer value through insights into a shift in business travel behavior. In the wake of the pandemic, worldwide revenue on business travel has dropped 58 % in 2020 compared to the previous year [28]. Especially air and railway travel have sustained severe losses. Seat capacity for airlines in Germany has been 65 % lower, compared to 2019 [35]. The German national railway operator Deutsche Bahn AG reports a 44.3 % year over year loss in RPKs in 2020. Due to low energy prices and changed consumer behavior, a better recovery of individual transportation modes, such as cars, is expected. [36] A recovery of both the aviation and business travel industry is expected earliest until the year 2025 [28], [37]. By adjusting modeling parameters, changes in consumer behavior can be modeled with the derived method to reflect e.g., increased willingness to pay due to health concerns. Assessment of the impact of the pandemic situation on the travel sector for different scenarios with this model might give further insights into the recovery of the industry.

6. REFERENCES

[1] J. P. Hofmann *et. al.*, „A Comprehensive Approach to the Assessment of a Hybrid Electric Powertrain for Commuter Aircraft", *AIAA Aviation 2019 Forum*, 2019.

[2] S. Kallas, M. Geoghegan-Quinn, "Flightpath 2050: Europe's Vision for Aviation: Report of the High Level Group on Aviation Research", European Union, 2011.

[3] B. Schwarze, K. Spiekermann, T. Holthaus, B. Leerkamp, J. Scheiner, "Methodische Weiterentwicklungen der Erreichbarkeitsanalysen des BBSR", *BBSR-Online-Publikation*, vol. 9, Bonn, 2019.

[4] S. Baur, S. Schickram, A. Homulenko, N. Martinez, and A. Dyskin, "Urban air mobility: The rise of a new mode of transportation", Roland Berger GmbH, 2018.

[5] Deutsche Flugsicherung GmbH, "Luftfahrthandbuch Deutschland: AIP - Aeronautical Information Publication", Offenbach Main, (accessed July 16, 2020).

[6] Statistische Ämter des Bundes und der Länder, "Ergebnisse des Zensus 2011", https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html?nn=3065474 (accessed Apr. 15, 2020).

[7] e.SAT GmbH, "e.SAT Silent Air Taxi." https://e-sat.de/de/silent-air-taxi/ (accessed Dec. 16, 2020).

[8] Dufour Aerospace, "Dufour aEro." https://dufour.aero/vision/ (accessed Dec. 16, 2020).

[9] Lilium GmbH, "Lilium Jet." https://lilium.com/the-jet (accessed Dec. 16, 2020).

[10] Rolls Royce plc, "Rolls Royce EVTOL." https://www.rolls-royce.com/media/our-stories/discover/2018/blue-sky-thinking-rr-unveils-evtol-concept-at-farnborough-airshow.aspx (accessed Dec. 16, 2020).

[11] G. Schuh, M. Spangenberg, Q. Zhang, "Economically driven requirements for a hybrid-electric 19-passenger commuter aircraft", *10th EASN Virtual International Conference,* under review, to be published in Q1 2021.

[12] A. Black, "The Chicago area transportation study: A case study of rational planning", *Journal of Planning Education and Research*, vol. 10, no. 1, 1990, pp. 27–37.

[13] M. Drličiak, J. Čelko, "Implementation of transport data into the transport forecasting in Slovakia", *Transportation Research Procedia*, vol. 14, 2016, pp. 1733–1742.

[14] Z. Karami and R. Kashef, "Smart transportation planning: Data, models, and algorithms", *Transportation Engineering*, vol. 2, 2020.

[15] PTV Planung Transport Verkehr AG, "Transportation Planning with PTV Visum." https://www.ptvgroup.com/en/solutions/products/ptv-visum/areas-of-application/transportation-planning/, (accessed Dec. 16, 2020).

[16] Verband Deutsches Reisemanagement e.V., "VDR Business Travel Report 2020", Volume 18, Frankfurt am Main, 2020.

[17] M. Schubert *et al.*, "Verkehrsverflechtungsprognose 2030 Los 3: Erstellung der Prognose der deutschlandweiten Verkehrsverflechtungen unter Berücksichtigung des Luftverkehrs", *Bundesverkehrswegeplan 2030,* Bundesministerium für Verkehr und digitale Infrastruktur, 2014.

[18] T. Worsley, R. Batley, M. Bauernfeind, F. Bruns, "What is the Value of Saving Travel Time?*",* *International Transport Forum*, 2019.

[19] K. W. Axhausen *et al.*, "Schlussbericht: FE-Projekt-Nr. 96.996/2011: Ermittlung von Bewertungsansätzen für Reisezeiten und Zuverlässigkeit auf Basis der Schätzung eines Modells für modale Verlagerungen im nicht-gewerblichen und gewerblichen Personenverkehr für die Bundesverkehrswegeplanung," ETH Zurich, 2015.

[20] A. J. Cook, G. Tanner, S. Anderson, "Evaluating the true cost to airlines of one minute of airborne or ground delay", European Organisation for the Safety of Air Navigation (EUROCONTROL), 2004.

[21] S. Landau, G. Weisbrod, G. Gosling, C. Williges, M. Pumphrey, M. Fowler, "Passenger Value of Time, Benefit-Cost Analysis, and Airport Capital Investment Decisions. Volume 1: Guidebook for Valuing User Time Savings in Airport Capital Investment Decision Analysis", The National Academies Press*,* Washington DC, 2015.

[22] M. Wardman, G. Lyons, "The digital revolution and worthwhile use of travel time: implications for appraisal and forecasting", *Transportation*, vol. 43, no. 3, pp. 507–530, 2016.

[23] M. Kreimeier, J. Reichmuth, E. Stumpf, "Evaluation of on-demand air mobility concepts with utilization of electric powered small aircraft", Dissertation, RWTH Aachen, 2018.

[24] X. Sun, S. Wandelt, E. Stumpf, "Competitiveness of on-demand air taxis regarding door-to-door travel time: A race through Europe", *Transportation Research Part E: Logistics and Transportation Review*, vol. 119, 2018.

[25] Bauhaus Luftfahrt, “OBUAM-Abschlusspräsentation”, https://www.bauhaus-luftfahrt.net/en/press-media/news/zusammenfassung-des-obuam-projektes/, (accessed: Oct. 12, 2020).

[26] Y. Paproth, F. Adam, V. Stich, A. Kampker, “Model for future thin-haul air mobility demand in Germany”, *2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 2020.

[27] K. O. Ploetner *et al.*, “Long-term application potential of urban air mobility complementing public transport: an upper Bavaria example”, *CEAS Aeronaut Journal*, vol. 11, no. 4, 2020, pp. 991–1007.

[28] Global Business Travel Association, “Business Travel Sees Steady Recovery in Europe”, https://www.gbta.org/blog/business-travel-sees-steady-recovery-in-europe/ (accessed March 03, 2021).

[29] E. Stumpf, M. Kreimeier, P. Strathoff, J. Luckhof, K.-U. Schröder, F. Janser, “Small Aircraft Concept for Regional On-Demand Air Mobility”, *31st Congress of the International Council of the Aeronautical Sciences*, Belo Horizonte, 2018.

[30] C. Sommer, F. Schäfer, G. Löcker, T. Hattop, S. Assadollah, “Mobilitäts- und Angebotsstrategien in ländlichen Räumen”, Bundesministerium für Verkehr und digitale Infrastruktur, Berlin, 2016.

[31] A. Dahl *et al.*, “Methodenhandbuch zum Bundesverkehrswegeplan 2030,” *Bericht zum FE-Projekt no. 97.358*, 2015.

[32] ADAC e.V., “ADAC Autokosten Herbst/Winter 2019/2020”, https://www.adac.de/_mmm/pdf/autokostenuebersicht_47085.pdf, (accessed Apr. 15, 2020).

[33] V. Gollnick, “Untersuchungen zur Bewertung der Transporteffizienz verschiedener Verkehrsmittel”, Dissertation, Technische Universität München, 2004.

[34] P. Berster, “Flugpreisanalyse von Low Cost Angeboten auf ausgewählten Strecken”, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln, 2018.

[35] C. Dongre, C. Fadnis, „Global Air Trends January 2021”, Phocuswright Inc., https://www.phocuswright.com/Travel-Research/Market-Overview-Sizing/Global-Air-Trends-January-2021, (accessed March 03., 2021)

[36] Deutsche Bahn AG, „Integrierter Zwischenbericht Januar-Juni 2020“, Berlin, 2020.

[37] International Air Transport Association, „20 Year Passenger Forecast Infographic”, https://www.iata.org/contentassets/e938e150c0f547449c1093239597cc18/pax-forecast-infographic-2020-final.pdf , (accessed March 03, 2021)

APPENDIX

Modelling parameters are found as defined

<table>
<tr><th>Transport mode</th><th colspan="3">Main leg</th><th colspan="3">First mile</th><th colspan="3">Last mile</th></tr>
<tr><td></td><td>Time</td><td>Distance</td><td>Costs</td><td>Time</td><td>Distance</td><td>Costs</td><td>Time</td><td>Distance</td><td>Costs as well</td></tr>
<tr><td>Car</td><td>Distance-dependent Excellent speed as in [29]</td><td>Spherical distance with detour factor 1.3 [28]</td><td>0.35 €/km [30] (low-end)</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td><td>/</td></tr>
<tr><td>CS-25</td><td>105 min waiting/apron taxi time

Trapezoidal speed profile @FL300, Vmax 833km/h</td><td>Spherical distance with detour factor 1.06 [31]</td><td>0.47 €/km, averaged from [32]</td><td rowspan="3">Distance-dependent Excellent speed as in [29]</td><td rowspan="3">Spherical distance with detour factor 1.3 [28]</td><td>MIV + Parking: 35€
or
Taxi: 3.8€ base fee, 1.98€/km working price (1€ from 50km)</td><td rowspan="3">Distance-dependent Excellent speed as in [29]</td><td rowspan="3">Spherical distance with detour factor 1.3 [28]</td><td rowspan="3">Rental:
Fee: 80€ [Check24, for MUC]
0.06 €/km fuel cost [30]
or
Taxi: 3,8€ base fee, 1.98€/km working price (1€ from 50km)</td></tr>
<tr><td>Long-distance train service</td><td>Query from DB API; average of 5 next-day connections</td><td>Query from DB API</td><td>Query from DB API; average of 5 next-day connections</td><td>MIV + Parking: 10€;
or
Taxi: 3.8€ base fee, 1.98€/km working price (1€ from 50km)</td></tr>
<tr><td>ODAM</td><td>45 min waiting/apron taxi time

Trapezoidal speed profile @FL100, Vmax 280km/h</td><td>Spherical distance with detour factor 1.06 [31]</td><td>0.65 €/km</td><td>MIV + Parking: free
or
Taxi: 3.8€ base fee, 1.98€/km working price (1€ from 50km)</td></tr>
</table>