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Market volume estimation of thin-haul On-Demand Air Mobility services in Germany

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Upcoming advances in the area of electric flight and flight automation enable provision of sustainable and price competitive thin-haul On-Demand Air Mobility (ODAM) services using pilotless CS-23 class aircraft in mid-term future. These services promise a significant increase in travel speed for a larger part of the population as an alternative to current ground based transportation systems. The competitiveness of ODAM services depends, amongst others, on access and egress times and costs to usable airfields, which significantly impacts the potential market volume. In order to estimate the thin-haul ODAM market volume for Germany, a comprehensive analysis of the entire German population and their distances to feasible airfields is performed, which is based on Census 2011 data dividing Germany into squares of one by one km². Additionally, a transport demand model as well as a preference choice model based on opportunity costs are derived for Germany. A market share of 19% or 235 million trips are estimated with this methodology assuming passenger specific costs of 0.4 €/km for ODAM services, 0.3 €/km for cars and 0.32 €/km for contemporary commercial CS-25 aircraft. The market share shows a distinct sensitivity on the cost gap between car and ODAM costs. If ODAM costs are 0.2 €/km more expensive than car costs the market share decreases to 2% or 24 million trips. Aircraft considered for ODAM services should achieve runway performances below 800 m, accommodate two to four passenger seats and achieve max. ranges of 400-500 km including reserves.

Nomenclature

α = Regional attractiveness factor
C = Costs
c = km-specific costs
d = Distance
P = Population
π_{ij} = Passenger transport volume between origin i and destination j
v = Velocity
χ = Exponential distance weighting factor
T = Time

I. Introduction

Recent and upcoming advances in flight automation and electric flight are likely to enable sustainable, pilotless aircraft in mid-term until 2030-2040[1–3]. Electric or hybrid electric propulsion concepts contribute to lower operating costs, however the main purpose of such concepts is to fulfill sustainability targets stipulated by the European Union with "Flightpath 2050"[4]. This agenda sets targets to reduce nitrogen oxides by -90% and carbon dioxide by -75%. The major enabler for lower operating costs especially for small aircraft with only two to six passenger seats is driven by pilotless aircraft as pilot costs account for ca. 25%-50% of the variable operating costs at such aircraft[6; 5]. Moreover, pilotless aircraft are likely to be utilized several times more than nowadays general aviation aircraft with only 150-450 hours per year, additionally reducing operating costs by lower km-specific fixed

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costs. Assuming an increase to 1,000 hours per year, which is well below the approximate 2,500 h/a (or more) utilization of today's commercial CS-25 aircraft, total service provision costs of ODAM aircraft of 0.5-0.7 €/km are realistic for a four passenger seated, electric, pilotless, fixed-wing aircraft without vertical take-off and landing (VTOL) ability if considering design ranges of up to 500-600 km at specific battery energy of 400 Wh/kg[5; 7]. Leverage of hybrid-electric propulsion concepts can increase the design range without a significant weight or operating costs penalty or enable operating cost benefits at a lower specific battery energy level[6].

Given the accessibility of pilotless aircraft incorporating (hybrid-)electric propulsion concepts, such aircraft can be used for thin-haul On-Demand Air Mobility (ODAM) services. These services require regional or local airfields as they are not equipped with a VTOL ability and their main application are regional transportation distances ranging from approximately 100-1000 km linear distance. These services can be mostly considered as an alternative to current ground based transportation systems, such as cars or trains and partly as an alternative to current commercial CS-25 air transportation at low distances. The proposed ODAM services shall resolve the so called "transportation gap"[8] of nowadays transportation systems. Ground based transportation options rarely exceed door-to-door linear distance speeds of 60-90 km/h[9] in Germany leading to long travel times at longer distances (>~200-300 km). On the other hand current CS-25 air transportation usually requires large, centralized airports leading to long commuting and transition times significantly lowering effective travel speed at low distances.

Several studies argue the general upside potential of ODAM services[10; 1–3; 7]. A case study performed by Antcliff focuses on intra-urban mobility for San Francisco, USA[11] requiring aircraft with VTOL ability. A study performed by Moore et. al[2] holds estimates on the number of passengers travelling with ODAM services for the United States depending on seat costs per mile leveraging the transport system analysis model (TSAM[12]). With 0.50 US-$/seat mile estimates range from approximately 200-450 mio. person trips declining to 60-160 at 1.00 US-$/seat mile. In another study also based on TSAM, Pu et. al[13] estimate 1.3%-5.5% share of ODAM with seat mile costs of 0.50 US-$ to 1.00 US-$ and a general assumption of 20 minute commuting time to and from feasible airfields. A sensitivity analysis is performed with regards to first and last mile travel distance and time, however the actual population distribution and their respective distances to and from feasible airfields is not considered in this context. This is only considered in the analysis of determining the share of travelers using ODAM services when commuting to work for seven metropolitan areas based on Census tracts. Results show, that only insignificant shares of 0.01%-0.001% of commuters choose ODAM services for traveling to and from work. TSAM only covers the US. Another study based on a willingness-to-pay approach demonstrated the economic competitiveness for the German market of thin-haul ODAM services for ranges between ~200-600 km linear distance using aircraft without VTOL ability[5]. Based on a sample of 50 door-to-door trips average first and last mile distances are used. Given the willingness-to-pay approach a market volume was not derived for Germany.

So far, an analysis with a substantiated estimation of thin-haul ODAM market volume considering first and last mile distance distribution based on the population distribution in the proximity of feasible airfields has not been conducted for Germany. Therefore, a profound analysis is conducted in this paper to estimate the potential market size of thin-haul ODAM services in Germany including determination of the most important influence factors. Additionally reasonable TLARs for ODAM aircraft are deducted.

II. Methodology to estimate thin-haul ODAM market volume in Germany

The market volume estimation can be separated into four steps. First, feasible airfields already existing in Germany are determined depending on the runway performance of potential aircraft in subsection II.A. The Jeppesen electronic airport directory[14] containing 465 airfields in Germany is leveraged in this context. Second, the number of people living in a certain distance to feasible airfields is calculated, which is described in subsection II.B. This analysis is based on publicly available Census 2011 data provided by the German Federal Statistical Office (Destatis)[15]. Within this database Germany is divided into more than 350,000 one by one square km. Third, the transport demand among people living in the proximity of feasible airfields is modelled in subsection II.C. This model is based on a law-of-gravity approach calibrated by reference data of the transport interdependency forecast ("Verkehrsverflechtungsprognose") conducted by Intraplan Consult and BVU Beratergruppe Verkehr+Umwelt on behalf of the Federal Ministry of Transport and Digital Infrastructure (BMVI)[16]. Last, a transport mode preference model is derived in subsection II.D to consider the different options people have for travelling and consequently simulating their transport preference for the intended trip. Cars and current CS-25 air transportation are considered as alternatives in this analysis as cars are the predominant choice at shorter distances and commercial CS-25 aircraft the one at larger distances. Trains are omitted in this analysis as on the one hand car traffic volume with more than one billion trips above 100 km is significantly larger than train volume with only 130 million long-haul trips[16] and on the other hand train modelling requires severe effort as first all train station locations need to be determined and second accurate modelling of train connections is difficult due to a heterogeneous railroad system (e.g., high speed railways vs. low speed railways). The preference model is based on opportunity costs being impacted by service provision costs and travel times as well as the individual income. Results are summarized in section III.

A. Feasible airfields

The Jeppesen electronic airport directory[14] contains all 465 airfields with an ICAO code in Germany. 36 of these airports are currently for pure military use, five for joint operations and ten in private use. 414 publicly operated, relevant airfields remain. However, large airports suitable for commercial CS-25 air transportation services often operate even today at their maximum capacity. Additional traffic due to ODAM services is unlikely at these airports. Therefore the largest top 20 airports regarding passengers are excluded from the analysis if not explicitly mentioned otherwise[17]. The lowest top 20 airport Friedrichshafen (EDNY) only handles slightly more than 500,000 passengers per year, which is a very conservative threshold for exclusion of ODAM services. Additionally, this database contains the GPS location as well as the altitude and detailed information regarding runway characteristics. In this database the runway length is distinguished between take-off run available (TORA), take-off distance available (TODA), accelerate-to-stop distance available (ASDA) and landing distance available (LDA). For the sake of brevity and simplicity the shortest available distance will be compared to the aircraft's longest required respective distance and considered as runway performance. Depending on the runway performance characteristics of thin-haul ODAM aircraft feasible airfields can be determined.

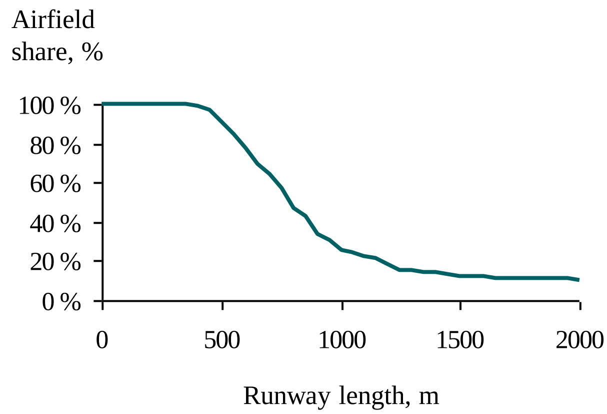

Fig. 1: Share of usable airfields in Germany depending on runway performance

Fig. 1 illustrates the share of usable airfields depending on the aircraft's runway performance at sea level (SL) and ISA atmosphere. A slow decrease can be observed until runway performances of about 500 m. 77% of the airfields are still feasible at a runway performance of 600 m. This decrease steepens from that point on making only 47% of the airfields feasible for aircraft achieving a runway performance of about 800 m. Fig. 2 illustrates the geographic location for (a) all airfields, (b) airfieldtravs with runways above 600 m and (c) above 800 m, whereas considered CS-25 airports are market with a red dot, ODAM suitable airfields with a smaller black one. A nearly even geographic decrease can be observed.

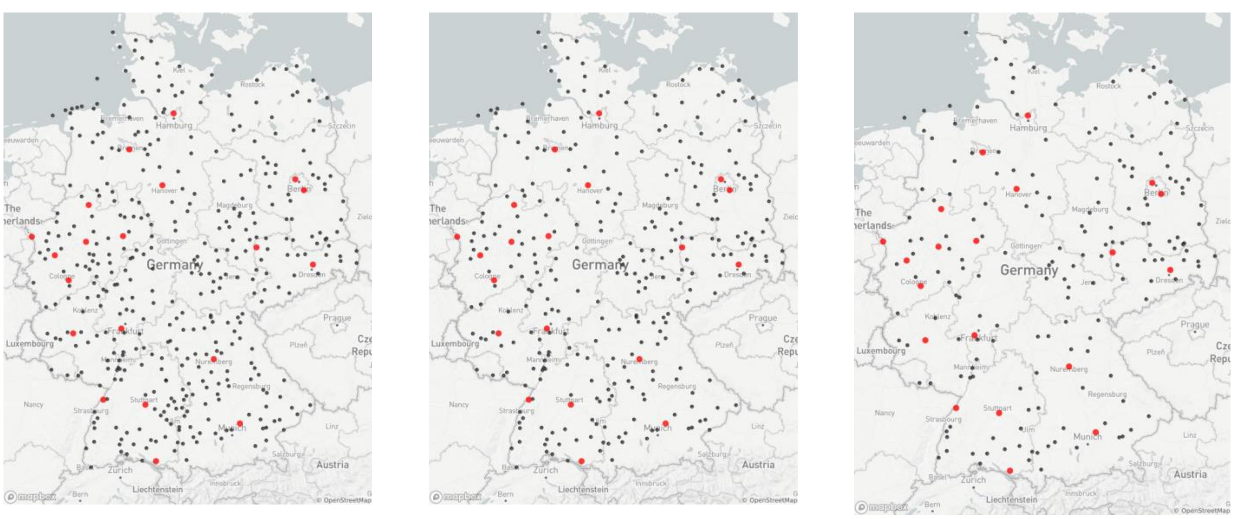

Fig. 2: Geographic locations of (a) all airfields, (b) airfields > 600 m runway and (c) > 800 m runway in Germany (red dot: CS-25 airports, black dot: ODAM suitable airfield)

B. Population in catchment area of airfields

The second important question to be answered is the amount of people living in a certain distance to feasible airfields. The Census 2011 database[15] holds information about the German population and includes 80,212,528 people and their residence location on a very granular discretization mesh of 1 km by 1 km resulting in ~350,000 rows. 214,633 boxes contain residents. It is noteworthy that a negligible share of inhabitants is omitted in the database if only one person lives inside a grid cell due to privacy reasons. However, the error amounts to less than 0.009% as the total population is listed on regional level with 80,219,695 at the same time[15]. Each box is allocated to exactly one airfield, which is – from a linear distance point of view – the closest feasible airfield.

As the discretization mesh is relatively small, the population distribution within one box can be neglected. This implies, that an entire box is assumed to be within a certain distance to the airfield if the mid-point is included. This results in a maximum error of half the box diagonal (~707 m) with an average error of ca. 400 m assuming a homogenous distribution within each box. This uncertainty is judged to be acceptable. With this database, it is possible to determine the number of people living within a certain distance to feasible airfields. The population share depending on the linear distance to the closest, feasible airfield is illustrated in Fig. 3 for four different categories of feasible airfields.

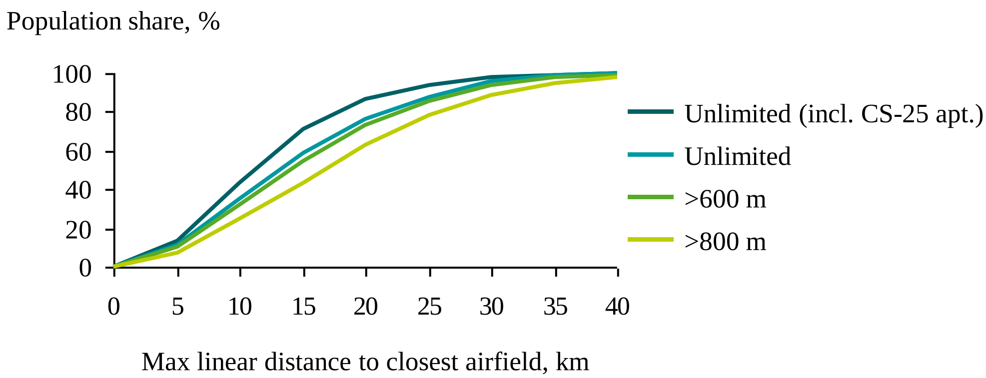

Fig. 3: Population share living in the proximity of an airfield depending on max linear distance

The upper bound of the population share is displayed by considering all airfields including large CS-25 airport "Unlimited (incl. CS-25 apt.)". In this case 43.7% (i.e. ~ 35 mio. people) live within 10 km linear distance and 86.3% within 20 km. The impact of omitting CS-25 airports leads to a moderate increase of 2-3 km linear distance to airfields when considering same population shares and a distance below 15 km. At same distances a decrease of 10% population share can be observed for distances in between 10-20 km with a narrowing gap at smaller distances. Additionally excluding airfields with runways below 600 m a minor increase of less than 1.0 km can be observed when considering same population shares. While only 62% of all airfields are feasible at runway performances of 800 m the impact on the linear distance is lower as population shares drop from 31.8% to 24.3% within 10 km and from 73.0% to 62.4% at 20 km. When considering same population shares the average distance to the closest airfield increases – similar to omitting CS-25 airports – by approximately 2-3 km.

C. Passenger transport demand model

Having determined the amount of people living within certain distances to feasible airfields it is necessary to estimate the passenger transport demand among these subsets. Consequently, a passenger transport demand model is derived and calibrated for Germany.

A typical approach to forecast transportation demand is based on gravity models[18], which was originally postulated by Lill in 1891 by observing railway traffic on the connection Vienna-Brno-Prague[19]. Introducing the calibration factors γ and χ, transportation demand volume π_{ij} between the two areas i and j can be calculated depending on both populations P_i resp. P_j and their linear distance d_{ij}:

$$\pi_{ij} = \gamma * \frac{P_i * P_j}{d_{ij}^{\chi}}$$

In variation to the formulation above, attractiveness factors α are introduced for each catchment area. These factors are multiplied with the number of inhabitants in area i to reflect a different regional attractiveness. The “gravity constant” γ can be omitted with introduction of these attractiveness factors α_i. The applied model can be summarized as follows:

$$\pi_{ij} = \frac{\alpha_i P_i * \alpha_j P_j}{d_{ij}^{\chi}} \tag{1}$$

The study transport interdependency forecast (“**V**erkehrs**v**erflechtungs**p**rognose”, VVP) conducted by Intraplan Consult and BVU Beratergruppe Verkehr+Umwelt on behalf of the Federal Ministry of Transport and Digital Infrastructure (BMVI)[16] represents the main data source to calibrate the model according to Eq. (1). This study contains an origin-destination matrix of estimated passenger transport demand on regional level. Germany consists of 412 regions leading to a 412x412 matrix with 169,332 none zero data points (demand within each region is not included). According to the source, transport volume is independent of the direction leading to a symmetric matrix. Ultimately the 413 parameters (412 attractiveness factors α_i and the exponent χ) are calibrated using the Levenberg-Marquard-Algorithm[20] to solve the non-linear least square problem.

However, the heterogeneous data sources and formats are challenging. On the one hand, the VVP data does not contain any information regarding the population size in the respective regions. On the other hand, the census grid cell database only contains geographic coordinates in Lambert-Azimuthal-Equal Area Projection (LAEA) format according to the European INSPIRE-norm of the respective grid cell and the number of people residing in this area. Information on the associated region is missing. Therefore multiple data sources are merged, which is displayed in Fig. 4.

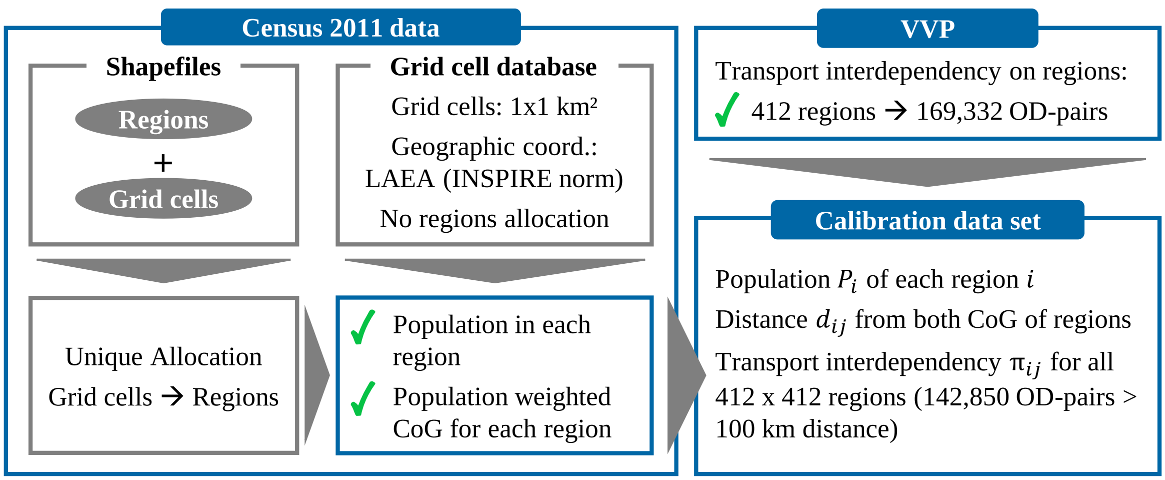

Fig. 4: Combined data sources to derive calibration data set for the transport demand model

Census 2011 shapefiles[21] containing geographic information on the boundaries of each grid cell are blended with a shapefile of the regions[22] using a geographic information system such as QGIS. Each grid cell can then be uniquely allocated to the respective region. Combined with the additional grid cell database information the population of each region and most importantly the population weighted center of gravity can be determined serving as reference points for the linear distance calculation. This data can then be merged with the VVP providing all necessary data required for calibration of Eq. (1). It is assumed that ODAM services are only relevant above 100 km linear distance. Consequently, OD-pairs are excluded if the linear distance is below 100 km. This reduces relevant OD-pairs to 142,850. Nevertheless, the resulting equation system is highly overdetermined because the applied model possesses only 413 parameters. A MATLAB model is developed for this calibration purpose using the Levenberg-Marquard-Algorithm[20].

Considering all relevant regional OD-pairs above 100 km linear distance a total annual travel demand of 1.17 bn trips can be estimated with the calibrated model totaling a volume of 239 bn km. The total values are in good accordance with the VVP-forcast as the deviation of the model is less than 0.6% for trips and volume. It is to be expected, that ODAM achieves significant market shares at distances in between 200-500 km. Hence, the accuracy in this range is crucial, which is the main reason for choosing parameters that slightly deviate from the optimal solution from a least square point of view that weights all trips equally. First, optimal parameters are determined based on a least square approach. In order to increase accuracy of distance categories the exponent χ is varied. The least-square optimal (lsq.-opt.) solution yields $\chi = 2.28$. As displayed in Fig. 5 the least-square optimal solution overestimates demand for distances in between 200-500 km with approximately 10%-20% and slightly overshoots total trips by 3.7%.

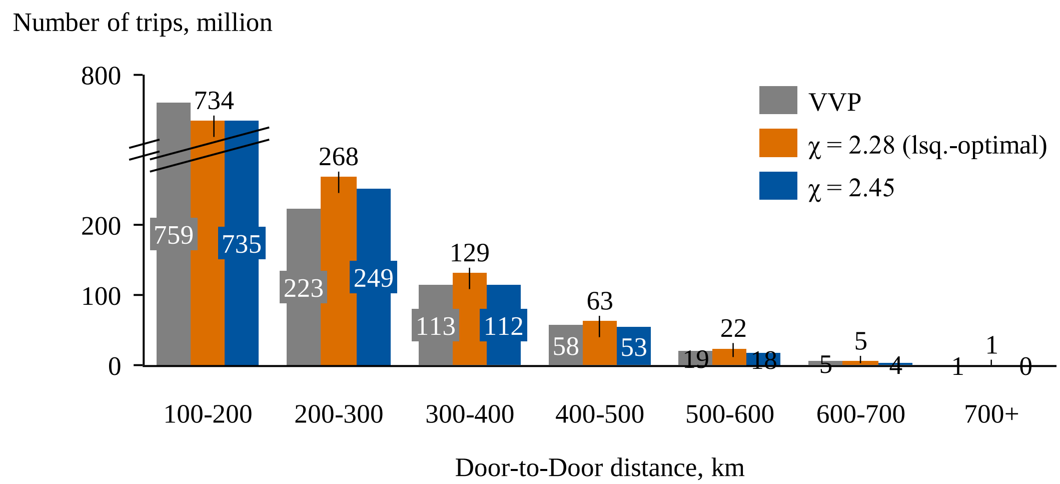

Fig. 5: Number of trips for baseline data (VVP), least-square optimal solution ($\chi = \mathbf{2.28}$) and a modified solution ($\chi = \mathbf{2.45}$)

Subsequently, different exponent values of χ are studied and the remaining 412 parameters solved with the least-square algorithm. A value of $\chi = 2.45$ holds more accurate results in terms of number of trips for distances between 200-600 km, which are particularly important for ODAM and achieves a significant better accuracy for total trips as mentioned above. On the other hand, the absolute standard deviation of the non-optimal least-square parameters only fairly deteriorates by 2.6% as illustrated in the left diagram in Fig. 6. The relative standard deviation, however, relatively decreases by more than 30%.

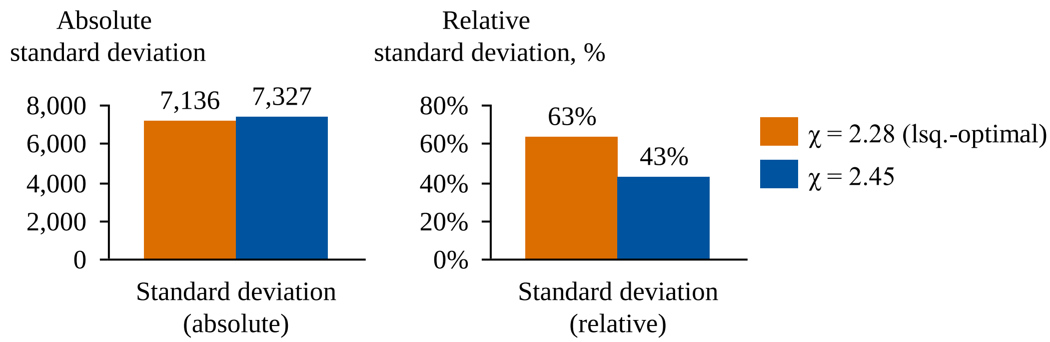

Fig. 6: Absolute (left) and relative (right) standard deviation of demand model compared to VVP baseline

D. Transport mode preference model

The share of trips for which ODAM services are chosen is determined in two steps. First, door-to-door trips for relevant transportation options are modelled in subsection II.D.1. This includes derivation of required costs and time for relevant transport modes and identification of the cheapest transport mode. Cars and current commercial CS-25 air transportation are chosen as alternative transportation options. Subsequently, opportunity costs are determined for faster, but more expensive transport modes. These opportunity costs serve as the basis for the transport mode preference model. Second, the opportunity cost distribution of the German population is determined in subsection II.D.2 in order to deduct the ODAM share.

1. Route modelling of considered transportation options

An illustration of the modelled transport paths is illustrated in Fig. 7 for each option. A calculation of OD-pairs based on each grid cell resulting in more than 40 billion connections is infeasible due to the tremendous computing effort. As first (access) and last (egress) miles are crucial for ODAM services, people living in the proximity of airfields are clustered by their linear distance to these airfields. This requires discretizing the catchment area of each airfield into rings rather than full-bodied circles. Moreover, when considering cars and CS-25 aircraft an additional radial discretization is required. In these cases, the impact of the diameter of the considered concentric rings around airfields on the travel distance needs to be considered especially at lower door-to-door distances. For example, considering a 25 km ring radius at both origin and destination airfield and a linear distance of $d = 150\,km$, the closest distance of both rings is $d_{min} = 100\,km$ and the longest distance $d_{max} = 200\,km$. It is conceivable, that the chosen transport mode differs between min and max distance. Additionally, this is particularly important when

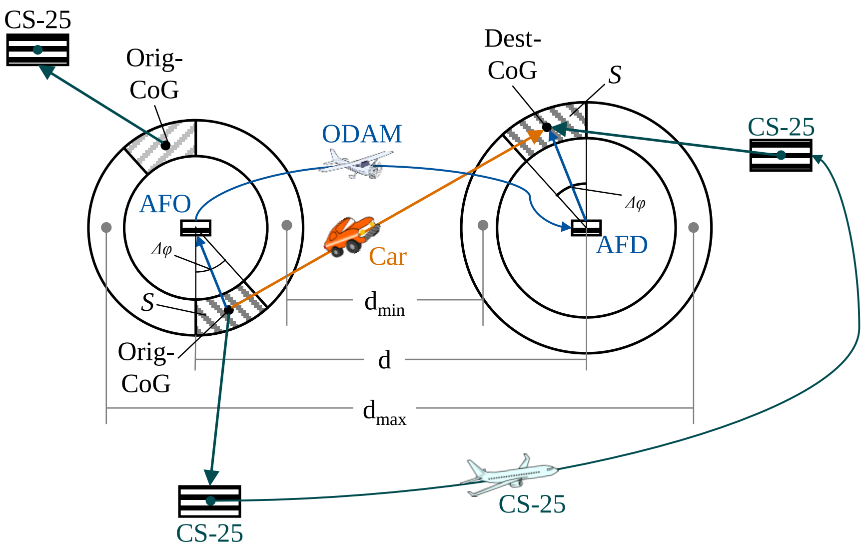

Fig. 7: Illustration of ring segmentation to increase accuracy of modelling car and CS-25 transport modes

modelling CS-25 air transportation. On the one hand first and last mile distance is important for CS-25 air transportation analogue to ODAM services, on the other it is also likely that, e.g., with a 50 km ring diameter the closest CS-25 airport differs depending on the precise location within the ring. This is illustrated in Fig. 7 on the left side (origin) with two different CS-25 airports. Therefore, each concentric ring is additionally separated into segments.

For application of the transport demand model according to subsection II.C., the population within each ring weighted by their regional attractiveness factor α is determined. It is noteworthy that a ring may cover several regions. Assuming a homogenous population distribution within each ring, the share of people within the considered ring segment can easily be determined. To increase the accuracy of results the center of gravity (CoG) is determined for each ring segment. From this CoG proper distances and hence time and cost can be calculated for other transport modes such as cars and CS-25 air transportation.

In the following a discretization mesh of four rings with each three segments is applied whereas each ring possesses a thickness of 10 km. With this ring discretization more than 99.3% of the population are covered. This leads to at most 4,968 origin and destination points if all airfields are considered resulting in more than 24.6 million OD-pairs. Considering that for each OD pair three transportation alternatives are modelled, a total of more than 74 million OD-connections are evaluated. The granularity of the discretization mesh is limited by computational capacities. With this resolution computation time requires

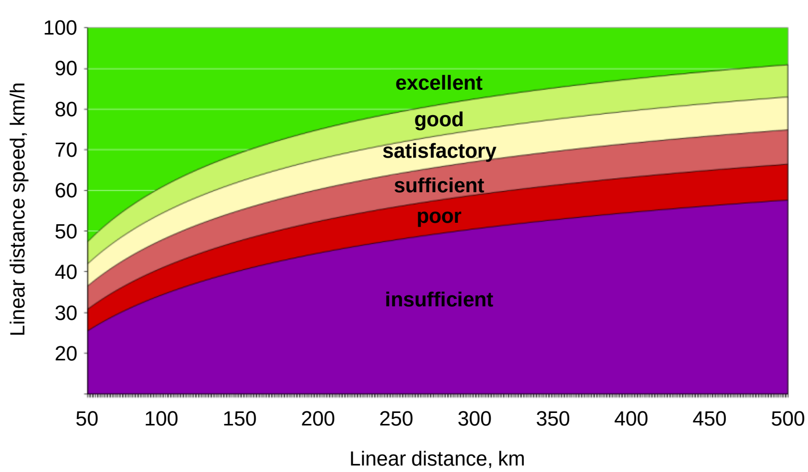

Fig. 8: Motorway speed depending on linear distance and quality category[9]

about two to four hours for one parameter set. Considering the aspiration to conduct sensitivity studies the applied discretization mesh is judged to be a suitable trade-off of accuracy and acceptable computation effort.

In case of usage of the transport mode **car** it is assumed that door-to-door trips start and end at the actual starting resp. destination points.

The German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) classifies motorways into different categories depending on the distance and their motorway speed v_{mw}, which is displayed in Fig. 8[9] . All roads are conservatively assumed to comply with the best category *excellent* in this analysis. The following regression formula is derived from these values to calculate the linear distance car speed v_{ij}^{car} depending on the linear distance d_{ij}:

$$v_{ij}^{car} = 19.975 * \ d_{ij}{}^{0.24794} \tag{2}$$

The German Automobile Club (ADAC) continuously determines total car costs for more than 1,800 cars during a usage of four years with 15,000 km per year. Considering only cars with a retail price less than 40,000 € and below 170 bhp, average km specific costs of 0.477 €/km can be determined. However, on the one hand the average German car is older than the analyzed period under consideration by the ADAC analysis and on the other hand perceived costs often exclude depreciation. Therefore, in accordance to the federal commuter allowance km-specific costs of $c^{car} = 0.3\ €/km$ are assumed. Because ground based transportation is required to circumvent obstacles such as bigger cities, lakes, mountains etc. a detour factor of 1.3 is introduced[23]. The costs C_{ij}^{car} and travel time T_{ij}^{car} for the transport option car can be determined for each OD-pair ij in dependence on the linear distance d_{ij} as follows:

$$C_{ij}^{car} = c^{car} * 1.3 * d_{ij}$$

$$T_{ij}^{car} = \frac{d_{ij}}{v_{ij}^{car}}$$

ODAM services are modelled in three steps. The so called *first mile* represents the trip from the actual starting point to the origin airfield (AFO). According to car modelling and Eq. (2) a linear distance speed of $v_{fm,ij}^{car}(d_{fm,ij}^{ODAM})$ is assumed for driving the first mile $d_{fm,ij}^{ODAM}$ distance to the airfield. An analysis conducted at the Munich airport shows that approximately 20% of the first and last miles are conducted by taxi[24]. The remaining 80% either drive with their own car or are a passenger. This share is also applied for ODAM services in the following, whereas car costs are doubled to conservatively account for forward and return way in case the traveller does not drive the car himself. Due to upcoming car sharing concepts such as Uber or car2go it is to be expected that taxi costs will significantly decrease. Consequently, km-specific costs of $c_{taxi} = 1.3\ €/km$ are assumed. This corresponds to approximately half of the current taxi costs for a 10 km trip. Due to the mixture of 20% taxi share and 80% car share an average costs of $c_{car/taxi} = 0.74\ €/km$ is applied. Transition times of each $t_{trans}^{ODAM} = 10\ min$ are considered at the airfield as well as taxiing times of each $t_{apron}^{ODAM} = 10\ min$. A cruise speed of $v_{cruise}^{ODAM} = 350\ km/h$ is assumed following results of NASA's LEAPTEC[25]. To account for slower climb and descend speeds only two third of the cruise speed is considered for the first d_{climb} resp. last $d_{desc} = 30\ km$. The linear distance $d_{mr,ij}^{ODAM}$ between both airfields is assumed as the total flight distance. Specific cost estimates for ODAM services range from 0.2 €/km-0.4 €/km[6; 5; 2; 7; 26] assuming an average passenger utilization of 50%-75% of a four seated, pilotless aircraft. For the following analysis a default value of $c^{ODAM} = 0.4\ €/km$ is applied for a conservative estimation. The last mile from the destination airfield (AFD) to the actual destination is modelled analogue to the first mile in dependence on the last mile distance $d_{lm,ij}^{ODAM}$. In summary, costs C_{ij}^{ODAM} and travel time T_{ij}^{ODAM} can be determined for the ODAM transport option for each OD-pair ij:

$$C_{ij}^{ODAM} = c_{car/taxi} * \left(d_{fm,ij}^{ODAM} + d_{lm,ij}^{ODAM}\right) * 1.3 + c^{ODAM} * d_{mr,ij}^{ODAM}$$

$$T_{ij}^{ODAM} = \frac{d_{fm,ij}^{ODAM}}{v_{fm,ij}^{car}(d_{fm,ij}^{ODAM})} + 2 * \left(t_{trans}^{ODAM} + t_{apron}^{ODAM}\right) + \left(\frac{d_{climb}^{ODAM}}{{}^{2}\!/_{3} * v_{cruise}^{ODAM}} + \frac{d_{mr,ij}^{ODAM} - d_{climb} - d_{desc}}{v_{cruise}} + \frac{d_{desc}^{ODAM}}{{}^{2}\!/_{3} * v_{cruise}^{ODAM}}\right) + \frac{d_{lm,ij}^{ODAM}}{v_{lm,ij}^{car}(d_{lm,ij}^{ODAM})}$$

Current commercial **CS-25 air transportation** is modelled similar to ODAM. First, the closest CS-25 origin and destination airports are determined for each OD-pair. First and last mile are calculate in accordance with first and last mile modelling of ODAM depending on the distances to and from origin and destination airports $d_{fm,ij}^{CS25}$ and $d_{lm,ij}^{CS25}$. Transition at the origin airport is assumed to be $t_{trans,orig}^{CS25} = 50\,min$ at the departure airport, $t_{trans,dest}^{CS25} = 15\,min$ at the arrival airport and a taxiing time of each $t_{apron}^{CS25} = 15\,min$. The flight model consists of three segments analogue to an ODAM flight. The cruise speed is assumed to be $v_{cruise}^{CS25} = 830\,km/h$ with a climb and descend speed of $v_{climb}^{CS25} = v_{desc}^{CS25} = 430\,km/h$ during the first $d_{climb}^{CS25} = 75\,km$ resp. last $d_{desc}^{CS25} = 75\,km$. With these values a random sample of 16 national connections shows good accordance with the provided airline flight times[5].

The linear distance between both airports is considered as the flight distance $d_{mr,ij}^{CS25}$. Based on the above mentioned analysis km-specific costs of $c^{CS25} = 0.32\,€/km$ can be determined. The Federal Association of the German Aviation Industry[27] (BDL) states an average one-way ticket fair of 184 € per national flight. The German Airport Association[28] (ADV) states that most passengers travel occurs in between 500-600 km distance. This results in 0.33 €/km. Due to the different data source a value of $c^{CS25} = 0.32\,€/km$ is used in the following. Consequently, the costs C_{ij}^{CS25} and travel times T_{ij}^{CS25} can be determined as followed:

$$C_{ij}^{CS25} = c_{car/taxi} * \left(d_{fm,ij}^{CS25} + d_{lm,ij}^{CS25}\right) * 1.3 + c^{CS25} * d_{mr,ij}^{CS25}$$

$$T_{ij}^{CS25} = \frac{d_{fm,ij}^{CS25}}{v_{fm,ij}^{car}(d_{fm,ij}^{CS25})} + 2 * \left(t_{trans}^{CS25} + t_{apron}^{CS25}\right) + \left(\frac{d_{climb}^{CS25}}{v_{climb}^{CS25}} + \frac{d_{mr,ij}^{CS25} - d_{climb} - d_{desc}}{v_{cruise}} + \frac{d_{desc}^{CS25}}{v_{desc}^{CS25}}\right) + \frac{d_{lm,ij}^{CS25}}{v_{lm,ij}^{car}(d_{lm,ij}^{CS25})}$$

2. Opportunity cost based transport preference model

The transport preference model includes two parts. First, based on the modelled costs and travel times of all considered transport modes the opportunity costs $C_{ij}^{opty,m-n}$ of the faster transport mode m regarding the slower competing mode n need to be determined for each OD-pair ij:

$$C_{ij}^{opty,m-n} = \frac{C_{ij}^{m} - C_{ij}^{n}}{T_{ij}^{n} - T_{ij}^{m}}$$

Consequently, three opportunity costs are determined for each OD-pair. If a transport mode is slower but more expensive, the mode is evaluated with negative opportunity costs. In this case the transport mode is dismissed for the OD-pair ij.

Secondly, assuming a homo oeconomicus the transport mode preference depends on the individual opportunity cost level. The individual opportunity costs mainly depend on the nature of the journey (private vs. business) and the individual resp. household income level. People with a higher salary are willing to pay more for a service that reduces travel time than people with less (disposable) income. The German Federal Statistics Office (Destatis) publishes every five years the household income distribution on national level based on a representative sample[29]. This distribution differentiates 12 income categories. Additionally, the average number of household members is published according to the 12 different income categories. Subsequently, the individual opportunity cost level is derived by dividing the household income by the average number of household members. The resulting opportunity costs are displayed in Fig. 9. Additionally, it is differentiated whether the purpose of the trip is of private or business nature. According to the Federal Ministry of Transport and Digital Infrastructure (BMVI) the share of business travel amounts to 16.8%[30]. In this case the opportunity costs are doubled to reflect higher employer costs compared to the net income of the employee.

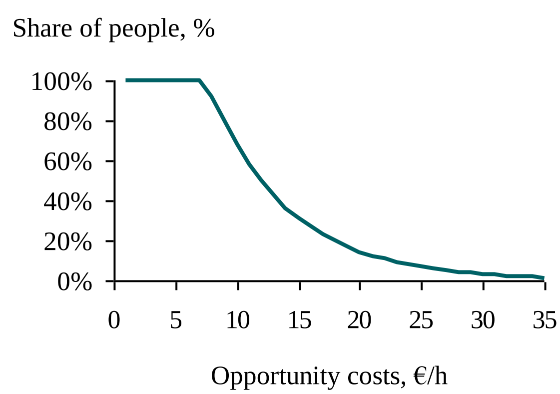

Fig. 9: Income and resulting opportunity cost distribution for a private trip

III. Thin-haul On-Demand Air Mobility market volume for Germany

The results of the applied methodology described in section II are discussed in this section, whereas all airfields except CS-25 airports are considered if not explicitly mentioned otherwise. The most important key figures and results of the modelled overall passenger transport demand according to the discretization mesh of four concentric rings around feasible airfields with each three segments (see subsection II.D.1) are summarized in subsection III.E. Results of the subsequently applied modal split according to subsection II.D and the deduction of reasonable TLARs for ODAM aircraft are discussed in subsection III.F. This includes a parameter study of the most sensitive parameters in order to analyze the stability of the recommended TLARs.

E. Total passenger transport demand

The described gravity model derived in subsection II.C can be used to estimate the passenger transport demand of people living in certain proximity of feasible airfields. The population in the catchment area of the respective airfield is weighted with the respective attractiveness factor α. It shall be noted that the catchment area may be comprised of grid cells associated with different regions. Due to the granual discretization grid of one by one sq. km and the unique allocation the different regional attractiveness factors can be properly considered. As described in subsection II.D concentric ring segments are applied for the catchment area of airfields rather than full-bodied circles. Due to the discretization of the catchment area of each airfield into four rings with each three segments a maximum of almost 5,000 origin and destination points are considered leading to approximately 25 million OD-pairs assuming all airfields are feasible. The total modelled demand results in 1.23 bn trips per year and a transport performance of 250.6 bn km, which is 5.6% higher than the total trips (or 4.9% regarding transport volume) according to subsection II.C due to a different discretization of Germany.

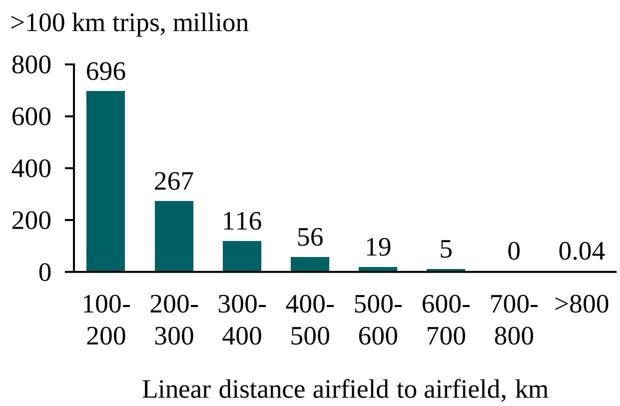

Fig. 10: Linear distance distribution of modelled trips

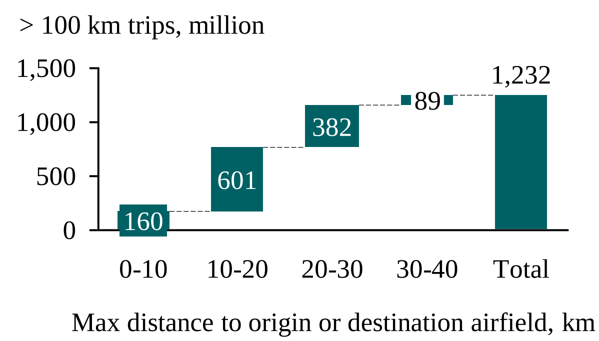

Fig. 11: Number of trips > 100 km linear distance depending on max linear distance to airfields

Fig. 10 illustrates the distribution of the modelled trips according to their linear distance. Given the high exponent value $\chi = 2.45$ and according to the data obtained from the VVP more than 99% of all trips possess a linear distance of less than 600 km. The longest trip distance is 928 km. Fig. 11 displays the generated trips depending on the max linear distance to either the origin or destination airfield. Approximately 13% of all generated trips possess a first and last mile to a local airfield of less than 10 km. Almost half of the modelled trips have a maximum distance in between 10-20 km.19

F. ODAM market volume estimation

This section comprises two parts. In the first part results are summarized using default parameters as described in section II. This includes a preliminary assessment of the two TLARs range and passenger seats. Subsequently, sensitivity studies are performed regarding ODAM service provision costs, cruising speed, runway performance and (perceived) car costs.

Reference value	Total	Car	CS-25	ODAM
Number [bn]	1.23	0.96 (77.8%)	0.04 (3.0%)	0.24 (19.1%)
Volume [bn km]	250.6	168.4 (67.2%)	16.0 (6.4%)	66.2 (26.4%)

Tab. 1: Summary of estimated annual transport mode demand and shares

Assuming default parameters as of section II high level results are summarized in Tab. 1. The transport mode car represents the dominant transport mode with 77.8% related to the number of journeys and 67.2% if related to the total transport volume. ODAM achieves a market share of 19.1% resp. 26.4% translating to 235 million trips per year. CS-25 air transportation achieves only 3.0% resp. 6.4%. Given the overall short distances and the declining demand with increasing distance CS-25 air transportation is expectedly inferior to ODAM on most routes.

This becomes clearer when considering the market share of the three transport modes depending on the linear door-to-door distance as displayed in Fig. 12. Car represents the predominant mode choice until distances of up to 150 km with a market share of 90% almost linearly decreasing to less than 20% at distances of 500 km. Beyond this, market share of cars continues to decrease until less than 10% at distances above 700 km. This course is in accordance with the initial hypotheses. The market shares of ODAM and CS-25 air transportation partly yields surprising results. ODAM becomes a viable alternative in between 100 km to 200 km linear distance reaching 20% market share at 200 km distance. This share increases to almost 50% at 400 km distances and stays at a fairly constant level until approximately 650 km. Two minor peaks of CS-25 market share can be observed at 500 km and 600 km. Connections between the three largest cities in Germany, Berlin and Hamburg (Northern Germany) with Munich (Southern Germany) are the reason for these peaks. OD-pairs that possess their CoG very close to these airports achieve an exceptional high share with at the same time an exceptional high transport volume due to the high population density. Beyond 650 km linear distance, the market share of ODAM, however, does not decrease (as one might expect), but increases significantly until reaching a share of almost 90% at 900 km, which is close to the maximum distance in Germany. Distances above 700 km are only possible for very few routes in Germany connecting the most distant northern parts with the most distant southern ones. Especially north East Germany shows a lack of CS-25 airports (see Fig. 2) as considered in this analysis. Additionally, no airports outside the country limits are considered leading to severe first and last mile distances making CS-25 air transportation unattractive. The impact of this circumstance, however, is minimal. Despite the high market share above 700 km, the absolute number of ODAM trips can be neglected as it amounts to less than 1% as illustrated in Fig. 13. 85% of the ODAM trips occur in between distances of 200-600 km with 60% in between 200-400 km.

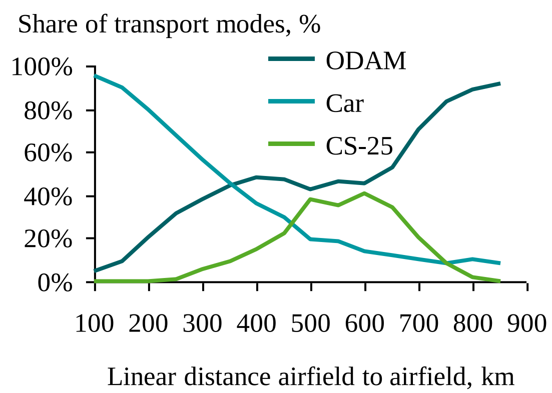

Fig. 12: Market shares depending on linear distance airfield to airfield

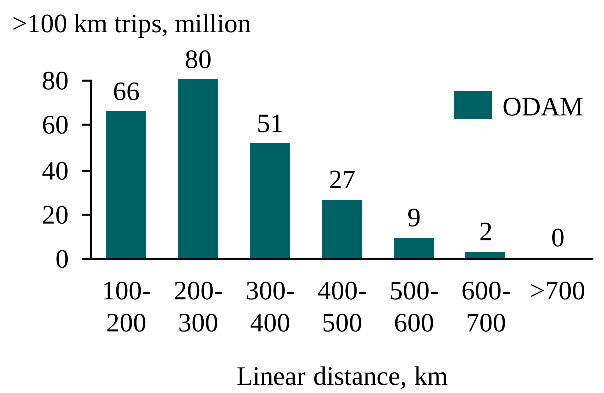

Fig. 13: Number of travelers with ODAM depending on linear door-to-door distance

Therefore, a potential ODAM aircraft fulfilling a TLAR of 400 km design range would cover 69% of the estimated ODAM demand and at 500 km design range 88%. Concluding a design ranges in between 400 km to 500 km seems most reasonable. The optimal design range can only be evaluated if aircraft design aspects (e.g., trade-off of additional service provision costs due to increased design range) are simultaneously considered. However, a significant shift either above or below the identified design range interval is unlikely. Preliminary studies indicate that the weight and hence operating cost benefits due to a decrease in design range is only moderate if 400-500 km design ranges are considered (assuming a battery specific energy of 400 Wh/kg)[32; 5; 3; 31; 7; 25]. Additionally, implementation of a hybrid electric powertrain further decreases weight and operating cost sensitivity also at lower battery specific energy levels[6].

In order to estimate a reasonable interval of ODAM aircraft passenger seat sizes, the number of travellers is illustrated in Fig. 14 and Fig. 15 for each connection of the 396 considered airfields. The daily demand is derived by dividing the forecasted annual demand through 365 days. The airfield to airfield connection can be separated into three segments. First, relatively few connections (only about 1%) contribute significantly to the overall ODAM demand and achieve a considerable absolute number of daily trips. Fig. 14 displays the almost 1,600 airfield to airfield connections (equaling 800 different airfield-pairs) with more than 50 estimated trips per day. For the top route between the airfields of Oberschleißheim (EDNX, close to Munich) and airfield Pattonville (EDTQ, close to Stuttgart) a daily demand of 938 passengers is calculated. A comparable high demand can only be observed at a handful of connections. The demand of the 11th AF-pair already decreases to less than 400 passengers per day. 60 different AF-pairs reach a demand of more than 200 travellers per day. The demand of these 1,600 routes although constituting only 1% of all connections amounts to more than 25% of the total share. The calculation of high peak numbers beyond 200 passengers per day is possible due to the absence of airfield capacity restrictions. In reality, such high numbers cannot be served as the busiest airfields are involved in numerous connections with the highest demand leading to a theoretical demand of several thousand passengers per day. Nevertheless, there seems to be a potential for a thin-haul ODAM system using aircraft with more than the initially presumed two to six passenger seats. A number of ten passenger seats seems reasonable.

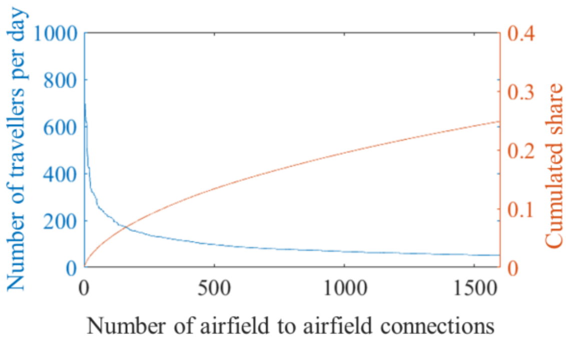

Fig. 14: Number of travellers ordered from highest to lowest airfield connection (above 50 travellers per day)

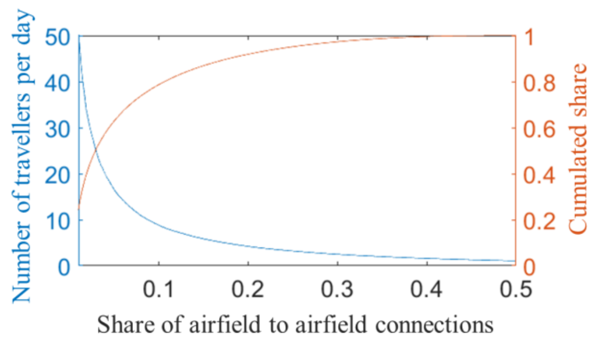

Fig. 15: Number of travelers per day ordered from highest to lowest airfield connection (below 50 travellers per day)

The second segment constitutes the bulk of the ODAM demand with 10-50 trips per day. Approximately 10% of all connections (~15,000 connections) belong to the second segment and account for approximately 55% of the entire ODAM trip volume. Small aircraft with two to four passenger seats seem suitable for this market segment. The remaining 80-90% of all connections seems less attractive constituting the last segment. Within this segment a borderline interval of 10% of all connections (i.e. interval in between 10%-20% in Fig. 15) with five to ten daily passengers can be identified. The estimated demand is too low for the remaining 80% of the connections with less than 5 passengers per day.

In conclusion, while there seems to be potential for a low double digit seated aircraft on more than 1,500 connections, a smaller aircraft of two to six passenger seats seems more feasible for the bulk of connections. Considering that demand would be lower during ramp-up phase of such ODAM services, a smaller aircraft seems to be more suitable as a starting point. A real "On-Demand" service seems only possible for the first segment with more than 50-100 travellers per day, whereas a gradual transition between an on-demand system and a scheduled service with several daily connections (e.g., hourly or every few hours) seems advisable for the second segment.

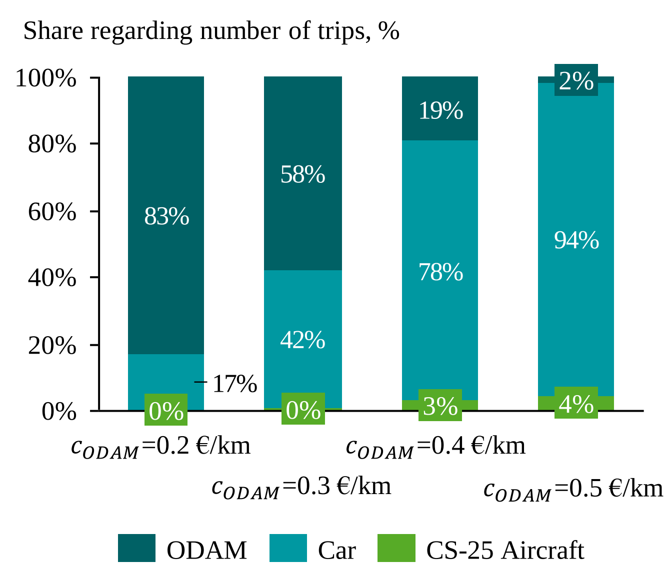

Fig. 16: Market shares regarding number of trips for different ODAM costs

Four sensitivities are investigated in the following whereas three can be attributed to the ODAM concept and one to the competing transport modes. The first ones include ODAM service provision costs, cruise speed and runway performance. (Perceived) car costs are analyzed as the latter one.

The results for four different ODAM service costs ranging from 0.2-0.5 €/km (per traveller) are summarized in Fig. 16. The market share of ODAM services shows an important sensitivity on service provision costs. A 25% cost increase to 0.5 €/km decreases the ODAM market share from 19% to 1.9% meaning a tenfold decrease in ODAM market size. Nevertheless, this low market share still corresponds to about 24 million trips per year. Assuming a similar course of number of travellers depending on the highest volume airfield to airfield connections (similar to Fig. 14), there are still 1,600 connections with more than five passengers per day and about 470 connections with more than ten passengers per day. Although an On-Demand service is not viable with these low numbers a low frequency scheduled service with small aircraft of four or less passenger seats may still be possible. In any case, 0.5 €/km is at best a borderline business case. Such costs are even less than service provision costs that would occur today if an airline would provide such services. The Hawaiian based local airline Mokulele provides services between the different islands with 16 Cessna Caravans EX accommodating up to nine passengers generating costs of 0.8 USD/per available seat mile[34; 33]. Assuming a utilization of 70% this results in costs of approximately 0.55 €/km. Furthermore considering generally higher expenses due to fuel taxes etc. even 0.6 €/km would be ambitious to achieve in Germany today. Hence, it becomes obvious why an ODAM system is currently infeasible. At lower operating costs of 0.3 €/km or even 0.2 €/km ODAM becomes the predominant transport mode on distances above 100 km. Obviously, at such high number of trips infrastructure capacity becomes the limiting resource rather than missing demand.

Variations of ODAM cruise speeds are summarized in Fig. 17. The estimated market share of 19.2% at 350 km/h cruise speed decreases by 38% to 11.9% if cruise speed is lowered to 250 km/h and by 17% to 16.0% if lowered to 300 km/h. On the other hand if cruise speed is increased to 400 km/h market share only increases by 12% to 21.5%. Concluding, at 250 km/h cruising speed of an ODAM aircraft the competitiveness could be significantly improved by increasing speed. Therefore a lower bound of 300 km/h cruising speed seems reasonable. On the other hand at 400 km/h an additional increase only gradually increases market share. Considering that the glide ratio generally decreases with increasing speeds for ODAM aircraft an upper bound of 400 km/h can be identified.

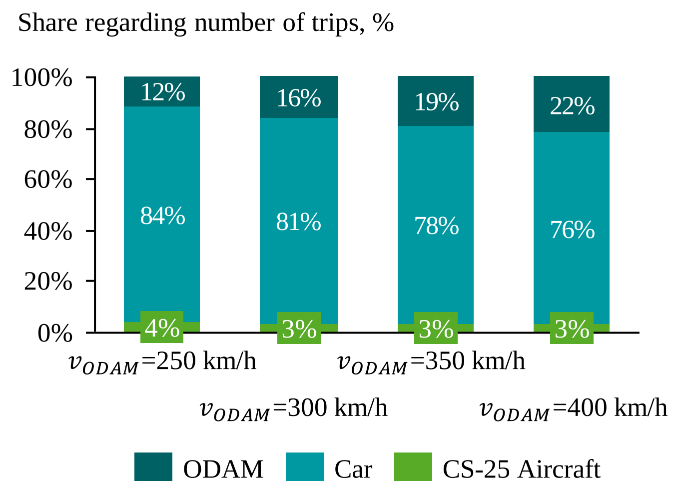

Fig. 17: Market shares regarding number of trips for different ODAM aircraft cruise speeds

Within certain regulatory limits (i.e., stall speed requirements §23.49, sustainable load factors §23.562, number of engines and climb requirements §23.67)[35] an efficiency increase at higher cruise speeds can be obtained by decreasing runway performance due to a lower wing area. This arouses the question on runway performance sensitivity, which is summarized in Fig. 18. If all 414 publicly operated airfields including the 20 largest passenger volume airports are considered ODAM trips can be increased by 23%. This is remarkable as the 20 CS-25 airports constitute only about 5% of all airfields. However, it is to be expected that such airports were built at particular suitable locations. On the other hand, market share decreases by 18% if only airfields with more than 600 m runway are considered. The sensitivity is fairly surprising as this only leads to a decrease of roughly 4% of the population when considering same distances to feasible

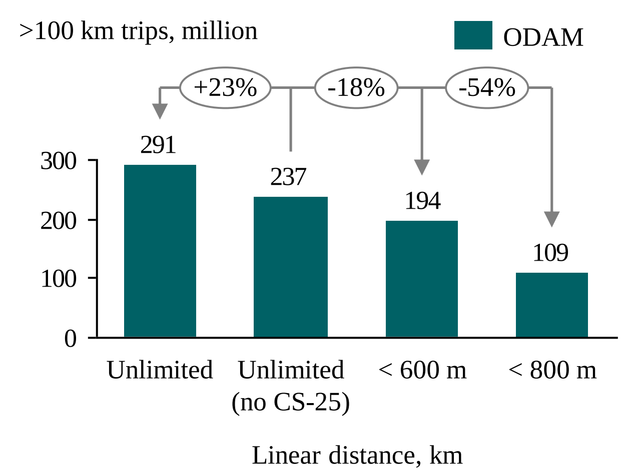

Fig. 18: Number of ODAM trips for different runway performances of ODAM aircraft

airfields according to Fig. 3. On the other hand this 4% corresponds to a relative decrease of 8%-10%. The remaining 90% need to be squared in order to determine the market share impact explaining the size of decrease. A further decrease to 800 m runways more than halves market share compared to all airfields except for CS-25 airports (second bar). ODAM aircraft with even poorer runway performance are not recommendable.

(Perceived) car costs similarly impact the ODAM market share as displayed in Fig. 19 as a change in ODAM costs (shown in Fig. 16). A 33% decrease to 0.2 €/km leads to an ODAM market share of 1.4%. As opportunity costs depend on the relative cost and time difference between available transport modes the cost gap between cars and ODAM is decisive and are required to be lower than 0.15-0.2 €/km for economically feasible ODAM services. The high sensitivity becomes obvious when considering a route of 350 km distance with 10 km first and last mile to the respective airfields. With default parameters as described in section II travel time saving amounts to 1.8 hours compared to using a car. The door-to-door trip costs with ODAM is 23 € more expensive. If operating costs of the car are lowered by 0.1 €/km (or ODAM service costs increased by 0.1 €/km) cost difference increases to 68 € (or 58 €). While 53% of the population have opportunity costs higher than 13 €/h, only 3.3% have opportunity costs higher than 38 €/h. An even larger gap of 0.3 €/km ($c_{car} = 0.1\,€/km$) decreases ODAM market share to 0.2% or a total of two million trips per year (considering more than 150,000 connections). An increase to 0.4 €/km car costs, which is closer to realistic operating costs of a car in Germany, increases the ODAM market share to 56%.

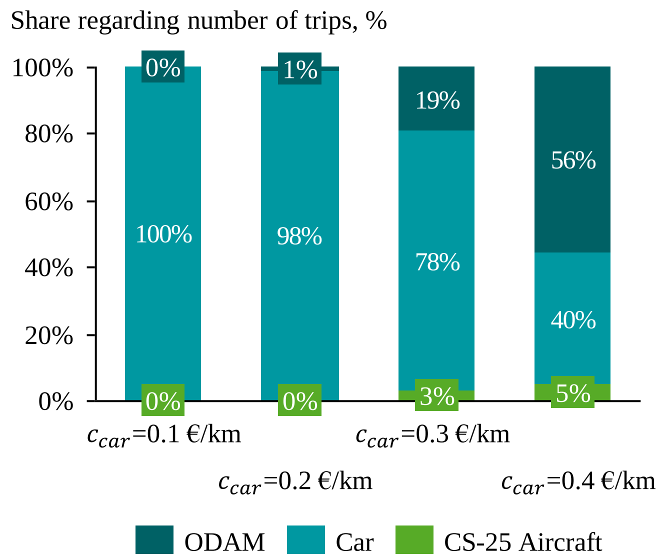

Fig. 19: Market shares regarding number of trips for different car costs

IV. Conclusion

Thin-haul ODAM concepts as described in this paper show great potential for distances above 100 km given a couple of prerequisites. At 0.4 €/km for ODAM services, 0.3 €/km for car costs and 0.32 €/km for CS-25 air transportation ODAM services obtain a market share of 19% or 235 million trips per year. The cost gap of ODAM services should be less than 0.2 €/km (better 0.15 €/km) more expensive than (perceived) car costs. A cruising speed of more than 300 km/h is recommended, while a speed above 400 km/h only gradually increases competitiveness. An ODAM aircraft with a max range of 400 km would cover 69% of the total estimated ODAM demand and at 500 km more than 88%. Hence, a range above 500 km does not seem very beneficial. Aircraft with a runway performance of 800 m would cover 44% less ODAM market volume compared to aircraft with runway performance of 600 m. Depending on the aircraft design trade-offs a performance of 600 m is desirable. The sensitivity of the assessment is important. Depending on the assumed ODAM-car cost gap the ODAM trip volume ranges from 24 million (at 0.2 €/km gap) to 235 million (at 0.1 €/km gap) and even to 680 million (at equality). The distinct sensitivity is founded in the assumed narrow opportunity costs based on net household income of the German population with less than 20% above 20 €/h. At a 0.1 €/km cost gap results hold more than 1,500 connections with more than 50 passengers daily leaving room for an aircraft with about 10 seats. However, given the sensitivities and a lower demand during ramp-up phase an aircraft with two to four passenger seats seems most reasonable.

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