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Economic Assessment of Air Mobility On-Demand Concepts

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Air mobility on-demand concepts promise a significant leap for regional transportation as an alternative to current ground-based options in terms of travel speed. Upcoming technology readiness in the fields of flight automation and electric engines is expected to enable a sustainable service provision with an improved cost basis. Because these concepts have yet to be implemented, it is crucial to assess their suitability from an economic point of view. A methodology to assess the economic feasibility of air mobility on-demand concepts is developed based on a willingness-to-pay approach of contemporary transportation options in Germany. The proposed air mobility on-demand concepts achieve door-to-door travel speeds of 80–200 km/h, resulting in a willingness-to-pay value of 0.5–0.8 €/km (monetary value in 2015) forecasted to 2030. With the potential for battery energy densities of 400 (W · h)/kg in 2030, design ranges of 500–600 km, including a 45 min holding reserve, are possible. All-electric aircraft show the most promising results, leading to passenger-specific door-to-door costs of 20–35% below the estimated willingness-to-pay values.

Nomenclature

AR	=	aspect ratio
C	=	costs
c	=	unit cost
D	=	drag
d	=	distance
E	=	energy
$\boldsymbol{E}$	=	quantity containing relevant exogenous factors with impact on operating costs
f_{Elec}	=	discount factor for electric engines
f_S	=	structural fraction
g	=	gravity acceleration
h	=	operating hours
$\boldsymbol{M}$	=	quantity of relevant mission segments
m	=	mass
n	=	cycles/number
P	=	power
$\boldsymbol{Q}$	=	quantity of relevant quantitative influence factors on willingness to pay
S	=	wing area
$\boldsymbol{S}$	=	quantity of relevant qualitative influence parameters on willingness to pay
$\boldsymbol{T}$	=	quantity containing relevant top-level aircraft requirements with impact on operating costs
t	=	time
v	=	door-to-door linear distance travel speed
v_{cruise}	=	design cruise speed of aircraft
Γ	=	evaluation criteria function
δ	=	battery degradation
Π	=	profit
φ_i	=	regression factors of qualitative parameters
χ_i	=	regression factors of quantitative variables

Subscripts

AP	=	airframe and powerplant
Bat	=	battery
BtT	=	battery to thrust
Char	=	charges
con	=	convenience
Des	=	destination
EOL	=	end of Life
Ener	=	energy
Eng	=	engine
flex	=	flexibility
Insp	=	inspection
Ins	=	insurance
Main	=	maintenance
ops	=	operations
Orig	=	origin
Over	=	overhaul (engine)
Pl	=	payload
PP	=	powerplant
Prop	=	propulsive
SGA	=	selling, general, and administration
spar	=	spare time
T	=	transport
Trans	=	transition

I. Introduction

COMMERCIAL air transportation today commonly requires large, centralized airports. Two factors associated with this circumstance cause the effective door-to-door travel time to be significantly prolonged: 1) journeys to and from the airport, and 2) high transition times at the airport. As a result, current air transportation is only superior to ground-based transportation for longer-distance missions (greater than ∼500 km linear distance). Although ground-based transportation modes offer acceptable door-to-door travel times for short-distance missions (less than ∼200 km), medium-distance missions (∼200–500 km) incorporate extended travel times using almost any currently available transportation mode. For example, effective door-to-door linear distance speeds for ground modes rarely exceed 60–90 km/h in Germany [1]. This, in particular, applies to rural areas, where effective linear distance speeds are even lower. The lack of transportation options offering appropriate travel speeds for medium-distance missions was first described by Bouladon [2] in 1967. This so-called transportation gap results from the limited speed of ground-based transportation modes and relatively long access, egress, and transition times of air-based modes. Considerable improvements with regard to door-to-door travel time for ground transportation options at regional distances are

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not expected over the next decades [1]. Additionally, inconveniences in bus, train, and current air transportation options due to multiple transitions will most likely remain commonplace, and therefore limit the spontaneity of travel. In 2011, the European Union released their vision for future aviation: *Flightpath 2050* [3]. As one of the stated goals is making door-to-door travel times of less than 4 h for 90% of travelers within Europe possible, a qualitative, lasting improvement of the effective door-to-door linear distance speed for regional distances up to ~500 km is required.

Therefore, the objective of this research is to assess a 24 h/day, seven day/week, on-demand air transportation system for intercity point-to-point connections from regional or even urban takeoff and landing sites by using small and highly automated aircraft with two to six seats as a general alternative to ground-based transportation in the medium term (around 2030/2035). We assume the ambitious sustainability targets stipulated by the European Union's *Flightpath 2050* agenda [3] are implemented; i.e., 90% NO_x reduction and 75% carbon dioxide reduction. To reach this, the implementation of a fully electric powertrain is expected to best achieve the target requirements. Thus, aircraft operations will be pollutant free; however, consideration should be given to the fact that emissions may still occur in the generation of electrical grid power dependent upon the source. With regard to technical practicability, sustainable, highly automated aircraft are expected to be a viable option in the period of consideration [4–6].

Due to the ongoing development of the technical prerequisites (i.e., highly automated, electric aircraft), air mobility on-demand (AMOD) services as described previously do not yet exist. Therefore, willingness-to-pay (WTP) values required for assessing the economic feasibility of these services are not easily obtained by analyzing the existing market. So far, specific economic studies for similar AMOD concepts provide limited results with respect to willingness-to-pay values and their influencing factors, especially for Germany [4,7–10]. In addition, more detailed analyses of total service provision costs when operating small, sustainable, highly automated aircraft need to be conducted, as most common operating cost estimation methods do not consider the specific features of AMOD concepts [11,12]. For example, (hybrid-)electric powertrains and pilotless aircraft operations have often been disregarded until recently. Moreover, not only service provision costs of the main run but the overall door-to-door journey need to be analyzed when evaluating AMOD concepts. A study investigating the economics of four- to nine-passenger aircraft envisioned for thin-haul commuter services was conducted by Harish et al. [13], who presented a model for direct operating costs (DOCs) of fully electric commuter aircraft. The results showed that the estimated DOCs were lower if compared to the DOCs of the current Cessna 402 commuter aircraft. However, DOCs were not compared to potential customers' WTP.

In conclusion, for a thorough economic assessment of AMOD concepts, both willingness to pay and service provision costs need to be considered. Therefore, the two key challenges that must be addressed for the proposed AMOD concept are, on the one hand, identifying conditions for economic feasibility; and on the other hand, deriving suitable top-level aircraft requirements (TLARs) with the focus on design range for the aircraft involved in these concepts. The economic feasibility assessment of AMOD concepts is conducted in three phases. First, in Sec. II, the willingness to pay for traveling by such services is analyzed. The analysis takes into account travel speed and distance. Furthermore, a scoring of transportation modes with respect to convenience, spare time for nontransport-related activities, and flexibility to travel is considered in the analysis. As willingness to pay is the maximum price at or below which a customer will definitely buy a product or service [14], this value allows a derivation of reasonable maximum specific operating costs for economically successful AMOD concepts. Second, the resulting door-to-door linear distance speed for different AMOD concepts as well as the specific operating costs for providing such services are determined in Sec. III. In the final, third phase (Sec. IV), results from both preceding sections are merged to assess the economic feasibility of such concepts and to derive reliable TLARs.

II. Determination of Willingness to Pay for Air Mobility On-Demand Services

According to Breidert et al. [15], methods to determine the willingness to pay can be classified into two major categories. Although stated preference methods are survey based, revealed preference methods use actual or simulated market data or experiments. Each category is further classified into several subcategories. An overview about methods for measuring the WTP, including a discussion of advantages and disadvantages, can be found in [15]. In recent years, random utility discrete choice models have become particularly relevant to the understanding and representation of the relationship between mode choice and traveler behavioral properties. However, as the output of these models is strongly dependent on the availability, extent, and quality of datasets for calibration, a meaningful application is not always possible. Therefore, as a first step, the authors have decided to employ a less complex model to analyze the WTP for future AMOD concepts. In this study, the WTP is derived by investigating the travel time and cost associated with current transportation options for which the proposed AMOD service can be considered a viable alternative. This investigation is carried out for a set of sample routes, as explained in the following paragraphs. The approach chosen in this study can be characterized as a revealed preference method based on actual market data [15]. The prices that customers actually paid for these services in the past are interpreted as the willingness to pay. As customers might have paid higher prices for the same services if ticket prices had been higher, this interpretation can be characterized as a conservative estimation. Private cars, rental cars, ride sharing, regional buses, trains, and (if applicable) current commercial CS-25[¶] air transport vehicles are considered as transportation options for regional distances [16]. The volume of chauffeur-driven rental cars or private planes is too small to be taken into account. To reflect different options of train travel, this transportation mode is differentiated into four categories based upon the two dimensions classes (first vs second) and flexibility (normal vs saving).

The WTP analysis consists of three parts. First, as the WTP is influenced by qualitative aspects (e.g., convenience, spare time, flexibility) of the different means of transportation, a scoring model is used to capture the influence of these qualitative aspects $\boldsymbol{S}$ in Sec. II.A. Second, quantitative factors $\boldsymbol{Q}$ such as the door-to-door linear distance speed v, costs C, and linear distance d are determined for a sample of 50 randomly selected routes in Germany in Sec. II.B. Third, both qualitative and quantitative dimensions are subsequently analyzed via multiple regressions in Sec. II.C to determine a functional relationship on the $\mathrm{WTP} = \mathrm{WTP}(\boldsymbol{S}, \boldsymbol{Q})$. As described before, costs C are interpreted as the WTP in this analysis. Qualitative scores $\boldsymbol{S}_{\mathrm{AMOD}}$ are also determined for AMOD concepts. The captured datasets can then be transferred to the qualitative level of the AMOD services in order to derive a functional description of the impact of travel speed and distance on the WTP. Relevant values are forecasted for 2030 because the introduction of AMOD concepts using highly automated, sustainable aircraft is unlikely before 2030.

A. Scoring Model for Qualitative Aspects

There are several qualitative reasons for choosing a specific transport mode [17–23]. Three main categories are chosen, summarizing the most relevant aspects. The convenience of a journey equally consists of freedom of movement within the transport mode, privacy, frequency of changes, and punctuality. The spare time of a traveler represents the aspect of whether the traveler can spend time on other nontransport-related activities while traveling (e.g., working, using the telephone, or watching a movie). The last aspect, which is flexibility to start a journey, includes the lead time to book the journey and the traveler's options with respect to choosing the starting time and place of the journey.

A scoring model as depicted in Fig. 1 is defined for evaluation of these qualitative aspects. The authors define five major categories

[¶]EASA certification specifications CS-23 [39] and CS-25 [16] correspond to Title 14 Code of Federal Regulations Part 23 and Part 25.

Fig. 1 Visualization of the scoring model.

ranging from insufficient to very good, which are scored with integers ranging from one to five. To capture even small differences between similar modes of transportation, the overall scores in the category of convenience have been determined by evaluating and scoring the different transportation modes with respect to the four subcategories of freedom to move, privacy, changes, and reliability, with integers ranging from one to five. For example, the subcategory of freedom to move has been scored by evaluating available legroom, the possibility of walking around in the transportation vehicle, as well as the possibility of staying in the vehicle's aisle. For each transportation mode, the overall convenience score is finally determined by calculation of the average value of the four subscores. It is mentioned that the proposed scoring is in fact only a ranking, although the values are treated as real-valued quantities in the subsequent analysis. This means that, for example, a score of four is not twice as valuable as a score of two. In the following paragraphs, the authors outline how they scored (after a thorough evaluation within the authoring team) the different transportation modes across the categories of convenience, spare time, and flexibility.

With regard to convenience, a private car offers the best privacy; furthermore, it generally requires no change along the door-to-door journey because (almost) every location can be reached by car. The perceived punctuality is rated high [24]. Only the freedom of movement is limited, leading to an overall score of 4.0 points. Assuming all other factors are identical to private car travel, the inconvenience of picking up and returning a rental car leads to a score of 3.5 points. Ride sharing ranks poorly within this category. Only the omittance of several changes and fair punctuality suffice for 2.0 points. Although a bus offers more freedom of space, privacy is limited, changes are usually required along the bus journey, and the perceived punctuality is limited [24]. Therefore, bus travel is rated with 2.25 points. First-class trains offer the best freedom of space, fair privacy, and a high punctuality [25]. As inconvenient changes are frequently required, a score of 3.25 points regardless of saving or normal booking is applied. Second class offers less privacy and less freedom of space, and it receives 2.75 points. Commercial aircraft as of today rank fair to poor in this category, except for an excellent perceived punctuality [24], leading to a score of 3.0. A considerable change until 2030 is not expected. As small aircraft are used in AMOD concepts, the convenience rating is comparable to CS-25 aircraft. The freedom of movement is slightly worse but, due to the significantly lower number of other passengers, privacy ratings are superior, leading to 3.25 points.

Steering a private car within the current traffic situation requires a high level of attention, leaving little spare time for nontransport-related activities. It is to be expected that only beyond the year 2025 will cars have such significant improvements in terms of autonomous driving to leave the driver with spare time [26]. However, as automotive-based transportation requires significant active decision making for obstacle avoidance, it is likely that only specific parts of the entire journey can be conducted without human input until approximately 2030. Moreover, it is likely that only more exclusive cars will be equipped with such technology, thus having little influence for most people. In conclusion, the category of spare time receives 1.5 points. Ride sharing does not require active driving of the traveler; although, due to limited space and conversations among passengers, the opportunity for nontransport-related activities is limited and scored with 2.0 points. First-class trains represent the best transport mode in this category with 5.0 points; second class and buses rank slightly lower with 4.0 points. Due to long transition times with security checks, as well as takeoff and landing procedures during CS-25 flights, the possibility of doing nontransport-related activities is worse than in second-class trains and rated with 3.0 points. AMOD concepts are comparable to CS-25 aircraft in this category and are scored with 3.0 points.

The flexibility to start a journey is the highest with a private car because no lead time is required and the starting point can be chosen freely. Therefore, private cars are scored with 5.0 points in this category. Assuming all other factors can be considered identical to private cars, rental cars only require a short period ahead of time for booking and are therefore rated with 4.0 points. Ride sharing and train saver categories receive only 1.0 points because these modes require significant lead time and offer little flexibility in terms of departure time due to comparably low frequencies or fixed booking. Bus travel ranks slightly higher with a score of 2.0 points because only some lead time is required, but the flexibility of when to begin the journey is low due to the low frequency of the intercity bus system in Germany. CS-25 aircraft offer more flexibility to start the journey due to a higher frequency when compared to a bus, but they still offer lower frequencies than trains. Therefore, CS-25 aircraft are rated with 3.0 points. Although the proposed AMOD concepts possess an on-demand character, scheduled operations similar to trains are likely during the rampup phase until a sufficient distribution is ensured. Thus, a score of 4.0 points is applied in order to reflect the gap to the flexibility of a private car. A summarizing overview of the scoring values as described before is given in Table 1.

For a more complete analysis, more factors could be taken into account (such as perceived safety, reliability, robustness to external influences, and environmental aspects) that could be considered when selecting a specific transportation mode. Some of them play a minor role; other factors are of different origin but have a similar impact. For instance, the variance in potential travel time is affected by (among others) external influences that can be different for different transportation modes. Although travelers using cars or buses can experience delays due to (for example) congestion, air transportation can be delayed due to weather. Therefore, additional qualitative factors that go beyond the categories of convenience, spare time, and flexibility are disregarded in this analysis.

Table 1 Applied qualitative scores of analyzed transportation modes

	Convenience					Spare time	Flexibility
Transportation mode	Freedom to move	Privacy	Changes	Punctuality/Reliability	⌀		
Private car	2	5	5	4	4	1.5	5
Rental car	2	5	3	4	3.5	1.5	4
Ride sharing	1	1	3	3	2	2	1
Bus	3	2	2	2	2.25	4	2
Train first class, saving	5	3	1	4	3.25	5	1
Train first class, normal	5	3	1	4	3.25	5	4
Train second class, saving	4	2	1	4	2.75	4	1
Train second class, normal	4	2	1	4	2.75	4	4
CS-25 aircraft	3	2	2	5	3	3	3
Air mobility on demand	2	3	3	5	3.25	3	4

Table 2 Summary of sample routes

Range, km	Sample size
100–200	13
200–300	7
300–400	17
400–500	8
500–600	4
Greater than 600	1

B. Analysis of Routes for Quantitative Values

In this subsection, the influence of three quantitative values is analyzed according to their effects on the WTP. The costs of the door-to-door trip need to be determined as a proxy for the WTP. The linear distance and the door-to-door linear distance speed are considered as well. As data availability for the total door-to-door trip are limited, a sample of 50 origin–destination (OD) pairs in Germany is analyzed with regard to the aforementioned three values. This subsection is therefore divided into two parts. Selection and details of the sample routes are discussed in the first part. The methodology to simulate the entire door-to-door journey is addressed in the latter part.

1. Selection of Sample Routes

Germany consists of approximately 4500 municipalities according to data from the end of 2013 [27]. These municipalities are used as the base set for randomly drawing OD pairs representing door-to-door journeys. Additionally, each municipality is weighted with the number of inhabitants to reflect that large municipalities generate a higher travel demand than lower-populated municipalities. The OD pairs are randomly selected by drawing two municipalities from this set. Only OD pairs with a linear distance of more than 100 km are considered for the following analysis. If not explicitly noted otherwise, distances and travel speeds are always calculated based on the linear distances. This is necessary to avoid a positive influence of transportation modes with a high detour factor. The midpoint of the respective municipality is chosen as the precise starting or end point of the door-to-door journey. The linear distance range distribution of the sample routes is summarized in Table 2.

There are more than 10 million possible OD pairs within Germany, including OD pairs with linear distances of less than 100 km. According to [28], for samples with a statistical population of more than $n \geq 10{,}000$, the margin of error e of the confidence level $z_{1-(\alpha/2)}$ can be estimated as

$$e = \frac{\sigma \cdot z_{1-(\alpha/2)}}{\sqrt{n}} \tag{1}$$

where σ is the standard deviation, and n is the sample size. It is reasonable to assume that the statistical population of OD pairs above a 100 km linear distance is still above 10,000; hence, applying this formula is feasible. As the standard deviation σ is unknown, the most conservative value of $\sigma = 50\%$ is used. A sample of $n = 50$ OD pairs leads to a margin of error of $e = 11.6\%$ for a confidence level of 90%. This is assumed to be sufficient for the purpose of this paper.

2. Door-to-Door Journey Analysis

Door-to-door journeys are generally divided into three parts. The first kilometer represents the path from the starting point of the traveler (e.g., home) to the closest or most reasonable entry point into the chosen transport mode network (e.g., departure train station or airport). The main run includes the journey until the most reasonable exit point of the transport mode network (e.g., arrival train station or airport). The last kilometer comprises the trip to the final destination point. Additionally, transition times are considered between the end of the first kilometer and the entry into the transport mode service network and between the exit of this network and the last kilometer (e.g., transition times at the train station or airport). The transport mode specific route modeling for 2030 is summarized in Table 3.

It is assumed that a private car can be used for the entire door-to-door journey. First and last kilometers are therefore omitted. According to a report of the largest German automobile club ADAC, the total specific costs of new cars with a usage of four years, a listed price of less than 40,000 €, and a system power of less than 170 bhp results in average costs of 0.477 €/km [29]. With an inflation-adjusted** real price increase of 10% until 2030, specific costs of 0.525 €/km are applied [30]. Route-specific travel times are determined using Google Maps. This also applies for rental cars and ride sharing. To account for parking, a transition time of two times 5 min is considered in 2015. A general efficiency increase of the transition times of existing transport modes until 2030 of 25% is applied. This leads to two times 3.8 min of transition time for private cars.

As a rental car usually requires a pickup and dropoff at designated stations, the first and last kilometers are used to represent this action. As rental stations are often close to or integrated into train stations, this is generally assumed. Public transportation is used as a default option for the first and last kilometers. If no viable public transportation option is available, a taxi cab is chosen. In case both of these options require either more than 30 min of travel time or generate costs of more than 20 €, a delivery or pickup from the rental company is considered with a cost of 25 € as of 2015. An analysis of common rental companies (such as Sixt, Europcar, Avis, and Hertz) results in an average price of 93 € per day for a Volkswagen Golf class including a oneway fee. An inflation-adjusted price increase of 10% until 2030 is applied with regard to the real price increase of a private car. Delivery and pickup cost are increased by 10% as well. An average fuel consumption of 5.1 liters/100 km and a diesel price of 1.17 €/liter are applied for 2015 [31]. A fuel consumption reduction of 35% and an assumed real diesel price increase of 2.0% per year [32,33] result in variable kilometer-specific costs of 0.052 €/km in 2030, which have to be paid in addition to the fixed rental fee. Transition durations of 15 min are assumed as of 2015 and 11.3 min in 2030. A price of 0.06 €/km is used for ride sharing in Germany [34] in 2015, leading to 0.066 €/km when considering the real price increase of 10% until 2030 with regard to the private car increase. Train stations are assumed as starting and end points of the shared ride. For the first and last kilometers, public transportation is used and, if no connection is available (in less than 10% of the sample routes), a cab is used. Transition times are assumed to be 20 min each, leading to assumptions of 15 min each in 2030. The same first and last kilometer methodologies are applied for buses and second-class trains. Travelers using first-class trains are considered to prefer the use of a taxi cab. For these modes, route-specific prices and durations are taken from online booking platforms. Transition durations are assumed to be 15 min in 2015 and 11.3 min in 2030.

Travelers using CS-25 air transportation are assumed to use private cars for the first kilometer, including a parking fee of 20 € and an assumed real price increase of 5% until 2030 [35]. For the last kilometer, the minimum costs of using a taxi cab or a rental car are applied. Both costs and travel times of the main run are determined for each sample route individually. Transition times are simulated with 45 min at the departure airport and 15 min at the destination airport for 2015. A transition time reduction of 25% until 2030 is applied as well.

If public transportation is used for the first and last kilometers, both the cost and duration are determined for each route investigated. A taxi cab is modeled with 2.50 €/km in 2015 [36] and 2.75 €/km in 2030 according to the real price increase of 10% for increased automobile costs and a route-specific determination of the travel duration. Unreasonably expensive and slow transportation modes for specific routes (especially for CS-25 air transportation) are not considered because the assumption (that offered prices represent the willingness to pay) is not valid in such cases. The door-to-door linear distance specific cost and travel speed of each transportation mode for the analyzed route sample are illustrated in Fig. 2.

**An inflation rate of 1.33% per year is assumed until 2030. This is the average customer price index from 1991 to 2014 in Germany [35].

Table 3 Sample route modeling for analyzed transport modes in 2030

Transportation mode	First/last kilometer	Main run costs	Main run duration	Transitions, min
Private car	——	0.525 €/km	Route specific	2×3.8
Rental car	Public transportation/cab to/from train station or if path > 30 min or greater than 20 €: Delivery and/or pickup with costs of 27.5 €	102.2€ + 0.052€/km		2×11.3
Ride sharing	Public transportation or cab to/from train station	0.066 €/km		2×15.0
Bus	Public transportation or cab to/from train station	Route specific		2×11.3
Train first class	Cab to/from train station	Route specific		2×11.3
Train second class	Public transportation or cab to/from train station	Route specific		2×11.3
CS-25 aircraft	Private car to airport + 21 € parking; Minimum of cab or rental from airport	Route specific		$26.3 + 11.3$

C. Willingness-to-Pay Results

In this subsection, the willingness to pay as a function of qualitative aspects $\boldsymbol{S}$ (described in Sec. II.A) and quantitative factors $\boldsymbol{Q}$ (described in Sec. II.B) is analyzed by applying a multiple regression model: $\mathrm{WTP} = \mathrm{WTP}(\boldsymbol{S}, \boldsymbol{Q})$. In general, the authors assume a linear dependence regarding qualitative and quantitative factors S and Q, respectively. In addition, to reflect the importance of the door-to-door linear distance speed v, the first and second orders of approximation of v are used. While the unknown linear coefficients $\boldsymbol{\varphi}_i$ correspond to the qualitative aspects $\boldsymbol{S}$, the coefficients $\boldsymbol{\chi}_i$ correspond to the quantitative factors $\boldsymbol{Q}$. The authors developed the following equation to estimate the WTP based on qualitative and quantative factors, linear door-to-door distance d, and linear door-to-door distance speed v:

$$\mathrm{WTP}(\boldsymbol{S}, \boldsymbol{Q}) = \varphi_{\mathrm{con}} \cdot S_{\mathrm{con}} + \varphi_{\mathrm{spar}} \cdot S_{\mathrm{spar}} + \varphi_{\mathrm{flex}} \cdot S_{\mathrm{flex}} + \chi_d \cdot d + \chi_v \cdot v + \chi_{v^2} \cdot v^2 \tag{2}$$

Because unreasonably long and expensive transport modes for specific routes are excluded according to Sec. II.B.2, every considered route and mode represents a viable option. Equation (2) is applied for every OD pair and transportation mode, resulting in an overdetermined linear equation system. A least-square method is used to solve this regression. As four different versions of the mode train are analyzed, each option is only weighed with 25% in the regression. The solution to the overdetermined linear equation system results in the following function:

$$\mathrm{WTP}(\boldsymbol{S}, \boldsymbol{Q}) = 0.053 \cdot S_{\mathrm{con}} + 0.0087 \cdot S_{\mathrm{spar}} + 0.104 \cdot S_{\mathrm{flex}} - 0.000622 \cdot d + 0.00098 \cdot v + 6.675 \cdot 10^{-6} \cdot v^2 \tag{3}$$

According to the coefficients, the qualitative aspects of convenience and flexibility have a stronger impact on the WTP than spare time. The kilometer-specific WTP decreases with increasing range and increases overproportionally with increasing velocity. The qualitative scores of the proposed AMOD concept can be applied to Eq. (3). The resulting WTP for those services is plotted in Fig. 3 in dependence on the door-to-door linear distance travel speed for different linear door-to-door distances. The WTP ranges from 0.4 to 0.7 €/km when considering linear distance speeds of 100–150 km/h and distances of 200–500 km.

To analyze the stability of the results, it is assumed that autonomous driving progresses faster than expected. For the sensitivity study, the scores of the qualitative dimension of spare time are increased from 1.5 to 3.0 points for private and rental cars, and are thus equal to the AMOD service. In another sensitivity scenario, private car specific costs are assumed to be 20% lower than determined. The result for exemplary values is summarized in Table 4. The applied changes in scenarios 1 and 2 only lead to minor changes on the identified WTP for AMOD services, whereas scenario 2 leads to a higher change when compared to scenario 1, with changes ranging up to 10%. In scenario 2, the difference decreases with increasing velocity.

III. Supply Analysis for Air Mobility On-Demand Services

The objective of this analysis is to determine if AMOD services can be offered at prices that are well within the identified WTP values of Sec. II. Therefore, in Sec. III.A, the door-to-door trip is determined for different concepts, depending on the travel distance d, the airspeed of the aircraft v_{cruise}, the travel time and costs to and from takeoff and landing sites, and the transition times. In Sec. III.B, the total specific operating costs for providing the main run of the AMOD services are analyzed. This, on the one hand, requires a performance estimation methodology to determine the most relevant technical parameters, such as maximum takeoff weight (MTOW) and required battery capacity. On the other hand, development of an operating cost estimation model is necessary. The main cost drivers are captured, whereby TLARs $\boldsymbol{T}$ and other uncertain exogenous factors $\boldsymbol{E}$ are considered. The results of these analyses are summarized in Sec. III.C. The maximum design range and degree of flight automation are analyzed as a subset of relevant TLARs $\boldsymbol{T}$, and the specific battery energy is investigated as a representative of uncertain exogenous factors $\boldsymbol{E}$.

A. Determination of Air Mobility On-Demand Door-to-Door Journey

To ultimately determine the profit as the key evaluation criterion, it is necessary to compute the door-to-door linear distance speed v for AMOD services with dependence on the door-to-door travel distance

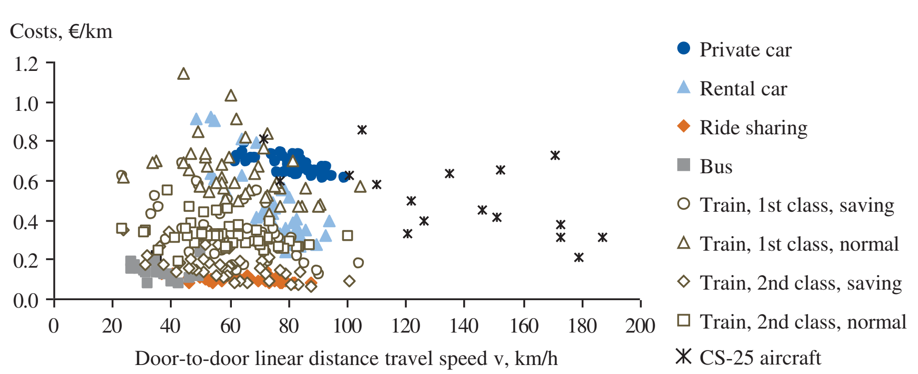

Fig. 2 Costs and door-to-door linear distance speed of analyzed transportation modes for sample routes.

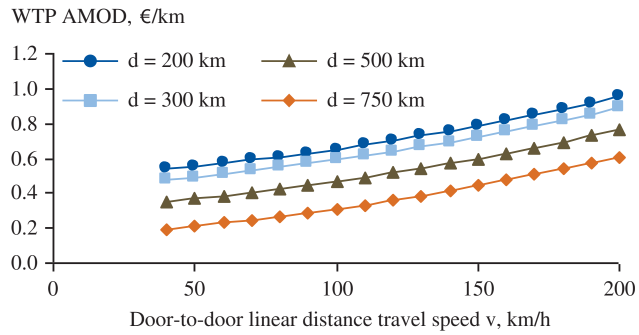

Fig. 3 Willingness to pay for AMOD services, depending on linear distance travel speed v and distance d.

d and the cruising speed v_{cruise} of the aircraft. To determine the door-to-door travel time t, it is necessary to derive comparable values for travel time and costs to and from takeoff and landing sites. Therefore, the same sample routes as described in Sec. II are analyzed to determine average values. Subsequently, the required averages are used to compute the door-to-door travel time depending on the door-to-door travel distance.

The two concepts, A and B, are analyzed. In the more conservative concept A, regional airports will be used as takeoff and landing sites. Within this concept, two usage modes are analyzed. In this first mode A1, for commuting to the origin airport, a private car will be used, resulting in a duration t_{orig} and costs C_{orig}. To travel the distance from the destination airport to the actual destination, a taxi cab will be used, resulting in a duration of t_{des} and costs C_{des}. The sample routes are modeled individually for the AMOD service. However, to avoid unreasonably long distances, the first and last kilometers are capped at 40 km and 60 min. In case an airport is distant enough to lead to last kilometer costs exceeding 110 € for a taxi cab fare, the AMOD service simply cannot be a viable option for this specific route. It is also conceivable that specific taxi cab costs are lower than the assumed 2.75 €/km for such long distances or that car sharing is a viable option, resulting in lower costs. General aviation airports require significantly less investment as compared to CS-25 airports and could therefore be built in regions with poor regional airport coverage at the moment. For 70% of the analyzed sample routes, less than 40 km are required to travel to or from a regional airport already existing today. A travel duration to or from the airport of less than 60 min suffices for 95% of the sample routes. Average costs of approximately 80 € are considered for the first and last kilometers in the following economic assessment. In usage mode A2, passengers will use public transportation for the first and last kilometers, which are assumed to take twice as long as compared to mode A1. However, passengers are assumed to only pay up to 20 € for commuting to and from the airport in mode A2.

Accumulated transition duration t_{trans} at both airports is assumed to be 20 min in total. The flight duration t_{flight} is calculated by assuming taxiing times of 10 min in total, and a climb and descend segment of 30 km each with only two-thirds of the cruise speed. Taking into account the envisioned cruise speed of the LEAPTech aircraft of 370 km/h (200 mph) [37], the aircraft in this study is assumed to cruise at $v_{\text{cruise}} = 350\ \text{km/h}$. An analysis of the flight distance in relation to the door-to-door linear distance shows a negligible difference. Therefore, d_{flight} is approximated with the door-to-door linear distance d:

$$t_{\text{flight}}(d, v_{\text{cruise}}) = \frac{60\ \text{km}}{(2/3) \cdot v_{\text{cruise}}} + \frac{(d - 60\text{km})}{v_{\text{cruise}}} + 10\ \text{min} \tag{4}$$

In the more visionary concept B, urban takeoff and landing sites are assumed to be used. These landing sites can be the rooftops of car parks, train stations, or large department store buildings. In this concept, commuting distances to and from the airports are reduced. We assume an average travel time of $t_{\text{orig}} = t_{\text{des}} = 5$ min each and costs of $C_{\text{orig}} = C_{\text{des}} = 5€$ generated by the use of public transportation to and from takeoff and landing sites. The averages of the travel times, flight distances, and door-to-door linear distance speeds of the considered 50 sample routes are illustrated in Table 5. Note that takeoff and landing sites in concept B are assumed to be in the midpoint of each municipality. This results in a similar average distance for the door-to-door distance and flight distance.

One of our research objectives is to determine reasonable TLARs for AMOD services. Therefore, the impact of the aircraft cruise speed v_{cruise} on the overall door-to-door linear distance speed v is analyzed in the following part. In Fig. 4, the door-to-door linear distance speed v is plotted as a function of the aircraft cruise speed v_{cruise} for different door-to-door distances d for concepts A1 and B. The impact on concept A2 is lower due to longer commuting times to and from the airport. In general, the impact of the aircraft cruise speed on door-to-door linear distance speed increases with increasing range. Moreover, door-to-door linear distance speed is slightly more sensitive to aircraft cruise speed in concept B than in concept A. A decrease of 14% from 350 to 300 km/h aircraft cruise speed leads to a decrease of 6% in linear distance speed at a 250 km range and 7% at a 400 km range for concept A, a 7% linear distance speed decrease at a 250 km range, and a 9% at a 400 km range for concept B. Because the aircraft cruise speed of 350 km/h is acknowledged by NASA's LEAPTech study (even up to 370 km/h) [37], the overall uncertainty that originates from the uncertainty of the aircraft cruise speed on the entire economic assessment is limited.

B. Performance and Operating Cost Methodology

In this section, a model to estimate the specific operating costs for AMOD services is described. This requires the determination of high-level performance parameters as a first step. Subsequently, these performance parameters can be used as input values of the operating cost estimation model. This section is limited to the operating costs of the aircraft.

1. *Performance Estimation*

Two interconnected major tasks need to be performed in order to estimate reasonable performance parameters for battery-powered

Table 4 Resulting WTP for AMOD services in case of higher spare time score for private and rental cars (scenario 1) and 20% lower costs for private car (scenario 2)

Speed v, km/h	Range d, km	Scenario default, €/km	Scenario 1: higher spare time score car (3.0), €/km	Scenario 2: 20% lower costs private car, €/km
50	300	0.49	0.48	0.44
100	300	0.59	0.58	0.55
100	500	0.47	0.46	0.43
150	500	0.60	0.59	0.57

Table 5 Average values for sample routes for different AMOD concepts

Item	Concept A1: regional airports (car and taxi cab)	Concept A2: regional airports (public transportation)	Concept B: urban takeoff and landing sites
Door-to-door linear distance $\bar{d}$	320 km	320 km	320 km
Flight distance $\overline{d_{\text{flight}}}$	319 km	319 km	320 km
Total door-to-door travel time $\bar{t}$	141 min	192 min	110 min
To origin airport $\overline{t_{\text{orig}}}$, $\overline{C_{\text{orig}}}$	24 min, 11.70 €	48 min, 10.00 €	10 min, 5.00 €
Flight duration $\overline{t_{\text{flight}}}$	70 min	70 min	70 min
From destination airport $\overline{t_{\text{des}}}$, $\overline{C_{\text{des}}}$	27 min, 67.60 €	54 min, 10.00 €	10 min, 5.00 €
Transition times $\overline{t_{\text{trans}}}$	20 min	20 min	20 min
Linear distance speed $\bar{v}$	136 km/h	100 km/h	175 km/h

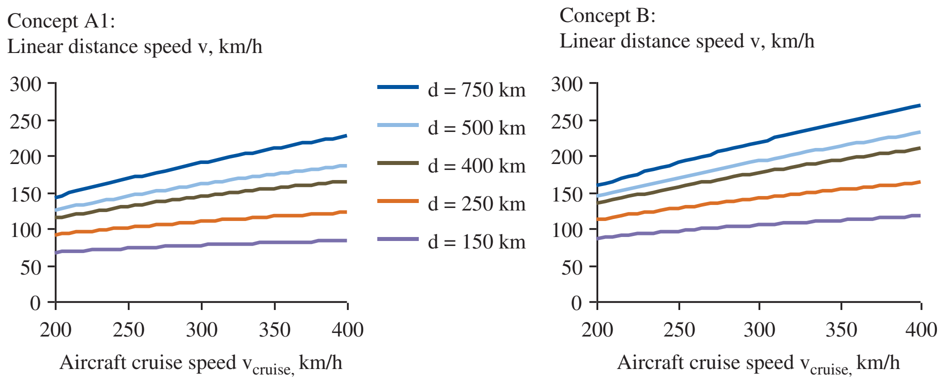

Fig. 4 Door-to-door linear distance speed v, depending on aircraft cruise speed v_{cruise} for concepts A1 and B.

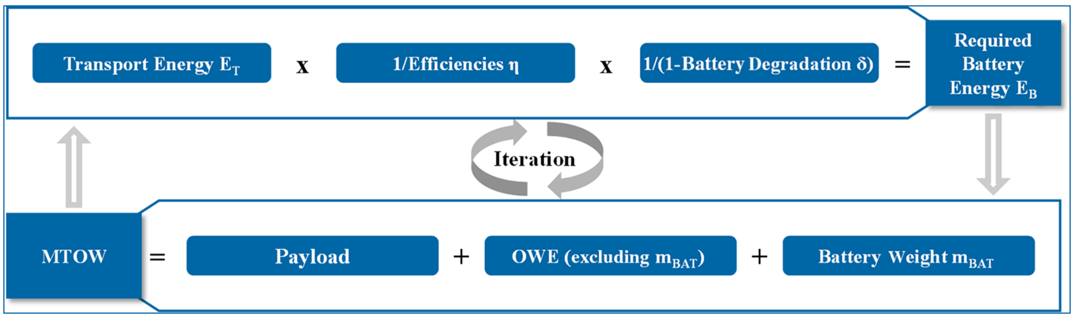

Fig. 5 Performance estimation algorithm.

CS-23 aircraft. On the one hand, the required battery energy E_{Bat} with respect to the MTOW needs to be determined. On the other hand, the MTOW needs to be determined in the dependence on the battery weight, which is directly linked to the required battery energy. These two tasks are iteratively performed. The algorithm is illustrated in Fig. 5.

The required battery energy E_{Bat} is calculated by first determining the transport energy E_T for the design mission, including a 45 min holding reserve; then applying efficiencies for relevant technical devices transforming battery energy into thrust η_{BtT}; and finally considering the level of battery degradation δ_{Bat} at the end of life (EOL). To avoid detailed (computational fluid dynamics) drag analyses, which require profound knowledge about the outer geometry of the aircraft, feasible L/D ratios are applied instead. Single-piston contemporary CS-23 aircraft (e.g., from Cirrus or Cessna [38]) have optimal L/D ratios of 15–20 at low speeds but only about 10 at cruising speed. The reason for this is the oversized wing that leads to low cruise lift coefficients, leading to a poor L/D ratio. The oversized wing is required to meet the 61 kt stall speed requirement (section 23.49 in CS-23) [39] with state-of-the-art high-lift devices ($c_{L,\max} \approx 2.0$–2.5) for single-engine aircraft. Joby Aviation and NASA demonstrated with the LEAPTech project that, when applying distributed electric propulsion, the maximum lift coefficient at 61 kt can be almost doubled. This is mainly due to the propeller-induced velocity. Thus, a smaller wing can be realized. As a result, L/D ratios of 20 or more at cruise speed [37] can be achieved. To account for offdesign flight states, a climb and descend L/D ratio of 3/4 of the cruise L/D ratio is applied. In consideration of a mandatory holding reserve E_{hold} that is required for $t_{\mathrm{hold}} = 45$ min with an engine power of $P_{\mathrm{hold}} = 55\% \cdot P_{\mathrm{cruise}}$, the transport energy E_T is calculated as follows:

$$\begin{aligned} E_T &= \sum_{i \in \boldsymbol{M}} (D_i \cdot d_i) + E_{\mathrm{hold}} \\ &= \mathrm{MTOW} \cdot g \cdot \sum_{i \in \boldsymbol{M}} \left(\frac{d_i}{(L/D)_i} \right) + P_{\mathrm{hold}} \cdot t_{\mathrm{hold}} \end{aligned} \tag{5}$$

where the quantity $\boldsymbol{M}$ represents the subset of the three mission segments climb, cruise, and descend; g is the gravity acceleration; and D_i is the drag in the respective mission segment i. The cruise power P_{cruise} results from the product of the cruise drag D_{cruise} and cruise speed v_{cruise}.

To determine the amount of required battery energy E_{Bat} in dependence on the transport energy E_T, four efficiencies along the battery-to-thrust conversion path are used. The overall battery-to-thrust efficiency η_{BtT} consists of internal battery losses η_{Bat}, losses from electric wires and controllers η_{wire}, inefficiencies from the electric engine η_{eng}, and the propulsive efficiency η_{prop}. An overall efficiency of $\eta_{\mathrm{BtT}} = 72\%$ is applied, which is slightly below the 73% proposed by Hepperle [5]. The applied efficiencies are summarized in Table 6. Finally, a battery degradation of $\delta_{\mathrm{Bat}} = 10\%$ at the end of life is taken into account.

To complete the iterative algorithm, the MTOW needs to be determined in dependence on the required battery energy E_{Bat}. The MTOW is determined in three steps. First, the payload m_{pl} is directly linked to the number of passenger seats, and therefore treated as a known TLAR. Second, the battery weight m_{Bat} can be derived by dividing the required battery energy E_{Bat} by the specific battery energy c_{Bat}. A value of 400 $(\mathrm{W} \cdot \mathrm{h})/\mathrm{kg}$ is assumed, which is assessed to be realistic for 2030, considering several company reports and academic reviews [40–43]. Third, the last step comprises the mass estimation of all other aircraft components. Except for the engine and smaller wing size (in order to achieve higher cruise L/D ratios), these components will only be slightly affected by the implementation of battery-powered electric propulsion. Therefore, the mass estimation of these components is conducted by first determining an empirical structural fraction f_s in relation to the MTOW, and then adjusting this

Table 6 Applied efficiencies for the battery-to-thrust conversion

Device	Efficiency η, %
Battery	95
Wires and controllers	96
Electric engine	93
Propeller	85
Battery to thrust	~72

Table 7 Relevant mass ratios of contemporary CS-23 aircraft

Category	Cessna Skyhawk 172	Cirrus SR-22	Pipistrel Panthera
MTOW, kg	1157 (100.0%)	1633 (100.0%)	1315 (100.0%)
OWE (% MTOW), kg	744 (64.3%)	1028 (63.0%)	815 (62.0%)
Dry engine weight, kg	126 (10.9%)	187 (11.5%)	189 (14.4%)
Installed engine weight estimate, kg	209 (18.1%)	301 (18.4%)	304 (23.1%)
Wing weight estimate, kg	116 (10.0%)	163 (10.0%)	132 (10.0%)
Other OWE, kg	419 (36.2%)	564 (34.5%)	379 (28.8%)
Power, kW	134	231	194

ratio for changes in the engine and wing weight. The relevant values of three contemporary aircraft are summarized in Table 7.

The operating weight empty (OWE) ratio ranges between 60 and 65% for conventional contemporary CS-23 aircraft. Siemens claims to manufacture a 260 kW electric aviation engine with a power-to-weight ratio of more than 5 kW/kg, leading to a dry engine weight reduction of more than 80% [44]. According to Raymer [45], the installed engine weight m_{EI} can be estimated in dependence on the dry engine weight m_{ED} as follows (note that the scaling factor is applied for metric units):

$$m_{\mathrm{EI}} = 2.42 \cdot m_{\mathrm{ED}}{}^{0.922} \tag{6}$$

This results in an installed engine weight reduction of 78.6% for electric engines. This formula is also used to estimate the installed engine weights in Table 7. NASA demonstrates the potential impact on the wing area and aspect ratio for an electric-powered aircraft for achieving significantly higher cruise L/D ratios with the LEAPTech technology. The wing area is reduced by 57% when considering a first-order approach to scale the wing area for equal gross weight. The aspect ratio is increased by 72% [37]. As no precise data for wing masses are publicly available, it is assumed that the wing mass is 10% of the MTOW. The empirical wing mass estimation formula by Raymer [45] is used to determine the relative weight change when only considering a change in the wing surface and aspect ratio [45]. The smaller-sized wing for the electric aircraft is denoted with index 1, and the reference is denoted with 0:

$$\frac{m_1}{m_0} = \left(\frac{S_1}{S_0}\right)^{0.758} \cdot \left(\frac{AR_1}{AR_0}\right)^{0.6} = 90.4\% \tag{7}$$

Additionally, a parachute safety device would be required for pilotless aircraft. The ballistic recovery system weighs 36 kg for the Cessna Skyhawk [46] and is optionally available, whereas a parachute safety device is already installed by default in the other two aircraft. Applying these adjustments to the aircraft, the structural fraction f_s (or OWE excluding battery weight) ranges from 43 to 53%, which is summarized in Table 8.

It is reasonable to assume that a clean sheet electric aircraft design will lead to an aircraft with a structural fraction in the vicinity of the lower bound of the OWE range in Table 8. Additionally, an optimization for the specific needs of an electric aircraft is most likely to result in even lower values due to the higher sensitivity of this fraction (e.g., lightweight construction becomes more relevant in electric-powered cars as compared to conventional ones). Nevertheless, a structural fraction of $f_s = 45\%$ is applied for the following calculations. The most important technical parameters are summarized in Table 9.

Table 8 Estimated OWE values for electric powered contemporary CS-23 aircraft excluding battery weight

Category	Cessna Skyhawk 172	Cirrus SR-22	Pipistrel Panthera
Dry electric engine weight, kg	26.8	46.2	38.8
Installed electric engine weight, kg	50.3	83.0	70.6
Adjusted wing weight, kg	104.9	147.4	118.4
Safety device, kg	36.0	By default	By default
Other OWE, kg	419.0	564.0	379.0
OWE excluding battery (% MTOW), kg	610.2 (52.7%)	794.4 (48.6%)	568.0 (43.2%)

Table 9 Summary of most important technical parameters used as default values

Parameter	Default value
L/D ratio	20
Cruise speed v_{cruise}	350 km/h
Structural fraction f_S	45%
Specific battery energy c_{Bat}	400 $(\mathrm{W \cdot h})/\mathrm{kg}$
Battery-to-thrust conversion η_{BtT}	72%

2. Operating Cost Estimation

The estimation of the total operating costs is divided into two parts. First, the development and production costs are estimated using the Eastlake model [47,48] in order to determine the selling price C_{Acft} of the aircraft. This selling price is required to calculate the aircraft depreciation as part of the indirect operating costs (IOCs) C_{IOC}. Due to the promising business case, it is assumed that the development costs can be allocated to a production of 500 aircraft yearly for a duration of 10 years. In the second major part, all direct operating costs C_{DOC} and IOCs are determined. As some parts of the operating costs can only be calculated per flight or per year, it is necessary to make assumptions regarding the operating model of the aircraft. This includes the average operational distance d^{ops}, the utilization hours per year h^{ops}, and the life expectancy of the aircraft $t_{\mathrm{Acft,EOL}}$. The average operational distance is assumed to be $d^{\mathrm{ops}} = 250$ km by default. As the AMOD services are envisioned to be highly commercialized, it is reasonable to assume a yearly utilization of $h^{\mathrm{ops}} = 1000$ h/a, which is still significantly lower when compared to CS-25 aircraft (~2500 h/a or more). A life expectancy of $t_{\mathrm{Acft,EOL}} = 15$ a is used in the following part. Battery depreciation is considered separately.

The direct operating costs are divided into fuel (i.e., energy C_{Ener}), and battery depreciation C_{Bat}, maintenance C_{Main}, operating crew C_{Pilot}, and charges C_{Char}. The indirect operating costs consist of aircraft depreciation C_{Acft} (excluding battery depreciation), insurance C_{Ins}, and capital expenditure C_{Capex}. Additionally, a selling, general, and administration (SG&A) contribution C_{SGA} is considered to reflect the total service costs rather than only the costs of goods sold (COGS).

Specific energy costs C_{Ener} can be calculated by considering specific power costs $c_{\mathrm{power}} = 0.30$ €$/(\mathrm{kW \cdot h})$ [49], the required transport energy for the operational mission E_T^{ops}, and the battery-to-thrust efficiency η_{BtT}:

$$C_{\mathrm{Ener}} = c_{\mathrm{power}} \cdot \frac{E_T^{\mathrm{ops}} \cdot \eta_{\mathrm{BtT}}}{d^{\mathrm{ops}}} \tag{8}$$

Assuming the battery can withstand $n_{\mathrm{EOL}} = 1000$ cycles with an end-of-life degradation of $\delta_{\mathrm{Bat}} = 10\%$ and specific battery costs of $c_{\mathrm{Bat}} = 300$ €$/(\mathrm{kW \cdot h})$[††] [41,50], the specific battery depreciation costs can be calculated:

[††]"Li-Ion Batteries for Electrified Mobility—Quo Vadis?" Bosch Battery Systems, GmbH, Hannover, Germany, 2016, http://files.messe.de/abstracts/72948_20160423_MobiliTec_Hannover_Vortrag__PDF.pdf [retrieved 19 December 2016].

$$C_{\mathrm{Bat}} = c_{\mathrm{Bat}} \cdot E_{\mathrm{Bat}} \cdot \frac{1}{n_{\mathrm{EOL}} \cdot d^{\mathrm{des}}} \cdot \frac{E_{\mathrm{Bat}}}{E_{\mathrm{Bat}} - E_{\mathrm{Hold}}/\eta_{\mathrm{BtT}}} \quad (9)$$

The last factor considers the larger battery size to incorporate the additional holding reserve rather than accomplishing the simple design mission. A linear dependency of battery life expectancy and discharge depth is assumed (meaning that, if the effective holding reserve would be responsible for half the battery size, the battery could withstand twice the number of the end-of-life cycles because the battery would only be discharged to 50% during each cycle).

Specific maintenance costs C_{Main} include the maintenance of the aircraft C_{AP}, engine overhaul C_{Over}, inspections C_{Insp}, and storage C_{Stor}. These costs are estimated as follows [48]:

$$C_{\mathrm{AP}} = 0.39 \cdot c_{\mathrm{AP}} \cdot \frac{t_{\mathrm{block}}^{\mathrm{ops}}}{d^{\mathrm{ops}}} \quad (10)$$

$$C_{\mathrm{Over}} = 5 \text{ €/h} \cdot \frac{t_{\mathrm{block}}^{\mathrm{ops}}}{d^{\mathrm{ops}}} \cdot n_{\mathrm{PP}} \cdot f_{\mathrm{elec}} \quad (11)$$

$$C_{\mathrm{Insp}} = 500 \text{ €}/a \cdot \frac{1}{d^{\mathrm{ops}} \cdot n_{\mathrm{Flight}}} \quad (12)$$

$$C_{\mathrm{Stor}} = 3000 \text{ €}/a \cdot \frac{1}{d^{\mathrm{ops}} \cdot n_{\mathrm{flight}}} \quad (13)$$

where $t_{\mathrm{block}}^{\mathrm{ops}}$ represents the block time per operational mission, $c_{\mathrm{AP}} = 50$ €/h is the fully loaded hourly cost rate for a certified mechanic, n_{PP} is the number of installed engines, n_{flight} is the number of operational flights per year, and f_{elec} a discount factor for electric engines overhaul costs because the original formula only applied to piston engines. It is assumed that the overhaul costs for electric engines can be reduced by 50% as compared to one piston engine.

Crew costs need to be differentiated whether a pilot is required aboard $C_{\mathrm{pilot,acft}}$ or only on the ground as a safety pilot $C_{\mathrm{pilot,ground}}$. In both cases, the same fully loaded cost rate of $c_{\mathrm{pilot}} = 50$ €/h is used. If a commercial pilot is required aboard, the required working time of this pilot is considered to be 50% higher than the pure block time of the aircraft: $t_{\mathrm{pilot,acft}}^{\mathrm{ops}} = 1.5 \cdot t_{\mathrm{block}}^{\mathrm{ops}}$. One pilot is expected to suffice to fly the aircraft. If the aircraft itself can fly without a pilot, a ground pilot is assumed to be required for safety reasons. However, as the ground pilot provides only standby service, several ground pilots can be responsible for multiple aircraft exceeding the number of pilots. It is assumed that, on average, one ground pilot can oversee $f_{\mathrm{gp-acft}} = 5$ aircraft:

$$C_{\mathrm{pilot,acft}} = c_{\mathrm{pilot}} \cdot \frac{1.5 \cdot t_{\mathrm{block}}^{\mathrm{ops}}}{d^{\mathrm{ops}}} \text{ for pilot aboard the aircraft} \quad (14)$$

$$C_{\mathrm{pilot,ground}} = c_{\mathrm{pilot}} \cdot \frac{t_{\mathrm{block}}^{\mathrm{ops}}}{f_{\mathrm{gp-acft}} \cdot d^{\mathrm{ops}}} \text{ for pilotless aircraft} \quad (15)$$

The charges consist of navigation, landing, and ground handling charges. Navigation charges are excluded because they are currently only required for aircraft with MTOW > 2000 kg in Germany [51]. Flights under visual flight rules are also excluded from these charges regardless of the MTOW.

Landing charges are estimated based on today's regional airport fees in Germany. Resulting from an analysis considering that electric-powered aircraft do not emit pollutants and significantly less noise, landing charges are estimated as follows:

$$C_{\mathrm{Char,ldg}} = (\mathrm{MTOW} - 500 \text{ kg}) \cdot 0.01 \text{ €/kg} \quad (16)$$

For an estimation of the specific ground handling charges with the payload $m_{\mathrm{Pl}}^{\mathrm{ops}}$, a value of $c_{\mathrm{Char,grdhdl}} = 0.1$ €/kg based on regional airport charges for German airports is applied [52,53]:

$$C_{\mathrm{Char,grdhdl}} = \frac{c_{\mathrm{Char,grdhdl}} \cdot m_{\mathrm{Pl}}^{\mathrm{ops}}}{d^{\mathrm{ops}}} \quad (17)$$

Specific depreciation costs as the first part of the indirect operating costs can be calculated as follows, considering the aircraft selling price C_{Acft} and a linear depreciation:

$$C_{\mathrm{Depr}} = \frac{C_{\mathrm{Acft}}}{(d^{\mathrm{ops}}/t_{\mathrm{block}}^{\mathrm{ops}}) \cdot h^{\mathrm{ops}} \cdot t_{\mathrm{Acft,EOL}}} \quad (18)$$

It is to be expected that insurance costs will initially rise for pilotless aircraft due to the (reasonable) risk aversion of insurance groups. However, from a fundamental point of view, insurance fees represent the expected losses plus additional SG&A costs required for the work of insurance companies. Gudmundsson proposed insurance costs of $c_{\mathrm{Ins},f} = 500$ € plus $c_{\mathrm{Ins},v} = 1.5\%$ of the aircraft selling price for CS-23 aircraft [48]. The worse accident probability of general aviation aircraft is the reason for these higher relative costs because commercial CS-25 aircraft are only charged with one-third of the relative price (approximately 0.5% of the aircraft selling price) [54–56]. As AMOD services are expected to be conducted in a more professional manner, and thus safer than the CS-23 operations of the present, and accident probability will decrease with certified pilotless aircraft, insurance rates will likely be comparable to CS-25 values. However, insurance rates for contemporary CS-23 aircraft are assumed in order to be on the safe side:

$$C_{\mathrm{Ins}} = 500 \text{ €} + 1.5\% \cdot C_{\mathrm{Acft}} \quad (19)$$

As the operating costs are modeled for an AMOD company, an exhaustive cost model needs to consider capital expenditures (CAPEX). A weighted average capital cost rate (WACC) of $f_{\mathrm{WACC}} = 6\%$ is used. Assuming a linear depreciation, the average CAPEX can be calculated as follows:

$$C_{\mathrm{Capex}} = \frac{1}{2} \cdot f_{\mathrm{WACC}} \cdot C_{\mathrm{Acft}} \quad (20)$$

The SG&A costs C_{SGA} are considered with a surcharge factor on COGSs of $c_{\mathrm{SGA}} = 10\%$ (e.g., Lufthansa ~12% and American Airlines ~5% in the past five years). COGSs comprise all previously listed cost items except for CAPEX:

$$C_{\mathrm{SGA}} = c_{\mathrm{SGA}} \cdot (C_{\mathrm{Ener}} + C_{\mathrm{Bat}} + C_{\mathrm{Main}} + C_{\mathrm{Pilot}} + C_{\mathrm{Char}} + C_{\mathrm{Acft}} + C_{\mathrm{Ins}}) \quad (21)$$

C. Impact on MTOW and Operating Cost

In this section, the results using the default values as described in the previous subsection, as well as the influence of the degree of flight automation, the L/D ratio, and the specific battery energy, are analyzed along with the impact of the design range on the MTOW and the specific operating costs of the aircraft. The first and last kilometer costs are excluded for this assessment.

The importance of the technological improvement of pilotless aircraft for offering AMOD services is underlined in Fig. 6. A pilotless aircraft designed with a maximum range of about 500 km including a 45 min holding reserve results in an MTOW of approximately 2000 kg. This aircraft can be operated with specific costs of around 0.7 €/km, given a utilization of 1000 h per year. When compared to an aircraft with a pilot aboard, two effects can be observed. A pilot aboard reduces the payload for the same design range. Hence, the aircraft size and weight increases in order to maintain the maximum payload of four passengers as compared to one without a pilot. The more severe impact, however, affects the operating costs because the commercial pilot accounts for approximately one-third of the total specific operating cost when considering design ranges up to about 500 km. Therefore, a pilotless aircraft represents a prerequisite for AMOD concepts as described in this paper.

Specific battery energy is another important aspect with respect to the MTOW and operating costs of a (hybrid-)electric aircraft.

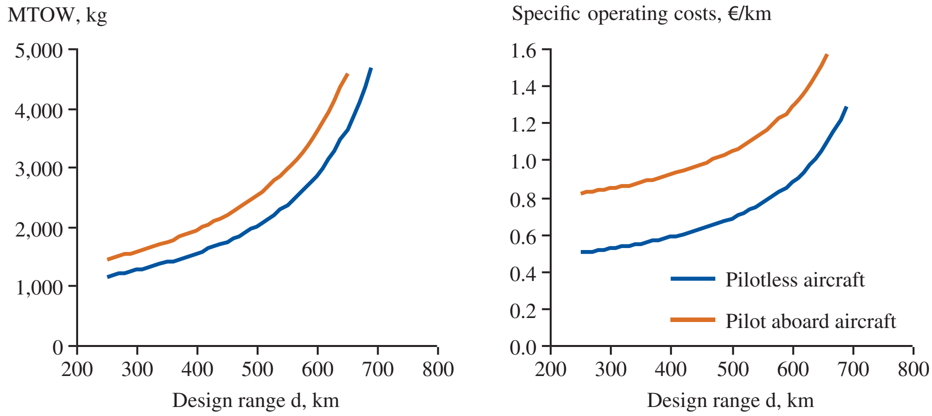

Fig. 6 Influence of pilot aboard vs pilotless aircraft on MTOW (left) and specific operating costs (right).

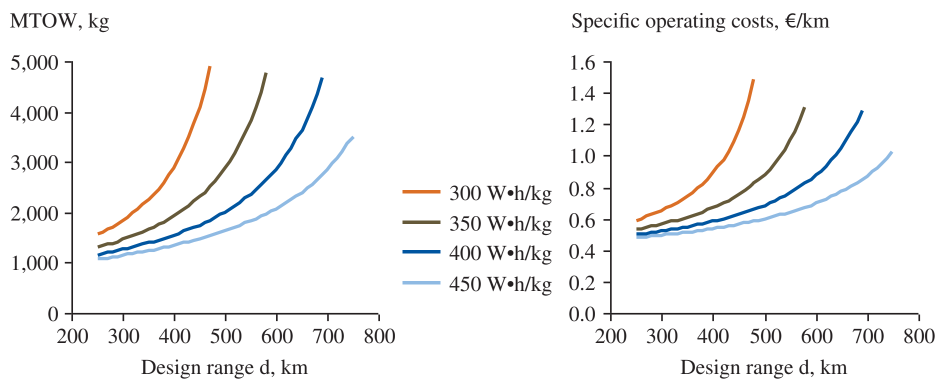

Fig. 7 Influence of the specific battery energy c_{Bat} on MTOW (left) and specific operating costs (right).

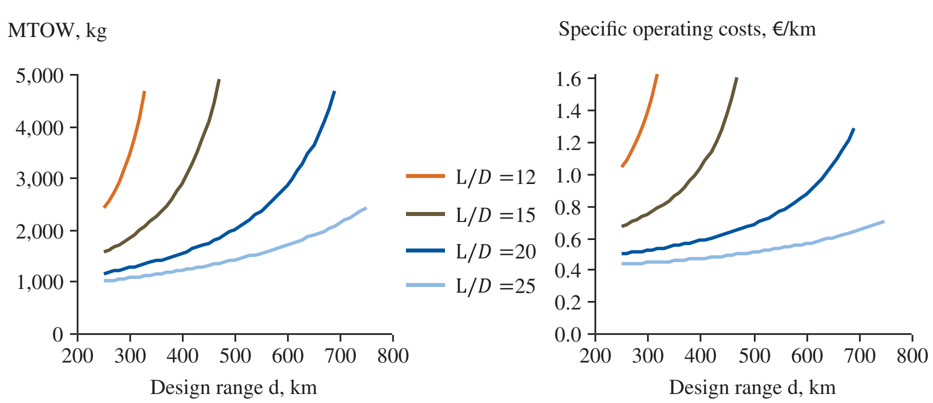

Fig. 8 Influence of L/D ratio on MTOW (left) and specific operating costs (right).

As illustrated in Fig. 7, a decrease of specific battery energy from 400 to 300 $(\mathrm{W}\cdot\mathrm{h})/\mathrm{kg}$ would result in a 2000 kg MTOW aircraft only being able to fly around 320 km, including the 45 min holding reserve. An even lower specific battery energy of 250 $(\mathrm{W}\cdot\mathrm{h})/\mathrm{kg}$ would not suffice to achieve a 250 km range with a MTOW lower than 2000 kg. Consequently, a specific battery energy of at least ~350–400 $(\mathrm{W}\cdot\mathrm{h})/\mathrm{kg}$ is required to provide AMOD services using all-electric aircraft. The specific operating costs scale accordingly.

As the third important aspect being discussed in this paper, the impact of the cruise L/D ratio is illustrated in Fig. 8. The L/D ratio determines the amount of required transport energy that can be translated into battery weight by applying specific gravimetric battery energy. It becomes obvious that both the L/D ratio and specific battery energy impact the MTOW similarly. However, there is a difference concerning the impact on operating costs. As a higher L/D ratio leads to a lower energy demand, the operating costs are impacted significantly more by the L/D ratio than by the specific battery energy.

In conclusion, an L/D ratio below 15 does not seem feasible for AMOD services because an aircraft with an L/D ratio of 15 (and a specific battery energy of 400 $(\mathrm{W}\cdot\mathrm{h})/\mathrm{kg}$) can only travel approximately 320 km. The high importance of maximizing the cruise L/D ratio when designing a fully electric aircraft becomes obvious when considering the impact of an L/D ratio of 25 instead of 20. This would increase the maximum range by more than 30% to 670 km for an aircraft below a 2000 kg MTOW. The specific operating costs could be decreased by 20% when compared with aircraft designed for a 500 km maximum range.

IV. Integration of Market and Service Provision Analysis to Determine Top-Level Aircraft Requirements

The integration to finally assess the economic feasibility of the proposed AMOD concepts with a focus on Germany is conducted in three steps. First, the door-to-door costs are determined for relevant operational distances. This includes first and last kilometer costs. Second, the door-to-door linear distance speed according to Sec. III.A is integrated with the WTP function according to Eq. (3). Third, profit can be calculated and an evaluation criteria Γ is defined for the assessment of the AMOD concepts.

To determine the door-to-door costs C, it is necessary to make an assumption regarding the average passenger utilization of the aircraft as the first and last kilometer costs occur for every passenger, whereas main run costs are split among all passengers. An average utilization of 50% is assumed in the following section. The door-to-door costs for concepts A1, A2, and B, as well as for different aircraft design ranges, are plotted in Fig. 9. For concept A1 (left), the first and last kilometers are considered with costs of approximately 80 € in total, for A2 with 20 €, and for concept B with only 10 € according to Table 5. At low distances, first and last kilometer costs dominate in concept A1, leading to significantly higher door-to-door costs when compared to the other concepts. As the main run costs are split among two passengers, the slightly lower operating costs of the aircraft when considering design ranges below 500 km have only limited impact on the overall specific door-to-door costs. A design range of more than 600 km leads to a steep aircraft weight increase, resulting in significantly higher operating costs.

A sensitivity study investigating the impact of average aircraft utilization on specific door-to-door costs is conducted. The results for an aircraft design range of 500 km and levels of utilization of 40 and 60% are depicted in Fig. 10. To allow for a comparison with the baseline assumption of an average utilization of 50% (i.e., 2 passengers), a curve for this case is shown for each concept as well. In conclusion, splitting the main run costs among more or less than two passengers has a similar relative impact on all investigated transportation concepts. An average utilization of 40% results in slightly higher specific door-to-door costs, whereas a higher average aircraft utilization of 60% is beneficial with respect to door-to-door costs. Furthermore, the results indicate that the impact of average utilization on specific door-to-door costs is approximately independent from operational distance.

The specific door-to-door costs can be compared with the identified willingness to pay in Sec. II when considering the door-to-door linear distance speed according to Sec. III.A. The door-to-door linear distance speed (left) and the willingness-to-pay results (right) as a function of operational distance are illustrated in Fig. 11.

In concept A1, the door-to-door linear distance speeds of 100–180 km/h can be achieved for distances up to 500 km. Due to the longer commuting times to and from the airport, effective speeds of 70–130 km/h are realistic in concept A2. Due to the shorter duration of the first and last kilometers in concept B, the travel speed increases to 130–210 km/h for distances of 200–500 km. The willingness to pay, especially for concept A1, remains relatively stable over a wide range of operations. The decreasing WTP is compensated for by an increasing door-to-door linear distance speed with increasing operational distance. The WTP decreases in concept A2 from approximately 0.6 €/km to approximately 0.5 €/km and is the lowest among all concepts. For concept B, the speed increase overcompensates the range decrease at lower ranges. The WTP is about 0.08–0.13 €/km higher for concept B than for concept A1 and about 0.15–0.25 €/km higher than concept A2.

The profit can finally be calculated as a function of operational distance. The results are displayed in Fig. 12. It should be noted that, due to the inclusion of capital expenditures, positive values represent an above-the-market profit expectation.

Concept A1 is profitable only for routes longer than 200–300 km. In concept A2, for aircraft design ranges up to 600 km, a travel distance of 150–200 km is sufficient for a positive business case. Taking into account reasonable aircraft design ranges, concept B is already profitable for routes shorter than 150 km. As an evaluation criteria Γ, profit Π is integrated among all profit adding distances d^+:

$$\Gamma(d) = \int_{d^+} \Pi(d)\,\mathrm{d}d = \int_{d^+} \mathrm{WTP}(d) - C(d)\,\mathrm{d}d \qquad (22)$$

A variation of the design range for concepts A1, A2, and B with regard to the evaluation criteria Γ and the minimum profit adding distance d^+ is summarized in Table 10.

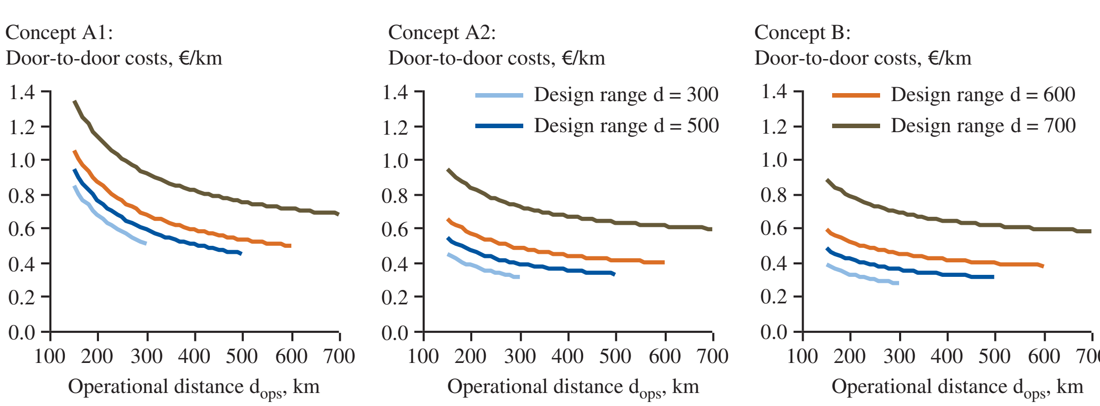

Fig. 9 Specific door-to-door costs for AMOD concepts A1, A2, and B for different aircraft design ranges.

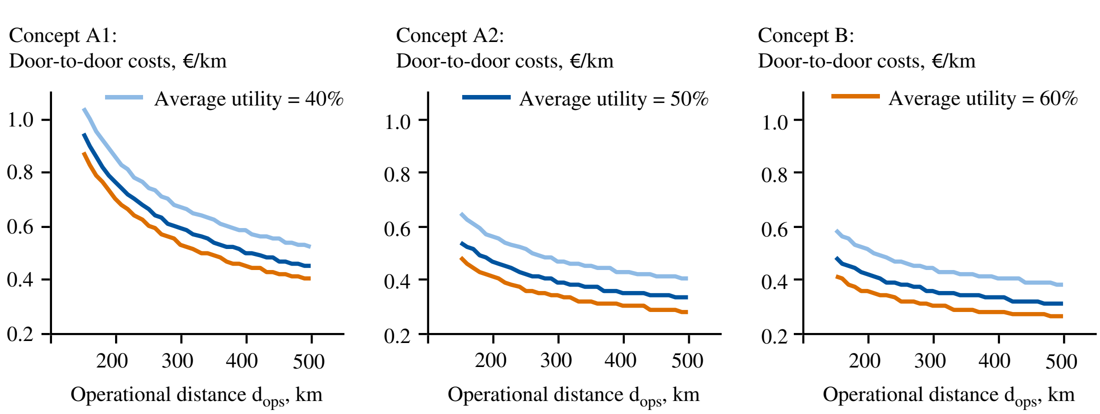

Fig. 10 Specific door-to-door costs for AMOD concepts A1, A2, and B for 500 km aircraft design range and different levels of utilization.

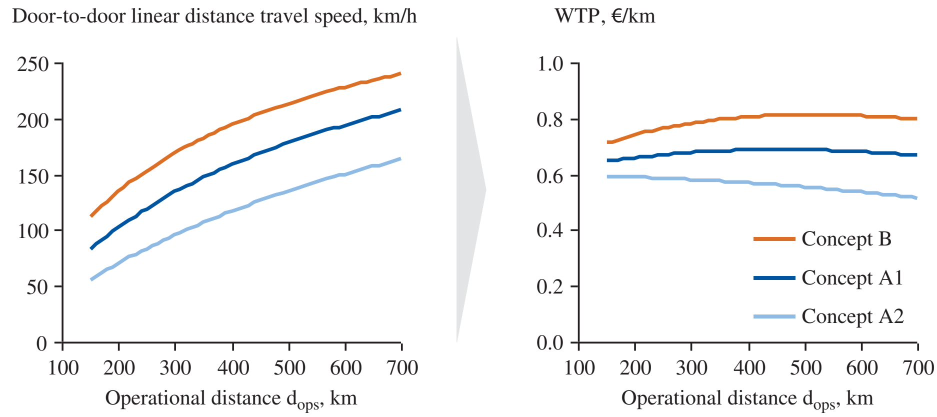

Fig. 11 Door-to-door linear distance speed and WTP for AMOD concepts A1, A2, and B in dependence on the operational distance.

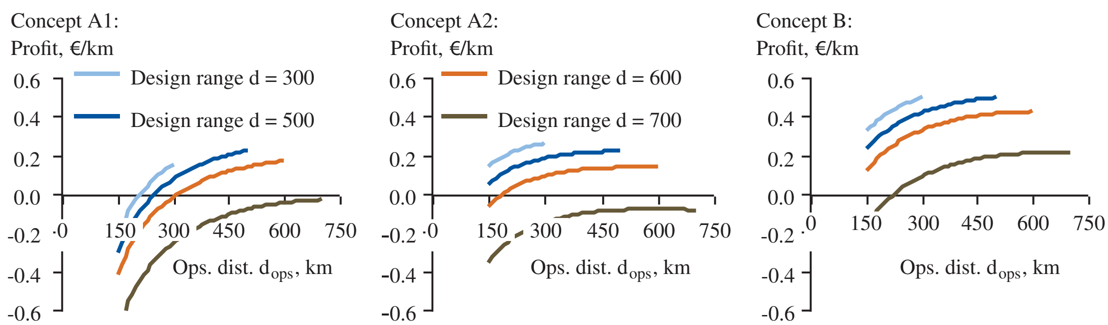

Fig. 12 Specific profit in dependence on the operational distance (Ops. dist.) for different aircraft design ranges and concepts.

For all concepts, 500–600 km represents the optimum range. Additionally, it needs to be considered that the MTOW increases from approximately 2000 to 3000 kg when increasing the design range from 500 to 600 km. Taking into account that aircraft with a MTOW below 2000 kg are exempted from navigation charges, reasonable TLARs for AMOD concepts include a design range of 500 km and a MTOW below 2000 kg.

With regard to the overall economic feasibility of AMOD concepts, the results indicate a clear business case for such concepts. Concepts A1 and A2 represent different usage modes of the same concept. Both modes result in a promising business case. Concept A2 seems especially suitable for an AMOD transportation concept due to the lower cost of using public transportation instead of private cars and taxi cabs. The analysis for concept A2 shows that the identified willingness to pay is 30–40% higher than the estimated door-to-door costs when considering a design range of 500 km. If the average passenger utilization could be increased from 50% to a typical CS-25 aircraft utilization of 75%, the gap would be above 50%, showing that passengers would be willing to pay twice as much as the service costs.

Table 10 Evaluation criteria Γ and minimum profit-adding distance d^+ for different design ranges and concepts

Concept	Design range	Evaluation criteria Γ	Minimum profit-addding distance d^+
A1	300 km	8.72	210 km
A1	500 km	36.88	250 km
A1	600 km	33.14	310 km
A1	700 km	0.00	All negative
A2	300 km	34.62	All positive
A2	500 km	64.24	All positive
A2	600 km	46.67	190 km
A2	700 km	0.00	All negative
B	300 km	67.21	All positive
B	500 km	149.00	All positive
B	600 km	158.98	All positive
B	700 km	78.96	250 km

When comparing concepts A1 and A2 with concept B, the visionary concept B is always superior because no penalties are applied on the aircraft in this concept, whereas all benefits are reaped. The higher WTP and profit margins of concept B can therefore be treated as an upside potential estimation. This result is in line with the findings of Pu et al. [9], who predicted a bigger demand of AMOD trips if takeoff and landing sites were in close proximity to the actual start and end points of travelers' journeys. For a more profound evaluation of the superiority of concept B to concept A, the restrictions of urban takeoff and landing sites need to be considered. Although the available runway length in urban areas is most likely shorter when compared to regional airports, more limited opening hours due to noise constraints as well as public acceptance in general need to be taken into account. However, with regard to limited runway length, a vertical takeoff and landing ability could be another technology enabler for the visionary concept B.

V. Discussion of Limitations of this Analysis and Proposals for Future Research

The calculation of operating costs of AMOD services is based on various assumptions and estimations regarding technical and operational prerequisites. Furthermore, the evaluation of calculated service provision costs is barely possible because comparable services do not yet exist. Therefore, progress in the development of aircraft and concepts of operation of AMOD services need to be carefully watched in order to adjust assumptions and, ultimately, the results of this analysis. Once again, it is underlined that findings of the economic feasibility assessment are strictly limited to Germany for two reasons. On one hand, the derivation of the WTP is based on an analysis of current travel options and costs in Germany. As the availability, costs, and scoring of qualitative aspects of the investigated transportation modes in other countries are likely to be different from Germany, corresponding WTP distributions would differ as well. On the other hand, the operating costs of aircraft for AMOD services are estimated based on cost components (e.g., labor, electricity) at a German price level. However, other studies investigating different regions and partly different concepts result in positive economic assessments as well. For example, Gawdiak et al. [57] concluded that AMOD concepts could become a very popular transportation mode for travel distances ranging between 300 and 500 miles (483–805 km) in the United States. In addition to intercity travel, the ride-hailing company Uber [58] sees great potential in AMOD concepts for short, intraurban connections.

The willingness to pay for AMOD services is derived from travel costs associated with current transportation options in Germany. The transportation options analyzed offer a range of door-to-door linear distance speeds (i.e., door-to-door travel times) at different price levels. Although the analysis takes population density into account in order to reflect a potentially higher demand for travel in densely populated areas, the impact of travelers' affluence or value of time is not explicitly included because the analysis does not consider distribution of income and wealth across different regions and cities. Moreover, there is no explicit distinction between private and business travel. Consequently, calculated willingness-to-pay values are averages across regions, social classes, and purposes of travel. However, it is conceivable that potential operators of AMOD services would use cross financing in order to balance less profitable routes with more lucrative ones. Therefore, the average WTP as estimated in this analysis is considered a reasonable assessment basis.

To determine the WTP depending on the door-to door linear distance speed, the multiple regression presented in Sec. II.C of this paper uses the variable door-to-door linear distance speed in the first and second orders. However, research into the perceived value of transportation characteristics has shown that there are more ways of portraying key relationships (e.g., the natural logarithm of important variables such as travel time). With regard to future research, it seems promising to investigate the willingness to pay for AMOD services in Germany from more points of view and compare results from different models. Further proposals for future research include a more detailed consideration of the impact of travelers' individual characteristics and the purposes of travel on the WTP, as well as an in-depth analysis of potential trip volume for AMOD services.

VI. Conclusions

The economic feasibility assessment of air mobility on-demand concepts for Germany is very promising. Technological prerequisites for a sustainable mobility concept are a significant improvement in specific battery energy (350–400 $(\mathrm{W}\cdot\mathrm{h})/\mathrm{kg}$) and advancements in flight automation to enable pilotless aircraft. Depending on concept and distance, door-to-door linear distance travel speeds of 80–200 km/h may be feasible and will lead to a qualitative leap in travel speed. The identified willingness to pay ranges from 0.5 to 0.8 €/km (monetary value in 2015), depending on the travel speed and distance in 2030. Aircraft with four passenger seats and an average utilization of 50% suffice for a promising business case. A maximum range of 500–600 km represents a reasonable top-level aircraft requirement. The cruise L/D ratio has a strong impact on the technical aircraft design, the resulting operating costs, and therefore on the entire profitability. The aircraft should have a cruise L/D ratio of around 20 or more. Moreover, the aircraft cruise speed should exceed 300 km/h; although, due to the high sensitivity of the L/D ratio, a slower cruise speed is acceptable if overcompensated by the improvement of the L/D ratio.

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