EXTERNAL REQUIREMENTS FOR ELECTRIFIED COMMUTER AIRCRAFT

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Abstract

With increasing power and energy storage capabilities, electrified aircraft for low-capacity transportation are moving to the focus of attention in aviation. Electrification is expected to curb the effect of aviation on the global climate, but also simplify aircraft operations. Moreover, commuter air services might reduce travel times by offering low-capacity connections and improving the accessibility of remote areas. This work derives top-level aircraft requirements for upcoming electrified commuter aircraft designs, focusing on assessing range requirements, implications on take-off field lengths, and cost comparisons. To do so, it analyses historic air traffic control data for current commuter and light regional aircraft and establishes a demand model to access future low-capacity connections within Europe. We show that commuter air services have developed into a niche, whereas light regional aircraft have acquired the role traditionally linked to commuter services. For Europe, we identified significant travel time benefits for range requirements of 500-700 km. Assuming the already existing airport infrastructure, total travel times could be improved by introducing bypass connections and shorter first/last mile transportation to the airfields. We identified the modes of transportation that commuter services would compete with for the analysed connections.

Commuter air services achieved a significant reduction of first and last mile transportation costs, which constitute a significant fraction of the total trip costs. However, the costs of the actual flight segment were considerably higher than for the reference modes of transportation. In total, the effect of higher costs for the commuter flight segment outweighed the cost reductions.

Keywords

Regional Air Transportation, Electrified Commuter, Electric Aircraft Propulsion

1. INTRODUCTION AND MOTIVATION

Aviation made fast and safe journeys over long distances accessible and affordable to an increasing part of the global population. However, along with these tremendous benefits, also the negative effects of air traffic are getting increasingly apparent, such as its essential contribution to global warming [15] and local noise emissions. One very promising approach to curb the negative effects of aviation is the electrification of aircraft propulsion systems. Developing from light, unmanned aerial applications, the power, and energy storage capabilities of electric propulsion systems have increased to levels which at a current technical state, can power light General Aviation aircraft [26].

Compared to the conversion from low-grade energy (chemical energy) to high-grade energy (mechanical power) for internal combustion engines, electrified propulsion converts high-grade energy (electricity) to another high-grade energy (mechanical power) at a high level of efficiency. Moreover, electric propulsion allows for a decoupling of power and thrust units [11]. Depending on the utilised source of energy, electric motors can be operated locally free of climate active gases and at reduced noise emissions [19]. From an operational perspective, electric motors have fewer rotating parts and are expected to cause fewer vibrations than reciprocating combustion engines in which energy conversion occurs intermittently. Bringing these factors into the context of aircraft operations, a reduction of vibration is likely to simplify maintenance effort and therefore costs. This concerns the propulsion unit itself, but also the airframe. Considering these potentials and the increasing power ratings for electric motors in aviation, as well as energy storage options, the next foreseeable and achievable step would be the electrification of commuter and light regional aircraft. This allows acquiring more experience with electrified propulsion systems, as larger aircraft applications are not yet ready to be electrified with the current technology.

Regardless of this role as a testbed for electric propulsion systems in aerial applications, electrified commuter and light regional aircraft have the potential to develop into leading players in a projected, intermodal transportation system, as they might offer fast and efficient low-capacity transportation. Further characteristics of commuter air services can be summarised as follows:

- Limited infrastructure required: apart from airfields, no significant en-route infrastructure is needed resulting in low capital investment and low emission of construction
- Travel times: short door-to-door travel times and connecting decentral airfields
- Flexibility: low capacity per flight allows to avoid

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complex aggregation of demand, therefore higher flexibility

Commuter and regional air services can cover the gap of intermediate distances which arises between emerging vertical take-off vehicles (VTOL) for inner- and intra-city transportation on one side and high-capacity high-speed (HS) trains connecting the major cities along corridors on the other site. Furthermore, they can be a cost- and time-efficient mode to serve bypasses in this intermodal system. Commuter air services have already existed before in North America and Europe. Focussing on business travellers, commuter aircraft have been connecting secondary cities on high frequencies at comparably high fares [16]. Previous publications have already addressed the development of commuter air services from the 1960s to its peak in the early 1990s. Since then, commuter flights have faced a stark and constant decline with an ageing fleet and only a few aircraft types still in production [25, 28]. The decline was mostly linked to the increasing market penetration of low-cost carriers, developing HS rail services and capacity constraints on major airports [25]. However with the discontinuity of commuter air services, often the accessibility of remote regions diminished [16].

With increasing capabilities and experiences with electric motors and systems for aerial applications, the question arises of how to exploit the potential of electrified propulsion for low-capacity air transportation systems. In recent publications, numerous electric commuter and regional aircraft concepts were presented and compared [17]. These designs are optimised based on previously defined assumptions on the requirements and available technology. Considering the impact that underlying assumptions have on the resulting aircraft designs, it becomes obvious how crucial these assumptions and requirements are. However, a review of recent aircraft design studies shows that a large fraction based its assumptions and requirements on conventional reference aircraft.

Clean-sheet aircraft designs are based on a set of requirements, which need to be defined before the actual design process takes place. The design process is iterative and involves weighing and prioritising requirements. These so-called top-level requirements (TLAR) are crucial for understanding and balancing the requirements of the design which decisively influence the later aircraft [29]. Torenbeek expressed the crucial importance of mapping the enabling technologies and their compliance with certification requirements, as well as a profound selection of parameters which identify and define a superior aircraft design in comparison to existing or competing concepts.

Regarding conventional aircraft, they state the general rule that at a given payload and mission performance, a reduction of fuel weight and take-off weight is always favourable [29]. This general rule is challenged in electric aircraft as electric propulsion systems clearly show higher efficiencies, but also imply significant higher aircraft weights for energy storage and power transformation [20]. Especially for battery-electric aircraft but also for hybrid-electric systems, the weight of energy storage scales to a much larger degree with the mission and range requirements as this would be expected for fossil fuel-driven aircraft. It is common practice to compare aircraft designs to already existing reference aircraft to achieve further improvements [29]; however, as the number of existing electric aircraft is very limited, a solid definition of requirements is an essential fundament for successful electric aircraft applications. In the context of electrified aircraft, Haran et al. [2022] especially stress the high sensitivity of aircraft range, weight, and energy-related operational conditions.

With a focus on hybrid-electric regional aircraft, Moebs and Eisenhut addressed and derived aircraft requirements. They underlined that requirements can be complex, and that single requirements can even interfere and contradict each other. Non-transparent or difficult to retrace design implications can therefore be the outcome. To avoid this, the developed method compared, weighted and filtered requirements to determine a set of binding requirements to streamline the aircraft design [18]. As an extension and implementation of this work, Moebs and Eisenhut applied the V-Model of systems engineering to conduct a stakeholder analysis. This identified passengers, operators, authorities, airports, air traffic management, supplier of energy, as well as the general public as significant stakeholders. However, with the predefined focus on hybrid-electric regional aircraft, this approach focused on replacing existing regional aircraft within the market requirements which proved to be beneficial for conventional turboprop aircraft [5].

As one aspect of the ELICA project, several European universities examined the market environment for the electrification of commuter aircraft [28]. Part of this was the assessment of travel time benefits and the identification of new route potentials. For this analysis, connections within Germany were calculated for individual car, railway, and airline connections. On this base, range requirements were developed and a comparison of consumer prices for each mode of transportation was made. They found a meaningful mission range of 370 km and assumed a cost per RPK of 0.53 €/Pkm.

Regarding potential range requirements, the existing research focuses on travel distances and durations in single countries with good availability of detailed regional data. These models and their implications hold true for specific countries, but it is challenging to transfer these results into the larger European or even general context. Just to name an example, Grimme et al. and the ELICA consortium studied German domestic connections and described range requirements [9, 28]. However, potential mission ranges are naturally limited by the geographical extent of the study area.

This work aims to identify and assess requirements for electrified low-capacity aircraft: It shall help to apply the existing potentials of electric propulsion in the context of efficient and successful regional aviation. To do so, it lays the foundation for a requirement framework which takes current commuter missions and applications, but also mission requirements of projected, low-capacity air services into account. This framework shall allow increasing the degrees of freedom by taking a broader approach to the analysed projected geographical market, but also to examine the underlying sensitivities for further work.

Thus, the following section focuses on assessing the mission requirements of current commuter and regional aircraft. The third section develops the framework, whereas the potential travel time benefits and the resulting costs are the first major factors to be analysed. Section 4 will combine the results of these approaches and discusses how this can influence the design of electric commuters.

2. THE STATUS QUO OF EUROPEAN COMMUTER AVIATION

Starting with the first pillar of a future commuter air transportation system, this section empirically characterises major operational parameters of current commuter and light regional aircraft missions.

Commuter aircraft and air services can be defined regarding the missions they serve, but also regarding the applied aircraft types. To allow a clear differentiation between aircraft classes, this publication refers to *Commuter* aircraft as fixed-wing aircraft which are certified under the FAR-23 / CS-23 Commuter paragraph [4]. These are transportation aircraft with a seating capacity of up to 19 passengers, and a take-off weight of 19,000 lb and not more than two propulsor units.

The corresponding larger aircraft class are *Regional* aircraft with a seating capacity of about 20-100 seats. A subdivision of this regional aircraft segment assumes that light regional aircraft with up to 50 seats are operated on classical commuter missions. Examining this assumption will be part of Section 2: Therefore, light regional aircraft (seating capacity ≤ 50) are also part of the scope of this paper.

The analysis focused on describing major mission parameters which can essentially influence the later optimisation of energy storage and propulsion systems of electric commuter aircraft. Common mission ranges, route networks, and utilization patterns are compared. In order to derive operational characteristics of current commuter and light regional aircraft, historic air traffic management (ATM) data for the airspace controlled by Eurocontrol was analysed [6]. The data represents all civil flights for March, June, September and December 2019. The detailed assignment of aircraft types to aircraft classes can be found in Appendix B.

2.1. Range

In the first step, the distribution of flights over the actual distance flown was analysed. Therefore, single flights were accumulated over their actual flight distance (including traffic-related derivations from the shortest route) for different aircraft classes. FIG 1 shows that 80% of missions operated by commuter aircraft are 600 km or shorter. For light regional aircraft, it can be seen that 80 % of missions are within a range of 570 km.

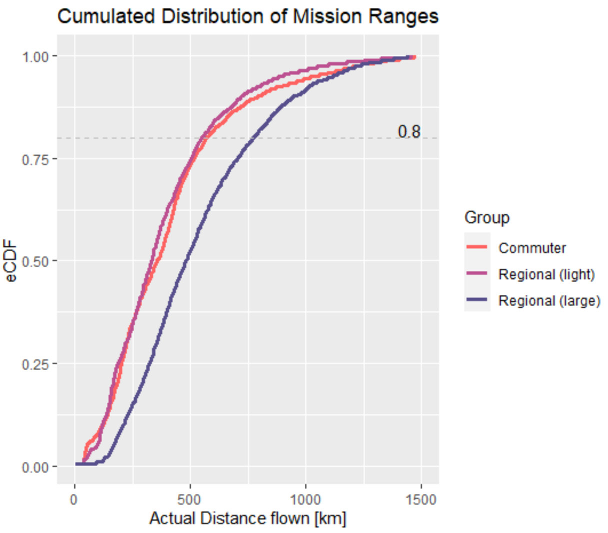

FIG 1. Cumulated distribution of mission range by aircraft classes for Eurocontrol area in 2019, own depiction based on [6]

To derive the first implications of required mission ranges, it is crucial to include mandatory reserves. In addition to the necessary fuel/energy to fly to the scheduled destination, IFR flights require reserves to reach any alternative airport en-route, as well as extra fuel for 45 min of loitering flight [30]. Eisenhut et al. examined the distance to en-route-alternates airports for the European airspace. They found that for 50 % of the possible en-route positions over continental Europe an alternate airport was less than 60 km away. For 95 % of the examined on-route positions, an alternate airport was not further than 120 km away [5]. Assuming to cover at least 75% of current commuter and light regional flights and routings along alternates which are not further than 60 km away, would result in a useful required mission range of 702.5 km (580 km mission and ca. 202.5 km IFR and loiter reserves) for the analysed current low-capacity aircraft.

2.2. Routes and Network

To better understand how and where commuter and light regional aircraft are applied, we tracked and illustrated the flights for an entire day in the European airspace. A representative day was chosen which avoids both the seasonal summer peak, as well as the low season in winter. The figures show all flights of the two aircraft classes on September 16th, 2019. FIG 2 shows the routes flown by 95 commuter aircraft on 284 flights. For most parts of Western Europe, it is apparent that most flights connect airports close to large conglomerations. Only for Scandinavia, a relevant share of flights connects remote areas with each other or to larger conglomerations.

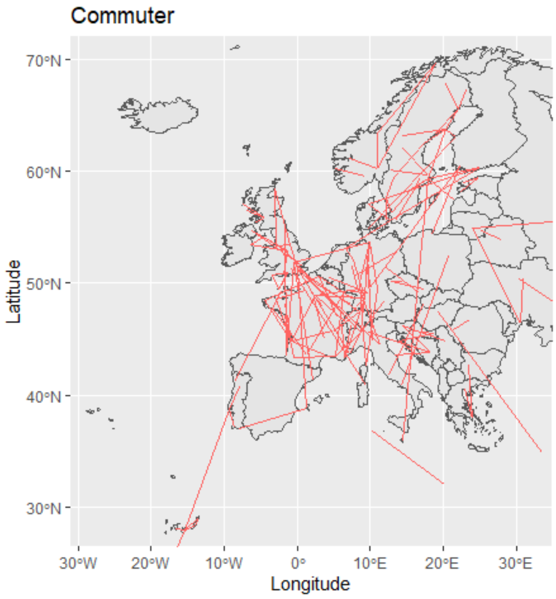

FIG 2. Cumulated flights of commuter aircraft on 16/09/19 in the Eurocontrol area, own depiction based on [6]

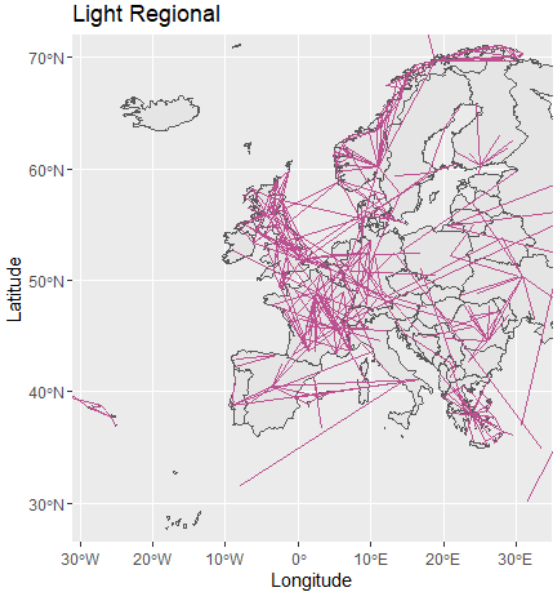

FIG 3. Cumulated flights of light regional aircraft on 16/09/19 in the Eurocontrol area, own depiction based on [6]

With 196 aircraft on 1,087 flights, light regional aircraft play a considerably larger role in European aviation. FIG 3 shows that light regional aircraft are especially applied to operate flights from international hubs to remote areas but are also applied to connect remote areas in the sparsely populated areas of Norway and the UK. This role was traditionally attributed to commuter aircraft.

2.3. Utilization

In a subsequent step, the ATM dataset was rearranged to derive schedules for each individual aircraft. Based on these schedules, operational utilisation parameters such as annual flight hours, annual cycles and average turn-around times (TAT) were analysed. As the dataset only consisted of data for 4 out of 12 months, the data had to be extrapolated. The covered months represent peak and off-peak months so a linear extrapolation was considered reasonable for a full 12-months-year.

TAB 1. Utilisation parameters of aircraft classes

	Unit	Commuter	Light Regional
Mean annual Block Hours	[BH]	251.88	704.56
Mean annual Cycles	[n]	225.37	696.43

Fehler! Verweisquelle konnte nicht gefunden werden. shows the utilization parameters of commuter and light regional aircraft. The annual block hours and annual cycles for commuter aircraft are remarkably low, resulting in on average 0.63 flights per day with a duration of 67 block min. Within the class of commuter aircraft, the variation in utilisation is high. The top 10% of the commuter fleet operates on average 2.7 flights per day with an average duration of 51.87 block min. Light regional aircraft performed on average 1.9 flights with an average duration of 60.7 block min. The top 10% of the light regional fleet operates on average 8.4 flights per day with an average duration of 44.33 block min.

Considering the low number of cycles per day, the turn-around times (TAT) are assumed not to be a critical requirement for the majority of current commuter and light regional aircraft. The analysis of TAT focuses only on the top 10 % of the fleets: it showed a minimum TAT of 8 min for commuters and 16 min for light regional aircraft. The mean TAT (excluding overnight stops) of 89 min for commuters and 33.6 min for light regional aircraft was observed.

2.4. Interim Conclusion

As previous works have already shown, commuter air services have been developing into a marginal phenomenon of European air traffic. A large majority of commuter flights are operated on short flights with distances of less than 600 km. For the analysed dataset, commuters were applied mainly on routes which connect secondary cities. The commuter traffic is concentrated on a few European countries.

The composition of light regional aircraft’s mission profiles shows that their mission requirements are very similar to commuter ones. Light regional air traffic has developed into the role which was traditionally attributed to commuter aircraft. They concentrate on connecting secondary cities as well as linking remote areas to international hub airports. Together, commuter and light regional aircraft cover 3.07% of scheduled passenger flights in the European airspace. However, 32.05% of the total operated flights are within the derived range requirement of 700 km, whereas the largest part is operated on narrow-body aircraft which are not optimised for such short flight distances.

The main difference between commuter and regional aircraft lies in their average utilisation. Light regional aircraft fly similar missions, but significantly more cycles. This is due to the fact that a large fraction of commuters is rarely used for scheduled flights. The missions and utilisation of the most intensively used commuters (fleet leaders) are similar to the light regional aircraft utilisation patterns. Since most commuter aircraft are used on very few daily flights, TAT are not critical for the majority of the fleet. However, the fleet leader's TAT are even shorter than the comparable TAT of light regional aircraft.

To summarize, commuter aircraft are very diverse in mission and utilisation profiles. The fleet-leaders of commuter and light regional aircraft are used on very similar mission and utilisation patterns.

3. DESCRIBING FUTURE DEMAND

In contrast to the analysis of existing commuter services, the second part of this paper focuses on the potential of a revived commuter air transportation system. As described in the introduction, the decline of conventional commuter air systems was linked to economic and operational circumstances. A major improvement of these might be achieved by the electrification of the propulsion system. These potentials refer essentially to improved maintenance effort and cost, improved availability and reduced cost of fuel [1], as well as lower climate-active gas emissions and lower noise emissions [28], both having the potential to affect the public acceptance of aviation. Especially noise improvements might enhance acceptance in local communities neighbouring the airfields, which could ease currently strict night curfew restrictions allowing for longer operating hours for electrified commuters.

Analysis of future transportation systems which have not been fully developed yet are linked to high uncertainty. Therefore, the general characteristics of the projected commuter air transportation system are derived from transportation policy publications such as the Flightpath 2050 plan [7]. The plan states that 90% of door-to-door journeys within Europe should be possible to complete in 4 h. Several studies have described this goal as not being sufficiently defined and perceived it to be difficult to implement [8]. However, the general necessity for fast and efficient transportation between cities and remote areas exists and is also expressed by other organisations [21].

3.1. Method

To take account of the uncertainty due to the considered market not being developed yet, this work follows a classical approach of system engineering. The so-called V-model was applied to transfer the assumed market and business characteristics into a set of technical requirements for aircraft design. The general framework is shown in FIG 4.

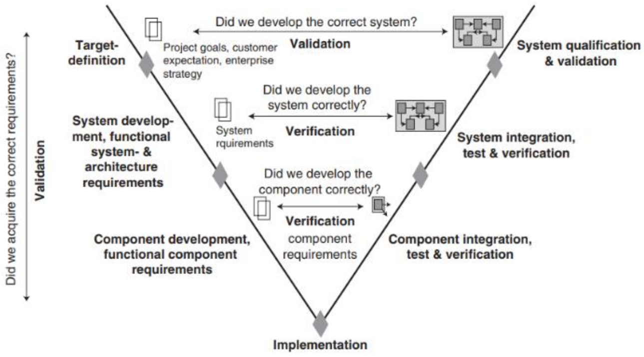

FIG 4. The V-model scheme as defined by Haberfellner [10]

Following the system engineering textbook Haberfellner [10] and the approach applied in Eisenhut [5], the target definition is based on an identification of major, external parties with significant interests in the system to be designed. These groups include the following: passengers, (air service) operators, airports, ATC, aircraft lessors, manufacturers, regulators, and the general public.

In the second step, the objectives and interests of these groups were organised and rearranged. Eisenhut et al. showed that multiple objectives can be linked and connected to a common base [5]. The derived parameters were enhanced and organised on three levels as can be seen in FIG 5. The superordinated level relates to parameters which are set by the definition of the transportation system. The second level of parameters focuses on aircraft design and the third level on operational parameters.

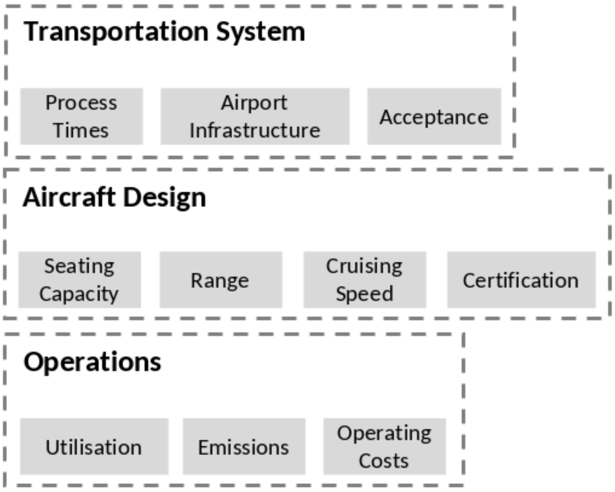

FIG 5. Identified requirement groups and their parameters

The following subchapters of this section address a selection of identified main parameters which are analysed and described in detail. The next subchapters of this work focus on travel time benefits, which essentially depend on the parameters of cruise speed and station and process time. Furthermore, a comparison of transportation costs was executed.

3.2. Travel Time Benefit

The dominating value proposition of a projected commuter air transportation system is a significant improvement in total travel times. For this paper, a model analysing travel time benefits were established. In the context of this work, travel time benefits (TTB) describe the reduction in total travel times of commuter air services compared to reference modes of transportation. This paper sets the reference cases to be individual road, HS rail, and mainline airline services. All these reference modes of transportation are considered in their current network.

The analysis focussed on Europe, which is defined as the EU27, Liechtenstein, Norway, Iceland, Switzerland, and the UK (overseas territories were excluded)). The study area was subdivided into one of 1,390 small, statistical regions (European NUTS level 3) with each region having a population of 150,000 to 800,000 inhabitants. Each combination of two regions was defined as a potential connection, which can be either domestic or transborder. For these connections, the travel times of commuters and the reference modes of transportation were analysed. Connections were filtered to exclude all those which appeared by default unsuitable for commuter air transportation. These connections have:

- a great circle (GC) distance of less than 75 km
- or a GC distance of more than 1,500 km

Furthermore, a simple gravity-based demand model was applied to identify those connections with a sufficient demand potential to fill at least daily commuter air services. The demand model has the number of air passengers as its dependent variable and takes the population, economic activities (as GDP per capita) and the GC distance between regions as independent variables into account. It is based on Hazeldine who established this parameter study to describe air traffic volumes on a local level for New Zealand [12]. All connections below a predefined threshold demand value were excluded from the calculation of TTB. The threshold demand was defined based on current European commuter connections with a maximum of one daily flight on a 19-seater-aircraft.

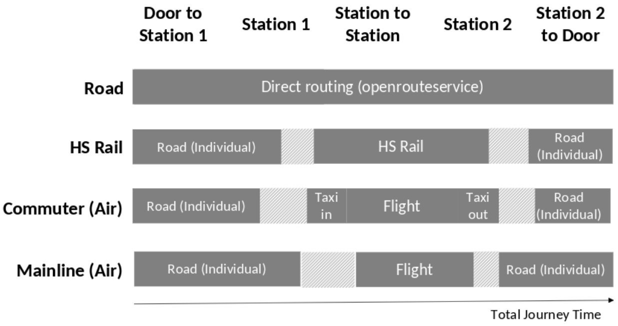

FIG 6. Journey segments and processes of modes of transportation, own depiction

As shown in FIG 6, the separate models to calculate the door-to-door journeys are based on different travel segments and stations. Each journey starts and ends at the geographic centroid of the region. It is assumed that the population of each region is concentrated in the centroid. The following sections provide detailed information on the models. An overview of the assumed speed and processing times per segment and station can be found in Appendix C.

3.2.1. Road

Calculations for individual road transportation assume a direct routing between the points of origin and destination. The distance and duration of journeys are calculated by embedding the *openrouteservice* API for dynamic route calculations [23]. Based on the current road network of Europe, the API calculated travel times and durations for a combination of two coordinates. Time for stops and breaks was not included. Road journeys of more than 1,000 km GC distance (~11-12 h driving time) were excluded as being assumed to be inferior per default due to the long self-driving times.

Apart from the usage of road transportation for the entire door-to-door journey, individual road transportation was also assumed for the first/last mile transportation to connect the HS railway station, airfields, and airports with the point of origin and destination. These first/last mile connections were not based on the API but calculated based on the distance of centroids to the nearest station or airfield with a distance factor of 1.3 to take account of non-direct routings at an average speed of 35 km/h for urban areas [2]. The first/last mile transportation to the closest airport was assumed at a distance factor of 1.3, but at a higher average speed of 45 km/h (as a mean for urban and rural speed) [2]. Individual route transportation excluded return or reallocation journeys of the vehicle, as this is reasonable to be assumed for car sharing operators.

3.2.2. High-Speed Rail

For HS rail connections, three travel segments and two processes were considered. The door-to-door journey started at the region of origin with road transportation to the closest HS train station. A general processing time of 20 min was included to take account of walking distances and connecting times. The HS train took the passenger to the HS train station closest to their destination. Another general processing time of 20 min at the station of disembarkment was assumed, followed by individual road transportation from the HS rail station to the destination.

In this early stage, the HS rail model is highly restricted and simplified. HS rail connections are assumed to be simple connections between the two stations with a universal distance factor of 1.18 to represent the derivation from the linear distance. In accordance with a benchmarking of average speeds on European HS lines, the average speed within the HS network is assumed to be 170 km/h. Future work on this model shall include a network-based route optimisation.

3.2.3. Commuter

Commuter journeys are considered as door-to-door journeys. Starting at the region of origin, the passenger used individual road transportation to reach the closest airfield. In accordance with an airport and runway database, appropriate airfields were defined as active airfields with an asphalt or concrete runway [24]. At the airfield, a processing time of 28 min was considered for check-in, security, and boarding. This is significantly shorter than today's processing time for mainline flights of 70 min; however, current US commuter operations prove these process times as realistic [3, 22, 27]. As commuter airfields are assumed to be less complex than airports, taxi-in and taxi-out times of 6 min in total were assumed. The actual flight was subdivided into three phases with a dynamic climb and descent phase at a vertical speed of 1,000 ft/min to the cruising altitude. Cruise altitudes of maximum FL 200 were assumed unless short flight distances indicated lower altitudes. The horizontal speed was assumed to be 50% of the maximum cruising speed. The cruise flight was assumed at a speed of 400 km/h but can be varied for later sensitivity analysis. Processing times at the airfield of disembarkment sumed up to 20 min. The passenger reached their destination by individual road transportation.

3.2.4. Mainline

For each region, a set of the closest airports served by mainline flights was created. On the base of the previously analysed Eurocontrol dataset from 2019, scheduled mainline flights which connected an airport from the set of possible origin airports with the set of possible destination airports were identified – regardless of the actual frequencies flown. Only if a direct connection between the two sets of airports existed, the combination of regions was considered for further analysis.

Just like in the previous models, the first/last mile transportation to and from the identified airports was assumed to be conducted on individual road transportation. The assumed processing time at the airport of origin was 70 min for check-in, security, and boarding, and 35 min at the airport of destination. The block times were derived from the Eurocontrol dataset and already included taxi-in and taxi-out phases [6].

3.2.5. Results of TTB Analysis

This work defines TTB as the time benefit from commuter services regarding their fastest reference mode of transportation. TTB can be calculated for every connection between two regions based on the total journey times t_i according to formula (1):

$$TTB_{Commuter} = min\,(t_{Road}, t_{Rail}, t_{Mainline}) - t_{Commuter} \tag{1}$$

The main result of this work focuses on potential TTB which can be realised by the introduction of commuter services. The distribution of TTB over flight distances allows first implications on range requirements for commuter aircraft in the context of this study. FIG 7 shows the TTB of the identified connections plotted by the GC distance between the coordinates of origin and destination. Per definition, all connections with distances of less than 70 km were excluded, as well as distances above 1,500 km, or respectively 1,000 km for individual road transport. In the figure, points with a positive TTB value indicate improvements in travel times due to the introduction of commuter services, negative values indicate that existing modes of transportation achieved faster travel times. The colour of the dots shows which reference mode of transportation achieved the shortest total journey time.

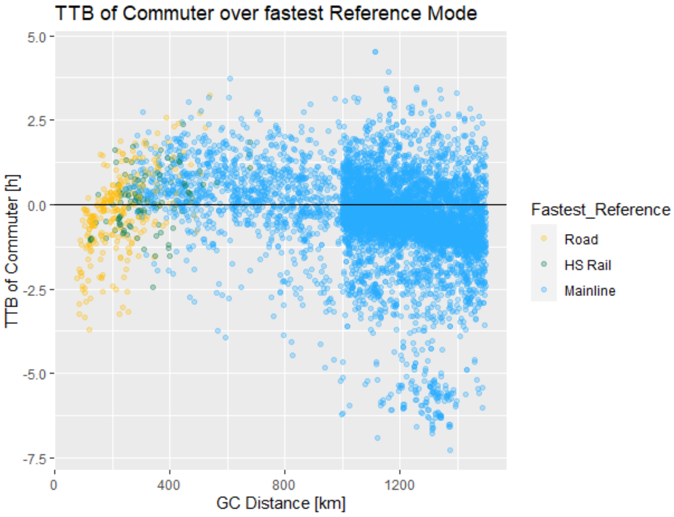

FIG 7. Travel times benefit of commuters by GC distance, own depiction

As expected, ground transportation demonstrated the shortest travel times for missions of up to 250 km. Starting with missions of about 500 km, an increasing number of connections showed the shortest travel times on mainline services. Nonetheless, commuter flights can achieve significant TTB over the entire analysed range. For connections of more than 500 km, commuter air services would almost exclusively compete with existing mainline services.

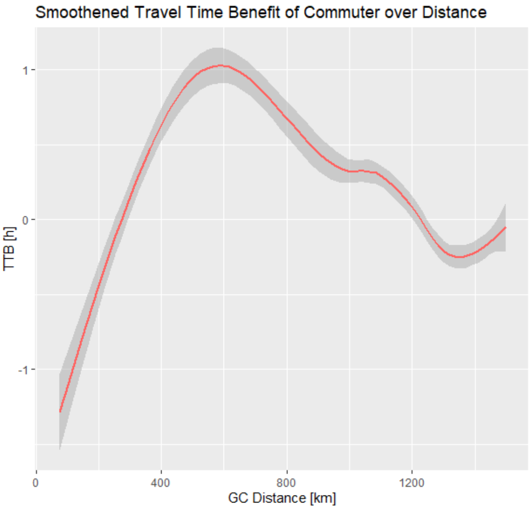

FIG 8. Smoothened TTB of commuters by GC distance, own depiction

FIG 8 shows the aggregated and smoothened course of commuters' TTB by distance as represented by the raw data of FIG 7. The data indicate that positive TTB are predominant for flights between 280 to 1,200 km, with the highest average TTB improvements between 500-700 km.

Positive TTB of commuters over mainline services resulted almost equally from an improvement in process times at the airfields/airport (-57 min) and shorter transportation times to/from the airport (on average -59 min). However, commuter services had a significantly longer flight segment due to the lower cruise speeds (on average +69 min). It is clear, that this effect increases for longer flight distances.

Moreover, the data showed that at a current state of infrastructure 782 active airfields meet the requirement for asphalt or concrete runway surfaces and were identified for commuter operations. Most of these airfields already serve commercial flights (14% large international airports, 50% airports with occasional flights). The identified airfields for commuter operations are closer to the assumed centres of the population. In comparison, 610 airports for mainline services were identified (26% large international airports, 66 % airports with occasional flights).

TAB 2 shows the minimum take-off field length (TOFL) of common conventional commuter and light regional aircraft. Assuming a realistic TOFL of 900-1,000 m, it can be seen in FIG 9 that the share of airfields which do not fulfil this requirement is significantly higher for airfields for commuter services (17%) than for airports for mainline services (6 %).

TAB 2. Minimum take-off field length of commuter and light regional aircraft

Aircraft	CS / FAR	TOFL [m]
Dornier Do 228	23	671
Fairchild Metroliner III	23	870
Beechcraft B1900D	23	1140
BAe JS 31/32	23	1380
Saab 340	25	1300

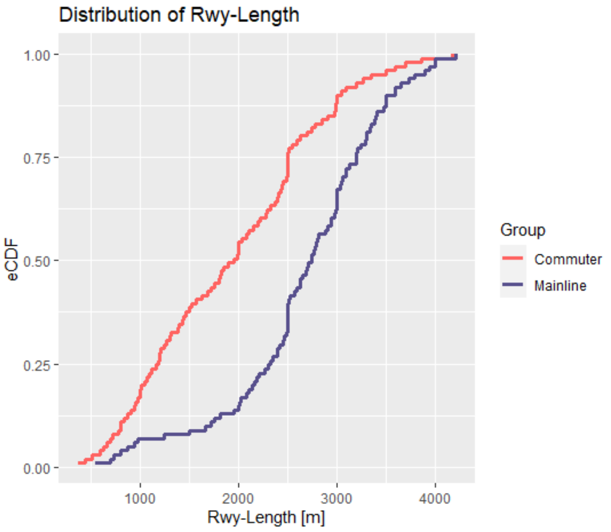

FIG 9. Distribution of runway lengths for commuter and mainline services, own depiction

3.3. Costs

The historic development of commuters showed that increasing cost disadvantages were major reasons for their decline. This moves the second proposition of commuter air transportation to the focus, which is the potential for efficient, low-capacity transportation. Especially in remote, sparsely populated areas, or on topographically challenging surfaces, it can be overly capital- and emission-intensive to provide sufficient ground infrastructure.

The cost model applied cost functions on the segment distances and durations which have been derived in Section 3.2. Cost functions were either fixed or depended on the distance and duration. This is a major difference from existing research (such as the ELICA project [28]) which evaluated the cost of different modes of transport regarding the end-user prices. However, consumer prices include various subsidies, tax incentives, and mechanisms to control and influence the demand. This work aims to provide a cost-based approach for the examined modes of transportation. To do so, it takes public expenditures into account. Nonetheless, it cannot claim to consider all subsidies or expenditures of local administrations. Therefore, the implications of this model are limited to qualitative comparisons within this model.

The following sections give a short overview of the applied models and their assumptions. Although this paper is addressing electrified commuters, the comparison of costs will consider conventional turboprop commuter aircraft. The costs of electrified commuters are still highly uncertain, so this cost comparison shall rather set a benchmark to describe necessary efficiency gains. Expenditures for marketing, corporate overhead, and passenger catering were neglected for all modes. Appendix D gives an overview of the cost assumptions.

3.3.1. Road

The costs of road transportation follow a cost per passenger-km consideration. A middle segment automobile (VW Golf 8, petrol engine) was assumed at an average annual mileage of 12,000 km and a service life of 9.5 years. The cost calculation includes fuel, scheduled maintenance, insurance, parking fees, taxes, and CO_2 compensation. The cost of road infrastructure for urban and rural areas was neglected, as the provision can be seen as a mandatory sovereign task. The usage of motorway infrastructure was assumed at 0.07 €/km per vehicle (based on average motorway tolls for European countries). At an average load of 1.41 passengers per vehicle, the cost resulted in 0.31 €/Pkm for urban areas (assumed for first / last mile transportation) and 0.334 €/Pkm for long-haul distances including motorway tolls.

3.3.2. HS Rail

The cost of HS rail follows a cost per passenger-km consideration. A mix of Intercity-Express and Intercity-trains was assumed. The cost included expenses on fuel/energy, staff, scheduled maintenance, rail and train station usage fees, capital cost of vehicles as well as the proportional share of public spending on rail infrastructure. The costs were determined in the context of Deutsche Bahn. At an average load factor of 56%, the cost resulted to be 0.0883

€/Pkm.

3.3.3. Commuter

The costs of commuter flights were calculated on the base of different reference values. Mission-related airport, ground services, and ATC fees were assumed to be fixed per mission. They were derived at a fixed MTOW on the base of official fee schedules of airports with a high fraction of General Aviation and commuter traffic.

The mission fuel consumption and its resulting costs (including CO_2 compensation) were determined based on the flight distance and basic aerodynamic parameters with the Breguet range equitation.

The costs for crew labour, maintenance, insurance, and aircraft depreciation are related to the flight duration. Commuter flights were assumed to be operated with two pilots, and in accordance with CS-23 without cabin crew members. The assumed load factor was 0.85.

Depending on the distances, commuter costs varied over the mission between 0.148-0.178 €/Pkm for flights of 500-700 km.

3.3.4. Mainline

The cost items of mainline flights were calculated following the commuter cost model. The assumed aircraft was an Airbus A320-200 with a seating capacity of 160. Additionally, the operation of mainline flights requires cabin crew members which were included in this model. The assumed load factor was set to 0.85. Depending on the distances, the cost of mainline services varied over the mission between 0.12-0.16 €/Pkm for flights of 500-700 km.

3.3.5. Results of Cost Comparison

For each in Section 3.2 identified connection, the total journey costs (incl. the first/last mile transportation) per passenger were calculated. FIG 10 shows the course of smoothened total travel costs over the GC distance for the studied modes of transportation. At the assumed load factors, the cost of individual road transportation increases linearly in the distance as it was defined. For the other modes of transport, the first/last mile transportation constitutes a significant fraction of the total transportation cost for HS rail (48.9%), compared to commuters (11%) and mainline services (25.3%). Commuter and mainline services have significant fixed cost per mission, which lessens the effect of an increase in distance on the total journey costs.

For mission ranges between 500-700 km (highest TTB), we see that the total journey costs of commuters are almost double of the costs of HS rail and mainline air services. However, the journey costs of commuters are similar to individual road transportation's costs for to the identified mission range.

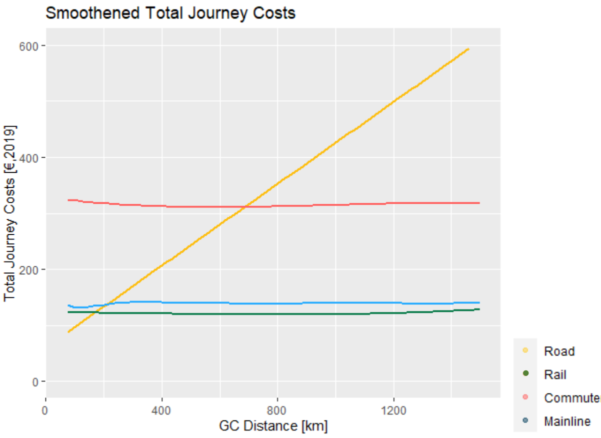

FIG 10. Total journey costs for modes of transportation, own depiction

4. DISCUSSION

This work identified and assessed external requirements for low-capacity electrified air services. To do so, it derived TLAR and stated parameters which are crucial for the design of successful electrified aircraft for commuter missions. As prior studies have already proved, required mission ranges are of utmost importance for electrified aircraft and highly influence the weight build-up and eventually the aircraft's operational characteristics [13].

For existing low-capacity air services, mission ranges which cover 80% of flights were determined at 600 km for commuters, and 570 km for light regional aircraft. The analysis of projected commuter services indicated the highest TTB for mission ranges of 500-700 km in Europe. It is noteworthy that these mission ranges require additional reserves which constitute a remarkable fraction of the total energy in accordance with current regulations.

Moreover, we described commuter air services in regard to their competing modes of transportation. As expected, ground transportation proved to be superior for short distances of up to 300 km. With increasing distances, obviously the fraction of mainline services offering the shortest travel times increased. Interestingly, we found that almost all commuter connections with a GC distance of more than 400 km would compete with existing mainline services. For further evaluations and comparisons of commuter and their requirements, it is of critical importance to define meaningful reference cases.

Concentrating on the comparison between commuter and mainline services, we saw that a large fraction of the realised TTB would result from shorter process times and shorter first/last mile transportation. Longer flight times counteracted and even overpowered this effect with increasing distances.

The identified airfields for commuter services showed on average shorter runway lengths with a significant share of airfields which would restrict the operation of today's conventional commuter and light regional aircraft. With air traffic moving closer to the centres of population, not only take-off field length and take-off performance would increase in importance. To ensure and facilitate the general acceptance of aircraft operating in populated areas, also a significant reduction of noise and local gas emissions would be necessary. It should be noted that the applied model assumed a concentration of the population (and the demand) in the centroid of the regions. For a detailed assessment of air traffic moving closer to densely populated areas, a geographically refined model would be needed. Furthermore, the model neglects the impact on air traffic management which an increase in the number of commuters operating from decentral airfields would have.

The cost model indicated significantly higher journey costs of commuter aircraft. While commuters could reduce the cost of first/last mile transportation, the higher cost of the flight segment outweighs these improvements. The comparably high fraction of fixed costs makes commuters on short distances economically less favourable. As other publications with a focus on the operating cost of electric aircraft have already been addressed, the potential cost reduction of electrified aircraft is unlikely to bridge the gap to the reference modes of transportation [14].

Current commuter utilisation patterns are very diverse with a majority of the fleet flying a low number of daily flights on short missions of about 60 min. However, we see that at least 10 % of commuter and light regional aircraft fleet shows a significantly higher utilisation with multiple flights and short TAT. Therefore, it would be challenging to derive reliable utilisation predictions on electrified aircraft. It is reasonable to assume the first generations of electrified commuters have higher vehicle purchasing prices/lease rates than conventional commuters. Thus, we can assume that operators would increase aircraft utilisations to reduce the cost of ownership per BH.

To make the benefit of significantly shorter travel times accessible for larger parts of the population, it will be a priority to reduce the operating costs of electrified commuters. Since the predicted costs of electrified commuters are still highly uncertain, we see the need for a detailed determination in further work.

5. CONCLUSION

Low-capacity air services offer short travel times over intermediate distances. Commuter air services have existed and played a major role in connecting secondary cities with each other and with international hubs. This work showed that commuter flights recoiled and that their traditional roles became indistinct from light regional aircraft's roles. This work aimed to identify and describe requirements which would facilitate the design of successful electrified aircraft enabling a revitalisation of decentralised commuter and regional flights. We identified required mission ranges, with the highest time improvements of circa 60 min for flights of 500-700 km. We showed that commuter flights would obviously compete with individual road transportation on shorter distances, but that for distances of more than 400 km commuter flights would almost exclusively compete with mainline services. Moreover, this work offered a cost comparison as a benchmark for projected electrified commuter aircraft. It aims to extend this cost model to electrified commuters.

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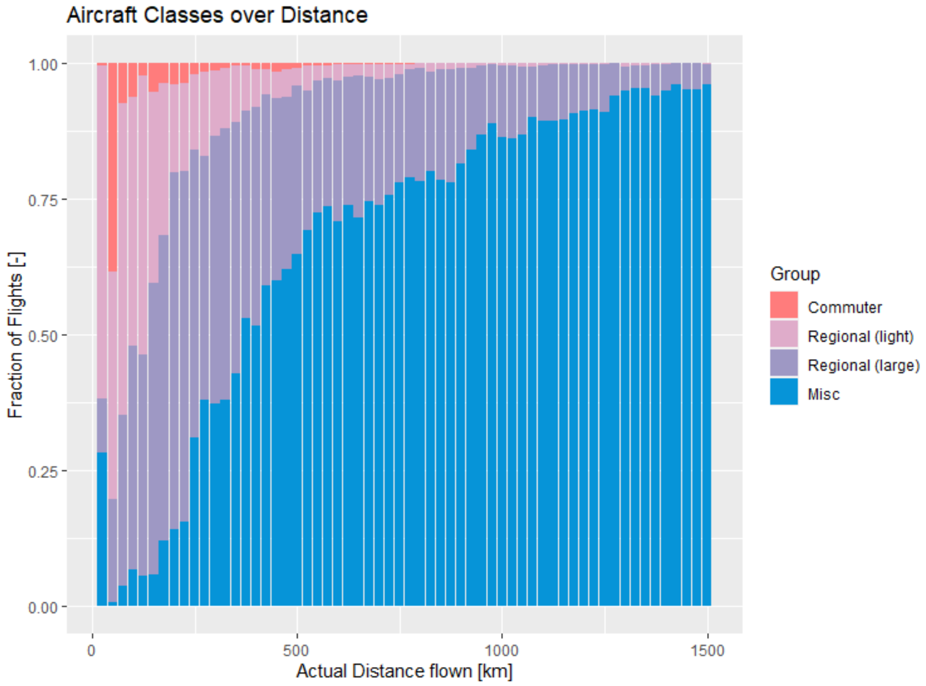
APPENDIX

A – AIRCRAFT CLASSES OVER FLIGHT DISTANCE



B – OVERVIEW MODES OF TRANSPORTATION

Commuter		Regional (Light)	
Manufacturer	**ICAO Aircraft Code**	**Manufacturer**	**ICAO Aircraft Code**
Beechcraft	B190	ATR	AT43, AT44, AT45, AT46
Beechcraft	B350	British Aerospace	ATP
Beechcraft	BE10, BE20, BE30, BE40	Canadair	CRJ1
Beechcraft	BE58	Canadair	CRJ2
Beechcraft	BE60	Dornier	D328
Beechcraft	BE9L	DeHavilland Canada	DH8A
Beechcraft	BE9T	DeHavilland Canada	DH8B
Britton-Norman	BN2P	Embraer	E120
Cessna	C208	Embraer	E135
Cessna	C402, C404, C414, C421, C425	Embraer	E145
Cessna	C441	Dornier-Fairchild	J328
Dornier-Fairchild	D228	British Aerospace	JS41
DeHavilland Canada	DHC6	Saab	SF34
Reims-Cessna	F406	Short Brothers	SH36
British Aerospace	JS31, JS32	Yak	YK40
Let	L410		
Mitsubishi	MU2		
Tecnam	P06T		
Partenavia	P68		
Piper	PA31, PA34		
Piper	PAY1, PAY2, PAY3		
Pilatus	PC12		
Fairchild Swearingen	SW2, SW3, SW4		
Britton-Norman	TRIS		
Partenavia	VTOR		

C - ASSUMPTIONS OF TTB MODEL

Mode of Transportation	**First/Last Mile**	**Main Segment**
Road	Direct routing	
HS Rail	Transport from centroid to nearest station/airfield/airport To station/airfield: linear distance with detour factor 1.3, average speed urban: 35 km/h. To airport: linear distance with detour factor 1.3, average speed urban/rural 45 km/h.	HS-station to HS-station, linear distance with detour factor 1.18, average speed 170 km/h, Processing time per Station 20 min.
Commuter		Airfield to airfield, linear distance with detour factor 1.03, cruising speed: 400 km/h, climb/descent speed: 0.5*400 km/h, climb/descent rate: 1000 ft/min, max. cruise altitude: FL200, processing time boarding: 28 min processing time deboarding: 20 min taxi-in/out: 6 min
Mainline		Based on historic ATM data processing time boarding: 70 min processing time deboarding: 35 min

D – ASSUMPTIONS OF COST MODEL

Mode of Transportation	**First/Last Mile**	**Main Segment**
Road	0.334 €/Pkm (at 1.41 Pax per vehicle)	
HS Rail	0.31 €/Pkm	0.0833 €/Pkm (56% load factor)
Commuter		base: Do 228 / Beechcraft 1900D fix: 433.55 €/mission per Pax: 22.77 €/Pax/mission per BH: 434.625 €/BH
Mainline		Base: A320-200 fix: 4367 €/mission per Pax: 35.69 €/Pax/mission per BH: 1338.25 €/BH