POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Studies of Time and Cost Benefits for a Hybrid-Electric Commuting Air Transportation System

Executive Summary - Laurea Magistrale in Aeronautical Engineering

Author: Antonio d'Aniello

Advisor: Prof. Lorenzo Trainelli

Co-Advisor: Dr. Francesco Salucci

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1 Introduction

Aviation is one of the fastest-growing sources of pollutants. Within the EU-funded research programmes aiming at reducing emissions, the Clean Sky 2 UNIFIER19 (Comm*uni*ty *F*r*i*endly Minilin*er*) project has the goals to develop a 19-passenger aircraft able to operate in Europe supporting Microfeeder (hub to/from smaller airports) and Miniliner (intercity) services, avoiding CO_2 and NO_x pollution altogether and drastically reducing acoustic emissions.

This sets the need to establish whether potential travellers will be willing to use such air service. While an assessment of travel time benefits with respect to ground vehicles has already been studied, little or no focus has been put yet on the predicted cost of the service for the final users. That is the motivation of this thesis, based on the customization and extension of methods developed at the Department of Aerospace Science and Engineering, Politecnico di Milano.

The current preliminary design, to be further investigated, envisages a tail pusher propeller, aimed at providing full cruise thrust, and Distributed Electric Propulsion on the wings, providing high lift during terminal maneuvers. The concept relies on fuel cells and batteries in order to produce a complete zero-emission flight.

2 The Miniliner Problem

Previously to this work, a hierarchical clustering technique brought to the selection of 109 secondary airports which could be activated on the Italian territory. This was done in order to reduce the number of used infrastructures, which would have led to high operating costs.

Potential demand estimation put its basis on the Commuting Origin-Destination Matrix $\bar{G}$, arising from the 2011 population census, and provided by the Italian National Institute of Statistics (ISTAT) [1]. To avoid unmanageable computational times, only cities with a minimum of 20 thousands inhabitants were selected. This down-scaled the matrix from nearly 8 thousand rows and columns to just 519 [2].

Criteria were established in order to assess travel time benefits with respect to car. Particularly, after having computed ground and air total times to travel, constraints shown in the following equations were applied.

$$T_{ground} - T_{air} \geq T_{ref} \qquad T_{air} < \frac{T_{ground}}{k} \tag{1}$$

Therefore, to be competitive, the new Miniliner was required to be faster than cars for a time $T_{ref} = 30$ minutes, and to have at least a 30% time gain (hence setting $k = 1.3$).

3 Commuters Data

To better estimate the potential number of travellers, though not expanding the OD matrix, a study was put in place in order to evaluate the number of occasional business passengers.

The concept is based on assuming that such passengers are reasonably equally spread in terms of space and time, namely on the Italian territory and during the year. Still, the model is considered conservative for two reasons: (1) as it will be described later, travels due to work are only a small percentage of the total, and (2) data does not include one-day trips.

This was possible thanks to two main ISTAT data sets [3, 4]. The first provides annual incoming occupancy data for Italian accommodation establishments, namely $PAX_{IT \to DM_j}$ for each $j-th$ Destination Municipality, while the second furnishes regional outgoing flows, namely $PAX_{OR_k \to IT}$ for each $k-th$ Origin Region.

The first step consisted in linking regional flows to each destination municipality, such that

$$PAX_{OR_k \to DM_j} = \frac{PAX_{OR_k \to IT}}{PAX_{IT \to IT}} \cdot PAX_{IT \to DM_j} \quad (2)$$

($PAX_{IT \to IT}$ being the total number of Italians travelling). This put the basis for the computation of single municipality to municipality fluxes, as shown in the following equation.

$$PAX_{OM_i \to DM_j} = \left\lfloor PAX_{OR_k \to DM_j} \cdot \frac{A_{OM_i}}{A_{OR_k}} \cdot \frac{\hat{M} \cdot \alpha_W}{30} \right\rfloor$$

A are the residents in municipalities DM_j or regions OR_k, $\hat{M} = 8.3\%$ the average percentage of monthly travellers, and $\alpha_W = 10.9\%$ the percentage of people travelling for work reasons [5].

Data was given for 7914 origin and 3288 destination municipalities: therefore, the resulting 7914×3288 matrix was reduced to a 519×519 one, named Z, in order to be comparable with $\bar{G}$. Hence, the matrix $G = \bar{G} + Z$ was generated.

The increase in travellers was 5065 units, which is very small-scale with respect to the number of commuters, namely more than 13.5 millions. However, it hugely increases the number of potential passengers given as output by SHARONA [6]. This has a very simple explanation. Commuters are in fact of general nature, and as such they may also refer to people moving from their city to an adjacent one, which would of course not result in a time gain when using Miniliner. With reference to Figure 1, more than 90% of commuters present in $\bar{G}$ do not satisfy the minimum activation threshold of T_{ref}, while business travellers are instead doing a proper medium-haul travel in the 95% of cases.

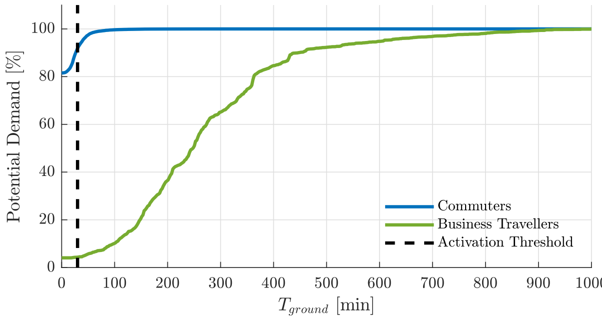

Figure 1: Travellers varying with T_{ground}.

The parametric analysis shown in Figure 2 highlights the potential demand increase for a runway length of 800 m and for different values of aircraft range and speed. The number of involved aerodromes, towns and population did not change with respect to [2]. The increment in potential demand instead grows with range and with runway length. The maximum increment is, for this value of runway, 47%, and saturation is reached at about 500 km of range.

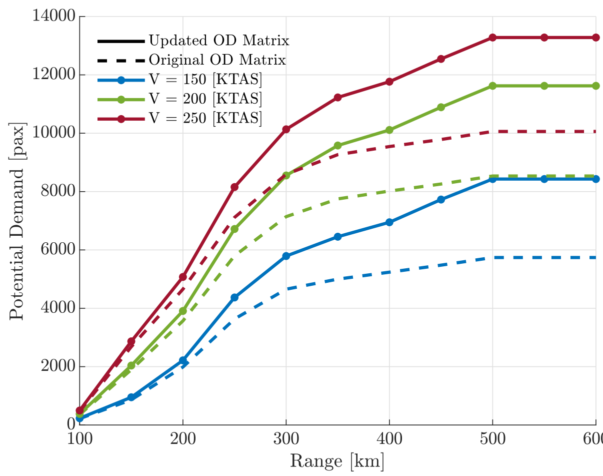

Figure 2: Potential Demand increase with G.

Finally, $G_E \supsetneq G$ matrix including six Isola d'Elba municipalities was set up, since none of the island cities are included in G (all are below the 20 thousand residends threshold) but they are of relevance for the Piaggio Aerospace case.

4 Models for Cost Analysis

Two cost models were implemented for the sake of evaluating ticket prices. The first one is based on TOC (Total Operating Costs), provided by Piaggio Aerospace, while the second is the original UNIFIER19 model described in D2.2 deliverable [7] and based on DOC (Direct Operating Costs). The main features will be highlighted.

4.1 Piaggio Aerospace Model

Given the number of round trip departures per year D_{year}, annual flight hours $FHPY$, passengers PAX_{year}, and flown kilometers $KMPY$ can be straightforwardly retrieved. T_{flight} [h] is the flight time, LF_{min} the load factor, and R [km] the range of the route under analysis.

$$FHPY = T_{flight} \cdot D_{year} \tag{3}$$

$$PAX_{year} = 19 \cdot D_{year} \cdot LF_{min} \tag{4}$$

$$KMPY = R \cdot D_{year} \tag{5}$$

Total annual variable costs per flight hour $VCPFH$ include maintenance, aerodrome charges, fuel cost, and supplies catering.

Maintenance. Maintenance costs are expressed as the combination of maintenance labor and maintenance parts. The first is evaluated through an ease of maintenance factor f_{ease} [MMH/FH] and an average wage per hour $C_{maintenanceLabor}$ [€/h], while the second accounts for expenses arisen from avionics, engine restoration (e.g. overhaul), lubricants, etc.

$$P_{maintenance}\left[\frac{€}{\mathrm{h}}\right] = C_{maintenanceLabor} \cdot f_{ease} + P_{maintenanceParts} \tag{6}$$

Fuel. Piaggio Aerospace considers conventional thermal engines: hence, fuel price is simply estimated as the consumption $F_{consumption}$ [L/h] times the cost of fuel C_{fuel} [€/L].

$$P_{fuel}\left[\frac{€}{\mathrm{h}}\right] = F_{consumption} \cdot C_{fuel} \tag{7}$$

Fees. Fees include charges due to takeoff, landing, ground handling, parking, and boarding.

$$P_{aerodrome}\left[\frac{€}{\mathrm{h}}\right] = P_{LND\&TO} + P_{boarding} + P_{handlingParking} \tag{8}$$

The annual total fixed costs per aircraft $FCPAC$ are considered as the sum of navigation and weather fees, insurance, sales, refurbishing, crew, crew training, hangar, aircraft modernization, airline management, and lease payment.

Lease Payment. Monthly lease payment accounts for depreciation and interests. f_{RV} is the residual value of the vehicle after the depreciation period DP, while f_{tax} the local sales tax. Money factor MF determines financing charges.

$$P_{lease}\,[€] = P_{aircraft} \cdot (1 + f_{tax}) \cdot \left[\frac{1 - f_{RV}}{12 \cdot DP} + (1 + f_{RV}) \cdot MF\right] \tag{9}$$

Weather and Navigation. Weather and navigation charges are evaluated according to Conklin & de Decker [8], in [$].

$$P_{weather}\,[\$] = \frac{700 \cdot FHPY}{450} \tag{10}$$

$$P_{navigation}\,[\$] = \frac{KMPY}{100} \cdot \sqrt{\frac{3.3}{50}} \cdot 66.02 \tag{11}$$

Insurance. Insurance yearly costs take into account a price proportional to the aircraft price and the SLL (Single Limit Liability).

$$P_{insurance}\,[€] = f_{insurance} \cdot P_{aircraft} + SLL \tag{12}$$

Sales and Refurbishing. Sales costs per passengers are expressed by C_{sales} [€], while refurbishing time per seat and refurbishing price are $H_{refurbish}$ [h] and $C_{refurbish}$ [€/h].

$$P_{sales}\,[€] = C_{sales} \cdot PAX_{year} \tag{13}$$

$$P_{refurbish}\,[€] = 19 \cdot H_{refurbish} \cdot C_{refurbish} \tag{14}$$

Crew. Crew costs consider a wage per pilot of C_{pilot} [€/h], while $C_{freelancePilot}$ [€/h] eventually envisages additional crew hiring on a need-to basis. N_{pilots} is the number of pilots per flight.

$$P_{crew}\,[€] = (C_{pilot} \cdot N_{pilots}) + C_{freelancePilot} \tag{15}$$

Crew Training. Crew training costs are composed by a fixed and a variable price, for the training of six pilots for five hours each. $P_{variable}$ [€/h] accounts for normal usual operating costs, such as fuel, maintenance, etc.

$$P_{training}\,[€] = 7500 + 6 \cdot 5 \cdot P_{variable} \tag{16}$$

The described variable and fixed costs give the total Annual Operating Costs (AOC).

$$AOC\ [€] = FHPY \cdot VCPFH + FCPAC \quad (17)$$

These, summed to the profit percentage α the airline has to achieve in a year, allow to estimate the ticket price as shown in the following.

$$P_{ticket}\ [€] = R \cdot \frac{(1+\alpha) \cdot AOC}{\underbrace{19 \cdot KMPY \cdot LF_{min}}_{\text{Revenue Passenger Kilometer}}} \quad (18)$$

Finally, a second version of the model can be setup in order to be applied to UNIFIER19, setting the relative parameters as specified in [9]. The main difference stands in the implementation of fuel price and maintenance costs, which are to be evaluated according to the Mininliner approach and as described in Section 4.2.

4.2 UNIFIER19 Model

UNIFIER19 cost model is based on a first evaluation of flight cycles per year F_{cycles} and relative block time T_{block} [h]. DOC components are fuel, crew, ownership, fees, and maintenance.

Fuel. Block energy used during a single flight for UNIFIER19 is $\chi_{battery} = 10\%$ of the total capacity B_{energy} [kWh]. The equivalent hydrogen consumption is instead evaluated starting from conventional fuel consumption F_{block} [kg], and then considering jet engine efficiency, fuel cell efficiency, and electric motor efficiency. γ is the ratio between jet fuel and hydrogen energy densities, while $C_{electric}$ [€/kWh] and C_{LH2} [€/kg] are the prices for electricity and liquid hydrogen.

$$E_{block}\ [\text{kWh}] = B_{energy} \cdot \chi_{battery} \quad (19)$$

$$H_{block}\ [\text{kg}] = F_{block} \cdot \gamma \cdot \left[\frac{\eta_{jet}}{\eta_{fuelCell} \cdot \eta_{motor}}\right] \quad (20)$$

$$DOC_{fuel}\ [€] = E_{block} \cdot C_{electric} + H_{block} \cdot C_{LH2} \quad (21)$$

Crew. According to CS23 regulations, no flight attendant is required for a vehicle of such category. Therefore, crew costs reduce to pilot wages. N_{crews} is the crew complement needed to ensure continuous operations, respecting maximum flight hours, vacations, training, etc.

$$DOC_{crew}\ [€] = N_{crews} \cdot (C_{pilot} \cdot N_{pilots}) \cdot T_{block} \quad (22)$$

Ownership. Ownership costs include depreciation, interest, and insurance. Now, interest rate IR is considered instead of the money factor.

$$DOC_{ownership}\ [€] = \left[IR \cdot \frac{1 - f_{RV}/(1+IR)^{DP}}{1 - 1/(1+IR)^{DP}} + f_{insurance}\right] \cdot \frac{P_{aircraft}}{F_{cycles}} \quad (23)$$

Fees. Charges are split in navigation, terminal, and aerodrome fees. The first two can be retrieved from Eurocontrol Guide to Charges [10], while the third is taken as a fixed price per flight (accounting for landing and ground handling).

$$DOC_{fees}\ [€] = K_N \cdot \left[\frac{MTOW}{50}\right]^{0.5} \cdot \frac{R}{100} + K_T \cdot \left[\frac{MTOW}{50}\right]^{0.7} + 236.85 \quad (24)$$

Maintenance. The tail engine is the only having a TBO (Time Between Overhaul) which is smaller than the aircraft life cycle. Distributed propulsion is instead used only during non-cruise phases of the flight, which stands for an average 7 minutes per block time. Maintenance parts will therefore account for motor, fuel cells, and battery overhaul, considering a restoration cost equal to 75% of the component price [7].

$$\begin{aligned} DOC_{maintenance}\ [€] &= f_{ease} \cdot C_{maintenanceLabor} \cdot T_{block} \\ &+ 0.75 \cdot \frac{C_{motor}}{TBO_{motor}} \cdot T_{block} \\ &+ 0.75 \cdot \frac{C_{battery}}{B_{cycles}} \\ &+ 0.75 \cdot \frac{C_{fuelCell}}{TBO_{fuelCell}} \cdot T_{block} \end{aligned}$$

Ticket price is finally computed as the sum of DOC divided by the aircraft capacity.

4.3 Implementation of Cost Models

Ground Prices. In order to compare ground and air prices, car costs between municipalities and between municipalities and aerodromes had to be evaluated with the use of viaMichelin API [11]. This was done for two values of fuel consumptions, namely for a utility car CAR1 and a compact car CAR2, and for a nominal fuel price of 1.6 €/L (September 2021 average [12]).

Such ground costs take into account fuel, tolls, ferries, and CCZ (Congestion Charge Zones). Car fuel prices can be then set to a desired value β [€/L] as shown in the following equation.

$$P_{car} = P_{toll} + P_{CCZ} + P_{ferry} + \frac{\beta}{1.6} \cdot P_{carFuel} \tag{25}$$

VoT. In transport economics, the VoT (Value of Time) constitutes the amount of money a traveller would be willing to pay in order to save time, or, equivalently, the amount they would accept as a compensation for the time loss.

Commuters in Italy are 66% composed by workers, while the remaining 33% are students. In accordance with [13, 14], relative average VoT are 27.5 and 12.5 €/h. Considering an inflation factor from 2016 (year of computation of the before mentioned VoTs) of $f_I = 2.4\%$, the value retrieved in the following equation can be used for evaluations in SHARONA.

$$VoT \left[\frac{€}{\text{h}}\right] = (0.66 \cdot 27.5 + 0.33 \cdot 12.5) \cdot f_I = 22.8 \tag{26}$$

Finally, once having retrieved overall ground and air prices (the latter including ticket price and prices for car travels to/from the origin/destination airports), the constraint can be implemented as shown in the following equation.

$$P_{air} \leq P_{ground} + (T_{ground} - T_{air}) \cdot VoT \tag{27}$$

Two implementation logics will be discussed: namely, AND or OR logic with respect to time.

5 Piaggio Aerospace Case Study

Piaggio Aerospace study case [15] is aimed at analyzing a network composed by two main hubs, Milano Bresso and Roma Urbe, which are connected to other nine smaller aerodromes. The case resembles a Microfeeder approach, even if potential demand does not follow its rules, but is instead evaluated through SHARONA. It is important to specify that the vehicle analyzed in this section is a turboprop, and hence has no reference to an hybrid-electric powertrain. The complete network is shown in Figure 3.

The Piaggio Aerospace model specifies a minimum door-to-door time gain of 2 hours (7200 seconds). Parametric analyses show however that to be able to activate all its 24 routes, the maximum T_{ref} should be reduced to about one hour and a half (precisely 5065 seconds).

When considering a two hours time gain in fact, routes Milan - Albenga, Albenga - Milan, and Rome - Ancona, are non feasible in terms of a time saving (road travel times are not symmetric, which is why the route Ancona - Rome is still declared feasible by the algorithm).

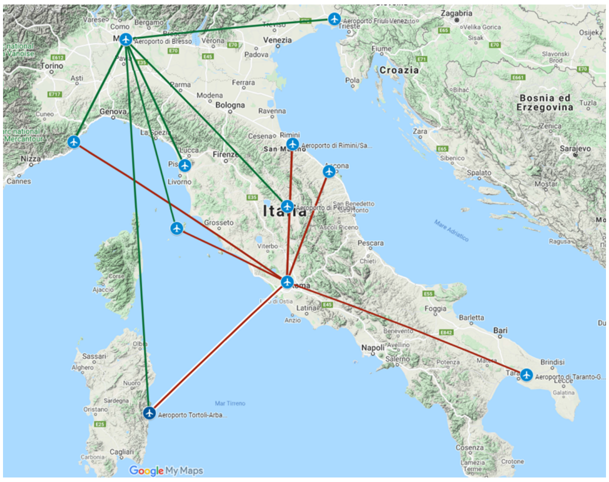

Figure 3: Piaggio Aerospace Network.

Concerning potential demand, it increases as more expanded matrix are used (namely $\bar{G}$, G, and G_E), as shown in Table 1, and is equal to 1527 in the case of $T_{ref} = 5065$ s and G_E.

Table 1: Potential Demand for two T_{ref}.

T_{ref} [s]	$\bar{G}$ [pax]	G [pax]	G_E [pax]
0	2392	3627	3668
7200	362	941	982

In terms of satisfying the minimum imposed load factor of 85%, of the 24 feasible routes activated when $T_{ref} = 5065$ s, five do not reach the minimum aircraft filling. However, when considering matrix G_H (which also adds leisure travellers with respect to G_E), non-activated routes drop down to three: Albenga - Milan, Milan - Albenga, and Elba - Rome.

Heretofore, all analyses have been executed without the introduction of the cost constraint. When applying the original Piaggio Aerospace cost model, with CAR2 fuel consumption and 1.6 €/L nominal car fuel price, the network does not change in terms of activated routes and routes satisfying the minimum load factor. However, a decrease in the overall potential demand is present, namely 23% with the AND logic.

5.1 SHARONA and Piaggio Results

Piaggio Aerospace declares not feasible in terms of a time saving the routes Milan - Albenga, Milan - Pisa, and Rome - Ancona (and ways back). Therefore, SHARONA brings to the activation of one extra route (actually two, considering return journeys), namely Milan - Pisa.

This happens because Piaggio Aerospace evaluates ground times between single municipalities. SHARONA involves instead some more complex evaluations, also considering neighbouring cities and respective potential time savings. Therefore, the time gain in the route Milan - Pisa of 1 hour and 40 minutes, raises up to a maximum value of 2 hours and 7 minutes, namely a 27% more, when applying SHARONA.

Concerning costs, the two independent approaches bring to the same results. Namely, all routes have a cost saving except for Milan - Albenga, which however has a difference in price with respect to car of less than 10 €.

6 Miniliner Results

Before analyzing the effect of cost models on potential demand, a study has been carried out in order to asses the effects of the two implementation logics. With reference to Figure 4, the OR logic brings to a maximum increase in potential demand which in no case is greater than 1%, and hence will be no further questioned.

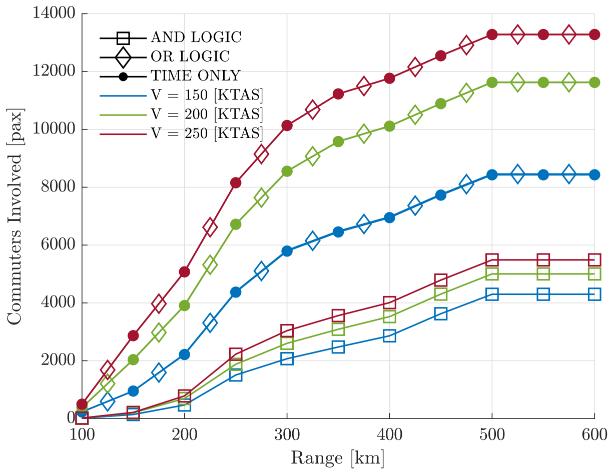

Figure 4: AND and OR Implementations Logics.

Concerning the AND logic, a visible reduction of potential commuters is shown. This reduction exhibits a little dependence on flight speed with respect to the TIME ONLY logic alone.

Moreover, the cost logic does not change the saturation range for any of the cruise speeds. Involved aerodromes also decrease in number, but their value goes back to the same as the TIME ONLY logic after a range of 250 kilometers.

Parametric analyses for ground fuel prices are shown in Figures 5 and 6, respectively when using the modified version of Piaggio Aerospace and UNIFIER19 cost models. The behaviour of potential demand appears in any case linear.

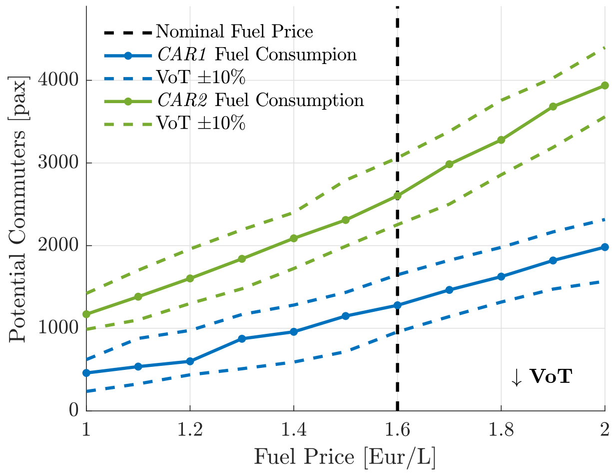

Figure 5: Ground Parametric for Piaggio Model.

According to the modified version of the Piaggio Aerospace model, potential demand slope increases if fuel consumption increases: this does not happen for UNIFIER19, for which only a translation along the y axis takes place.

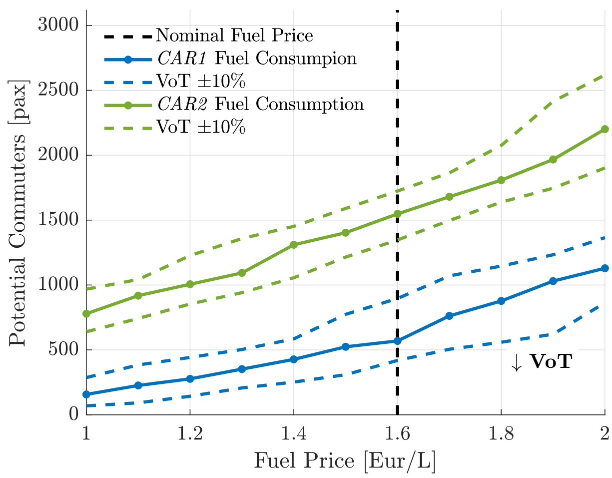

Figure 6: Ground Parametric for UNIFIER19.

Piaggio Aerospace model brings to higher demands with respect to UNIFIER19. This happens because of the higher ticket prices involved for UNIFIER19 cost method at low values of range, as shown in Figure 7. Perhaps, this could show the benefits of using a cost model which spreads costs on a whole year and on flight hours, rather than on single flights.

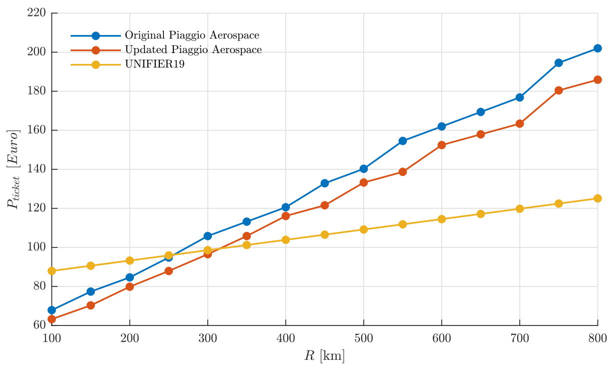

Figure 7: Comparison between Cost Models.

The reduction in potential demand is 70% and 82% for the two cost models, and when considering the nominal value for fuel price. Maximum number of activated aerodromes is instead 57% and 51% of all possible infrastructures.

Cost for liquid hydrogen has also been left vary in order to asses potential demand sensitivity. In this case, potential demand variations follow an higher-than-linear behaviour, as shown in Figures 8 and 9. Particularly, a fast drop starts when hydrogen price raises above the value of 2 €/kg. This behaviour is more clear-cut when looking at the UNIFIER19 cost model.

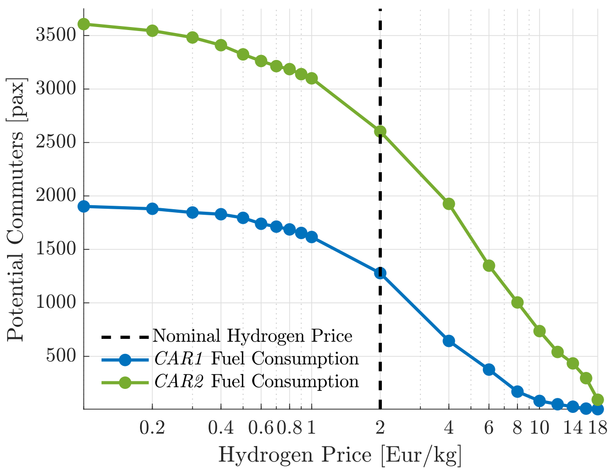

Figure 8: H_2 Parametric for Piaggio Model.

Involved aerodromes are heavily impacted by increases in hydrogen price. For the high fuel consumption case, the value keeps constant until a price of liquid hydrogen of about 10 €/kg, then starts dropping significantly. This is of course

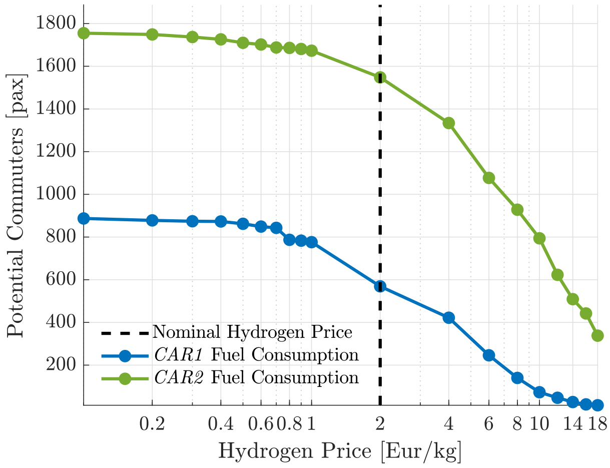

Figure 9: H_2 Parametric for UNIFIER19.

due to the reduction in potential demand. However, the maximum value does not vary depending on the used cost model, and is about 64% of all possible infrastructures.

Finally, SHARONA busiest routes are shown in Figure 10: minimum runway is set to 800 meters, velocity is 200 knots, and the UNIFIER19 cost model is applied with the AND logic. Nominal values are used for fuel and hydrogen prices.

Figure 10: SHARONA Busiest Routes.

Rome has the greatest number of incoming travellers, while Firenze has the greatest outgoing flow. Only the first 20 busiest routes are shown. Rendering of the image was possible with the use of Flowmap.blue [16].

7 Conclusion

Potential demand was augmented by considering occasional business travellers apart from usual commuting flows. This led to a demand increase of about 50% and more. The process did not raise the number of activated aerodromes, thus not leading to higher operating costs.

Piaggio Aerospace and UNIFIER19 cost models were then implemented. The first lays on the evaluation of total operating costs spread on a whole year, while the second follows the path of establishing direct operating costs per flight. The first approach led to lower ticket prices for very short-haul flights, namely until a route range of about 300 kilometers.

Piaggio Aerospace network was examined, composed by two main hubs and nine minor aerodromes. Conclusions arising from SHARONA have shown to be comparable with results coming from Piaggio Aerospace, thus confirming the right functioning of the cost implementation. Moreover, SHARONA brought to an increment in the number of activated routes, showing the benefits of demand gathering among municipalities, with respect to methods based on single origin to destination fluxes.

Finally, when cost models were applied to SHARONA, considering a cost OR a time saving did not lead to a significant increase in potential demand (in no case the increment overcame the value of 1%). On the contrary, for a cost AND a time saving, potential demand reduced.

Parametric studies showed that variations in potential passengers are approximately linear with respect to fuel price for ground vehicles, and that the introduction of the cost models almost halved the number of activated aerodromes.

Furthermore, potential demand resulted also very sensitive to variations in liquid hydrogen price, this time in a higher-than-linear way: significant reductions appeared after a price of 2 €/kg. Activated aerodromes now reduced to 64% of all possible infrastructures.

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