Article

Analytical Models for CO_2 Emissions and Travel Time for Short-to-Medium-Haul Flights Considering Available Seats

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Abstract: Recently, there has been much interest in measuring the environmental impact of short-to-medium-haul flights. Emissions of CO_2 are usually measured to consider the environmental footprint, and CO_2 calculators are available using different types of approximations. We propose analytical models calculating gate-to-gate CO_2 emissions and travel time based on the flight distance and on the number of available seats. The accuracy of the numerical results were in line with other CO_2 calculators, and when applying an analytical fitting, the error of interpolation was low. The models presented the advantage with respect to other calculators of being sensitive to the number of available seats, a parameter generally not explicitly considered. Its applicability was shown in two practical examples where emissions and travel time per kilometre were calculated for several European routes in a simple and efficient manner. The model enabled the identification of routes where rail would be a viable alternative both from the emissions and total travel time perspectives.

Keywords: emissions calculation; analytical model; short-haul flights; modal shift; travel time

1. Introduction

Until 2019 and before the COVID-19 crisis, air traffic had been constantly increasing, punctuated only by exceptional events (e.g., 11 September 2001, the financial crisis, 2008–2010 [1]). Between 2013 and 2019, flights in the European Civil Aviation Conference (ECAC) area grew by 15.4%, corresponding to 1.5 million additional flights [2]. This increase in the number of flights negatively impacts the environmental footprint of aviation resulting from Greenhouse Gas (GHG) emissions (e.g., CO_2, NO_x) and contrails. While other industries, including within the transport sector, might be able to substantially decarbonise, aviation faces serious challenges with a current focus on technological solutions [3,4], sustainable aviation fuels [5] and carbon compensation mechanisms [6,7]. Beside these approaches, reduction of traffic, e.g., by shifting demand towards more sustainable transport (such as rail), could also be pursued by policy makers [8].

In order to properly compare the impact of different means of transport and travel alternatives, indicators considering both emissions and the number of passengers should be considered. However, currently available models to assess the emissions of aviation (as detailed in Section 2.2) tend to focus on simple linear relationships between distance and/or time and emissions or to be based on detailed fuel consumption models, which require detailed parameters (e.g., fully defined trajectories) on a flight-by-flight basis. This limits the possibility of performing analysis at the network level, where the tradeoff between passengers transported (linked with aircraft type and frequency) and distance flown is required.

The operational network of an airline is a strategic asset that is carefully designed considering destinations according to margins and demand robustness. Therefore, the choice between an aircraft's capacity (measured in number of seats) and frequency (measured in

number of expeditions) is a fine balance, as indicated in [9,10]. Both of these factors have an impact on the balance sheets and on profit and loss accounting and could drag down the competitiveness and flexibility of airlines. For example, trends in the industry show that airlines have incentives for long-haul flights with smaller aircraft if these are more accessible in terms of capital cost and more efficient in terms of fuel and crew requirements [11,12]. A model that relates emissions, distance and seats transported is critical for a deeper understanding of these tradeoffs and to provide airlines with a tool to support them in their network design, particularly for short- and medium-haul segments. On these routes, competition and cooperation with other means of transport (e.g., rail, road), where time and emissions should be considered, could be present. These types of operations are the focus of this paper.

When contrasting the environmental impact of aviation with other means of transport, it is paramount to consider the number of passengers transported. In this paper, we focus on the environmental impact of the served demand and therefore on the indicator of grams of CO_2 (gCO_2) per Available-Seat-Kilometres (ASK) (gCO_2/ASK). Other standard Key Performance Indicator (KPI)s generally used when comparing the environmental impact of different means of transport include: fuel per Passenger (PAX) (fuel/PAX) per 100 km (to reflect the actual passengers transported (load factor)), fuel/ASK and gCO_2 per Passenger-Kilometres (pkm) (gCO_2/pkm) (including a measure of the load factor). Note that it is possible to relate fuel and CO_2 with a linear proportion (CO_2 (g) = $3.157\times$ fuel burnt (g), [13]) and that seats transported and the number of passengers differ in the consideration of the load factors. In this article, we used kilometres as the units of distance, instead of nautical miles, as generally used in air transportation, as kilometres are more broadly used for comparison across means of transport. Finally, for the comparison of transport alternatives, not only emissions, but travelling time should also be considered; for this reason, we also estimated travel time for aviation.

In this paper, we present analytical models calculating gate-to-gate CO_2 emissions and travel time depending not only on the stage distance, but also on the number of available seats provided by aircraft for short- and mid-haul flights. The objective was to offer a model that is independent of the specific aircraft type, with the goal of providing a tool estimating emissions and travel time with a low error while considering the demand supplied. Such a model could be useful for policy makers when assessing the tradeoffs between transport modes and the evaluation of transport networks from an environmental and supply perspective.

Section 2 expands the background on the environmental impact of aviation and presents different approaches used for the computation of aviation emissions. The methodology and development of the model for the estimation of emissions and trip time for short and medium flights considering the number of seats offered are presented in Section 3. Section 4 applies the model to two case studies: an evaluation of emissions at the network level and a comparison of aviation and high-speed rail on selected routes. The paper closes with Section 5, which draws the main conclusions and presents the future work.

2. Background

2.1. Environmental Impact of Aviation and Mitigation Strategies

Based on the data from European Environment Agency (EEA), aviation (domestic and international) accounted for 3.8% of total EU28 GHG emissions (4.7% of CO_2 emissions) in 2018 [14]. Though this proportion could be considered to be comparatively small, aviation is one of the fastest-growing sources of GHG emissions in Europe. Furthermore, aviation currently contributes to a small, but significant radiative forcing of global climate change, estimated to be between 3.5% and 4.9% of total anthropogenic radiative forcing [15]. Note that this radiative forcing is not only generated by CO_2 emissions, but also by other factors such as NO_x or cloud effects. Non-CO_2 emissions account for approximately three-times the rate of that associated with aviation CO_2 emissions alone [16]. Whereas the total GHG emissions in Europe decreased by 22.5% between 1990 and 2018, the total emissions from

aviation increased by 118% compared to the 1990 levels, reaching 144 million tonnes in 2018 in the EU28 area (+78 million tonnes with respect to 1990). As a result, the percentage of aviation emissions with respect to total GHG grew from 1.4% in 1990 to 3.8% in 2018.

The relative share of aviation in total GHG emissions is expected to continue increasing in the next few years, as aviation activity based on fossil fuels continues to grow, after recovering from the COVID-19 crisis, while other industrial sectors (such as road transport) increasingly decarbonise over time. To avoid this increase, different strategies are considered: technical improvements on systems and operations, emissions compensation and modal substitution.

2.1.1. Technological Improvements

The European Single European Sky ATM Research (SESAR) programme aimed at modernising the air traffic management system sets a high-level goal of reducing the effects of flights on the environment up to 10% with respect to the 2012 values by 2035. These improvements are expected thanks to the introduction of new operational and technical solutions [3]. The Clean Sky 2 programme supports technological research aimed at reducing the environmental impact of aviation with the goal of a reduction of up to 30% of emissions by 2035 with respect to the best-available performance from 2014 [4].

Electric aircraft may be seen as a possible way to support decarbonising aviation on short-haul flights, but it will require more technological development to achieve enough capacity, measured in terms of the number of seats and range autonomy [17]. The earliest expected prototypes consider few seats and short distances, while larger electrical aircraft are not expected until 2035 at least [17]. These new technologies will require not only progress on the technological maturity path as complex as electrical or hybrid technology, but also the concurrence of technological developments in the energy sector, as well as the development of infrastructure and logistical systems beyond the aviation sector [18].

Sustainable Aviation Fuels (SAF) can help to mitigate the environmental impact of medium-to-long-haul flights, which are more difficult to substitute with electric or hybrid aircraft. Nevertheless, the production processes of these fuels are energy intensive, and increasing the share of SAF will only help with decarbonising aviation if production is fully based on renewable sources [5]. Some studies have shown that though SAF would relevantly decrease CO_2 emissions, it still does not reach a comparable level of emissions obtained with alternative transport modes such as High-Speed Rail (HSR) for short and medium routes [19].

2.1.2. Emissions' Compensation

Offsetting emissions is also considered by the industry as an approach to reducing the environmental impact of aviation. CO_2 emissions from aviation have been included in the European Union Emission Trading System (EU-ETS) since 2012. Under the EU-ETS, airlines are required to monitor, report and verify their emissions and to surrender allowances against those emissions [6]. ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) requires airlines to offset their emissions from routes in the scheme by purchasing emissions units generated by projects that reduce emissions in other sectors [7]. These schemes aim at mitigating the impact of emissions by supporting the reduction in other sectors and by inciting airlines to reduce their emissions. However, this offsetting approach might not be effective to mitigate the impact of the emissions [20,21]; the air transport sector's share of emissions continues to proportionally increase with respect to other sectors, which can decarbonise easier.

2.1.3. Modal Substitution

Finally, demand can be mitigated leading to a reduction in flights and hence the impact of aviation. Market-based measures, including climate change levy schemes, are other possible instruments to address the climate impact of aviation and are part of the comprehensive approach needed to reduce aviation's CO_2 emissions. They can influence

actors' behaviour, but there is no clear agreement on what the most convenient type of tax is, what its value should be and what the expected impacts would be [22]. Some evidence indicates that carbon pricing on its own is not a strong enough factor to affect demand at current emissions price levels [23].

For short (and some medium) flights, the possibility of substitution for more environmentally friendly transport systems could also be considered, even if this shift might require some policy changes in order to be effective. In this context, and following the advice of a French citizens' climate convention, which originally suggested forbidding flights with equivalent rail links of less than 4 h, the French national assembly voted in April 2021 to ban domestic flights on routes that could be travelled via train in under 2 h 30 min, excluding connecting flights [8,24]. Previous research indicated that this approach can lead to significant emissions reductions [25,26] even if the infrastructure needs to be deployed [27].

When considering these modal shifts, not only emissions, but time and passenger characteristics should be considered. It has been reported that on high-speed train lines of less than 2 h 30 min, between Paris and other cities, the train captures almost all the market, eliminating the flight competitor [28]. This is due to the fact that the total travel time is usually shorter with train than with flight, making business customers choose this option. However, once the rail link increases to 3 h, business customers split at 50% between rail and flight. This huge shift between two- and three-hour rail links is due to the fact that business customers consider the round trip time. Once the rail link goes above 3 h 30 min, 80% of business customers switch to air transport. Though business customers only represent 20% of the demand, they account for more than half of the benefit margin. On top of the time consideration, above 700 km, the production cost of seats/kilometre by flight becomes less than that of rail [28]. Thus, only very short links could shift from air to rail if economic factors are solely considered.

2.2. Computation of Aviation Emissions

The first step to calculate CO_2 emissions is always to estimate the fuel burnt, as there is a linear proportion between fuel and CO_2 emissions (CO_2 (g) = $3.157\times$ fuel burnt (g), [13]). Several tools are available for calculating CO_2 emissions for a flight: calculators from international organisations (e.g., EUROCONTROL's Advanced Emission Model (AEM), ICAO's carbon emissions calculator or MyClimate.org's calculator (a Swiss-based nonprofit organisation focused on a CO_2 offsetting project and recognised by the United Nations Framework Convention on Climate Change (UNFCCC)), models developed and used in academic research and emissions calculators directly provided by airlines. Each of these approaches makes some assumptions and presents different capabilities and limitations.

EUROCONTROL's AEM uses EUROCONTROL's Base of Aircraft Data (BADA) for estimating fuel burnt and emissions for more than 200 types of aircraft [29,30]. ICAO also provides a carbon emissions calculator [31], where fuel consumption is estimated for each airline, on each sector of a scheduled flight, based on information reported by airlines [32]. The ICAO calculator, as many other carbon calculators, uses only a few generic types of aircraft instead of the specific aircraft that is operating the actual flight. This can lead to difficulties in assessing the actual impact of a given flight, as the number of passengers potentially transported is not considered. The flight carbon footprint calculator from MyClimate.org provides a model similar to ICAO, but instead of being based on a (distance-dependent) database, fuel consumption of any flight distance is approximated with a second-order polynomial fit for short-haul and long-haul flights, whereas fuel consumption for distances between 1500 km and 2500 km is linearly interpolated [33,34]. Their function uses a constant average seat number. Further work on the potential mitigation and cost of emissions in air transport network was carried out [35], and a specific integrated model, Aviation Integrated Model (AIM), was developed [36] by University College London (UCL), integrating different modules to estimate several aspects, such as emissions, noise, competition, costs, etc. In particular, the CO_2 emissions

model considers different aircraft size classes, and it integrates a calculator of emissions for each flight phase based on the Piano-X model [37] (this model is integrated in a software that is conceptually quite similar to BADA), but it only proposes an analytical model for the cruise phase based on distance and payload and an average value for the other phases.

Previous academic research considering the environmental impact of aviation tended to use simpler approximations for fuel burnt and hence for emissions. For example, a linear relationship is considered between fuel and distance, as well as with aircraft weight (as a proxy for seating capacity) in [38]. They aimed to calculate the total flight cost and did not need a very precise model for fuel consumption. In [39], fuel flow was modelled for a flight using BADA, integrating each of its composing phases starting from the departure gate and ending at the arrival gate. Then, a linear approximation for fuel flow as a function of altitude was considered, producing a model that can provide lower bound results for flight planning, but not considering the number of passengers.

The characteristics of the aircraft used for a particular passenger itinerary has a significant role in the total emissions generated. In [26], fuel data, leading to CO_2 emissions, were extracted for 16 city pairs in Finland from the European Monitoring and Evaluation Programme (EMEP)/EEA Air Pollutant Emissions Inventory Guidebook [30], based on the aircraft type and Great Circle Distance (GCD) plus a lengthening factor, in order to compare the emissions and travel time of short-haul flights with those obtained for existing non-high-speed trains. A comparison of the carbon emissions of selected flights in several geographical markets showed that the specific flight used by passengers for a given itinerary can produce significant differences in the environmental performance of the passenger trip [40]. Fuel burn in kilograms per seat per nautical mile for aircraft using the EMEP/EEA aircraft inventory database was calibrated in [41]. The results showed the geographical heterogeneity of fuel burn rates among a variety of routes, while controlling for seat configuration and stage distance. The paper found that stage lengths centred on 1500–2000 Nautical Miles (NM) have the lowest fuel burn rates under the current technology, fleet composition and seat configuration. Even the same aircraft type operated on the same characteristics (e.g., route, load factors) might produce different emissions as a function of its equipment, and in particular the actual aircraft engine installed, as shown in [42].

This variability of CO_2 emissions as a function of the individual flight characteristics is illustrated in Figure 1, where the emissions per Passenger-Kilometres (pkm) as a function of distance were calculated using CO_2-calculators provided by different airlines [43–45]. As presented, for the same route (distance), the CO_2 emissions estimated can double depending on the calculator and/or on the aircraft model. While the AirFrance and Lufthansa CO_2 calculators use average values of emissions, Finnair offers a much more precise calculator, based on the actual cargo, passenger and fuel consumption data for Finnair's air transportation in the previous financial year. The fuel consumed is calculated for each flight in relation to the weight of the cargo and passengers [44]. The calculator considers the specific aircraft type flown by Finnair on the route. For example, on a Helsinki to Amsterdam flight, CO_2 emissions could vary from 89 g/pkm with an Airbus A320-214 to 185 g/pkm with an Embraer E190.

Taking into account the number of PAX, or alternatively the number of available seats, is therefore of great importance when modelling the CO_2 emissions of flights. This paper provides an analytical model for emissions and flying time for short and medium routes while considering the transport supply provided (number of seats).
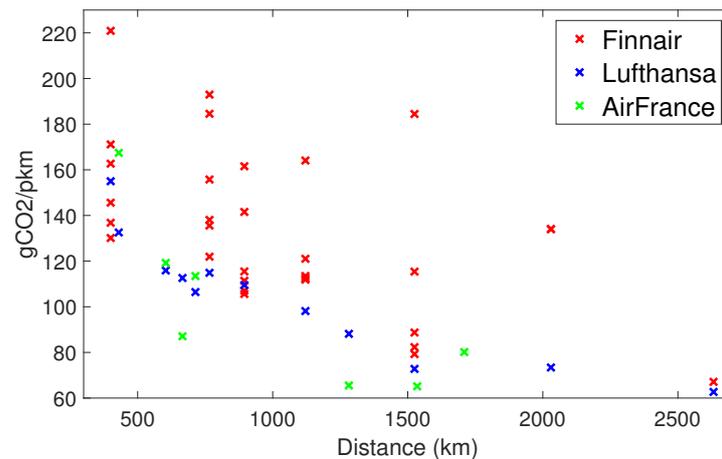
Figure 1. gCO$_2$ emissions per passenger vs. distance for different airlines calculators (gCO$_2$ computed based on [43–45])

3. Methodology and Model Development

This section presents the methodology used to develop analytical models of gate-to-gate CO$_2$ emissions per Available-Seat-Kilometres (ASK) and time/kilometre versus distance and available seats transported for short-to-medium-haul flights.

Figure 2 presents the approach followed to develop such models. The emissions of a flight depend on the distance covered, the aircraft type, the Flight Level (FL) used and other operational parameters, such as aircraft weight and vertical and speed profile. In order to develop generic models, which depend only on the Great Circle Distance (GCD) between the origin and destination and the number of seats offered on that route, we relied on fuel and time computations from EUROCONTROL's IMPACT tool.
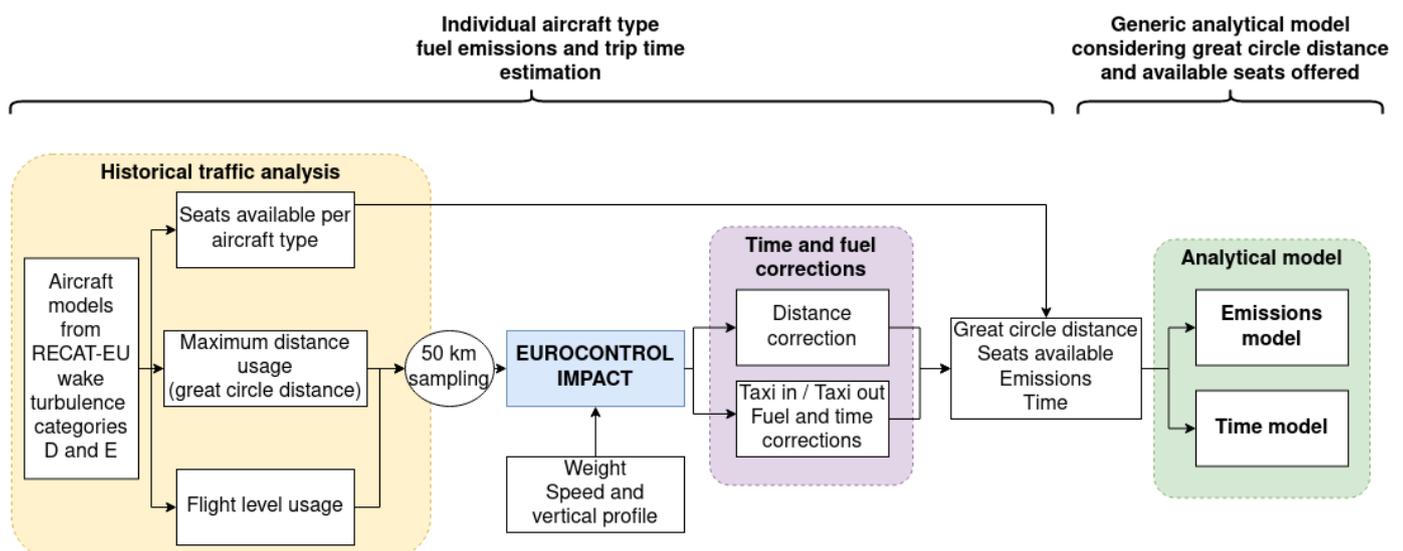

Figure 2. Methodology for developing emissions and time models

IMPACT is able to estimate the fuel (and emissions) for a given specific flight and is able to use some nominal parameters as identified by EUROCONTROL's aircraft performance database and models BADA. In order to identify the different values of travelling time and emissions for a given distance and seat capacity, we performed an analysis of historic flight operations. This analysis would enable us to select realistic operational parameters (e.g., range and FL usage) per aircraft type, so that the domain of the model remains valid.

The steps followed to generate the generic analytical gate-to-gate emissions and time models can be summarised as:

- Estimation of emissions and travel time for individual aircraft types:

    - First, a historical analysis of which aircraft types are used on different routes was performed so that their operational range (maximum distance usage) could be established;
    - Then, an analysis of which flight levels were selected as a function of the distance to be covered was performed;
    - An analysis was also carried out to identify the seats available per aircraft type;
    - EUROCONTROL's IMPACT model was used to estimate emissions per aircraft type every 50km in their domain of use considering the FL previously identified. In this case, nominal weights, speed and vertical profiles were used;
    - Time and fuel corrections were applied afterwards to account for inefficiencies in the system, e.g., distance flown between the origin and destination longer than GCD, and ground operations (taxi-in and taxi-out) to obtain the estimate of gate-to-gate time and emissions per individual flight;

- The definition of generic analytical models depending on GCD between the origin and destination and on the number of available seats provided, computed as the fittings of the individual flights' performances previously computed.

Note that the actual emissions (and time) for a specific flight would depend on many operational parameters such as FL, speed (or Cost Index (CI)), weight (including payload) [46], aircraft configuration (e.g., actual engine model [42]) or weather (e.g., wind aloft) [47]. In this work, we aimed to produce a model able to estimate average expected emissions and time for flights, so that it can be used for strategic decision-making and analyses. Therefore, we aimed to consider "nominal" operational parameters. A full sensitivity analysis on the impact of different operational parameters was out of scope of the presented work and should be conducted as future research.

3.1. Historical Traffic Analysis

Since the focus of this study was on short-to-medium-haul flights, we focused on commercial aircraft used in these types of operations. Therefore, only medium-sized categories were considered for this study. Namely, aircraft types of Categories D (upper medium) and E (lower medium), corresponding to the RECAT-EU wake turbulence categories [48], were used for the model implementation. Table 1 shows the specific models of aircraft considered in this study.

In order to estimate the time and emissions, first, the different distances between possible origins and destinations in GCD were sampled. For each of these distances, a microscopic emissions model was used to estimate these performance parameters. Therefore, the first consideration was to identify for each aircraft type the domain of usage. Figure 3 presents the 10th, 50th and 90th percentile of the distance between the origin and destination (measured as the GCD) for the different individual aircraft types considered in CAT D and CAT E. As observed, the 90th percentile of distance varied per individual aircraft type, being always lower than 2800 km, and only for a couple of models was it above 2500 km. Given that 2500 km is also commonly considered as a limit for medium-haul flights [34], this was the maximum distance for the analytical model, and the 90th percentile of distance would provide for each aircraft type the maximum GCD to be considered. As for the minimum distance, it was chosen as 200 km, both for the model and for all aircraft types, based on Figure 3.

Table 1. List of aircraft types considered per category.

RECAT-EU Category	Aircraft Types
CAT E	CRJX, E195, E190, B734, B735, B712
CAT D	A321, A320, A319, A318, B738, B737, B736
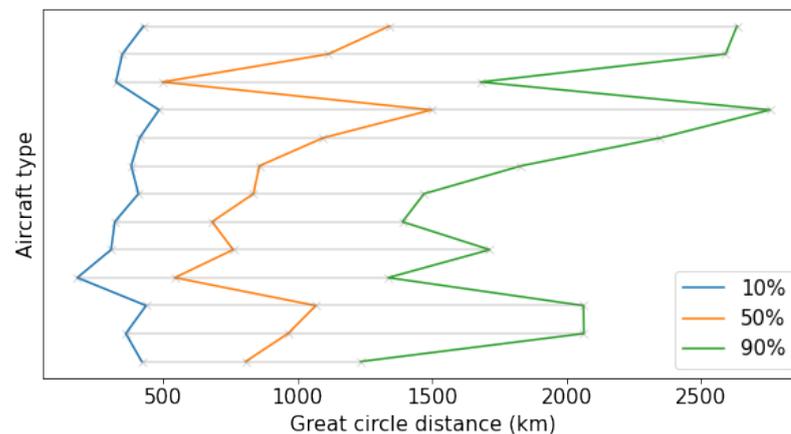
Figure 3. The 10th, 50th and 90th percentile of the great circle distance per aircraft type in CAT D and CAT E for AIRAC 1709.

The performance of the aircraft will vary as a function of some operational parameters and crucially the Flight Level [46]. As shown in Figure 4, for the same aircraft type and distance, different FL could be operated. To provide a suitable FL, the mean maximum operated FL every 400 km was computed considering the flight levels used by all the individual flights. It is worth observing how even if the historical selected FL per flight might differ for the same distance to be covered, when the mean was estimated, the flight level tended to present few variations and be rather constant after covering some short distances (lower than 1000 km), for which an optimal flight level cannot be reached. This emphasises the underperformance on very short flights as optimal flight levels cannot be reached.

Finally, to consider the number of passengers who can be transported, the average available seats for each aircraft type in Table 1 were extracted from [49]. The models considered here ranged from 72 to 190 available seats, which corresponds to the number of seats for which the model proposed in Section 3.5.2 is valid.

The outcome of this historical traffic analysis was the number of available seats for each aircraft type, and every 50 km between the minimum and maximum GCD, the maximum *nominal* FL was computed as the mean of the maximum FLs for that particular distance.

3.2. IMPACT Fuel and Time Computations

Once we had generated a sampling on the distance and flight levels for each aircraft type, the web-based modelling platform IMPACT from EUROCONTROL was used to estimate fuel burn and emissions. Based on an extensive reference data warehouse, IMPACT includes a common input data processor, which calculates detailed 4D trajectories, for user-defined aircraft operations, along with engine thrust and fuel flow information [50]. We considered a nominal speed, vertical profile and aircraft weight as provided by IMPACT using EUROCONTROL's BADA performance model.

For all flights (FL and distance dependent) considered, IMPACT provides, among other parameters, the flight time and fuel consumption estimated using BADA for all flight phases between take-off and landing. IMPACT also has a specific module of the calculation of emissions such as CO_2, NO_x or Particulate Matter (PM). These were not used in this

paper, but they could be of interest for environmental studies. Figure 5 shows, in light blue, the results obtained with IMPACT for emissions per ASK for all aircraft in Category D. Note how different aircraft types have different domains, i.e., different maximum distances.
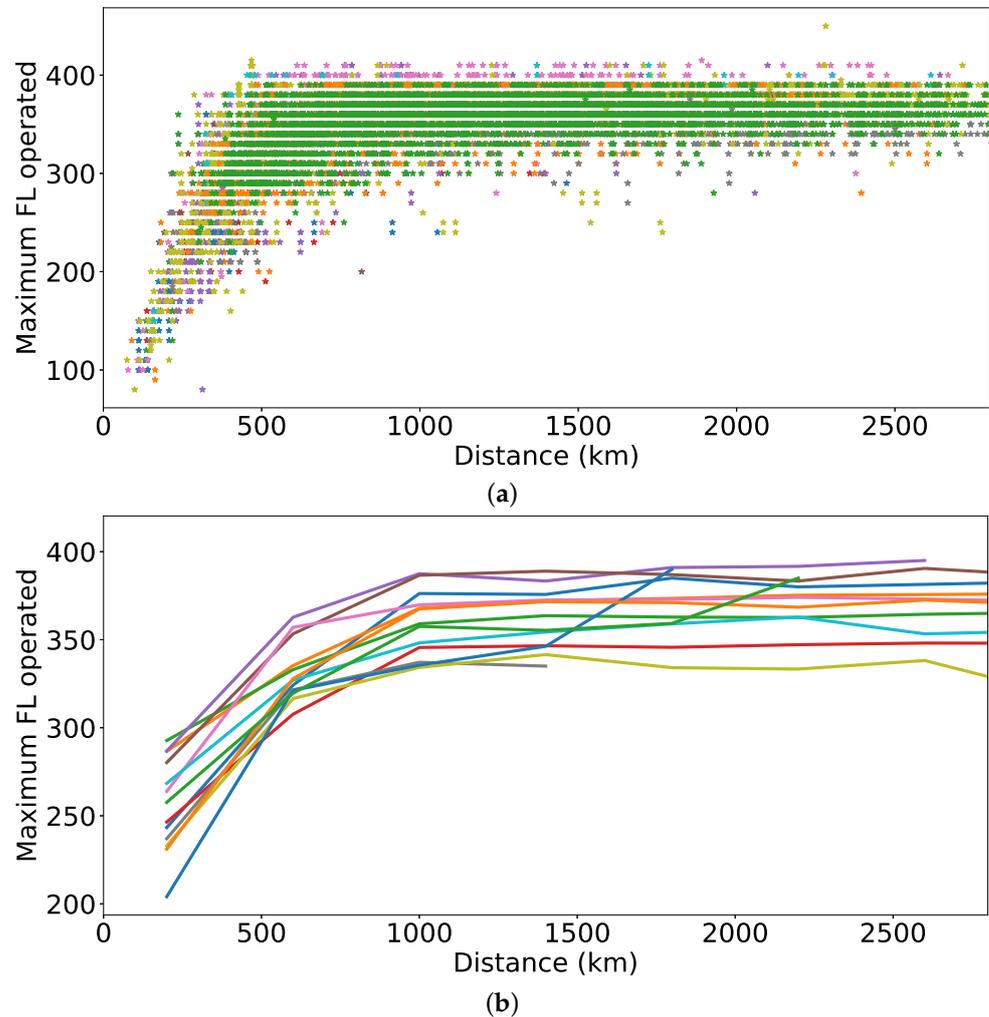

(a)

(b)

Figure 4. Flight levels operated for different aircraft types in Categories D and E. (**a**) Flight levels used per individual flight, as in the historical data (one day of operations). (**b**) Mean flight level grouped every 400 km.

3.3. Correction Factors

IMPACT estimated the emissions and flying times from take-off to landing considering GCD between airports. Therefore, for each performance computed, two correcting factors were applied.

3.3.1. Distance Correction

IMPACT considers the trajectory following the GCD. A correction factor is needed to include the distance flown in excess of the GCD due, for example, to air traffic procedures, airspace route availability, tactical traffic conflicts or weather-driven deviations. Following the reference from the ICAO methodology [32], 50 km were added to flights less than 500 km and 100 km to those above 500 km. Trajectory distance was consequently corrected to take this into account.

3.3.2. Fuel and Time Taxi Corrections

Taxi time and consequent fuel consumption should also be considered. This allowed us to create a model that considers the travel time gate-to-gate, but most importantly, it accounts for emissions on-ground, which might be relatively large for short flights.

The ICAO Engine Exhaust Emissions Databank usually considers that engines are in idle mode for 26 min while taxiing before take-off and after landing (19 min and 7 min, respectively). However, for many airports in Europe, the time spent with the engine thrust set to idle can differ. To improve the accuracy of the model, we therefore replaced the default ICAO taxi-in and taxi-out times with actual average annual airport taxi-in and taxi-out times. Following the mean values from EUROCONTROL during the winter in 2019–2020 [51] for medium aircraft, a mean value of 13.6 min was considered for taxi-out and 6 min for taxi-in. We then considered an average value of the fuel burn index of 0.12 kg/s of fuel per engine (considering twin-engine aircraft, note that some airlines use single-engine taxi operations, which could potentially reduce this fuel consumption), following the data from [52]. Overall taxi operations represent an average extra time of 19.6 min and 282.24 kg of fuel to the take-off to landing data obtained from IMPACT.

Once the total fuel burnt had been computed, it was converted into CO_2 emissions, using the fact that 1 kg of aviation fuel burnt produces 3.157 kg of CO_2 [13].

Figure 5 illustrates the effect of applying the aforementioned corrections, to include the distance flown in excess of the GCD and fuel consumed during taxiing operations. For the sake of clarity, only Category D aircraft are represented in this figure; Category E aircraft showed a very similar tendency. It can be seen that, as expected, the correction factors had a highly relevant effect on very-short-distance flights: the fuel consumed during taxiing and trajectory inefficiencies during approach were proportionally more important: for example, for Category D aircraft at 500 km, the increment of emissions due to the correction factors was 24%, while at 2000 km, it was only 9%.
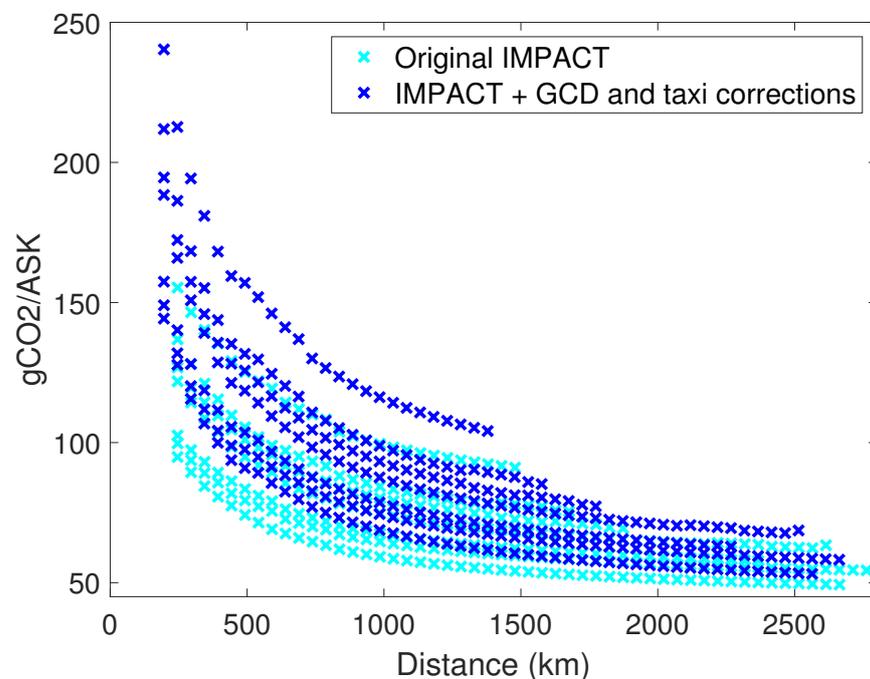

Figure 5. Effect of applying correction factors on the IMPACT results for Category D aircraft.

3.4. Comparison of Individual Emission Estimations with Other Calculators

To validate the approach followed to estimate the emissions obtained flight-by-flight, as some assumptions were considered (e.g., FL, GCD and taxi-in and -out corrections), a comparison with the values obtained from other calculators for short- and medium-haul flights (from 200 km to 2800 km) was performed.

Figure 6 shows in blue the results obtained with IMPACT for Category D aircraft with the assumptions presented in Section 3.1, once the distance correction had been applied to the GCD and the fuel corresponding to taxiing had been added (as described in Section 3.3). It can be seen how distinct models followed different lines: since each model would have a specific fuel burn rate, different FL could be used and different seats available. The blue line corresponds to the mean value of emissions for all Category D aircraft considered here. Even though it only represents a small set of aircraft types, this mean value helps to identify the general tendency of emissions versus distance.
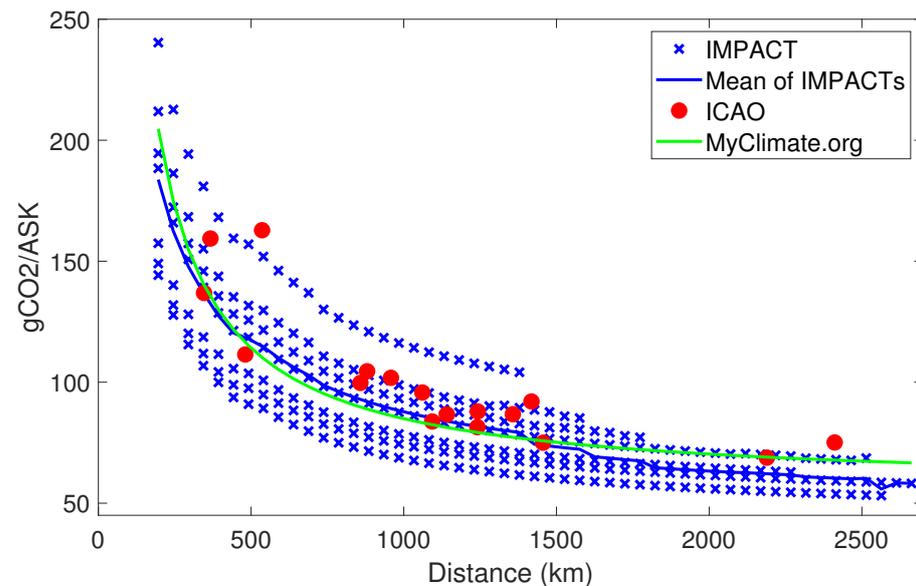

Figure 6. gCO_2 emissions per ASK vs. distance for different models of Category D.

We start by comparing our results with those from the ICAO Carbon Emissions Calculator [31]. In their calculator, the fuel burnt to flight distance relationship was extrapolated from the ICAO Fuel Consumption Formula, which includes factors such as the passenger load factor, flight distance, block time, proportion of the overall payload represented by passenger traffic, cabin class flown and type of equivalent aircraft flown. The amount of fuel used on a route is the weighted average of total fuel burnt based on the frequencies of the scheduled aircraft types flown [32]. ICAO's model provides the CO_2 emissions as a PAX measure. For this, the total CO_2 emissions of the flight are multiplied by the passenger-to-freight load factor and divided by the available number of seats (in a two-class configuration) multiplied by the load factor of the flight, taken as a mean value [32]. For example, for inter-Europe routes, a PAX load factor of 82.3% and a PAX to freight factor of 96.12% were considered. Since the output of ICAO provides data of emissions/PAX, we had to convert these results, taking into account the load factors, to obtain emissions/ASK.

Several European routes were chosen to obtain a sampling for short-to-medium-hauls flights. We can see in Figure 6 how the ICAO data (red dots) correctly followed the tendency of the mean emissions as per the IMPACT estimations. We recall that ICAO's results of emissions do not distinguish the result as a function of the aircraft type. They use a weighting factor as the ratio of number of departures for each equivalent aircraft type, to the total number of departures, to take into account that different models of aircraft fly the same route. This is why some points can be seen as outliers: for a specific route, it may be that the model mostly used those that are not the most optimal ones from an emissions point of view.

We also compared our results with the analytical model used by MyClimate.org (green line) [34]. Their original model considered some specific parameters to take into account all sources of CO_2. Here, to obtain emissions/ASK, and not per PAX, and to properly compare

their model to our calculation, we neutralised some of them, such as the passenger load factor, the cargo factor, the cabin class weighting factor, the multiplier factor accounting for potential non-CO_2 effects, the CO_2 emissions factor for preproduction jet fuel and the airport infrastructure emissions. Again, a very good agreement was found between the MyClimate model and our mean result from IMPACT. This can be explained by the fact that both use BADA for the fuel burnt estimation even though, in Figure 6, we averaged the results for all Category D aircraft, whereas MyClimate.org uses an average seat number fixed to 153.51.

These comparisons show that our hypothesis were valid and matched the ones commonly used in flight carbon emissions calculators. Note that the main difference that we offer with respect to the previously presented models is that the number of available seats was considered as an input instead of being averaged, as commonly done. The drawback is that a full occupancy was assumed.

It is also interesting to validate the result of the fuel consumption per passenger and per 100 km, which is a typical metric often published to compare flight performance with other transport means such as road transport.

Figure 7 shows the fuel consumed per passenger per 100 km ratio as a function of the distance flown. Only for this figure, emissions were considered per PAX, and not per ASK; thus a load factor of 82.3% and a PAX to freight factor of 96.1% were considered [32,53]. As expected, very short flights presented lower performances; for flights under 1000 km, the fuel per passenger lied between 5 L and 6 L per 100 km. Medium-haul flights reached an average close to the value of 3.4 L of fuel per passenger per 100 km, which is the ratio stated by EUROCONTROL from the 2019 data [53], represented in this figure by a discontinuous horizontal line. This mean value has shown a steady improvement over the last 15 y, but hides the difference between very short flights, for which the fuel burnt during the taxiing, take-off and landing cycle is the major component of fuel consumption, and more efficient medium-haul flights.
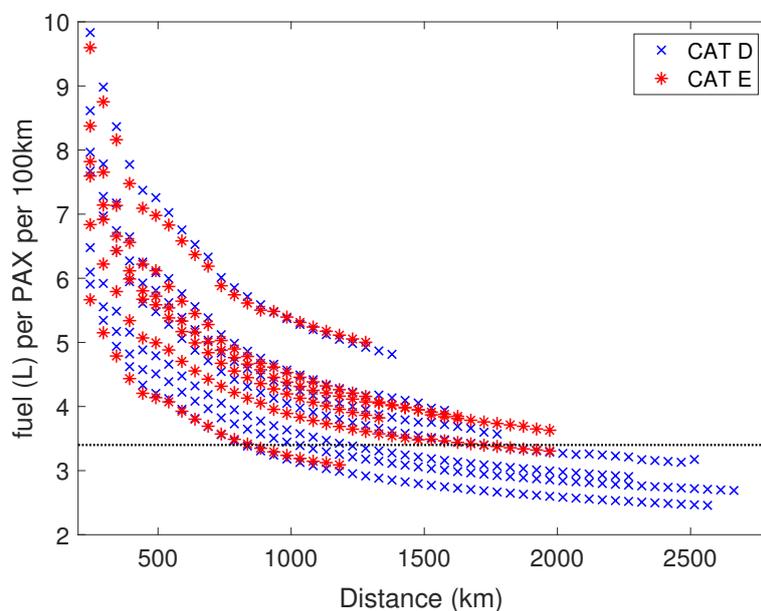

Figure 7. Fuel consumption (L) per passenger (assuming an 82.3% load factor and a PAX to freight factor of 96.1%) and per 100 km vs. flight distance.

3.5. Analytical Model Development

The methodology described in the previous sections allowed us to obtain the results of gate-to-gate emissions and flight times for the models considered in Table 1 and the range of distances mentioned in Section 3.1. These values were disaggregated per aircraft type (as shown in Section 3.5.1).

These data were then used to fit analytical models to directly estimate gate-to-gate emissions and time as a function of distance and available seats. Note that, usually, the fuel performance model would rely on MTOW instead of available seats as a variable, as fuel (and emissions) would be correlated with aircraft size (MTOW). This is particularly relevant for long-haul flights, as cargo plays an important role. However, in this paper, we aimed to fit the model considering available seats since this is more relevant for short- and medium-haul transport.

3.5.1. CO_2 and Gate-to-Gate Time Estimations

Figure 8 shows the ratio of emissions of CO_2 in grams per available seats and per kilometre (gCO_2/ASK) as a function of available seats and stage distance.
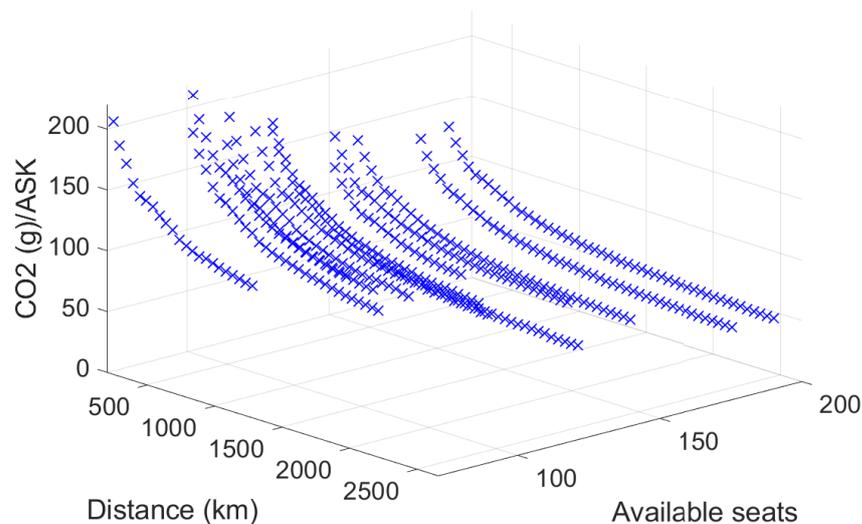

Figure 8. CO_2 emissions (g) per ASK vs. flight distance (km) and available seats.

The blue crosses refer to the discrete data obtained after applying the correction factors in Section 3.3 to the IMPACT calculations performed with the assumptions of Section 3.1. A steep increase of gCO_2/ASK was observed for short distances, as well as a more moderate increase for a low number of available seats.

Figure 9 shows the evolution of flight time per kilometre, as a function of flight distance and available seats. Here, though again a steep increase in time per kilometre was observed for short distances, the influence of available seat numbers, corresponding to the influence of the model of aircraft, was rather low. The relative flight time was in general almost constant with the model of aircraft considered, though larger aircraft within Categories D and E would operate slightly faster.
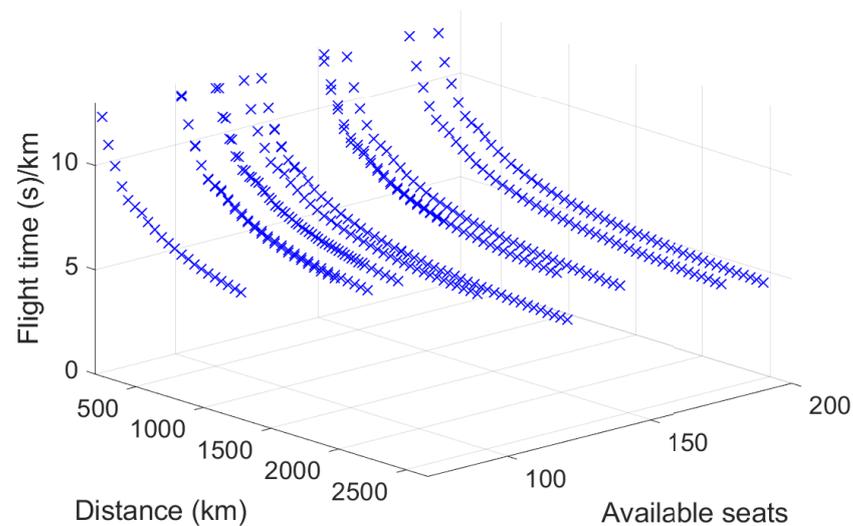
Figure 9. Flight gate-to-gate time (s) per kilometre vs. flight distance (km) and available seats.

3.5.2. Analytical Fitting

Two analytical models were developed: one relating CO_2 emissions to the great circle distance and available seats provided and another focusing on travel time. Three-dimensional figures relating the different variables were used to represent their relationship.

CO_2 Emissions

Figure 10 shows the analytical fitting that was obtained for the ratio of emissions of CO_2 in grams per available seat and per kilometre (gCO_2/ASK) as a function of available seats and stage distance.
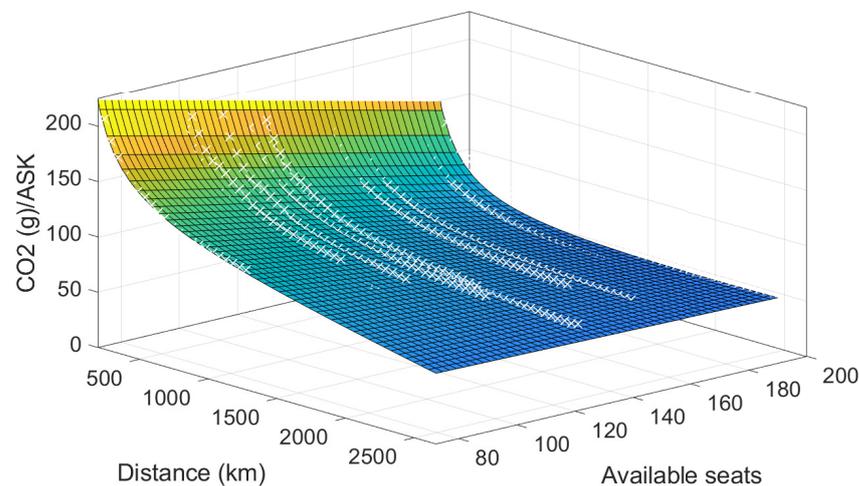

Figure 10. CO_2 emissions (g) per ASK vs. flight distance (km) and available seats and fitting surface.

Several polynomial fittings were tested, including high-order ones. However, it was found that increasing the polynomial order did not lead to any improvement of the goodness-of-fit statistics. It was thus found that the best fitting to relate gCO_2/ASK to the flight distance (d) and available seats (as) could be expressed as:

$$gCO_2/ASK = 167.8 + \frac{2.153 \times 10^4}{d} - 4.083 \times 10^{-2}d - 0.679as + 2.39 \times 10^{-4}d \times as$$

with $72 \leq as \leq 190$ and $200 \leq d \leq 2500$ (km) (1)

The analytical expression obtained was consistent with the model presented in [34], which relates emissions per passenger versus distance through a second-order polynomial in the distance variable. Here, the number of seats was additionally explicitly included in the analytical model.

Gate-to-Gate Time

Figure 11 shows the surface fitting of flight time per kilometre, as a function of flight distance and available seats. Given that the relative flight time was rather constant with the model of aircraft considered, a simpler expression was thus obtained to model the relation between flight time (in seconds) per kilometre, flight distance (d) and available seats (as), which can be expressed as follows:

$$\text{Flight time per kilometre} = 5.112 + \frac{1805}{d} - 2.308 \times 10^{-4}d - 2.855 \times 10^{-4}as$$

$$\text{with } 72 \leq as \leq 190 \text{ and } 200 \leq d \leq 2500 \text{ (km)} \quad (2)$$
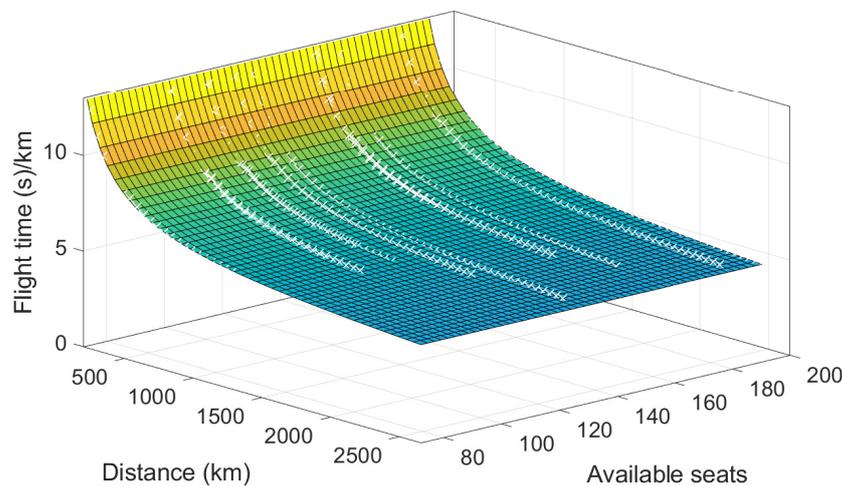

Figure 11. Flight gate-to-gate time (s) per kilometre vs. distance (km) and available seats and fitting surface.

In both cases (emissions and time), the penalisation (in CO_2 emissions and in time) of short flights was shown by the presence of a term $1/d$ in the fitting function. Furthermore, as mentioned, while the flight time per kilometre only depended slightly on the available seats, the influence of the number of available seats was much more important in the computation of gCO_2/ASK.

3.5.3. Accuracy of the Analytical Fitting

We now want to check the level of accuracy of the analytical fitting functions of Equations (1) and (2). Table 2 shows the goodness-of-fit statistics for both models. Fuel consumption, and thus CO_2, showed more variation with the type of aircraft (see Figure 7) than the flight time, which was more constant for all aircraft models. Goodness-of-fit statistics were thus better for the time model than for the emissions one, but in both cases, acceptable values were obtained. A RMSE of around 7 g was obtained for an order of magnitude of gCO_2/pkm ranging from around 60 g to 120 g in the distance range of interest.

Table 2. Goodness-of-fit statistics for emissions and time models: Sum of Squares due to Error (SSE), R-square and Root-Mean-Squared Error (RMSE).

Model	SSE	R-Square	RMSE
CO_2 (g) emissions per seat per kilometre	2.1×10^4 g	0.945	6.929 g
Time (s) per kilometre	4.6 s	0.996	0.103 s

Table 3 helps further estimate the level of error made by applying a fitting function to the IMPACT results (including correction factors) by selecting a few routes and a few models of aircraft (represented by different numbers of available seats).

It can be seen that the fitting error was consistently around 5% to 6% with the obtained value of RMSE. It is worth mentioning that this is well below the difference obtained in gCO_2/pkm between an aircraft with 128 available seats and another one with 190 (which can reach around 30%), a difference that would not be accounted for if an average number of seats was considered. Hence, the presented model provided this dimension while maintaining the simplicity and with a small error on the emissions estimated.

Table 3. Error between results from IMPACT (IMP gCO_2/pkm) and analytical fitting (FIT gCO_2/pkm) for several routes and several available seats (*as*).

DEP	ARR	*d* (km)	*as*	IMP gCO_2/pkm	FIT gCO_2/pkm	Error %
LFPG	LFLL	406.15	128	125.11	129.74	3.70
LEBL	LEMD	476.87	128	116.16	121.15	4.30
LEBL	LEMD	476.87	190	89.99	86.12	4.29
LEBL	LFPG	845.43	128	92.32	97.70	5.83
LEBL	LFPG	845.43	158	77.00	83.39	8.30
LEBL	LFPG	845.43	190	72.56	68.13	6.10
LEMD	LFPG	1048.61	158	72.11	77.83	7.93
LFPG	UUEE	1328.9	158	60.02	61.95	3.22
LFPG	UUEE	1328.9	190	56.80	58.78	3.48

4. Application

Two different applications of the model are provided as examples: an analysis of emissions for short-haul flights within the Western European network and a comparison of emissions and total trip time for rail and air on specific routes in Europe.

4.1. Analysis of Emissions in the Short-Haul Western European Network

4.1.1. Methodology

We applied the analytical model to all departure flights from Western European countries during 2017, using data available from Marketing Information Data Tapes (MIDT). The main purpose was to understand the usability of the model in the calculation of emissions of a flight network in the strategic decision-making phase at the company or policy level. We also aimed to compare the relative importance that very short flights have in terms of emissions and capacity. The dataset provided, for each origin-destination airport pair and for each operator and aircraft model, the number of departure flights, the number of average seat capacity and the distance flown. The analytical model from Equation (1) was applied to the subset of flights whose lengths were within the range of 2500 km, totalling 7,049,388 flights for which emissions can be seamlessly computed without requiring complex simulations.

4.1.2. Results

The results of Cumulative Distribution Function (CDF) of the number of flights in the subset, the total amount of CO_2 emissions and the ASK compared with distance are shown in Figure 12.

The first relevant observation is that flights below 750 km accounted for a significant percentage (48.8%) of the subset analysed, but were not significant when analysed in terms of capacity (ASK), accounting for only 19.1%. These flights were inefficient in terms of capacity and emissions (gCO_2) because for a given distance value, the cumulative percentage of emissions was higher than the cumulative percentage of capacity. Moreover, most of these flights were located in territories with land accessibility, and some had other transport alternatives. The second observation is that in the first part of the distribution, up to 750 km, the ASK CDF evolved much more slowly than the emissions CDF, until the difference stabilised in the flight range between 750 km and 1500 km. In the last part of the distribution, in particular above the 2000 km range, the number of flights was lower, but they added more capacity than emissions in the relative values. This reinforces the argument that very short-haul flights provide little capacity to the system, but comparatively generate high levels of emissions, making them difficult to justify from an environmental point of view, except in cases where they are decisive for ensuring territorial accessibility. In particular, financing sustainable modes of transport or innovations in the field of clean propulsion in aviation with a tax on these short flights could be a transport policy worthy of an ad hoc study.
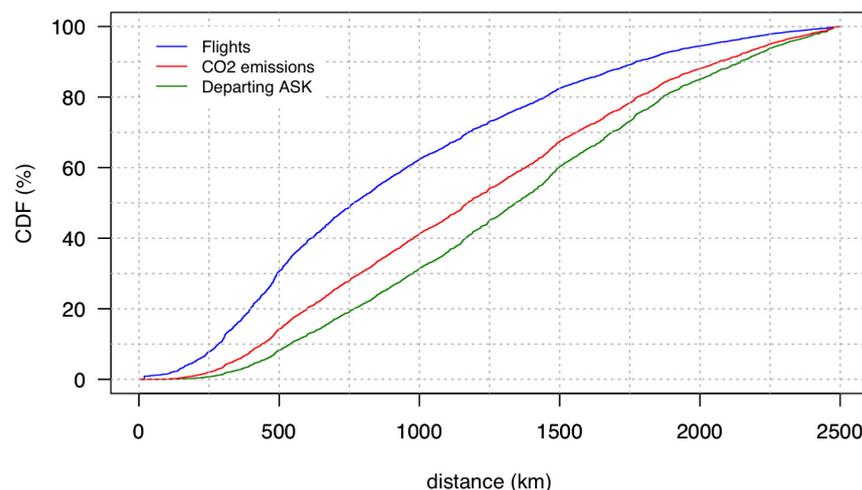

Figure 12. Comparison of the CDF of the number of flights, CO_2 emissions and ASK for all departures in Western European airports in 2017.

4.2. Comparison with Rail

4.2.1. Methodology

We now applied the analytical model to thirteen European routes that have direct rail connections and three additional routes from Paris with one train change only, in order to compare total (door-to-door) travel time and generated emissions between rail and flight. The criteria for the selection of direct routes was that they should have the highest possible commercial speed, so corridors were selected in countries with a consolidated high-speed service and a minimum number of intermediate stations (as this is one of the factors influencing energy consumption and commercial speed). These criteria aimed at having a preliminary qualitative comparison of competitive HSR services with aviation, in the absence of a specific demand model, which may be the subject of future work. The first filtering of candidates was performed with the European Rail Timetable [54], and the final selection was performed with the EcoPassenger search engine to obtain this qualitative sample of thirteen direct routes and three with an intermediate change (which helped to extend the comparison over 1000 km, in the absence of direct HSR services over these travel

distances without crossing borders). To that end, we used the EcoPassenger calculator to obtain the rail travel time and CO_2 emissions [55], which are detailed in Table 4 .

EcoPassenger calculates the specific energy consumption (Wh), then considers the total energy chain and converts the required energy into CO_2 emissions. In this calculator, specific values per passenger-kilometre for different train service types were used for routes within Germany and Spain and average values over all service types for France and Italy [56]. We selected the model feature *maximum load factor* for which the specific energy values per seat-kilometre (load factor = 100%) were used and the option of *national mix of electricity production*. This mix is specific to each country and reflects the national strategy of electricity production, which involves different sources of energy (carbon, nuclear, solar, etc.), which eventually comes to the rail industry to power electric trains (all rail journeys considered in this paper were electric-powered). EcoPassenger's model uses data from Eurostat [57] and IEA [58] to calculate the energy split of electricity consumption and the energy efficiency and emissions factors of the electricity supply for railway transport in European countries. The length of the train routes is calculated in EcoPassenger based on the length of the polygon defined by all in-between stops of a train. The length of the train route between two connected stations is calculated by the line-of-sight distance, which is extended by a corrector factor of 20%-30% depending on the case [56]. Note that for the comparison with flights, the travel distance given in Table 4 is the GCD of the route. For these routes, flight time and CO_2 emissions were calculated applying Equations (1) and (2) to the route GCD and to the average available seat number obtained from [31].

Table 4. Train time, CO_2 emissions and the corresponding GCD for some European routes (train time and CO_2 computed based on [55]). Note that Paris-Madrid, Paris-Roma and Paris-Napoli are one train change routes .

DEP	ARR	GCD (km)	Time (h)	kgCO$_2$/PAX
Faro	Lisboa	222	3.57	4.40
Porto	Lisboa	277	2.67	4.60
Madrid	Valencia	285	1.80	5.78
London	Paris	346	3.18	4.00
London	Brussels	349	2.02	2.70
Madrid	Sevilla	394	2.63	8.48
Paris	Lyon	410	1.93	6.61
Berlin	Munich	462	4.00	10.90
Barcelona	Madrid	481	2.50	10.80
Paris	Stuttgart	489	3.65	8.80
Paris	Bordeaux	525	2.15	5.00
Paris	Marseille	650	3.30	7.30
Paris	Barcelona	859	6.65	11.70
Paris	Madrid	1061	10.52	22.50
Paris	Roma	1099	11.72	22.10
Paris	Napoli	1287	13.10	26.40

To objectively compare travel times, we needed to add an additional time reflecting the time needed to go from the city centre to the rail station or to the airport [59] and the buffer time needed in both cases to account for boarding, security checks, etc. Since a precise study of this additional time was out of the scope of this paper, constant values of 2 h 30 min and 50 min were added respectively to the flight time and rail time. These times accounted for access to public transport, waiting, in-vehicle and transfer times to main rail stations or airport terminals [60]. For air transportation, 50 min was allocated for travel from the city centre to the airport terminal, 50 min to allow for different processes inside the airport terminal and an extra 50 min to go from the airport to the city centre. For rail, considering that rail stations are located within the city, 20 min was allowed for

travel from the city centre to the station, 10 min to allow for different processes inside the station and 20 min to come back to the city centre. These values were estimated with a set of consultancies with Google Maps, but for a more precise approximation, a proper analysis would be required in future work.

4.2.2. Results

Figure 13 compares the air total travel time and flight emissions calculated with our analytical model with the rail total travel time and train emissions obtained from [55]. First, note that as mentioned in Section 3.5.2, the analytical model for flight time hardly depends on the available seat numbers, and thus, the flight time regularly decreases with distance. On the contrary, the CO_2 emissions model showed an important dependency on the available seat number. Therefore, we can observe that, though the global tendency was that gCO_2/ASK decreased with distance, some peaks were present. One of them was, for example, on the Paris–Stuttgart route, where the number of available seats was low (78) leading to a high value of gCO_2/ASK (148 g).

For the rail data, since no analytical model was used, the time and emissions variables showed more irregularities. While rail gCO_2/ASK was fairly constant with distance and always well below air emissions, rail travel time per kilometre first decreased, reaching an optimal value in the 400–650 km range, and then increased for the four longest routes considered. This increase was due to the fact that the Paris–Barcelona rail link is not completely high-speed and that the three longest routes included one train transfer (with the subsequent increase in total travel time). Therefore, the relationship of HSR emissions with distance was established with a metamodel based on these data and was intended to be preliminary and qualitative. There was an inherent error arising from the EcoPassenger calculator's own errors and other errors introduced when selecting the sample route. For example, between Berlin and Munich, there were at least two options (ICE1001 and ICE503), which differ in whether or not they pass through Leipzig, leading to a longer travel time (+11%) and more emissions (+13%), but we selected the shortest one, following the criteria explained above. The same distance in another country may lead to different emissions due to technology, slope or the national mix of energy production. Rigorous analysis of these sources of variability and errors may be the subject of specific future work.
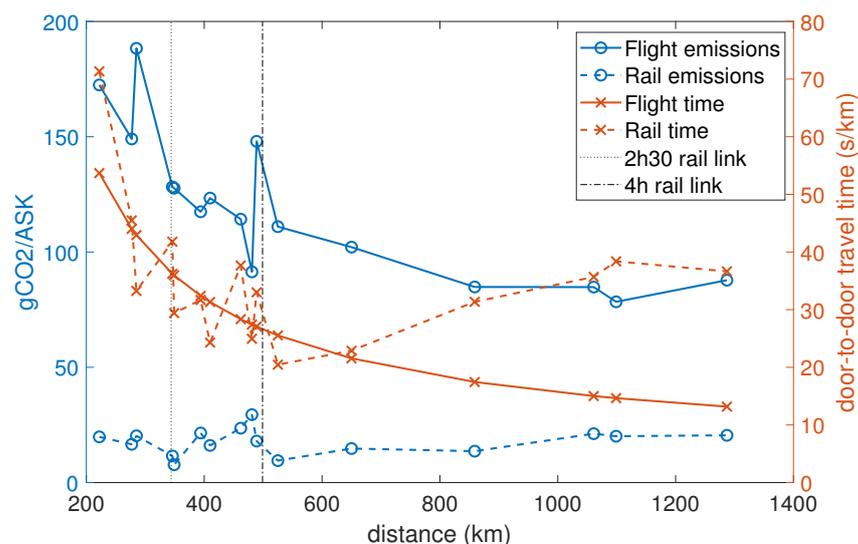

Figure 13. Comparison of total travel time and CO_2 emissions between train and flight for 16 European routes.

As expected, gCO_2/ASK was always much lower for rail than for air, but this was especially true for flights less than 600–700 km where gCO_2/ASK were extremely high

for air due to the penalising effect of taxiing, take-off and landing fuel consumption. From distances around 700–800 km, the difference in emissions between air and rail stabilised to air emissions being around four-times higher than rail. More interestingly, travel time was seen to be equivalent for both means of transport until distances of around 600 km. Only after this value did the time travel graphs start diverging at the clear disadvantage of rail. Up until this distance, rail was clearly competitive with air from a door-to-door time point of view, with a huge advantage for emissions. Considering an average rail time per kilometre of 34.9 s/km for the routes considered in this case study, we also plotted two lines corresponding to 2 h 30 min and 4 h rail links. It can be seen that they corresponded to distances below 600 km, and thus, there was no clear time penalty in using rail instead of air. The model proposed here could be used in the future on a larger panel of routes in order to study in more detail which air routes could be substituted by rail, following time and emissions considerations.

5. Discussion

An analytical model computing gate-to-gate gCO_2/ASK and time/kilometre for a given distance and a given number of available seats was proposed for short-to-medium-haul flights. The accuracy of the numerical results were in line with other CO_2 calculators, and when applying an analytical fitting, the error of interpolation was low for CO_2 emissions (around 7%) and very low for travel time per kilometre (around 0.5%). The model presented the advantage with respect to other calculators of being sensitive to the number of available seats, a parameter generally not explicitly considered. Its applicability was shown in two practical examples where emissions and time per kilometre were calculated for several European routes in a simple and efficient manner. The model allows stakeholders to identify on which routes rail would be an appropriate alternative from the perspective of both CO_2 emissions and time.

Future work should improve some parts of the modelling, in particular the consideration of the total door-to-door trip time, studying more precisely the airport access and egress times and airport processes and buffers, which could then be incorporated into the analytical model. A more detailed study of taxi time might also be worth exploring. Large airports tend to have longer taxi times, but generally offer longer flights, while regional airports would have shorter taxi times and shorter flights. Finally, more aircraft types could be taken into account to obtain a more precise model. In particular, this paper focused on jet aircraft, while different emissions and time models might be required for turboprop aircraft, which tend to show higher fuel efficiencies, but are seldom used due to other operational aspects (lower operating speeds and capacities) [61,62].

The model developed in this research provides an expected average indication on emissions and travel time as a function of the Great Circle Distance between origin and destination airports. We consider this to be useful for strategic analysis and decision-making. For this reason, "nominal" operational parameters were considered and historical analysis conducted. However, as previously indicated, the actual emissions of a particular flight might diverge with respect to this average due to operational aspects and constraints, e.g., the selection of a suboptimal Flight Level or actual payload. As an example, a CAT D flight on an 850 km route can experience around a 1.6% difference in total fuel usage (and emissions) (considering the corrections applied in this paper), if the cruise FL selected changes from the FL380 to the lower FL340. A more detailed analysis of the impact of the variation on these parameters (with their usage on historical flights) and their translation into errors on the model should be conducted. This will lead to a characterisation of the error of the model being able to be used for the identification of confidence intervals to both emissions and travel time.

Cost should also be taken into account to add an economic decision factor into the comparison of different means of transport. The demand in air transport can be seen as continuous, while the supply is discrete (as adding one aircraft adds a given amount of

seats). Therefore, tradeoffs between supply offered and load factors arise. The sensitivity of the actual load factor on emissions generated should also be considered.

Finally, more complex applications could be studied, such as applying the proposed model to a full network of rail links, to determine which air routes could be substituted by rail, taking into account time, CO_2 emissions and, possibly cost, serving as a decision tool for policy-makers.

The analytical nature of the model provided enables modellers to explicitly consider the impact of different parameters on fuel consumption, emissions and travel time. This could be incorporated into strategic economic models without requiring complex simulations to obtain these fuel and emissions estimations.

References

1. EUROCONTROL. Challenges of Growth—European Aviation in 2040. 2018. Available online: www.eurocontrol.int/publication/challenges-growth-2018 (accessed on 17 September 2021).
2. EUROCONTROL. Performance Review Report An Assessment of Air Traffic Management in Europe during the Calendar Year 2019. 2020. Available online: www.eurocontrol.int/sites/default/files/2020-06/eurocontrol-prr-2019.pdf (accessed on 17 September 2021).
3. SESAR Joint Undertaking. European ATM Master Plan—Executive View. 2020. Available online: www.sesarju.eu/masterplan2020 (accessed on 17 September 2021).
4. Clean Sky 2. Joint Technical Programme. 2015. Available online: ec.europa.eu/research/participants/data/ref/h2020/other/guide-appl/jti/h2020-guide-techprog-cleansky-ju_en.pdf (accessed on 17 September 2021).
5. DLR. DEPA 2050—Development Pathways for Aviation up to 2050. Technical Report, German Aerospace Center. 2020. Available online: http://elib.dlr.de/142185/1/DEPA2050_StudyReport.pdf (accessed on 17 September 2021).
6. European Commission. Regulation (EU) 2017/2392 of the European Parliament and of the Council of 13 December 2017 Amending Directive 2003/87/EC to Continue Current Limitations of Scope for Aviation Activities and to Prepare to Implement a Global Market-Based Measure from 2021. 2017. Available online: www.legislation.gov.uk/eur/2017/2392/adopted/data.pdf (accessed on 17 September 2021).
7. ICAO. Resolution A40-19: Consolidated Statement of Continuing ICAO Policies and Practices Related to Environmental Protection—Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). 2019. Available online: www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-19_CORSIA.pdf (accessed on 17 September 2021).
8. Convention Citoyenne pour le Climat. Avis de la Convention Citoyenne Pour le Climat sur les Réspones Apportées par le Gouvernement à ses Propositions. 2021. Available online: www.conventioncitoyennepourleclimat.fr/wp-content/uploads/2021/03/CCC-rapport_Session8_GR-1.pdf (accessed on 17 September 2021).

9. Lederer, P.; Nambimadom, R. Airline network design. *Oper. Res.* **1998**, *46*, 785–804.

10. Trapote-Barreira, C. Methodology for Optimal Design of Efficient air Transport Networks in a Competitive Environment. Ph.D. Thesis, Universitat Politecnica de Catalunya, Barcelona, Spain, 2015.

11. Grimme, W.; Maertens, S.; Bingemer, S.; Gelhausen, M. Estimating the market potential for long-haul narrowbody aircraft using origin-destination demand and flight schedules data. *Transp. Res. Procedia* **2021**, *52*, 412–419. Available online: www.sciencedirect.com/science/article/pii/S2352146521000892 (accessed on 17 September 2021).

12. Cooper, T.; Reagan, I.; Porter, C.; Franzoni, C. Global Fleet and MRO Market Forecast 2021–2031. Technical Report, Oliver Wyman. 2021. Available online: www.oliverwyman.com/content/dam/oliver-wyman/v2/media/2021/feb/Global_FLeet_and_MRO_Market_Forecast_2021-2031_OW.pdf (accessed on 17 September 2021).

13. IATA. IATA Carbon Offset Program—Frequently Asked Questions. Version 10.1. 2020. Available online: https://www.iata.org/contentassets/922ebc4cbcd24c4d9fd55933e7070947/icop_faq_general-for-airline-participants.pdf (accessed on 17 September 2021).

14. EEA. EEA Greenhouse Gas—Data Viewer. Available online: www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (accessed on 14 April 2021).

15. Lee, D.; Fahey, D.; Forster, P.; Newton, P.; Wit, R.; Lim, L.; Sausen, R. Aviation and global climate change in the 21st century. *Atmos. Environ.* **2009**, *43*, 3520–3537.

16. Lee, D.; Fahey, D.; Skowron, A.; Allen, M.; Burkhardt, U.; Chen, Q.; Doherty, S.; Freeman, S.; Forster, P.; Fuglestvedt, J.; et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* **2021**, *244*, 117834, doi:10.1016/j.atmosenv.2020.117834.

17. IATA. Aircraft Technology Roadmap to 2050. 2020. Available online: www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf (accessed on 17 September 2021).

18. Jiménez-Crisóstomo, A.; Rubio-Andrada, L.; Celemín-Pedroche, M. The Constrained Air Transport Energy Paradigm in 2021. *Sustainability* **2021**, *13*, 2830.

19. Prussi, M.; Konti, A.; Lonza, L. Could Biomass Derived Fuels Bridge the Emissions Gap between High Speed Rail and Aviation? *Sustainability* **2019**, *11*, 1025.

20. Anderson, K. The inconvenient truth of carbon offsets. *Nature* **2012**, *484*, 7, doi:10.1038/484007a.

21. Polonsky, M.J.; Grau, S.L.; Garma, R. The New Greenwash?: Potential Marketing Problems with Carbon Offsets. *Int. J. Bus. Stud.* **2010**, *18*, 49–54.

22. Arnaldo Valdés, R.; Gomez Comendador, V.; Braga Campos, L. How Much Can Carbon Taxes Contribute to Aviation Decarbonization by 2050. *Sustainability* **2021**, *13*, 1086.

23. Markham, F.; Young, M.; Reis, A.; Higham, J. Does carbon pricing reduce air travel? Evidence from the Australian 'Clean Energy Future' policy, July 2012 to June 2014. *J. Transp. Geogr.* **2018**, *70*, 206–214, doi:10.1016/j.jtrangeo.2018.06.008.

24. Ministère de la Transition Ecologique. Projet de loi Climat & Résilience—Les Députés Viennent de finir L'examen des Articles du Titre III « Se déplacer » : Ça Change Quoi Dans nos Vies? Available online: www.ecologie.gouv.fr/projet-loi-climat-resilience-deputes-viennent-finir-lexamen-des-articles-du-titre-iii-se-deplacer-ca (accessed on 3 June 2021).

25. Baumeister, S. Replacing short-haul flights with land-based transportation modes to reduce greenhouse gas emissions: The case of Finland. *J. Clean. Prod.* **2019**, *225*, 262–269, doi:10.1016/j.jclepro.2019.03.329.

26. Baumeister, S.; Leung, A. The emissions reduction potential of substituting short-haul flights with non-high-speed rail (NHSR): The case of Finland. *Case Stud. Transp. Policy* **2021**, *9*, 40–50, doi:10.1016/j.cstp.2020.07.001.

27. Robertson, S. The potential mitigation of CO2 emissions via modal substitution of high-speed rail for short-haul air travel from a life cycle perspective—An Australian case study. *Transp. Res. Part D Transp. Environ.* **2016**, *46*, 365–380, doi:10.1016/j.trd.2016.04.015.

28. Spinetta, J. L'avenir du Transport Ferroviaire. Rapport au Premier Ministre. 2018. Available online: www.ecologie.gouv.fr/sites/default/files/2018.02.15_Rapport-Avenir-du-transport-ferroviaire.pdf (accessed on 17 September 2021).

29. EEA. EMEP/EEA air Pollutant Emission Inventory Guidebook 2019, 1.A.3.a Aviation 1 Master Emissions Calculator 2019. 2019. Available online: www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-a-aviation-1-annex5-LTO/view (accessed on 17 September 2021).

30. EEA. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019, 1.A.3.a Aviation 2019. 2019. Available online: www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-a-aviation/view (accessed on 17 September 2021).

31. ICAO. Carbon Emissions Calculator. Available online: www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx (accessed on 14 May 2021).

32. ICAO. Carbon Emissions Calculator Methodology. Version 11. 2018. Available online: www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v11-2018.pdf (accessed on 17 September 2021).

33. Foundation Myclimate. Offset Your Flight Emissions! Available online: http://co2.myclimate.org/en/flight_calculators/new. (accessed on 14 May 2021).

34. Foundation Myclimate. The myclimate Flight Emission Calculator. 2019. Available online: www.myclimate.org/fileadmin/user_upload/myclimate_-_home/01_Information/01_About_myclimate/09_Calculation_principles/Documents/myclimate-flight-calculator-documentation_EN.pdf (accessed on 17 September 2021).

35. Schäfer, A.; Evans, A.; Reynolds, T.; Dray, L. Costs of Mitigating CO2 Emissions from Passenger Aircraft. *Nat. Clim. Chang.* **2016**, *6*, 412–417. Available online: https://www.nature.com/articles/nclimate2865 (accessed on 17 September 2021).

36. Dray, L. AIM2015: Documentation, 2019. Air Transportation Systems Lab. UCL Energy Institute. Available online: http://www.atslab.org/wp-content/uploads/2019/12/AIM-2015-Documentation-v9-122019.pdf (accessed on 17 September 2021).

37. Lissys. Piano-X: Aircraft Emissions and Performance. User's Guide. 2008. Available online: https://www.lissys.uk/piano-x-guide.pdf (accessed on 17 September 2021).

38. Swan, W.; Adler, N. Aircraft trip cost parameters: A function of stage length and seat capacity. *Transp. Res. Part E Logist. Transp. Rev.* **2006**, *42*, 105–115, doi:10.1016/j.tre.2005.09.004.

39. De Lemos, F.; Woodward, J. Calculating block time and consumed fuel for an aircraft model. *Aeronaut. J.* **2021**, *125*, 847–878.

40. Baumeister, S. 'Each Flight is Different': Carbon emissions of selected flights in three geographical markets. *Transp. Res. Part D: Transp. Environ.* **2017**, *57*, 1–9, doi:10.1016/j.trd.2017.08.020.

41. Park, Y.; O'Kelly, M. Fuel burn rates of commercial passenger aircraft: Variations by seat configuration and stage distance. *J. Transp. Geogr.* **2014**, *41*, 137–147.

42. European Union Aviation Safety Agency (EASA). ICAO Aircraft Engine Emissions Databank. Available online: https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank (accessed on 17 September 2021).

43. AIRFRANCE. Calculateur Carbone. Available online: http://corporate.airfrance.com/fr/co2/calculateur (accessed on 27 May 2021).

44. FINNAIR. Finnair Emissions Calculator. Available online: www.finnair.com/FI/GB/emissions-calculator (accessed on 27 May 2021).

45. COMPENSAID Lufthansa. Compensate Your Flight. Available online: http://lufthansa.compensaid.com/contribute/flights (accessed on 27 May 2021).

46. Delgado, L.; Prats, X. En Route Speed Reduction Concept for Absorbing Air Traffic Flow Management Delays. *J. Aircr.* **2012**, *49*, 214–224, doi:10.2514/1.C031484.

47. Delgado, L.; Prats, X. Effect of Wind on Operating-Cost-Based Cruise Speed Reduction for Delay Absorption. *IEEE Trans. Intell. Transp. Syst.* **2013**, *14*, 918–927, doi:10.1109/TITS.2013.2246864.

48. EUROCONTROL. RECAT-EU—European Wake Turbulence Categorisation and Separation Minima on Approach and Departure. Edition: 1.2. Edition Date: 14 February 2018. Available online: www.eurocontrol.int/sites/default/files/2021-07/recat-eu-released-september-2018.pdf (accessed on 30 August 2021).

49. SeatGuru. Find Your Seat Map. www.seatguru.com (accessed on 2 June 2021).

50. EUROCONTROL. Integrated Aircraft Noise and Emissions Modelling Platform. www.eurocontrol.int/platform/integrated-aircraft-noise-and-emissions-modelling-platform (accessed on 14 April 2021).

51. EUROCONTROL. Taxi Times—Winter 2019–2020. www.eurocontrol.int/publication/taxi-times-winter-2019-2020 (accessed on 14 May 2021).

52. Khadilkar, H.; Balakrishnan, H. Estimation of Aircraft Taxi-out Fuel Burn using Flight Data Recorder Archives. In Proceedings of the AIAA Guidance, Navigation, and Control Conference. Portland, OR, USA, 8–11 August 2011.

53. EUROCONTROL. Aviation Intelligence Unit. Flying the 'Perfect Green Flight': How Can We Make Every Journey as Environmentally Friendly as Possible? 2021. Think Paper #10. Available online: https://www.eurocontrol.int/publication/eurocontrol-think-paper-10-flying-perfect-green-flight (accessed on 17 September 2021).

54. European Rail Timetable. European Rail Timetable. May 2021. 2021. Available online: http://www.europeanrailtimetable.eu. (accessed on 17 September 2021).

55. EcoPassenger. Compare the Energy Consumption, the CO_2 Emissions and other Environmental Impacts for Planes, Cars and Trains in Passenger Transport. http://ecopassenger.hafas.de/bin/query.exe/en?L=vs_uic& (accessed on 2 June 2021).

56. Knörr, W.; Hüttermann, R. EcoPassenger Environmental Methodology and Data Update. Institut für Energie- und Umweltforschung Heidelberg gGmbH. 2016. Available online: http://ecopassenger.hafas.de/hafas-res/download/Ecopassenger_Methodology_Data.pdf (accessed on 17 September 2021).

57. Eurostat. Energy Statistics—Quantities, Annual Data, 2015. Available online: http://ec.europa.eu/eurostat/data/database (accessed on 17 September 2021).

58. International Energy Agency. *Key World Energy Statistics*; IEA: Paris, France 2015, doi:10.1787/key_energ_stat-2015-en.

59. DLR. Airport Accessibility in Europe (Edition 1.02). Technical Report, Air Transport and Airport Research. 2010. Available online: http://ec.europa.eu/transport/sites/default/files/modes/air/studies/doc/intermodality/2010-airport-accessibility-in-eu.pdf (accessed on 17 September 2021).

60. Transportation Research Board. TCRP Report 165: Transport Capacity and Quality of Service Manual. Third Edition. 2013. Available online: www.trb.org/Main/Blurbs/169437.aspx (accessed on 17 September 2021).

61. Babikian, R.; Lukachko, S.P.; Waitz, I.A. The historical fuel efficiency characteristics of regional aircraft from technological, operational, and cost perspectives. *J. Air Transp. Manag.* **2002**, *8*, 389–400, doi:10.1016/S0969-6997(02)00020-0.

62. Ryerson, M.S.; Hansen, M. The potential of turboprops for reducing aviation fuel consumption. *Transp. Res. Part D Transp. Environ.* **2010**, *15*, 305–314, doi:10.1016/j.trd.2010.03.003.