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# ENVIRONMENTAL LABELS IN AVIATION – AIRCRAFT, AIRLINE AND FLIGHT LABEL

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**Abstract**

The aviation sector is subject to increasing scientific and regulatory examination due to its disproportionate contribution to global climate change. While $CO_2$ emissions have traditionally dominated the public and regulatory discourse, scientific consensus now recognizes the significant role of additional climate-relevant factors, such as nitrogen oxides ($NO_x$) and water vapor emitted at high altitudes, which contributes to aviation-induced cloudiness in the form of (persistent) contrail cirrus. Despite the availability of carbon calculators and offsetting tools, there is no standardized and transparent framework for labeling the environmental impact of air travel. The approach presented here incorporates not only non-$CO_2$ climate effects, but also noise and local air pollutant emissions in the vicinity of airports. This paper introduces a comprehensive framework of environmental labels for aviation, covering three domains: Aircraft Labels, Airline Labels, and Flight Labels. These labels offer a unified method for evaluating and comparing environmental performance using certified aircraft data, life cycle assessment (LCA) methods, and emissions modeling. A fourth construct, the Multimodal Trip Score, extends the labeling concept by integrating travel time and cost, enabling holistic comparisons across travel alternatives. Analyses of typical narrowbody and widebody aircraft, major international airlines, and comparisons between multi-leg and direct flights demonstrate the feasibility and utility of this labeling system. The proposed framework aims to enhance transparency, influence consumer behavior, and support climate mitigation policies in the transportation sector.

## 1. INTRODUCTION

Aviation is responsible for approximately 3 % of global $CO_2$ emissions, yet its true climate impact is significantly underestimated when non-$CO_2$ effects are excluded. Studies have shown that aviation's radiative forcing is not driven by $CO_2$ emissions alone. Contrails and aviation-induced cloudiness (AIC) represent the dominant share, contributing about half of the total effect. Carbon dioxide accounts for roughly one third, while nitrogen oxides ($NO_x$) contribute around one sixth [1].

The industry has responded to these findings with announcements of "green growth," electric aircraft, and hydrogen propulsion. However, such solutions face substantial technical, economic, and infrastructural barriers, especially in long-haul operations. The time lag between development and widespread implementation further increases the need for interim tools that can influence passenger decisions toward more climate-friendly options in the short term.

While synthetic fuels and battery-electric propulsion are often presented as future solutions, their applicability remains severely limited. Batteries possess only a fraction of the gravimetric energy density of kerosene, restricting their use to short-haul flights [2].

Hydrogen, while offering a high gravimetric energy density, presents volumetric challenges, the need for cryogenic fuel storage, and a greater volumetric output of water vapor, the climate effects of which are not yet fully understood [3]. This underscores the need for strategies that transparently communicate the environmental consequences of flight choices to consumers.

As a result, a substantial share of aviation's climate impact will persist in the medium term. Against this backdrop, demand-side transparency tools offer a complementary mitigation approach. By making the environmental consequences of travel options visible and comparable, such tools can influence passenger behavior and create market incentives for cleaner operations.

This paper introduces and evaluates a three-tiered system of Environmental Labels for aviation. The *Aircraft Label* quantifies environmental performance at the level of individual aircraft types based on four core metrics:

- Fuel performance
- Climate impact via $CO_2$-equivalent emissions
- Local air pollution through $NO_x$ emissions in the landing and take-off (LTO) cycle
- Noise emissions

The *Airline Label* aggregates these aircraft-level scores over an airline's fleet, weighted by aircraft frequency and seating configuration. The *Flight Label* incorporates routing, stopovers, and cabin class to represent the environmental performance of individual flight itineraries.

Additionally, the *Multimodal Trip Score* integrates the Flight Label with time and cost considerations, enabling comprehensive comparisons across transport modes. The framework is based on certified aircraft data, life cycle assessment (LCA) methodologies, and published fleet

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registries, and is designed for seamless integration into consumer-facing travel platforms.

## 2. LITERATURE REVIEW

Current tools for estimating the environmental impact of air travel are focusing on benchmarking actions related to one or few of so-called green indicators inter alia fuel consumption, aircraft utilization rate and efficiency determinants or fleet assignment. These tools often rely on proprietary assumptions, frequently omit non-$CO_2$ effects, and lack comprehensive treatment of aircraft types, routing, or class configuration [4].

The new EU "Flight Emissions Label" (FEL) by EASA has its home on https://www.flightemissions.eu. It is based on real airline performance data, but this data is secret. Basically, the airlines can report any data. It gets accepted by EASA as long as it is plausible. EASA started work on the FEL in 2019, but in 2025 a practical application seems still to be missing.

One of the most established examples of an airline ranking is the Atmosfair Airline Index (AAI). It covers around 150 international passenger airlines and is based on the ICAO carbon emissions calculation method. In addition to $CO_2$, the AAI also accounts for $NO_x$ emissions, while considering factors such as aircraft type, engine, seat and cargo capacity, load factors, and the use of winglets [5].

But despite the availability of emissions data and modeling frameworks, no existing tool integrates all relevant dimensions – climate, local air pollution, and noise – into a single, aircraft-specific label, as it is done by our Aircraft Label depicted in Figure 1.

In 2015, Hamburg University of Applied Sciences (HAW Hamburg) started work on an "Ecolabel for Aircraft" (http://ecolabel.ProfScholz.de). Many students contributed to the project. The work culminated so far in a Master Thesis [4], which is the basis of this paper.

## 3. AIRCRAFT LABEL

The Aircraft Label combines four criteria, each contributing to a weighted overall environmental score. *Fuel performance*, expressed in kilograms of fuel per seat-kilometer, reflects the aircraft's thermodynamic efficiency and degree of design optimization. *Climate impact* is quantified as $CO_2$-equivalent emissions, integrating direct $CO_2$ output with the radiative forcing contributions from $NO_x$-induced ozone formation and aviation-induced cloudiness (AIC) [6]. *Local air pollution* is assessed through $NO_x$ emissions during the LTO cycle, while *noise impact* is determined from a weighted average of EPNdB levels measured in approach, lateral, and flyover tests, normalized to ICAO Chapter 4 limits.

To ensure comparability, all results are normalized (e.g. per seat-kilometer or per unit of thrust), thereby accounting for differences in aircraft size and seating density. Each criterion is normalized across a database of typical commercial aircraft, then weighted as follows in the overall score:

- Fuel performance: 20 %
- $CO_2$-equivalent climate impact: 40 %
- Local air pollution ($NO_x$): 20 %
- Noise pollution: 20 %

This scoring system ensures that both global (resource depletion, climate) and local (pollution, noise) impacts are captured in a consistent, multi-dimensional format, allowing comparisons across generations and categories of aircraft. Figure 1 illustrates the Aircraft Label format for a representative modern aircraft (Airbus A350-900).

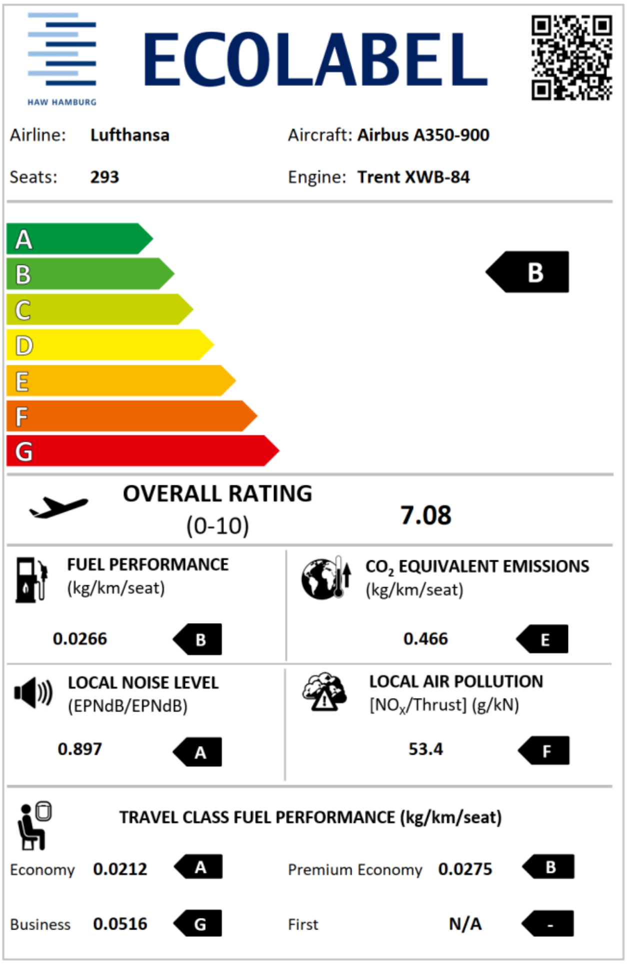


FIG.1 Ecolabel for Passenger Aircraft [4]. Calculated is an Overall Rating. 0 is worst performance, 10 is best performance. The Overall Rating is mapped to a score from A to G. The label shows the score also separately for the four environmental dimension and for the different classes. Passengers flying the economy class fly with a better score than passengers in first class.

### 3.1. Fuel Performance

Fuel consumption is a good indicator for the contribution of aviation to oil depletion, but aircraft manufacturers rarely disclose this information in a standardized matter. There are different methods to calculate fuel consumption, which are discussed by Hurtecant [7] and Kühn [8]. The updated Aircraft Label [4] uses a point performance metric known as "Extended Payload-Range". It is derived from the extended payload-range diagram. It only needs the maximum take-off weight (MTOW) $m_{MTOW}$, the maximum zero fuel weight (MZFW) $m_{MZFW}$, the range at maximum payload ($R_1$) – also called harmonic range – and the number of seats $n_{seats}$ of an aircraft to determine the fuel consumption $C$ per passenger, kilometer and seat via (1).

$$C = \frac{1}{n_{seat}} \cdot m_{MTOW} \cdot \left(1 - \frac{m_{MZFW}}{m_{MTOW}}\right) \cdot \frac{1}{R_1} \quad [\text{kg/km/seat}] \qquad (1)$$

This data can be obtained from openly available documents from the aircraft manufacturer usually called "Airplane Characteristics for Airport Planning" (Boeing) or similar.

These documents include aircraft mass data and payload-range diagrams from which the range at maximum payload can be obtained. However, the various designations of these documents highlight a lack of standardization, making it challenging to obtain accurate data. For instance, the Airbus A320 comes in 19 different weight variants, with Maximum Takeoff Weights (MTOWs) ranging from 66,000 kg (WV006) to 78,000 kg (WV017), each with its own Maximum Zero-Fuel Weight (MZFW) [8]. Unfortunately, not all weight variants have corresponding payload range diagrams, which limits the available harmonic range data for different weights.

## 3.2. Carbon Dioxide Equivalent Emissions

The environmental impact of aviation encompasses more than just carbon dioxide emissions. $NO_x$ emissions at high altitude result in the formation of ozone, a potent greenhouse gas, and reduce ambient methane, a cooling agent, thereby leading to net warming. Water vapor emissions at cruise altitudes, under suitable meteorological conditions, contribute to the formation of persistent contrail cirrus clouds. These clouds trap outgoing longwave radiation and thus produce a short-term but intense warming effect. Contrail cirrus is now recognized as the single largest contributor to aviation's net radiative forcing [1].

Importantly, the formation and persistence of these clouds depend on specific atmospheric conditions, making their modeling complex and regionally sensitive. This altitude-dependent effect is reflected in the forcing factors established by Schwartz [9], which vary for each emission species and are used to calculate the characterization factors (CF) for NOx and AIC to incorporate these emission effects in the Aircraft Label, as detailed by Hurtecant [7].

The $CO_2$-equivalent metric integrates multiple contributors to radiative forcing into the mass of equivalent CO2 $m_{CO2,eq}$, expressed in kilograms of $CO_2$-equivalent per seat-kilometer. The base component is direct $CO_2$ emissions, derived from fuel burn multiplied by a constant emission index $EI_{CO_2}$ (3.16 kg $CO_2$/kg fuel). $NO_x$ emissions are estimated using the Boeing Fuel Flow Method 2, with engine-specific parameters obtained from ICAO's Aircraft Engine Emissions Databank.

$NO_x$ and AIC emissions are converted into $CO_2$-equivalent values using established characterization factors *CF*. The altitude dependence of both effects is incorporated through the application of altitude-specific forcing factors.

The impact of AIC is modeled to be directly proportional to fuel consumption per nautical mile $f_{NM}$ at the aircraft's specific cruise altitude, so that more fuel-efficient aircraft generate correspondingly less AIC. The total $CO_2$-equivalent value is obtained by aggregating the individual contributions from direct $CO_2$ emissions, AIC, and $NO_x$-related climate effects. This composite metric displayed in (2) is explained fully in [4]. It captures both short-lived climate forcers and long-lived greenhouse gases, addressing the full radiative impact of a flight.

$$m_{CO2,eq} = \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,CO_2} + \frac{EI_{NO_x} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NO_x} + \frac{R_{NM} \cdot f_{NM}}{R_{NM} \cdot f_{NM,ref} \cdot n_{seat}} \cdot CF_{midpoint,AIC} \qquad (2)$$

## 3.3. Local Air Pollution

The LCA methodologies provide a structured approach for converting so-called midpoint impact categories such as photochemical ozone formation and particulate matter along certain damage pathways to the so-called endpoint area of protection, which could be damage to human health effect. The ReCiPe 2016 framework [10], in particular, offers global normalization and characterization factors that can be applied to aviation emissions.

Anthropogenic particulate matter PM2.5 is acting as a primary aerosol, nitrous oxide and sulfur dioxide as secondary aerosols. Their damage to human health is displayed in Figure 2. The main contributor is not the primary aerosol itself with only a small share of 1.59 %, but rather secondary aerosols formed because of nitrous oxide (90.4 %) and sulfur dioxide (8.01 %). Nitrous oxide has by far the largest share because their emissions are up to 2-3 orders of magnitudes higher compared to PM2.5 and one order of magnitude compared to sulfur dioxide.

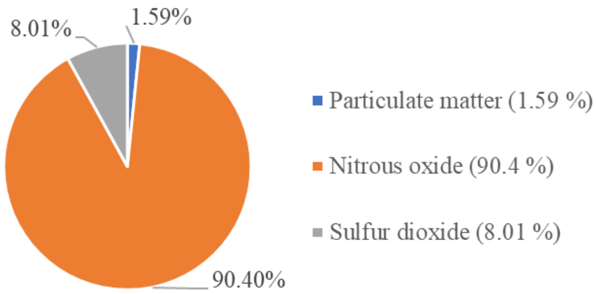


FIG. 2 Contribution of aerosols to the impact of particulate matter formation on human health of a Trent 1000-J3 [4]

Health damage due to photochemical ozone formation caused by aviation can be attributed to the four kinds of emissions displayed in Figure 3. The combined emissions of sulfur dioxide (0.53 %), carbon monoxide (5.02 %) and hydrocarbons (3.03 %) are not even resulting in a 10 percent share. By far the biggest share is represented by nitrous oxide emissions again.

Since the goal of an environmental label is to provide a single source of easily accessible, easy-to-understand data

– it was decided to base the local air pollution rating solely on the emission of nitrous oxide.

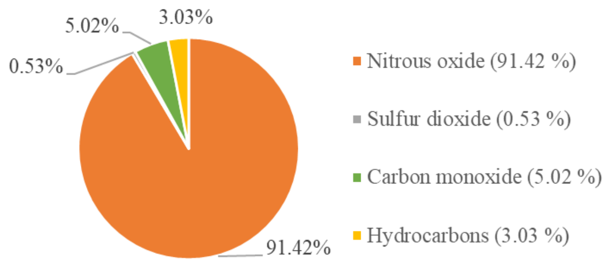


FIG. 3 Contribution of pollutants to the impact of ozone formation on human health of a CFM56-5B4/3 [4]

The Aircraft Label evaluates local air pollution based on emissions during the LTO cycle, including take-off, climb-out, approach, and taxi phases. $NO_x$ emissions are obtained from ICAO databank values and scaled using actual thrust settings and engine time-in-mode distributions. The metric is expressed in grams of $NO_x$ per kilonewton of thrust, then normalized per seat-kilometer for label scoring. This approach reflects the public health implications of airport-proximate emissions and is calculated via (3).

$$Normalized\ amount\ of\ emitted\ NO_x = \frac{(NO_x)_{LTO}}{Rated\ thrust} \quad (3)$$

### 3.4. Noise Pollution

Noise pollution is evaluated based on the Effective Perceived Noise in Decibels (EPNdB) at three certification points: approach, lateral (sideline), and flyover. These values are sourced from type certification data published by EASA and FAA, with an averaging scheme that mirrors ICAO's noise evaluation standard. Each aircraft's average EPNdB is then compared to baseline values and normalized relative to the most and least noisy aircraft in the dataset, characterized by the Noise Index Value *NIV*. This criterion provides a measure of community noise burden associated with typical operation and is calculated via (4).

$$NIV_{average} = \frac{NIV_{lateral} + NIV_{flyover} + NIV_{approach}}{3} \quad (4)$$

## 4. AIRLINE LABEL

The Airline Label builds upon the methodology of the Aircraft Label. As such, it also incorporates $CO_2$-equivalent emissions, local noise levels, and air pollution in addition to common efficiency indicators such as fuel performance and $CO_2$ emissions, providing a more comprehensive measure of environmental performance.

This Airline Rating *AR* is calculated via (5), using the following variables:

- $N_{Aircraft}$: *Number of aircraft type in fleet*
- $S_{Aircraft}$: *Number of seats per aircraft*
- $O_{Aircraft}$: *Overall aircraft rating*
- *i*: *ID of the aircraft type of an airline.*

$$AR = \frac{\sum N_{Aircraft,i} \cdot S_{Aircraft,i} \cdot O_{Aircraft,i}}{\sum N_{Aircraft,i} \cdot S_{Aircraft,i}} \quad (5)$$

The fleet of an airline is usually comprised of a variety of aircraft types in different number. An example is provided by the Lufthansa fleet shown in Table 1, which consists of 16 different aircraft types. The individual overall rating for each aircraft type reaches from 4.8 (Boeing 747-400) to 8.44 (Airbus A320 Neo).

A low-cost carrier operating a homogeneous fleet of fuel-efficient narrowbodies with high seat density will generally score better than a legacy airline operating older aircraft with premium-heavy cabin layouts. This label provides a snapshot of the airline's technical environmental performance, independent of actual load factors or routing choices.

TAB. 1 Lufthansa aircraft fleet and airline rating [4]

| ID (I) | Aircraft type | No. of Aircraft (*N*) | Seats per Aircraft (*S*) | Overall Rating (*O*) |
|---|---|---|---|---|
| 1 | Airbus A319-100 | 35 | 138 | 7.38 |
| 2 | Airbus A320-200 | 52 | 168 | 7.31 |
| 3 | Airbus A320 Neo | 35 | 180 | 8.44 |
| 4 | Airbus A321-100 | 20 | 200 | 7.12 |
| 5 | Airbus A321-200 | 37 | 200 | 6.93 |
| 6 | Airbus A321 Neo | 17 | 215 | 8.01 |
| 7 | Airbus A330-300 | 10 | 255 | 5.82 |
| 8 | Airbus A340-300 | 17 | 279 | 4.32 |
| 9 | Airbus A340-600 | 10 | 297 | 4.39 |
| 10 | Airbus A350-900 | 21 | 293 | 7.08 |
| 11 | Airbus A380-800 | 8 | 509 | 5.03 |
| 12 | Boeing 747-400 | 8 | 317 | 4.8 |
| 13 | Boeing 747-800 | 19 | 364 | 5.36 |
| 14 | Boeing 787-9 Dreamliner | 5 | 294 | 7.53 |
| 15 | Bombardier CRJ-900 | 28 | 79 | 6.42 |
| 16 | Embraer E190LR | 7 | 100 | 6.57 |
| | Total: | 329 | **Airline Rating: 6.55** | |

The Airline Label allows for a direct comparison of the environmental performance of major carriers. Table 2 illustrates the distribution of Airline Label scores across the "50 most important international carriers", demonstrating substantial variation attributable to fleet strategy.

In the ranking shown in Table 2, airlines such as IndiGo, easyjet, and Ryanair achieve high scores due to their use of modern aircraft (e.g., A320neo, 737 MAX) and high-density seating configurations. In contrast, full-service carriers (FSCs) with mixed fleets and premium class seating tend to score lower due to higher emissions per passenger-kilometer.

But IndiGo's leading position is not explained by fleet modernity alone. The decisive factor is its extensive deployment of ATR 72 turboprops, which – despite the

A320neo's superior fuel efficiency and lower noise – deliver substantially lower $CO_2$-equivalent values per seat. This advantage is driven by the ATR 72's lower cruise altitudes, which markedly diminish the contribution of AIC to total climate impact.

TAB. 2 Airline ranking calculated via the Aircraft and Airline label [4]

| Ranking | Airline | Airline Rating |
|---|---|---|
| 1 | IndiGo | **8.18** |
| 2 | SAS Scandinavian Airlines | **7.86** |
| 3 | Spring Airlines | **7.79** |
| 4 | easyjet (UK) | **7.78** |
| 5 | Spirit Airlines | **7.78** |
| 6 | Azul | **7.72** |
| 7 | TUIfly | **7.51** |
| 8 | vueling Airlines | **7.50** |
| 9 | Avianca | **7.48** |
| 10 | Ryanair | **7.33** |
| 11 | Eurowings | **7.31** |
| 12 | LATAM Airlines Brasil | **7.26** |
| 13 | GOL Linhas Aereas | **7.26** |
| 14 | Shandong Airlines | **7.26** |
| 15 | Xiamen Airlines | **7.23** |
| 16 | Air New Zealand | **7.21** |
| 17 | WestJet Airlines | **7.20** |
| 18 | Sichuan Airlines | **7.20** |
| 19 | Southwest Airlines | **7.17** |
| 20 | American Airlines | **7.13** |
| 21 | Air India | **7.12** |
| 22 | China Southern Airlines | **7.11** |
| 23 | Shenzhen Airlines | **7.06** |
| 24 | Air Canada | **7.06** |
| 25 | Hainan Airlines | **7.04** |
| 26 | JetBlue Airways | **7.00** |
| 27 | China Eastern Airlines | **7.00** |
| 28 | Vietnam Airlines | **6.99** |
| 29 | Aeroflot | **6.82** |
| 30 | Condor | **6.76** |
| 31 | Air China | **6.73** |
| 32 | Japan Airlines | **6.73** |
| 33 | Air France | **6.73** |
| 34 | Alaska Airlines | **6.72** |
| 35 | Turkish Airlines | **6.66** |
| 36 | Delta Airlines | **6.66** |
| 37 | KLM | **6.65** |
| 38 | All Nippon Airways | **6.65** |
| 39 | Saudi Arabian Airlines | **6.61** |
| 40 | Lufthansa | **6.55** |
| 41 | Qatar Airways | **6.53** |
| 42 | United Airlines | **6.47** |
| 43 | Garuda Indonesia | **6.43** |
| 44 | British Airways | **6.36** |
| 45 | Korean Air | **6.35** |
| 46 | Qantas | **6.33** |
| 47 | Cathay Pacific | **6.23** |
| 48 | Delta Connection | **6.20** |
| 49 | Singapore Airlines | **6.10** |
| 50 | Emirates | **5.47** |

SAS Scandinavian Airlines attains a similarly high ranking primarily because it operates a comparatively large share of ATR 72s relative to other carriers. Although SAS's A320neo and ATR 72 configurations are typically more spacious – slightly reducing per-seat density and nudging up per-seat metrics – the sizable ATR contribution offsets this effect. In combination, these factors explain SAS's strong position in the ranking alongside IndiGo.

The negative effect of LCCs: With LCCs operating often a more environmentally friendly fleet (expressed by the Airline Rating, AR), this unfortunately does not translate into a global advantage for the environment. Higher efficiency and lower costs stimulate additional demand (here especially from the many people with lower income) leading in the end to more pollution. This is known as the Rebound Effect or Jevons Paradox (with respect to aviation see [11]). Today, flying is not anymore restricted to the elite as it was in the 1950s. This is a positive social development, but it is not good for the planet.

The positive effect of LCCs: LCCs offer a way for people, with e.g. one return flight per year, to undertake these two flights at the smallest possible environmental footprint for a given flight distance.

In contrast, frequent flyers have a huge environmental footprint: By definition, they undertake a questionable high number of flights per year. They often choose an FSC with lower AR. They generally choose a more luxurious travel class (first or business) with a bad score towards E, F, or G.

Atmosfair decided to simply exclude LCCs from its Atmosfair Airline Index (AAI) [5] because of the negative effect of LCCs. This is an arbitrary decision and only helps heavily polluting airlines to a better place in the ranking by getting rid of their obnoxious competition.

Aviation is facing a big environmental challenge by its expected continuous growth. Today only 1 % of the world's population (frequent flyers) cause 50 % of commercial aviation's emissions, 19 % cause the remaining 50 %. 80 % of the world's population have never set foot on an airplane. [6] For sure, these 80 % will also demand aviation's connectivity for themselves. It would be better to meet this demand with LCCs than with FSCs.

The Airline Label does not currently incorporate dynamic operational variables such as actual load factors, maintenance performance, or route-specific efficiency. It represents a technical benchmark based on published fleet composition and standardized performance data. Future extensions could include dynamic scoring based on monthly or annual fuel consumption reports, or real-time emissions tracking.

## 5. FLIGHT LABEL

The Flight Label constitutes the most detailed tier of environmental labeling, building upon the Aircraft and Airline Labels by incorporating operational variables and itinerary-specific parameters. While aircraft and airline scores provide static evaluations of technical efficiency, the Flight Label captures additional variables such as routing, stopovers, class of travel, and actual distance flown. It is designed to offer passengers a meaningful, transparent environmental score for individual flight options during the booking process.

One way of calculation of the Flight Label involves the sequential evaluation of all flight segments in a given itinerary. For each segment, the aircraft type is identified, and its corresponding Aircraft Label data is retrieved.

The environmental impact is calculated for the actual great-circle distance plus additional 50 kilometers for each flight to account for flight inefficiencies caused by ATM. For itineraries with stopovers, the fuel burn and emissions are summed across all segments.

The resulting per-passenger environmental impact is assessed with the four criteria known from the Aircraft label. Class of travel adds an additional layer of normalization, as business and first-class seats occupy more space and contribute greater weight per passenger, thereby increasing the proportional environmental impact. These effects are accounted for by adjusting the values accordingly and converting them into a unified Flight Label score, applying the same weighting logic used for the Aircraft Label.

A useful benchmark is provided by a reference medium-haul direct flight on a Boeing 737-800 over a typical distance of 2,400 km. Such a reference point allows for meaningful comparisons, as platforms like Google Flights often limit their analysis to emissions differences within the same route, for example reporting up to 24 % lower emissions than the average flight on that route.

However, analysis shows that a direct long-haul flight from San Francisco to Singapore can impose an environmental burden 5.7 times greater than the reference flight. The impact can be even more pronounced for multi-leg journeys over the same distance, reaching up to 10.3 times the reference value. Presenting these differences clearly can encourage passengers to consider alternatives such as direct flights between different departure and arrival airports, integrating other transport modes, or selecting direct flights at alternative times.

Ideally, such alternatives should be reflected in the Multimodal Trip Score. In addition to supporting consumer choice, the Flight Label can also function as an incentive mechanism for airlines to operate more efficient aircraft on popular routes or to reduce reliance on long detour-prone networks. Integration with loyalty programs or carbon pricing tools could further amplify its effectiveness.

## 6. MULTIMODAL TRIP SCORE

While the Flight Label enhances transparency within the aviation sector, travelers often compare air travel with other transport modes such as rail, bus, or car. The *Multimodal Trip Score* is proposed as an extended label that integrates environmental impact with two additional decision criteria: total travel time and monetary cost. This score enables passengers to compare the total utility of competing travel options across transport modes, aligning environmental considerations with practical planning needs.

The Multimodal Trip Score is calculated using a weighted sum of three criteria:

- Environmental impact (*E*)
- Time (*T*): Total travel time
- Price (P): Including base fare and optional carbon offsetting

The traveler or platform algorithm assigns weights ($w_E$, $w_T$, $w_P$) to each component according to user preference or policy objectives. The total score is then computed as described in (5):

$$Multimodal\ Trip\ Score = \mathrm{w_E} \cdot E + w_T \cdot T + w_P \cdot P \qquad (6)$$

This formulation allows for flexible prioritization. A climate-conscious traveler might assign high weight to environmental impact, while a business traveler may emphasize time. The score can be implemented dynamically in digital platforms to produce ranked travel options.

The integration of the Multimodal Trip Score into digital booking systems would enable real-time comparisons between, for example, a high-speed rail trip and a short-haul flight. The underlying environmental data can be sourced from standardized labels, while time and cost are already components of existing fare search algorithms.

Beyond individual decision-making, transport authorities or travel management companies could utilize this score to guide travel policy, promote modal shifts, or design incentives. By incorporating the broader dimensions of travel planning, the Multimodal Trip Score transforms the label from a static metric into a decision-support tool.

## 7. RESULTS

The Aircraft Label has been applied to a representative selection of commercial aircraft, including narrowbodies such as the Airbus A320 and Boeing 737 families, widebodies like the A330 and A380, and regional turboprops such as the ATR 72. The label scores reveal considerable variation in environmental performance even within the same aircraft category.

Figure 4 displays the disaggregated $CO_2$-equivalent emissions of some reference aircraft. The ATR 72, being a low-speed turboprop optimized for regional routes, exhibits the lowest overall emissions per seat-kilometer, followed by the A320 Neo.

The A380, despite its high passenger capacity, records the highest emissions per passenger. The design of the A380 had to make many (aerodynamic) compromises to incorporate the big aircraft into existing airport geometry. The A380 was designed for a stretched version, which never came. This made the aircraft heavy.

Furthermore, it can be seen in Figure 4, that there is no big difference in the distribution of contributing factors of $CO_2$ equivalent emissions between an Airbus A320 and a Boeing 737 and their different engine options. The typical distribution of factors contributing to $CO_2$ equivalent emissions is shown in Figure 5.

Some aircraft emit more nitrous oxides. From Figure 6 it seems that aircraft with four engines emit more nitrous oxides. A closer look [12] shows that Overall Pressure Ratio (OPR) and combustor technology are decisive.

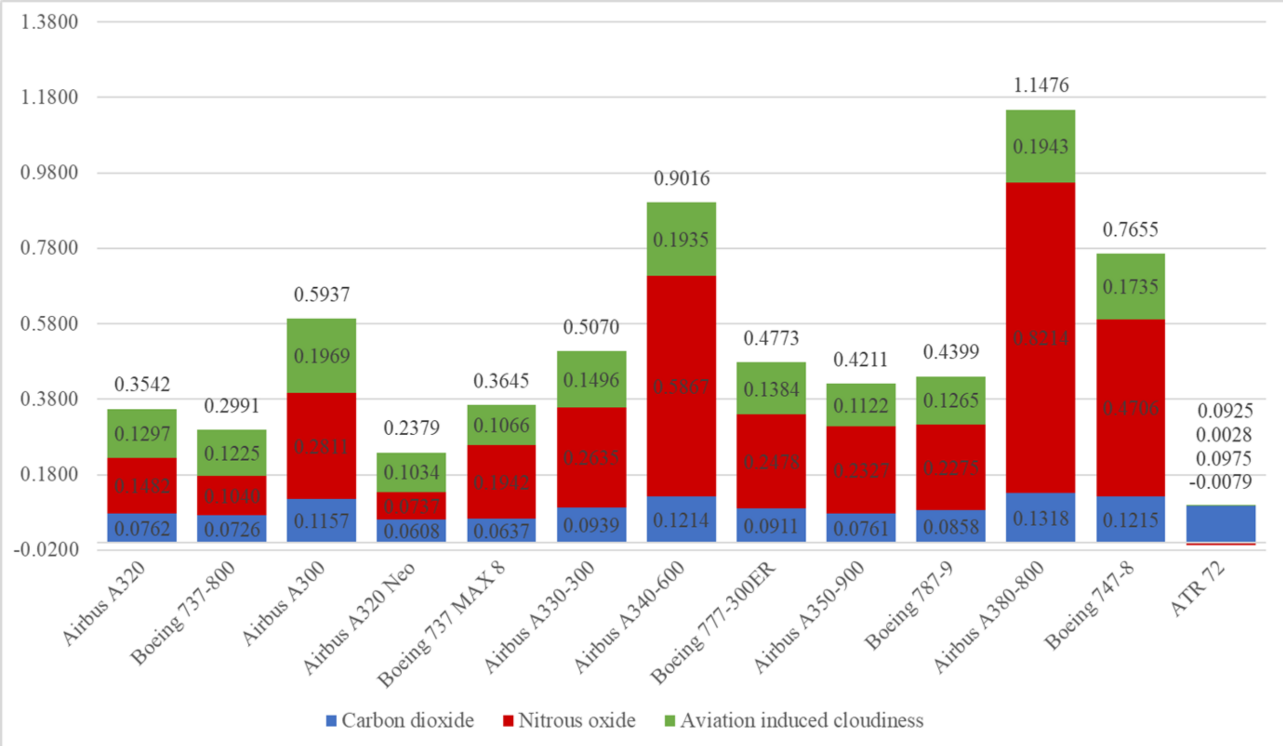


FIG. 4 Comparison of contributions to equivalent $CO_2$ emissions of different aircraft (kg $CO_2$/km/seat) [4]

Aircraft with turboprop engines do cause the least environmental burden. Due to their low cruise altitude they show almost no Aircraft Induced Cloudiness (AIC) as can be seen from Figure 7. At low cruise altitude $NO_x$ can even have a cooling effect.

Lee [1] showed that radiative forcing from aviation is largely driven by aviation-induced cloudiness (AIC), which accounts for roughly half of the total effect, while carbon dioxide contributes about one third and nitrogen oxides ($NO_x$) around one sixth. This may be true for a global average of all aircraft. A more detailed view (Figures 5, 6, and 7) illustrate that the relative contributions of $CO_2$, $NO_x$, and AIC to CO2-equivalent emissions vary significantly depending on the specific aircraft–engine combination.

For the Airbus A320, the relative contributions of $CO_2$ and $NO_x$ differ from the overall average: $NO_x$ plays a more prominent role, while AIC is comparatively less relevant. This is most likely explained by the aircraft's improved fuel efficiency relative to the reference case, which reduces contrail formation.

Turboprop aircraft, on the other hand, show a fundamentally different distribution of $CO_2$-equivalent emissions due to their lower cruise altitudes. The ATR 72 achieves the lowest overall environmental burden, as its low operating altitude results in almost no formation of AIC. NOx emissions from such aircraft may also shorten the atmospheric lifetime of methane [13].

The analysis indicates that $CO_2$-equivalent emissions are strongly influenced by the specific aircraft–engine combination, with substantial variation even among aircraft of similar size and thrust. For example, the Airbus A340 produces more than twice the $NO_x$ emissions of the Boeing 777-300ER, leading to markedly different ratios of $CO_2$ to non-$CO_2$ effects. This variability challenges the common practice of applying a constant multiplier – such as the factors of two or three used by tools like Atmosfair – to account for non-$CO_2$ impacts. A more accurate approach would apply a variable factor that reflects the characteristics of each specific aircraft – engine pairing.

These results demonstrate that the Aircraft Label effectively differentiates between aircraft types based on objective performance criteria and highlights the benefits of fleet modernization and aerodynamic refinement.

The Airline Label was applied to a dataset of 50 major international carriers using publicly available fleet information. Table 2 presents a selection of the results, showing that low-cost carriers such as IndiGo, easyjet and Ryanair achieve the highest scores, while legacy carriers such as Lufthansa, British Airways, and Air France generally receive lower scores. This pattern largely reflects differences in fleet composition, seating density, and route structure – LCCs typically operate newer, homogenous fleets of fuel-efficient aircraft on short average stage lengths, whereas FSCs tend to maintain mixed fleets that include older widebodies, long-haul operations, and premium-heavy cabin configurations.

Beyond these general trends, rankings are also influenced by the use of specific aircraft types such as the ATR 72, whose lower cruise altitudes reduce the climate impact of aviation-induced cloudiness (AIC). This effect can be observed across both carrier types – for example, in SAS Scandinavian Airlines' strong performance despite being a full-service carrier, due in part to its relatively high share of ATR 72 operations. These results reinforce the importance of fleet renewal and network design in determining an airline's environmental efficiency.

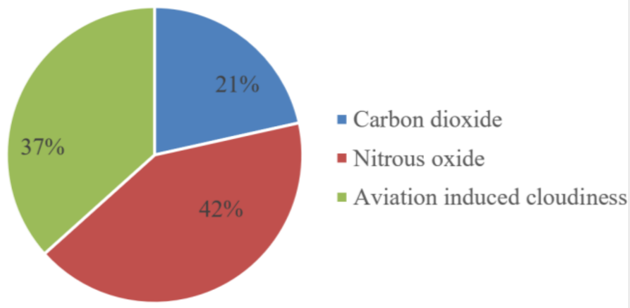


FIG. 5 Contribution to equivalent CO2 emissions of an Airbus A320 with a CFM56-5B4/P engine [4]

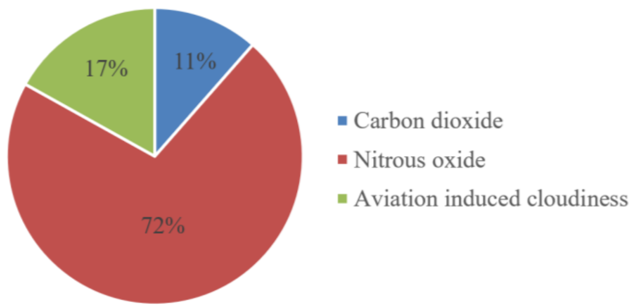


FIG. 6 Contribution to equivalent CO2 emissions of an Airbus A380-800 with a GP7270 engine [4]

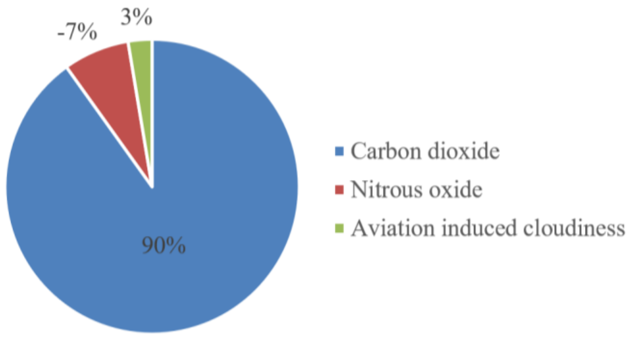


FIG. 7 Contribution to equivalent CO2 emissions of an ATR 72 with a PW127 engine [4]

## 8. DISCUSSION

Determining the fuel consumption of an aircraft is a significant challenge in establishing accurate Aircraft, Airline, or Flight labels. The point performance method known as "Extended Payload-Range" (based on only three parameters) provides a reasonable indication.

Due to a lack of data, this method does not account for the variations in fuel consumption between different engines on the same aircraft type. Luckily, differences in fuel consumption between engines offered on the same aircraft type are generally small. More importantly, point performance methods ignore the strong variation of fuel burn with flight distance [8].

Unfortunately, this effect can only be accounted in an Airline Label by considering all flights of an airline with each of its aircraft types. This would require an unbearable effort and may in the end not change much in the ranking of the airlines.

It is difficult to find comparable data across manufacturers to calculate fuel consumption. It seems timely, to define a standardized fuel consumption metric for passenger aircraft and to require manufacturers to provide such data to the public. Industry's secrecy seems to be in the way. Unfortunately, public data to a clearly defined fuel metric will not be available in the near future.

The recent adjustment of the Aircraft Label to make the environmental impact of aircraft-induced cloudiness (AIC) dependent on fuel consumption is a step forward. However, it needs more. Different aircraft-engine combinations influence AIC due to the unique chemical composition of exhaust emissions. In this respect, the amount of emitted soot seems to be decisive. It strongly depends on the combustor technology.

Future iterations of Aircraft, Airline, and Flight labels could consider incorporating the amount and impact of different pollutants on AIC formation for a more sophisticated assessment.

The labeling system described in this study is designed for integration into digital booking platforms such as Google Flights, Skyscanner and similar services. Currently, such platforms may display estimated emissions but rarely provide standardized, transparent methodologies. The Aircraft, Airline, and Flight Labels, combined with the Multimodal Trip Score, offer a rigorous scientific approach with high transparency because the method is only based on information available in public.

Label integration could occur through color-coded indicators, filter functions, or even default sorting by environmental performance. Application Programming Interfaces (APIs) – automated data connections that allow booking platforms to request and receive specific information from external databases – could deliver Aircraft and Airline Label data during fare searches, while the Flight Label and Trip Score could be computed dynamically at the itinerary level.

Such integration would empower users to consider environmental factors alongside price and duration, without reverting to a separate tool, which would require the user to input flight data again.

Several behavioral studies have demonstrated that environmental labels can influence consumer preferences even in price-sensitive markets. When presented with environmental performance information at the point of decision, a measurable share of travelers is willing to select a greener option, even if slightly more expensive or longer in duration.

The Flight Label and Multimodal Trip Score thus serve not only as informational tools but also as behavioral nudges. Combined with carbon offsetting programs, rewards for low-impact travel, or corporate travel policies, these labels could contribute to systemic demand shifts and modal rebalancing.

Long-term behavioral adaptation may also emerge from repeated exposure to environmental performance scores, especially when labels are consistent and reinforced by trusted third parties or regulators.

From a policy perspective, environmental labeling in aviation could complement existing measures such as the EU Emissions Trading Scheme (EU ETS) and ICAO's CORSIA framework. While these mechanisms operate at a regulatory or industry level, labels provide a bottom-up approach that can engage consumers and foster voluntary compliance.

It must be noted that a flight booking decision based on the best environmental data will always be a prediction of the flight. The actual flight will vary from the prediction. The airline may use an aircraft for the flight different form the one announced.

The passenger load factor can be different from the one assumed. In an extreme case, the passenger could be flying in an almost empty aircraft. A night flight may produce a contrail called a "big hit" with severe global warming effect.

In contrast, a daytime flight may have a cooling effect, whereas the AIC effect was calculated before the flight on global averages. An environmental decision for a particular flight offer can only be a decision based on a probability that the flight will perform as predicted.

The choice of an airline based on the Airline Ranking is only a choice based on the average of all its aircraft in the fleet. The passenger can well end up in the one very polluting type operated by this airline.

In the long run, label standardization would be necessary with industry-wide coordination and oversight. A regulatory body or independent third party may be needed to certify, maintain, and update the underlying data and algorithms.

We see some form of standardization already. On the one hand, we see the emerging EU "Flight Emissions Label" (FEL) by EASA, which is strongly influenced by interests of the aviation industry.

On the other hand, we see Google Flight with emissions calculated by the "Travel Impact Model" (TIM) (https://travelimpactmodel.org) overseen by an independent Advisory Committee. This could develop into a de facto standard based on usage.

However, Google Flight writes: "Beginning in July 2025, whenever available, we use the EASA Flight Emissions Label, which is based on an airline's own verified historical data for a specific route." So it seems, merging of the two big players is already on the way, with the aviation industry taking over.

## 9. SUMMARY AND CONCLUSION

This study introduces a comprehensive, scientifically grounded framework for environmental labeling in aviation, encompassing aircraft types, airline fleets, individual flights, and multimodal journeys. Through the systematic application of LCA methods, certified emissions data, and normalization per seat-kilometer, the proposed labels provide a transparent and comparable basis for evaluating the environmental performance of air travel.

The *Aircraft Label* differentiates aircraft based on fuel efficiency, climate impact (including AIC and $NO_x$), local air pollution, and noise. The *Airline Label* aggregates these results at the fleet level, offering insights into structural efficiency. The *Flight Label* captures route-specific parameters such as stopovers and class of travel, while the *Multimodal Trip Score* integrates environmental impact with time and cost considerations, enabling cross-modal comparisons.

Applied to real-world data, the labels reveal significant differences in performance across aircraft types, airlines, and itineraries. Turboprops and modern narrowbodies show superior environmental performance, while low-cost carriers operating fleets with high density cabin layouts and often modern aircraft rank higher than legacy carriers. Direct flights typically offer lower emissions than multi-leg routes, particularly in short- and medium-haul contexts.

The proposed framework fills a critical gap in current emissions transparency tools, which often focus solely on $CO_2$ and neglect non-$CO_2$ effects or passenger-related parameters. By providing a standardized labeling approach, this system can enhance consumer awareness, support climate-conscious behavior, and complement policy instruments such as emissions trading schemes.

Future work should focus on incorporating gained knowledge into the global discussion about aviation labels and the environmental evaluation of flights. The developed Aircraft, Airline and Flight Labels need institutional support for label certification, governance, and dissemination.

With increasing societal and regulatory pressure on aviation to decarbonize, environmental labeling represents a low-cost, high-impact strategy to foster informed travel decisions and accelerate the transition to sustainable mobility.

## NOMENCLATURE

### Symbols

| | |
|---|---|
| $C$ | Fuel Consumption |
| $CF_{midpoint,AIC}$ | Characterization factor AIC |
| $CF_{midpoint,CO2}$ | Characterization factor $CO_2$ |
| $CF_{midpoint,NOx}$ | Characterization factor $NO_x$ |
| $E$ | Environmental Impact |
| $EI_{CO2}$ | Emission index $CO_2$ |
| $EI_{NOx}$ | Emission index $NO_x$ |
| $EI_{AIC}$ | Emission index AIC |
| $f_{NM}$ | Fuel consumption per nautical mile |
| $f_{NM,ref}$ | Reference fuel consumption per nautical mile |
| $i$ | ID of the aircraft type of an airline |
| $m_{CO2,eq}$ | Equivalent mass of $CO_2$ emissions |
| $m_{MTOW}$ | Maximum Take-Off Weight |
| $m_{MZFW}$ | Maximum Zero Fuel Weight |
| $N_{aircraft}$ | Number of aircraft type in fleet |
| $NIV_{approach}$ | Noise level of aircraft at reference point approach |
| $NIV_{average}$ | Average noise level of aircraft |
| $NIV_{flyover}$ | Noise level of aircraft at reference point flyover |
| $NIV_{lateral}$ | Noise level of aircraft at reference point lateral |
| $NO_{x,LTO}$ | Impact of nitrous oxide formation on human |

| | |
|---|---|
| | health during an LTO cycle |
| $n_{seat}$ | Number of seats |
| $O_{aircraft}$ | Overall aircraft rating |
| $P$ | Price of a flight ticket including base fare and optional carbon offsetting |
| $R_1$ | Range at maximum Payload (Harmonic Range) |
| $R_{NM}$ | Stage length |
| $S_{aircraft}$ | Number of seats per aircraft |
| $T$ | Travel Time |
| $w_E$ | Weighting Factor Environmental Impact |
| $w_P$ | Weighting Factor Price |
| $w_T$ | Weighting Factor Travel Time |

## Abbreviations

| | |
|---|---|
| AAI | Atmosfair Airline Index |
| AIC | Aviation Induced Cloudiness |
| API | Application Programming Interface |
| AR | Airline Rating |
| ATM | Air Traffic Management |
| CF | Characterization Factor |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| EASA | European Union Aviation Safety Agency |
| ETS | Emissions Trading Scheme |
| FAA | Federal Aviation Administration |
| FEL | Flight Emissions Label |
| FSC | Full Size Carrier |
| ICAO | International Civil Aviation Organization |
| LCA | Life Cycle Assessment |
| LCC | Low Cost Carrier |
| LTO | Landing and Take Off |
| MTOW | Maximum Take Off Weight |
| MZFW | Maximum Zero Fuel Weight |
| NIV | Noise Index Value |
| TIM | Travel Impact Model |

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