

Aviation and the environment: Rating airlines on their CO₂ efficiency

Niels van Dorland¹ and Frank van der Zwan²

Delft University of Technology, 2629 HS Delft, The Netherlands

Stefaan Ghijs³ and Sicco Santema⁴

Delft University of Technology, 2629 HS Delft, The Netherlands

and

Richard Curran⁵

Delft University of Technology, 2629 HS Delft, The Netherlands

The aviation industry contributes about 2% to the total global manmade CO₂ emissions, which is seen as the main (manmade) greenhouse gas inducing climate change. This paper focuses on the design of a CO₂ rating system which makes it possible to make a fair comparison of the environmental performance of airlines with respect to CO₂ on the basis of public available data. It is argued that airlines can be best compared on the amount of CO₂ emitted per revenue ton kilometer (CO₂/ RTK) on the basis of distance sectors. Therefore, an airline is rated on various distance sectors. The CO₂ efficiency scores of an airline within a distance sector can then be compared with other airlines. For nine airlines the CO₂ efficiency is modeled, and the distance sector boundaries are determined. It is shown that the relative positions of airlines may change when choosing a different boundary, since the CO₂ efficiency changes with distance. It is also shown that on the basis of public available information it is difficult to accurately determine the CO₂/ RTK of an airline, which is due to lack of detail in public available data. A sensitivity analysis has been performed to show on which parameters information in greater detail is needed.

I. Introduction

CLIMATE CHANGE is a “hot” topic nowadays. The average Earth surface temperature is increasing due to human activities. Carbon dioxide (CO₂) is seen as the main manmade greenhouse gas which induces climate change, and it is emitted in almost every industry, including aviation. Although aviation only contributes 2% to the global man made CO₂ emissions¹, this share is expected to increase due to the rapid growth of the aviation industry. Besides CO₂, there are other greenhouse gases emitted by aviation which induce climate change. In addition, aviation also has other environmental concerns such as noise and local air quality issues around airports.

¹ MSc student, Air Transport & Operations, Faculty of Aerospace Engineering, Delft University of Technology, PO Box 5058, 2600 GB Delft, The Netherlands.

² Assistant professor, Air Transport & Operations, Faculty of Aerospace Engineering, Delft University of Technology, PO Box 5058, 2600 GB Delft, The Netherlands, AIAA member.

³ Airline project manager, Air Transport & Operations, Faculty of Aerospace Engineering, Delft University of Technology, PO Box 5058, 2600 GB Delft, The Netherlands.

⁴ Professor, Air Transport & Operations, Faculty of Aerospace Engineering, Delft University of Technology, PO Box 5058, 2600 GB Delft, The Netherlands.

⁵ Chair, Air Transport & Operations, Faculty of Aerospace Engineering, Delft University of Technology, PO Box 5058, 2600 GB Delft, The Netherlands, AIAA Senior member.

On most white good consumer appliances the performance in terms of energy use can be compared. All cars in the European Union (EU) are nowadays rated for their CO₂ emission per kilometer. Further, financial institutes are rated for their creditworthiness by companies such as Standard & Poor's. For aviation however, there is no rating which makes it possible to compare the environmental performance of airlines in terms of CO₂ efficiency. In this paper, a rating methodology will therefore be designed. Although it is noticed that beside CO₂ emission there are other environmental concerns, this paper will focus on CO₂.

The main research question is defined as: *"How is it possible to indicate how well or how bad an airline scores with respect to other airlines on their CO₂ efficiency on the basis of public available parameters/data in order to make a justified comparison of airlines (a rating) and to give an initial advice to airlines for areas of improvement?"* In addition, to evaluate whether a rating which only rates on CO₂ emission covers 'aviation and environment', a concise literature review is presented about the effects of aviation on the environment.

A. Environmental Concerns Aviation

Besides CO₂ there are various other environmental concerns relating to aviation: aircraft noise, local air quality, and global emissions (climate change)². Aircraft noise is a subjective matter and is difficult to measure, i.e. one person may perceive aircraft noise as nuisance whereas another doesn't.

Local air quality (LAQ) is about the air quality at and around airports, and primarily relates to human health and welfare². The International Civil Aviation Organization (ICAO) has regulated the emissions from engines during the so-called landing and take-off cycle (LTO) which includes the operations below 3000 ft. Engine manufacturers have to comply with standards set by ICAO. Apart from the emissions from aircraft, the LAQ also includes emissions which are due to ground supporting activities, auxiliary power unit (APU) usage, and ground transport at or near airports².

Climate change is caused by the emission of greenhouse gases (GHGs). Due to these GHGs the composition of the atmosphere changes and this affects the warmth balance of the Earth. By the combustion of fuel, various products are formed dependent on the completeness of the reaction: CO₂, NO_x, H₂O, SO₂, and soot¹. Due to chemical reactions with substances in the atmosphere and microphysics, these substances change the radiative active substances in the atmosphere and therefore the radiative forcing, i.e. CO₂, ozone, methane, N₂O, H₂O, aerosols and clouds¹. Radiative forcing (RF) is defined as the global, annual mean radiative imbalance to the Earth's climate system caused by human activities¹. The radiative forcing index (RFI) is used to express the perturbation of a substance to the atmosphere with respect to the radiative forcing of CO₂ alone. On the whole, the aircraft emissions cause the Earth's surface temperature to increase. The quantities of the pollutants emitted by aircraft are solely dependent on the fuel consumption for CO₂ and H₂O, i.e. for CO₂ the mass of combustion product per unit mass of fuel is 3.15³. Further, the effect of emitting one ton of CO₂ at ground level is the same as in the air¹. For other pollutants, the impact on climate change depends on amongst others the altitude where it is emitted.

The other pollutants emitted by engines are dependent on the equivalence ratio Φ which is used to indicate the fuel-air mixture, i.e. lean, stoichiometric, and rich³. Therefore the quantity emitted by the engines is dependent on the thrust setting. Further, the level of scientific understanding of the radiative forcing of these substances is fair or poor⁴, i.e. for cirrus clouds which develop after the formation of contrails the scientific understanding is poor. Only for CO₂ emission the scientific level of understanding is good. When considering the RFI index of Sausen et al.⁴, the total radiative forcing is about 1.9 as high (excluding cirrus) as the RF of CO₂. Including non-CO₂ emissions could be done by using a multiplier such as RFI to account for the non-CO₂ emissions. Other metrics that could be used to calculate the effect of the individual substances on radiative forcing are Global Warming Potential and Global Temperature Potential. However, RFI as well as the aforementioned metrics are not directly applicable to aviation⁵, and proper methods should be established by further research⁶.

There are trade-offs between the environmental issues, i.e. decreasing CO₂ emission of an engine may increase the NO_x emissions. Further, more silent engines can be heavier, and therefore may result in a higher CO₂ emission⁷. Therefore for a rating, using a multiplier to include non-CO₂ emission may result in distortion.

From this literature review it can be concluded that besides CO₂ emission, other environmental issues are linked to aviation. Rating only on CO₂ will thus not cover 'aviation and environment'. As was mentioned in the introduction, the scope of this research is on the CO₂ emission of an airline. The CO₂ emission of an airline can be divided into CO₂ emission due to ground supporting activities (catering, fuel vehicles etc.) and air operations (caused by the power source of the aircraft itself). It has been decided to scope on the CO₂ emissions caused by air operating activities, which covers the fuel used by the power source of the aircraft, i.e. the engines and APU. To put this into perspective, 99% of the total CO₂ emission was due to air operation activities for Air France/KLM⁸ in 2007/2008 and only 1% for ground operations.

B. Existing Ratings

There are various ratings on the market which compare the performance of products or companies. In analogy with these existing ratings, the airline rating methodology can be set-up. Therefore we have explored how existing ratings rate 'white goods', cars, aircraft, and companies.

The EU energy label gives 'white goods' a class score (A-G) to indicate the performance of a product. For consumer goods, the energy efficiency of a product is typically the metric used for comparison. The energy efficiency metric for a washing machine has been defined as the energy use (in kWh) kg washing load. The washing load has been included in the metric because there are washing machines with different loading sizes. Excluding the latter would make small washing machines in general more energy efficient. Further, to measure the energy consumption and make a comparison possible, a standard washing program has been defined by the EU⁹. To reduce the CO₂ emitted by cars and to reach the GHG reduction target agreed upon by the EU at the Kyoto conference in 1997, the EU decided to label cars for their CO₂ emission. The metric used in the rating is gram CO₂ emission per kilometre.

Flybe, a UK regional airline, has developed a methodology to compare the environmental performance of aircraft¹⁰. They rate aircraft separately on three aspects: noise, LTO CO₂ emission, and journey CO₂ emission. For the noise rating, they use the average quota count of an aircraft for departure and arrival. The LTO CO₂ emission is based on the absolute CO₂ emission, and for the journey CO₂ emission they rate aircraft on both absolute CO₂ emission as well as CO₂ emission per seat. Furthermore, they rate aircraft on several distances in order to compare aircraft which serve the same routes with each other. Since an aircraft has a certain range, it is rated only at distances on which it can operate. Flybe assigns a rating score (A-G) by determining the best and worst performer of a distance (in terms of CO₂ per seat or absolute CO₂ emission) and dividing the difference between six equal bands.

DeCicco and Thomas¹¹ designed a "Green Rating" for cars which considers elements of the life cycle of a car. For the various car emissions, the cost to the environment has been established (i.e. dollar/gram of emission), and an environmental damage cost index has been used to calculate the impact of emissions on environment. Due to lack of data and resources, DeCicco and Thomas focused on the use-phases energy and air pollution effects for the material production, product manufacture and product use phase¹¹. Because multiple environmental issues were taken into account, DeCicco and Thomas gave equal importance to the impacts of GHG emissions as to health-related pollution for a typical car¹¹.

Standard & Poor's (S&P's) give their opinion on the capacity and willingness of a company to meet its financial commitments on time¹². Both quantitative and qualitative factors are used by S&P's to form an opinion on the credit risk. Each company has a business risk- and a financial risk profile from which a rating score is determined. The rating is forward looking, which means that S&P's also considers market trends and take into account the business cycle. When a company is active in different segments, each segment is analyzed separately, followed by an analysis of how important each segment is to the overall organization, and is weighted accordingly¹².

II. Methodology Approach

In analogy with existing ratings, a CO₂ airline rating will be set-up. Therefore a metric for the CO₂ efficiency is determined. Further it is decided how to compare airlines in a justified way. When a metric has been defined and it has been chosen how to rate airlines, the CO₂ efficiency of several airlines (i.e. network, regional and low cost carrier) will be calculated. This is done by making a model which includes all flight phases in order to estimate the CO₂ emission of an airline. This model is made on the basis of public available sources.

Since no actual fuel data of airlines is used, assumptions are made which will affect the accuracy of the rating. For each phase/parameter the range in which it typically varies are determined (on the basis of public available information), and a base value is chosen. Further, to evaluate the CO₂ emission model, a validation is performed on actual airline U.S. BTS data¹³. This will give insight in how well the model estimates the CO₂ emission of an airline. In order to determine which parameters need to be known most accurately for a CO₂ rating a sensitivity analysis is performed. From this analysis, together with defined ranges, it can be shown on which parameters the focus should be for rating accuracy improvement.

By analyzing several airline types, differences in CO₂ efficiency between airlines may be observed, and it may be possible to group airlines and give them a class score, such as A, B, C etc.

III. Building the model

In this section a CO₂ efficiency metric is defined, followed by a discussion of how to rate airlines. Finally, the airline fuel modeling for the different stages of the landing and take-off (LTO) cycle is determined.

A. Fuel Efficiency / CO₂ efficiency metric

Since the CO₂ emission from an airline is directly related to the fuel consumption, the CO₂ efficiency equals the fuel efficiency (multiplied by a constant factor). IPCC¹ defines transportation efficiency as the fuel required to transport one person over a distance of 1 kilometre-the energy required per passenger-km. Further they mention that freight may be compared on the basis of energy use per ton-km. Mak et al.¹⁴ compared the environmental reports of airlines and found differences in the fuel efficiency definition that airlines use. It is found that the common definition used for fuel efficiency is the fuel used per passenger distance or fuel per RPK. However, also fuel per RTK (revenue ton kilometer) and fuel per ASK (available seat kilometer) are used by airlines. The fuel efficiency definition depends on whether one wants to compare passenger or freight transport. When rating on fuel per ASK the fact that besides passenger also cargo can be transported is neglected. Further it does not take into account how airlines use their capacity. Fuel over RPK takes into account how airlines use their seat capacity, however again neglects cargo transport. Although there are airlines such as low cost carriers that only transport passengers, network carriers usually transport both, i.e. in the belly hold of a passenger aircraft it can carry freight.

To include both passengers and cargo transport in a metric, the fuel efficiency is defined as the fuel required to transport revenue weight (cargo as well as passengers) over a distance unit, i.e. CO₂/ RTK. A typical weight should then be assigned to a passenger (including baggage). When rating on CO₂/ RTK, airlines are rated on how efficient they use their transport output, i.e. how well do they use their available capacity in terms of both passenger and cargo transport. RTK is commonly used in the aviation industry as a measure of the transport output.

B. Comparing Airlines on their CO₂ Efficiency

In the Flybe aircraft rating, aircraft are rated on several distances on which they operate. This makes it possible to compare aircraft that operate on the same (fixed) distances. In analogy with this, an airline could also be rated on fixed distances. However comparing airlines is more complex since an airline is composed out of aircraft types that are put on several routes, for which the CO₂ efficiency differs per route and aircraft. Although one particular aircraft of an airline may be very efficient, the CO₂ airline rating should rate the total CO₂ efficiency of an airline and how it uses its fleet. Therefore, it could be decided to determine the CO₂ efficiency by dividing the total CO₂ emission and RTK production of an airline. However, is it fair to compare airlines that operate on totally different hauls? Could a regional carrier's CO₂ efficiency score be compared with one of a network carrier? Since in general the efficiency in terms of fuel per km increases with distance, a regional carrier might by definition be less efficient than a network carrier. The CO₂/ RTK score of a network carrier is predominantly determined by its long haul flights. For example, for one of the analyzed airlines the shares of CO₂ emission and RTKs with respect to the airline's total are respectively 85% and 92% for flights above 1,500 kilometers, whereas they cover only 23% of the airline's total flights. This means that an airline's CO₂/ RTK score is predominantly determined by its flight above 1,500 km in this example. Whereas the CO₂ efficiency of the regional flights of this carrier are very CO₂ inefficient has no significant effect on the rating score. Therefore when rating airlines on CO₂/ RTK in this way, the CO₂ efficiency cannot be compared in a justifiable way.

One could argue that the CO₂/ RTK could be calculated per flight, and then that the overall score would be determined by adding up all single scores and divide it by the total number of flights. However, in that case the airline in the example would be predominantly rated on its flights below 1,500 km since it performs 77% of its flights in that sector. Therefore, another approach should be followed to make a justified comparison between airlines.

One could see an airline as a composition of various 'products', i.e. the transport of payload on regional haul routes, short haul routes etc. An airline decides which aircraft they put on its routes, which can be based on various reasons which are beyond the scope of this research. When comparing the CO₂/ RTK on so-called distance sectors, the same sort of 'products' are compared, i.e. the regional network of a network carrier would be compared with a regional carrier. Whether an airline uses an aircraft which is designed for long haul or puts 130 seats instead of 150 seats in an aircraft to accommodate business passengers is their choice. For the rating only the CO₂/ RTK matters which considers how an airline performs in a sector. How the distance sectors will be defined will be determined later in the analysis. It should be noted that when an airline is rated in a distance sector it does not mean that all flights of that airline are less/more CO₂ efficient than these other airlines.

Concluding, the approach for which it is believed that a justified comparison can be made is to rate an airline on CO₂/ RTK on several distance sectors. This approach is illustrated in Fig. 1, which shows seven airlines operating in various distance sectors. An airline will only be rated when it is operating in a distance sector. The number of distance sectors and the position of the boundaries will be discussed later.

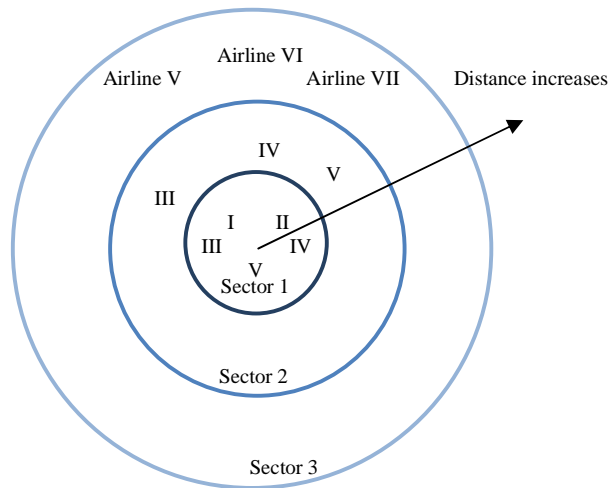


Figure 1. Rating airlines on distance sectors on their CO₂/ RTK

C. Airline Fuel Modeling

Since the scope is on CO₂ emitted during the air operation activities, the CO₂ emission of an airline from the engine as well as the APU needs to be determined. When the CO₂ emission and RTKs of an airline are known, the efficiency can be calculated.

Similar to existing emission models (such as AEM3 by Eurocontrol¹⁵), the fuel of a flight is composed out of two components: the LTO cycle fuel (below 3,000 ft), and the climb/cruise/descent fuel (above 3,000 ft). The LTO cycle comprises the following phases: taxi-out, take-off, climb-out, descent/landing, and taxi-in. Apart from these phases, the parking phase has been added in order to account for the fuel used by the APU. Figure 2 shows an illustration of the phases included in the model.

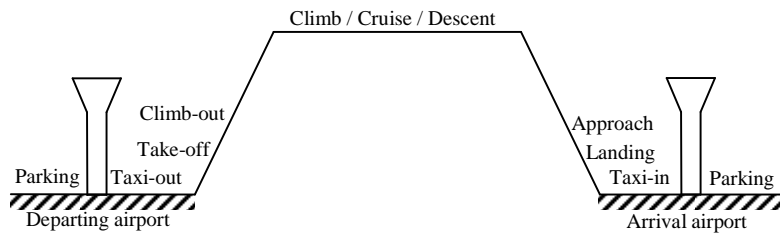


Figure 2. Flight phases considered in the model

For all of these flight phases the parameters affecting the fuel of the phases have been investigated. Although each phase basically depends on thrust setting and duration, the relation between these two is not well known, i.e. a lower thrust setting may result in a longer duration which could mean a reduced CO₂ emission, however also the opposite. Therefore it was decided to set for each phase (excluding climb/cruise/descent) a standard thrust setting and duration, which is referred to as base values. The typical range in which the fuel varies for a phase with respect to the fuel calculated by using the base values was then determined. This could then be used in a sensitivity analysis to show whether a phase or parameter was needed in more detail or not, i.e. when a change in parameter only has a minor effect on the rating output, then using a base value may suffice. It is further used to get insight on what parameters the focus needs to be for further research.

1. LTO phases

For the LTO cycle standards defined by ICAO have been used for thrust setting and duration. This means that for each engine, the fuel flow has been used as filed in the ICAO Engine Emissions Databank¹⁶, which is based on the defined thrust setting. Eurocontrol¹⁵ have also used for their emission model the ICAO LTO thrust setting and durations, and validated it with actual airline data. From their results, the range in which the fuel varies (normalized) was determined.

2. Parking phase

For the parking phase, the duration and fuel flows of the APU were deduced from Unique¹⁷, which specifies for a number of aircraft type which APU type is typically used and the average fuel consumption per hour. When an aircraft is parked at a pier it only uses the APU for about 8 minutes (at Zurich Airport), however when at a remote stand it may use the APU for about 41 minutes. A ground power unit may also be used, however, from ASPIRE¹⁸ it was noted that some airports charge excessive fees for the use of these units. Some airports limit the duration of APU because of LAQ issues¹⁹, however for most airports it is known that they have not such restrictions. Therefore it was decided to use 41 minutes as base value for the APU duration. Further research is necessary whether this duration can be used on all aircraft types since Unique¹⁷ shows that there are significant differences between turboprop and short haul aircraft.

3. Climb/cruise/descent phase

For the climb/cruise/descent phase fuel flow data from the Emission Inventory Guidebook (EIG)²⁰ was used, also referred to as EMEP/CORINAIR data. It gives the fuel consumption for 44 aircraft types on several distances, i.e. 125 nm, 250 nm etc., which are deduced from calculations by PIANO (Project Interactive Analysis and Optimization). Although the assumptions on which the calculations are based are not mentioned in EIG, it has been assumed that the fuel information represents optimal flight conditions, which are typically used in emission inventories, i.e. NASA²¹ mentions for their model: no winds, no cargo, optimal flight profile, optimal operating rules, direct distance etc.

Therefore, the fuel data of EIG²⁰ cannot be directly used to estimate the CO₂ emission of an airline. In the model the following aspects are corrected for: altitude, speed, payload weight, engine deterioration, centre of gravity position, and additional distance with respect to the great circle distance (GCD). Other aspects which influence the fuel consumption are weather conditions (wind), and temperature difference at altitude with respect to standard conditions, however are assumed to cancel out.

Airbus²² analyzed the factors that affect the fuel consumption of aircraft. They investigated the effect of flying lower/higher than the optimal altitude for several aircraft. According to Airbus²³, aircraft typically fly about $\pm 2,000$ ft near their optimum altitude, due to amongst others Air Traffic Control (ATC). Further, it should be noted that the optimum altitude is not fixed, i.e. the aircraft becomes lighter due to the burning of fuel and therefore has a different optimum altitude. This causes the fuel to increase by about 1-2%. However flying at altitudes farther below or above the altitude will cause a fuel penalty higher than 2%, i.e. an Airbus A320 which operates 4,000 ft below its optimal altitude will have a 5-6% fuel penalty compared to optimal²². For the model it has been decided to correct the fuel used during the climb/cruise/descent phase by adding 2% of extra fuel to the total fuel consumption during this phase. It should be noted that this value should be investigated further, i.e. whether it may be applied on long haul flights as well as regional flights and whether there are differences between aircraft etc. From Airbus²² it can be deduced that there are differences in fuel penalty between aircraft types.

For the EIG (2007) fuel data it has been assumed that the speed at which an aircraft operates is the speed at which 99% of the specific air range can be achieved, also known as the long range cruise (LRC) speed. This assumption is commonly used in emission inventories such as NASA²¹ and AERO2K²⁴. The speed at which the minimum fuel is used is the maximum range cruise (MRC) speed. However, the time gain by using the LRC speed instead of the MRC speed is significant, and therefore airlines typically fly faster than the MRC speed. Since fuel costs are only part of the total operating cost of airlines, the so-called cost index (CI) is used to express the cost of time versus cost of fuel. Airlines use the CI to determine the speed which is most economical. This speed is different for each airline (due to a different cost structure), and might even differ per route²⁵. The flight management system of an aircraft has a feature which allows a pilot to select a certain CI, from which the climb/cruise/descent speed is determined²⁵. For several Airbus aircraft Airbus²³ determined the fuel increase using a typical cost structure of an airline. For the analyzed aircraft the fuel increase could be up to 7% between the extremes, i.e. MRC and maximum operating speed. However neither extremes are used by airlines. Although it is expected that airlines operate at higher speed than MRC and LRC, it cannot be exactly quantified. It has been decided to add 1% of fuel due to speed to the EMEP/CORINAIR climb/cruise/descent fuel.

The weight of the aircraft influences also the fuel consumption of an aircraft. Airbus²² found that increasing the maximum take-off weight by 1% will increase the fuel consumption of about 0.8-1.2%, dependent on the aircraft type. Although operating empty weight differences between airline operators will cause the fuel consumption to vary, the largest weight differences will be in the traffic load weight, and in the fuel load carried. The fuel that an airline loads depend on the trip fuel needed to reach the destination plus contingency fuel for safety reasons and extra fuel. The latter can be added by the captain for various reasons, i.e. weather conditions, lack of confidence in flight planning etc.²². The traffic load consists of the weight of the revenue passengers and cargo. For the EMEP/CORINAIR data it is known that for the turboprops a passenger load factor (PLF) of 65% is used²⁰. For the turbojets the PLF is not known, however as mentioned before emission inventory models typically use a 70% PLF. This means that when using the EMEP/CORINAIR data in the model, the climb/cruise/descent fuel needs to be corrected for airlines that operate with a different PLF. The PLF only tells how much seats in an aircraft are occupied, however it does not tell how much of the payload capacity is used in an aircraft. The weight load factor expresses that instead, which is defined as the ratio of the weight transported over the capacity available. The relation between the weight load factor (WLF) and fuel consumption was investigated by LIDO for University of Westminster²⁶. They analyzed the fuel flow differences between different WLF: 50%, 65%, and 80%. On the basis of this research it has been calculated what the effect of a 1% increase in WLF is on the fuel consumption of an aircraft. It was found that the fuel consumption increase depends on the aircraft, i.e. the one aircraft has a higher payload capacity than the other. In general a 1% increase in WLF will cause the fuel consumption to increase between 0.18-0.32%. This means that flying with a WLF of 0% instead of 100% will let the fuel consumption decrease by 18-32% dependent on the aircraft type.

A 65-70% PLF load factor of EMEP/CORINAIR does not directly tell how much of the payload capacity is used. For the model, it has been assumed that a PLF of 65-70% equals 50% of the WLF, and a relation was set-up to account for the additional weight of an airline compared to modeled by EMEP/CORINAIR.

Due to a misplaced centre of gravity (CG) position the fuel consumption may also increase. Airbus²² analyzed for several Airbus aircraft types the difference in specific range due to an aft and forward CG. Since it is assumed that an airline will typically operate with a CG which is close to optimal, it has been assumed that due to CG an additional fuel quantity of 1% of the total fuel consumption is used.

In addition to the direct route or GCD between airports, excess distance is flown caused by amongst others: ATC, Standard Instrument Departures (SIDs), Standard Terminal Arrival Route, weather conditions and course reversals. Kettunen et al.²⁷ suggests that the additional distance may vary between geographic regions. Faber et al.²⁸ has calculated the mean excess distance for several distance sectors, which is used to correct the GCD between airports in the model.

Engine deterioration causes the fuel consumption to increase due to dirt accumulation, mechanical wear, and erosion²⁹. Eurocontrol³⁰ mentions that on the basis of information provided by some airlines, the increase in fuel use due to engine deterioration is between 2-6%. Based on NASA²¹, a logarithmic formula was derived to correct for the increase in fuel consumption due to engine deterioration.

The parking, LTO phase, and climb/cruise/descent phase have been used to calculate the fuel consumption in the model. For US carriers that report both fuel consumption and airline schedule data, the fuel consumption has been calculated using the model in order to see whether the estimation is close to actual reported fuel data. Although, the sample size is small, the objective is to verify whether the fuel estimation is close to actual. Differences can be explained due to assumptions and variations in the phases and parameters. Some of the results are shown in Table 1.

Table 1. Fuel calculation for several aircraft types of airlines.
For quarter 1 and 2 of the year 2008 (based on US BTS data)

Aircraft types	Calculated vs. Real	Rev a/c airborne hours / total airborne hours
A319	1.02	1.00
A320	0.98	1.00
A330	1.07	1.00
AT72	0.90	1.03
B733	1.06	1.00
B735	1.07	1.00
B737	1.10	1.00
B738	1.03	1.00

Aircraft types	Calculated vs. Real	Rev a/c airborne hours / total airborne hours
B742	0.95	0.96
B752	1.01	1.00
B753	1.04	1.00
B763	0.99	1.00
B772	1.04	1.00
DH8B	1.46	0.99
DH8D	1.27	0.99
MD82	1.01	1.00

The ratio of calculated vs. real is defined as the modeled fuel divided by the actual reported fuel of US carriers, i.e. when this ratio is 1 the calculated fuel equals the reported fuel. The revenue aircraft airborne hours over the total airborne hours indicates whether the schedule over which the fuel has been calculated is the fuel over which an airline has reported its data, i.e. 95 means that the fuel calculation is made on the basis of only 95% of the total flown hours for which the fuel is reported. From the results it cannot be deduced whether the fuel of phases have been determined correctly; only the total can be compared.

The results show that the fuel calculation reasonably equals the actual reported fuel consumption. The largest difference between calculated and actual fuel is in aircraft that operate on regional/short haul distances. This may indicate that the LTO fuel is overestimated since the share of LTO is greater for short flights. However, further research is necessary in order to adjust the model.

IV. Model CO₂ Efficiency Airlines

In order to calculate the CO₂ efficiency of an airline one has to determine besides the CO₂ emission the RTK production. The RTK production of an airline is dependent on the payload weight transported and the flown distance. Therefore an estimation about the payload needs to be made. Further in order to determine the CO₂ efficiency of an airline, some airline specific parameters have to be set besides the general parameters (i.e. CG, additional distance etc.) which were treated in the previous section. The CO₂ efficiency of airlines will be determined on the basis of actual flight data (schedule, aircraft, frequency) provided by Eurocontrol. This data file contains all flights performed in January 2004. The use is however limited to flights only departing and arriving from European countries (ECAC), which means that flights outside this area are not included, i.e. a flight from Hong Kong to Sydney. However, it is not expected that this makes a significant difference in rating score.

When the CO₂ efficiency of several airline types have been determined, the scores can be compared and the boundaries of the distance sectors will be determined. Since an answer needs to be found on whether airlines can be rated on the basis of public available data, the range in which each parameter varies has also been analyzed. Therefore, for each parameter/phase the range in which the fuel can vary has been determined. By a sensitivity analysis, the effect of these ranges on the rating output are analyzed. From the sensitivity analysis, it can then be seen which parameters need to be known more accurate to rate an airline on the basis of public available data. An overview of the model is shown in Fig. 3.

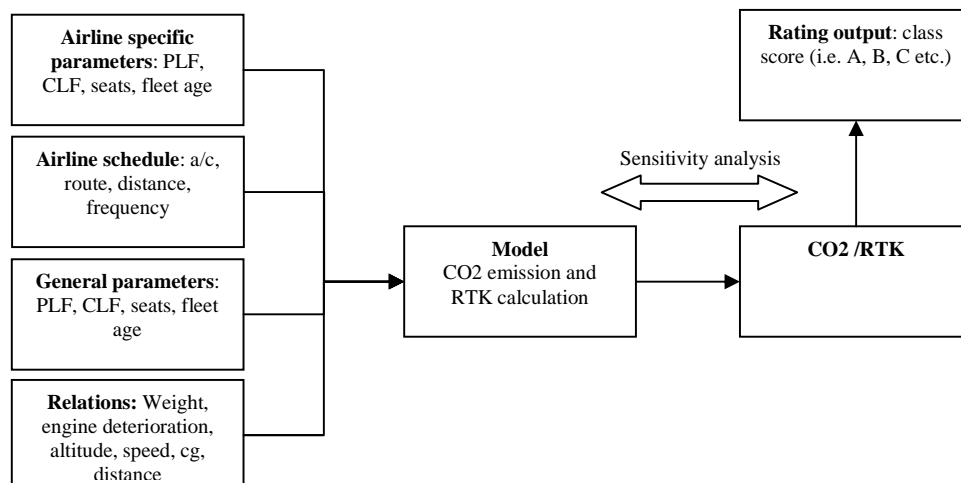


Figure 3. Overview of model which calculates the CO₂ efficiency of airlines

For the analysis, in order to find differences in CO₂ efficiency between different business types it was decided to select 3 low-cost carriers (LCCs), 3 network carriers (NWs), and 3 regional carriers (REGs), which are abbreviated as shown in Table 2. A low cost carrier is defined as a carrier with a high seating density and typically active on distances below about 2000 km. A network carrier is active on all distances, from regional to ultra long haul. Further, a regional carrier is predominantly active on distances below about 1000 km.

Table 2. The airline types and names assigned to the airline cases

Airline type	Airline name	Airline name	Airline name
Network Carrier	NW1	NW2	NW3
Low Cost Carrier	LCC1	LCC2	LCC3
Regional Carrier	REG1	REG2	REG3

A. Airline specific parameters

The PLFs for the airlines are derived from an IATA survey of 2008. The PLF information in the survey is either compiled out of IATA World Air Transport Statistics or out of airline annual reports. Since it was decided to rate airlines on certain distance sectors which are defined later, the PLF should be determined on these sectors. Using an annual PLF for an airline's total flight may result in inaccuracy in the rating. However, since airlines usually provide no PLF per distance and no specific information could be found about the PLF, the average annual PLF is used for all (to be defined) distance sectors.

Mainly network carriers transport besides passengers also cargo. However, the share of cargo transported is not well known. On the basis of US BTS¹³ data, the cargo load factors from/to US from the selected network carriers have been determined. For the three selected network carriers the cargo load factor (CLF) varied between 20-30%. Since this CLF may not be representative for all flights of a network carrier it has been decided to make a distinction between CLF for distances below 1,500 km (regional/short haul) and above 1,500 km. The CLF of all NWs have been set at 25% for flights with a distance larger than 1,500 km. For flights below 1,500 km, it has been decided to only use a 4% CLF for network carriers, since the share of cargo is usually low for European routes. For REG carriers and LCC carriers no cargo has been taken into account.

The payload capacities of aircraft have been derived from US BTS data¹³. For each aircraft the available payload capacity of a passenger aircraft have been determined. The number of seats in an aircraft differs per airline, and might even differ within an airline for the same aircraft type. The number of seats of the analyzed airlines were taken from either the airline's website or seatguru.com³¹. In the case an aircraft type was no longer used by an airline, typical seating configurations for a carrier were used instead.

The fleet age have been used from airfleets.net³² which is a website for which from each airline the average weighted age can be obtained. Whether it is appropriate to use the average weighted fleet age to correct for engine deterioration should be investigated, i.e. the fleet age does not necessarily say something about the engine age, i.e. an airline could have replaced an engine in the meanwhile.

It should be mentioned that the accuracy of the airlines specific parameters is low. This is because airlines do not publish the data in the preferred detail. Further research is necessary in the airline specific parameters and the effect on the rating score. In order to see on which parameters the focus needs to be for data improvement, the typical or expected range in which a parameter varies and the effect on the rating output will be investigated using tornado diagrams. In the next section the model results will be discussed and the distance sectors will be defined.

V. Results

For each of the airlines the CO₂ efficiency score has been determined. Before proceeding with the base-case results discussion, the distance boundaries needs to be determined as well as the number of sectors for which the CO₂ efficiency needs to be calculated. The first distance sector will start at 0 km, and the boundary of the distance sector on the right needs to be determined. Therefore the CO₂/ RTK score of airlines have been calculated by increasing the right boundary from 0 to 2,000 km as shown in Fig. 4 below.

The reason why the CO₂/ RTK score decreases is because the CO₂ efficiency increases in general with increasing distance. This is because a flight that travels farther spends relatively more time in the fuel efficient cruise phase. Further the share of the LTO-cycle to the total decreases. From Figure 4, one can conclude that basically three groups of airlines are formed with about the same CO₂ efficiency score: LCC1-3; NW1-3 and REG1,3; and REG1.

The choice of where to put the right boundary of distance sector 1 affects the relative position of airlines with each other, i.e. in the figure a cross means that the relative position of one carrier changes with the other. It can also be seen that for the regional carriers, the CO₂ efficiency stays constant after about 1,000 km. This due to that these carriers don't operate on these distances. This means that when putting the boundary at distances after 1,000 km the comparison becomes invalid. The boundary needs to be placed at a position in which still a comparison can be made, i.e. when all (or most) carriers perform flights in a distance sector. When one chooses the boundary below distances of about 500 km, the relative position of airlines changes considerably. It has been decided to put the first

distance sector at 750 km, because the relative position of airlines changes not that much anymore. The first distance sector is thus defined as: 0-750 km.

It should be noted that a change in rating score would not directly mean that the class score (i.e. A, B, C) differs. Therefore the way the rating score is mapped onto a class score may also be considered when choosing the boundary. The distance should be set at places where the least class score changes occur, and at such a place that a comparison can still be made.

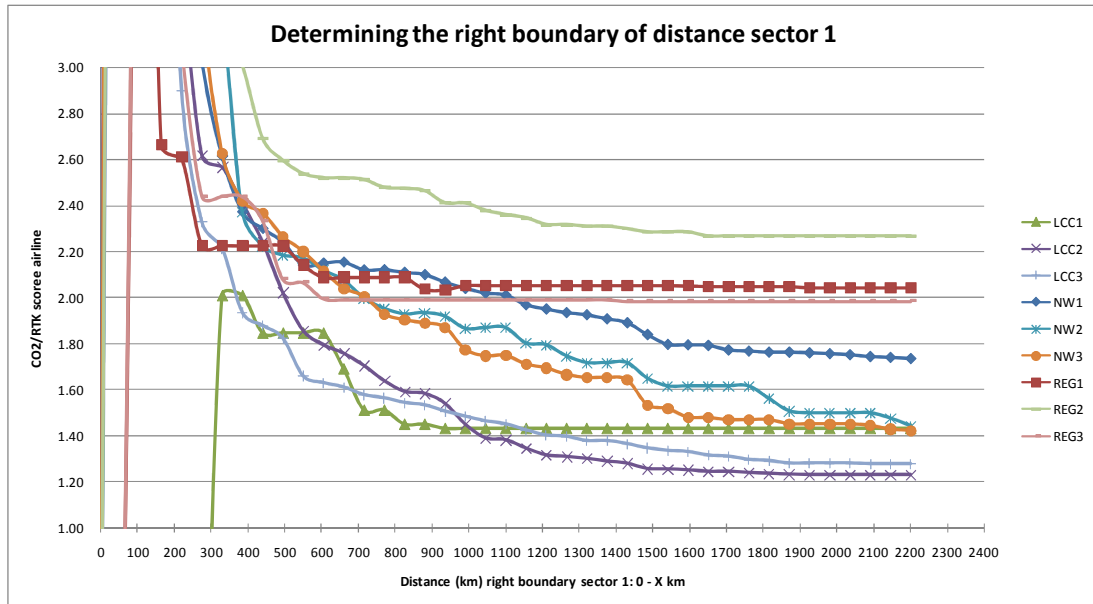


Figure 4a. CO2/ RTK score of selected airlines while extending the right boundary to determine distance sector 1.

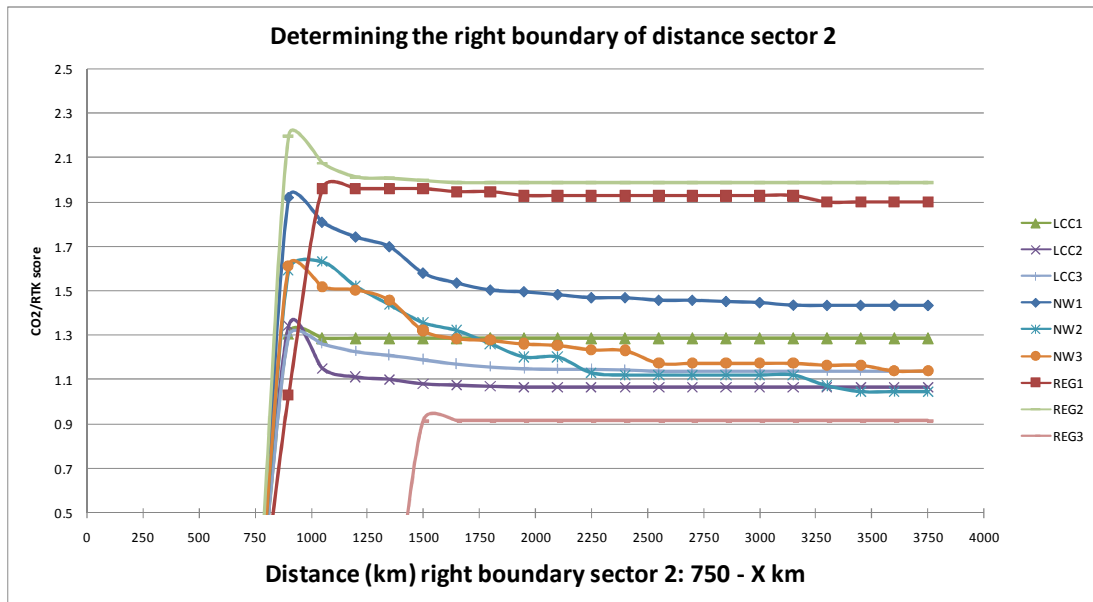


Figure 4b. CO2/RTK score of selected airlines while extending the right boundary to determine distance sector 2.

For the second distance sector, the left boundary is 750 km, and the right boundary will now be determined following the same approach. Figure 4 shows the CO₂/ RTK score when calculating the CO₂ efficiency from 750 km onwards. It can be seen that the position of airlines do not change anymore significantly. Due to the assumption that network airlines have a CLF of 25% from 1,500 km onwards, the CO₂ efficiency of NW carriers increases after that distance. Regional carriers 1 and 2 have only few flights after about 1,500 km which can be seen by the constant CO₂/ RTK score. Regional carrier has only 1 route-pair at a distance above 1,500 km, which is the reason why the score starts at that distance. Four groups can be distinguished: REG1-2; NW1; LCC1-3, NW2-3; and REG3. For this distance sector it has been chosen to put the boundary at 2,000 km. The second distance sector is thus defined as: 750-2,000 km. It should be noted that when considering more airlines these distance sectors may be chosen differently.

In a similar way, distance sector 3 has been set at 2,000-4,000 km, and distance sector 4 at 4,000 km and above. It has been decided to define only four distance sectors because adding an additional distance sector would not considerably change the relative positions of airlines with respect to the latter.

Table 3 shows the CO₂/ RTK score of airlines when using the base case input data, i.e. using standardized durations and thrust settings for the LTO phase, etc. It should be mentioned that by rating airlines on distance sectors, the rating score indicates which airline has a higher CO₂ efficiency score based on the flights performed by an airline within that sector. It does not tell whether an individual flight of an airline in that category is more CO₂ efficient than that of a competitor, i.e. an airline might operate with some very inefficient aircraft while also operating the most efficient aircraft. The results as well as ways to map the rating score on a class score will be discussed after the sensitivity results.

Table 3. Base case CO₂/ RTK rating scores on the several defined distance classes

	Sector 1	Sector 2	Sector 3	Sector 4
Airline	0-750km	750-2000km	2000-4000km	4000km >
LCC1	1.51	1.29	-	-
LCC2	1.65	1.07	-	-
LCC3	1.58	1.15	0.99*	0.93*
NW1	2.12	1.50	0.88	0.87
NW2	1.99	1.20	0.78	0.86
NW3	1.99	1.26	0.92	1.07
REG1	2.09	1.93	0.81*	-
REG2	2.51	1.99	-	-
REG3	2.00	0.92*	-	-

*: very few flights in distance sector

A. Sensitivity Analysis

The CO₂ emission composition of airlines differs with respect to each other, i.e. the one airline will have a higher share of taxi-CO₂ emission whereas has a higher share for the cruise phase. The consequence is that changing for example an LTO parameter will affect the rating score for the one carrier different than for the other. A sensitivity diagram shows for each carrier how a change in parameter affects the rating score. A tornado diagram shows what the effect is on the rating score when varying the parameter in a typical range.

1. Sensitivity diagram

A sensitivity diagram has been made for each distance sector and airline. Figure 5 shows the sensitivity diagrams for NW1 and REG1. Basically, the steeper the line, the larger the effect of changes in a parameter on the CO₂ rating score. Not all the parameters affect the rating score in a distance sector, i.e. the additional distance for distances between 1,500-2,900 km is not applicable, because the distance sector is from 0-750 km.

One can conclude that the LTO phases are more sensitive to changes for REG1 than for NW1. This is because regional carriers have relatively shorter flights and thus the influence of LTO is larger. On the contrary, the cruise fuel is less sensitive to changes for REG1 than for NW1. Although not shown, the sensitivity diagrams of other distance sectors show that the rating output is becoming less sensitive to LTO parameters (including APU), whereas the cruise phase will more significantly affect the rating. This is caused by the fact that the LTO fuel share to the total gets less when the distance increases, while the cruise fuel increases.

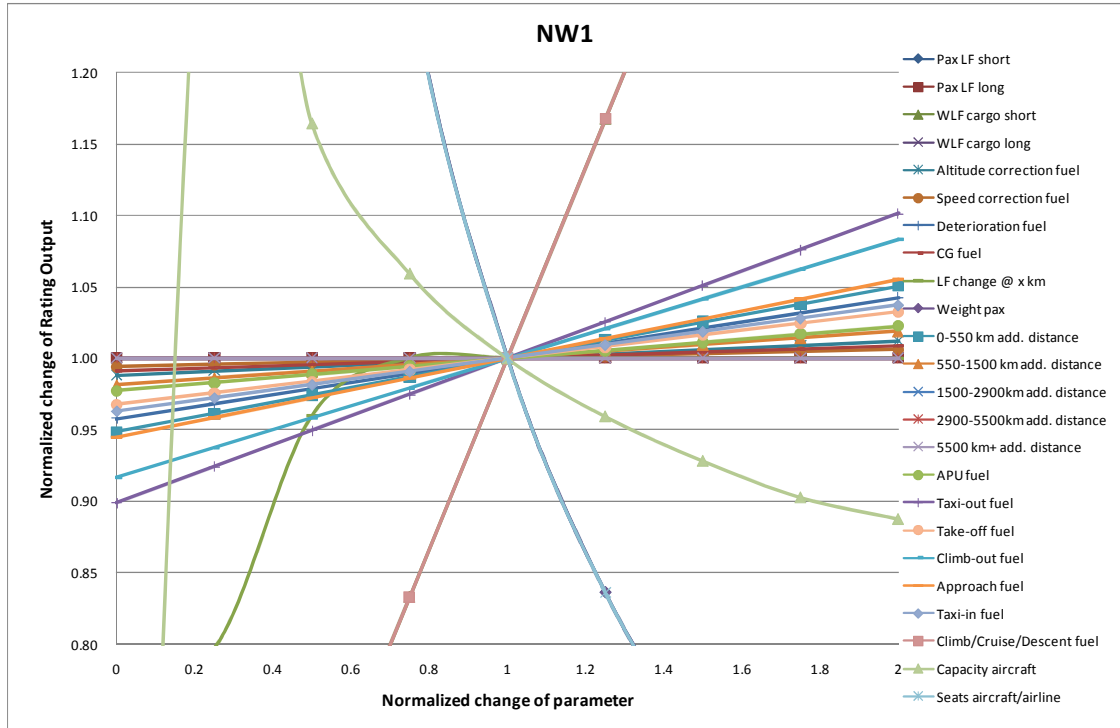


Figure 5a. The sensitivity diagram for NW1 for distance sector 1, showing what the effect is of changing a parameter (normalized) on the rating output (normalized).

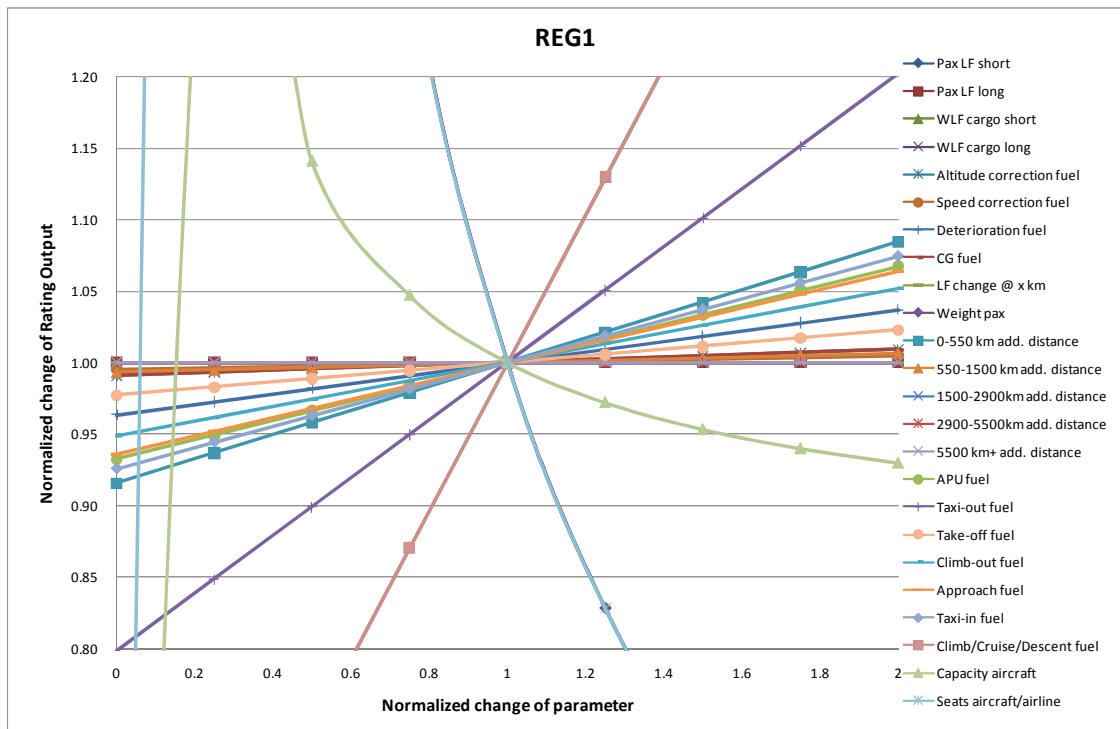


Figure 5b. The sensitivity diagram for REG1 for distance sector 1, showing what the effect is of changing a parameter (normalized) on the rating output (normalized).

It can be seen that the parameters affecting the RTKs of an airline have all steep curves, which means that the rating output is very sensitive to changes of these parameters. This is because a change in the payload weight affecting RTK will only have a minor affect on the fuel consumption.

In the sensitivity diagram the parameters are all normalized and varied from 0-2. However, the range in which a parameter varies differs per parameter. Therefore when including these ranges, it can be deduced which parameters affect the rating the most significant, and therefore can give insight on which parameter to focus to improve accuracy of the rating.

2. Tornado diagram

For each parameter it has been investigated what the typical range is in which it varies. When analyzing what the effect on the rating score is of the left and right boundary of such a range, it can be determined which parameter causes the largest variance in the rating score. This is illustrated by a so-called tornado diagram, in which the parameters that most affect the rating score are on top. Figure 6 shows the tornado diagrams for NW2 and REG2 for distance sector 1. It can be seen that due to uncertainty in the parameters affecting RTK's the rating score can be significantly affected. Further, the parameters affecting the LTO phase also affect the rating score considerably. From the figure it can be deduced that when a carrier has a different taxi-out time than ICAO standards, its CO₂/RTK score can be about 10% lower or 6% higher. It can be concluded that the additional distance affects the rating only slightly compared to LTO, cruise and RTK parameters. For REG carrier the influence is however higher, because additional distance flown have a relatively higher impact when the distances flown are small, i.e. the effect of 50 km on 200 km is larger than on 500 km.

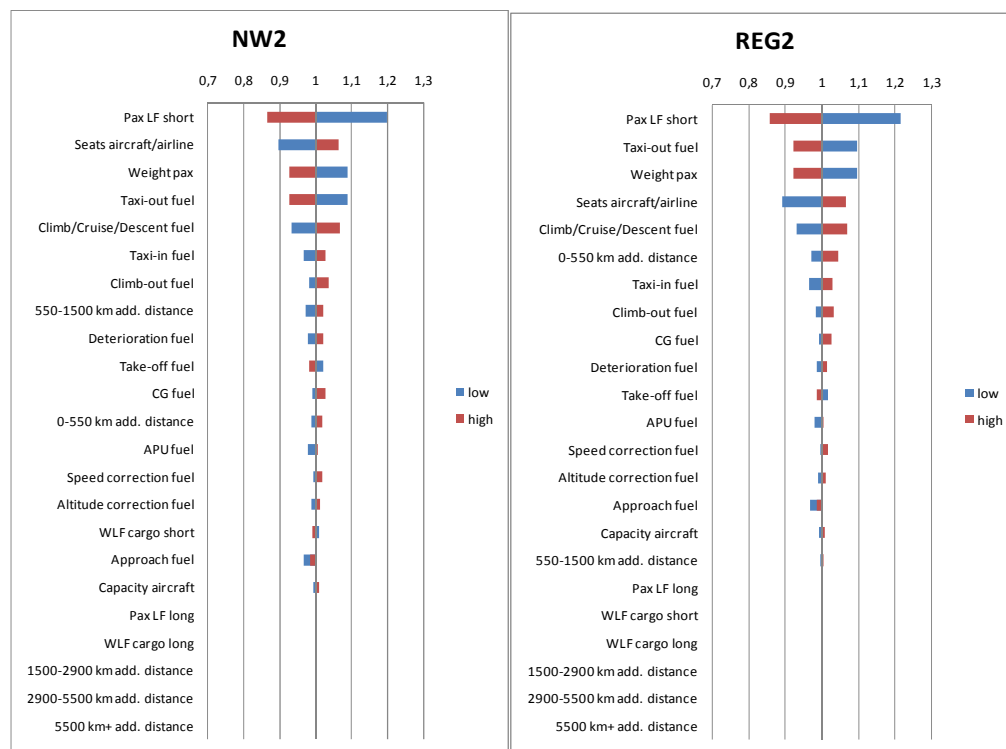


Figure 6. Tornado diagrams for a) NW-2 and b) REG-2 for distance sector 1

The total uncertainty in a CO₂/RTK score has not been determined, and should be investigated in further research. Due to the uncertainty in CO₂ and RTK, from the diagrams it can be concluded that rating purely on the basis of public parameters is not possible unless the accuracy is improved of certain parameters. Without showing the tornado diagrams for the other distance sectors, it can be stated that the influence of RTK remains still significant, and that the influence of uncertainty in parameters affecting LTO get less important. On the contrary, the cruise fuel/CO₂ emission gets however more important. This difference is caused by the fact that the shares of fuel are different for the sectors.

It can be concluded that due to uncertainty in input parameters, the CO₂ efficiency of carriers may vary significantly. Therefore further research should be performed to increase the accuracy of parameters that affect the rating score significantly. Due to differences in fuel composition in distance sectors there are differences on where the focus should be in the defined sectors i.e. for distance sector 4 the cruise fuel is more important to know accurate than for sector 1, whereas for the parameters affecting LTO it is the opposite. To design a rating, in the next section the CO₂ efficiency scores of airlines will be mapped on a class score.

B. Rating Mapping

When the CO₂/ RTK has been determined for each airline in a distance sector, it can be mapped to a class score such as A, B, and C. For the airline CO₂ rating, it has been decided to use a similar approach as how the class scores of the EU energy labels have been determined. The base case rating scores have been determined for the considered airlines for the distance sectors (see Table 3). A linear mapping approach has been chosen to divide the airlines into 3 classes: A, B and C. The difference between the worst and best score of each distance sector (see Table 3) has been divided by 3 and the result has been added to the minimum CO₂/ RTK score. The CO₂/ RTK scores belonging to a class score are shown in Table 4.

Table 4. A linear approach for the rating classes

	Min CO ₂ /RTK	Max CO ₂ /RTK	A	B	C
Distance category 1: 0-750 km	1.51	2.51	<1.84	1.84-2.18	2.18>
Distance category 2: 750-2000 km	0.92	1.99	<1.28	1.28-1.63	1.63>
Distance category 3: 2000-4000 km	0.78	0.99	<0.85	0.85-0.92	0.92>
Distance category 4: 4000+ km	0.85	1.07	<0.92	0.92-1.00	1.00>

It may be later decided to divide in more classes; however this will amongst others depend on the accuracy of the data. In analogy with S&P, it could also be decided to rate in 3 classes and to assign a '+' or '-' sign to the class score, i.e. A+ to show the relative standing of an airline with respect to another airline in a class,. For such relative standing, again the accuracy is important.

When the linear approach is followed, the airlines will get a class score as presented in Table 5. It should be noted that limited conclusions can be made, since the score of an airline may vary as was shown in the sensitivity analysis. When considering the base case values, LCCs have a higher CO₂ efficiency than other airlines in distance sector 1, and NW carriers and REG carriers score about the same.

It can be concluded that although an airline may have a low CO₂ efficiency with respect to other airlines in the one sector, it may have be better one on the other sector. When considering the base-case results, only LCC2 has an 'A' score in all sectors where it's active. Further NW2 scores 'A' on three of the four distance sectors.

Table 5. Airline ratings on the several defined distance classes

	Sector 1 0-750km	Sector 2 750-2000km	Sector 3 2000-4000km	Sector 4 4000km >
Airline				
LCC1	A	B	-	-
LCC2	A	A	-	-
LCC3	A	A	C	B*
NW1	B	B	B	A
NW2	B	A	A	A
NW3	B	A	B	C
REG1	B	C	B*	-
REG2	C	C	-	-
REG3	B	A*	-	-

*: very few flights in distance sector

VI. Conclusion

Aviation and environment cannot be represented by CO₂ emission alone. Also other environmental concerns are caused by aviation such as noise and local air quality. CO₂ is seen as the main man-made greenhouse gas which induces climate change, and it is known that emitting it at the ground has the same effect as in the air. Other non-CO₂ GHG also play a role but the scientific knowledge about their impacts on the climate is less well known. By including non-CO₂ gases, the ranking of an airline in a CO₂ airline rating may change. The research has scoped on the CO₂ emissions which are emitted by the power source of the aircraft. When considering aviation and climate change, at the moment rating on CO₂ seems appropriate given the uncertainty in impact of the other GHG on the climate.

CO₂/ RTK is the best ratio to express the CO₂ efficiency of airlines, since it takes into account both the aircraft types as well as how aircraft use their aircraft. The ratio cannot be used directly to compare airlines in a justified way on their CO₂ efficiency. Instead the CO₂/ RTK needs to be determined in distance sectors.

It was shown that when considering base case values, the CO₂ efficiency of an airline differs per distance sector as well as the class score, i.e. a carrier can have a low CO₂ efficiency compared to other airlines on the one distance sector, whereas on the others it may have a higher score. A model was designed that estimates the CO₂ emission and RTK production of airlines. However, due to lack of data availability, the CO₂ emission and RTK production of an airline are difficult to estimate, i.e. it was shown that the calculated CO₂ efficiency score may differ from actual. At the moment, on the basis of the data used, it is not possible to accurately determine the CO₂/ RTK score of an airline. Therefore, it is necessary to improve the accuracy of parameters that significantly affect the rating score.

Initial advice to airline can be given only on a high level of abstraction: an airline should strive to fill their aircraft as full as possible (either cargo or passengers), use CO₂ efficient aircraft, and put aircraft on distances for which they are designed. Airlines should focus on the parameters that influence the rating the most.

A. Further research and recommendations

When one wants to rate airlines on the basis of public parameters, further research is necessary to improve the accuracy of the modeled parameters. Further research should be focused on how to improve the level of detail of the parameters that affect the rating score significantly. The accuracy of fuel and RTK estimation should be increased. The RTKs could for example be determined with more accuracy when using data from ICAO, which stores traffic by flight stage information of carriers.

Further research is necessary to decide where to place the boundaries of the distance sectors. The period on which an airline is rated should also be decided, i.e. airlines could be rated on the basis of one-month schedule, or on a yearly schedule. Since typically airlines decide in a late stadium which aircraft they put on a route, the use of data from the previous year is recommended since then the aircraft used on which route is known.

Further, it should be investigated how to introduce the rating on the market. Airlines could be given a preliminary rating score, and a verified rating score when real data is provided by the airline itself.

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