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Environmental impact of disruptions and airspace inefficiencies in Europe

Final report

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Key findings

Fuel efficiency improvements through airline investments

- Investments in new aircraft technology and operations improve fuel efficiency on intra-EEA flights by 1.9% per year;
- Over the 2015-2017 period, these investments saved 3.9 Mt (Megatonnes) of fuel and 12.2 Mt of CO_2, corresponding to around 1 million commercial passenger flights or two months of flying within the EEA.

Environmental impact of ATC-strikes and technical failures at European ANSPs

- Europe faced 33 strikes at Air Traffic Control (ATC) and 64 technical failures at Air Navigation Service Providers (ANSPs) over the 2015-2017 period, most of which occurred in France;
- ATC-strikes on average affect more flights (3,468 per day) than technical failures (1,329 per day);
- The impact of ATC-strikes on flight efficiency was also larger than that of technical failures:
  - An average strike increased flight distance by 70,000 kilometres per day requiring 200 tonnes of additional fuel;
  - An average technical failure increased flight distance by 3,000 kilometres per day, requiring 10 tonnes of additional fuel;
- Together ATC-strikes and technical failures increased flight distance by 4.6 million kilometres over the 2015-2017 period. As a result, fuel consumption and CO_2-emissions increased by 13.7 kt (kilotonnes) and 43.0 kt respectively, corresponding to around 3,500 commercial passenger flights within the EEA;
- ATC-strikes were responsible for most of the increases in flight distance (4.4 million kilometres), fuel consumption (12.9 kt) and CO_2-emissions (40.7 kt);
- French strikes and technical failures were responsible for almost 98% of this increase in fuel consumption and emissions. This is explained by the relatively high number of French strikes and technical failures, the central geographic location of France in Europe, the relatively long duration of French strikes (2 days on average) and the fact that not all overflights are accommodated.

Environmental impact of ATM-inefficiencies in European airspace

- Due to inefficiencies in European Air Traffic Management, flight distances for intra-EEA flights were 0.61-0.76% longer than technologically possible over the 2015-2017 period;
- These inefficiencies resulted in 229 kt of additional fuel burn and 721 kt of additional CO_2 over the 2015-2017 period, corresponding to around 60,000 commercial passenger flights or 4 days of flying within the EEA.

Executive summary

Climate change is one of the major challenges facing our generation. The aviation industry has committed itself to reduce its impacts on the climate. Airlines continuously invest in more fuel-efficient aircraft and improving their flight operations. Their achievements are (partly) offset by inefficient flight operations caused by disruptions (strikes and technical failures) at European Air Navigation Service Providers (ANSPs) and the fragmented design of European airspace. Such inefficiencies result in suboptimal flight paths causing additional fuel consumption and CO_2-smissions. Previous studies have analysed the economic impacts of disruptions and the design of European airspace. This study for the first time provides an in-depth analysis of the environmental impact of disruptions and Europe's fragmented airspace.

First, the study describes the technological and operational measures that airlines have taken to improve their fuel-efficiency and quantifies their environmental impact for intra-EEA flights over the 2015-2017 period. Second, it outlines which disruptions have occurred at European ANSPs over the same time period and estimates their impact on the environment. Third, the study describes the progress made in reforming European airspace design, the inefficiencies that remain and their impact on the environment.

Airline measures to improve efficiency

In 2009, the aviation industry recognized the need to address climate change and adopted a set of goals for the short-, medium- and long-term reduction of its CO_2-emissions:

- Short-term (by 2020): improve fuel efficiency and CO_2 emissions by 1.5% per annum;
- Medium-term (after 2020): cap emissions providing carbon-neutral growth (CNG2020);
- Long-term (by 2050): reduce net CO_2 emissions by 50% compared to 2005 levels.

Airlines contribute to these goals by investing in more fuel efficient technologies and operations. Due to technological innovations new generation aircraft are around 15% more fuel efficient than the models they replace. Furthermore, airlines optimize operations, for instance by increasing load factors. Over the past decade, the average load factor for intra-EEA flights increased by almost 10 percentage points to around 82%.

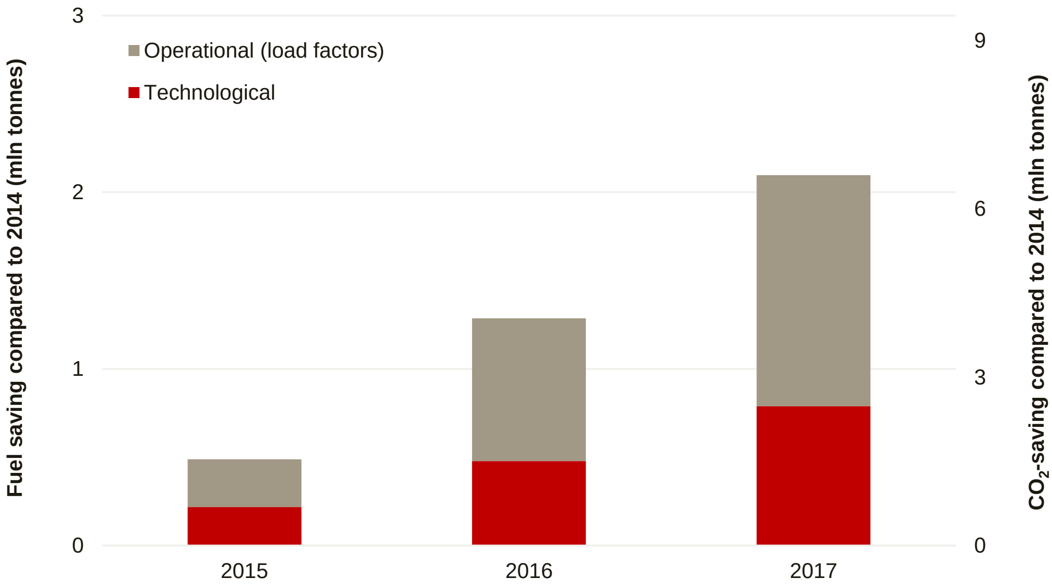
Methodology
First we determine to what extent fuel efficiency for intra-EEA flights has increased as a result of technical and operational (higher load factors) measures taken by airlines. For all scheduled passenger flights sourced from OAG's Schedule Analyser, we calculated the associated fuel consumption per seat kilometre in the various flight phases using our in-house emissions model. The development in the fuel consumption per seat kilometre represents the contribution of investments in new aircraft technology on fuel efficiency. Next, we use average industry load factors for the EEA to estimate fuel consumption per passenger kilometre. This shows the added contribution of higher load factors to fuel efficiency. Based on the increases in fuel efficiency we

calculate how much fuel and emissions were saved within the EEA over the 2015-2017 period because of technological and operational measures taken by airlines.

Results

The average fuel efficiency of intra-EEA flights has improved by almost 2% per year over the last decade. Technological and operational measures both contributed to higher fuel efficiency. Figure S.1.1 shows the fuel and emissions savings through technical and operational measures taken by airlines for intra-EEA flights in the 2015-2017 period. Fuel and emissions savings increase year by year, reflecting continuous technological and operational improvements. The fuel savings over the 2015-2017 period cumulate to 3.9 Mt (Megatonnes)[1], translating into over 12.2 Mt of CO_2. This corresponds to the fuel consumption and emissions of around 1 million commercial passenger flights or two months of flying within the EEA.

Figure S.1.1 Technological and operational measures saved over 12 Mt of CO_2



Source: SEO/To70 analysis

Disruptions

Disruptions due to strikes at Air Traffic Control (ATC) and to technical failures at ANSPs may lead to the temporary closure or limitation of available capacity of certain airspace sectors. Such capacity reductions may cause delays, flight cancellations and the rerouting of aircraft, negatively impacting passengers, airlines and the environment. Passengers are confronted with longer travel times disrupting their travel plans. Airlines are confronted with cost increases as a result of compensation payments to passengers, the implementation of contingency plans, extended working time for personnel and increased fuel consumption. The latter also translates into more CO_2-emissions, which negatively impacts the environment.

[1] One Megaton equals 1,000 kilotonnes or 1,000,000 tonnes.

Previous studies have assessed the economic impacts of ATC-strikes at ANSPs. One study assessed the impact of strikes on flight distance. No study estimated the impacts of technical failures at ANSPs on flight efficiency yet, nor did the studies assess the environmental impact of disruptions. This study is the first to provide an in-depth analysis of the impacts of strikes and technical failures at ANSPs on flight efficiency and the environment.

Methodology

To estimate the EEA-wide environmental impact of ATC-strikes and technical failures at ANSPs we use a four-step approach:

1. **Identification of affected flights.** For each disruption, we identify which airspace sectors were affected using Eurocontrol's DDR/NEST data. Next we analyse which routes crossed these sectors *one week before the disruption actually took place*. All flights that also operated on these routes on the day of the disruption were identified as affected flights;
2. **Estimation of additional flight distance per affected flight.** Second, we estimate the additional horizontal flight distance of the affected flights due to the airspace disruptions. For this estimation we use an econometric method called *difference-in-difference* (DiD). This method allows us to compare the horizontal flight distance of the affected flights with the flight distance one week before, while controlling for possible time trends;
3. **Translation of additional flight distance into fuel consumption.** Third, we use Eurocontrol BADA data to translate the increases in horizontal flight distance into additional fuel consumption;
4. **Translation of additional fuel consumption into additional CO_2-emissions.** Finally we translate the additional fuel burn into CO_2-emissions.

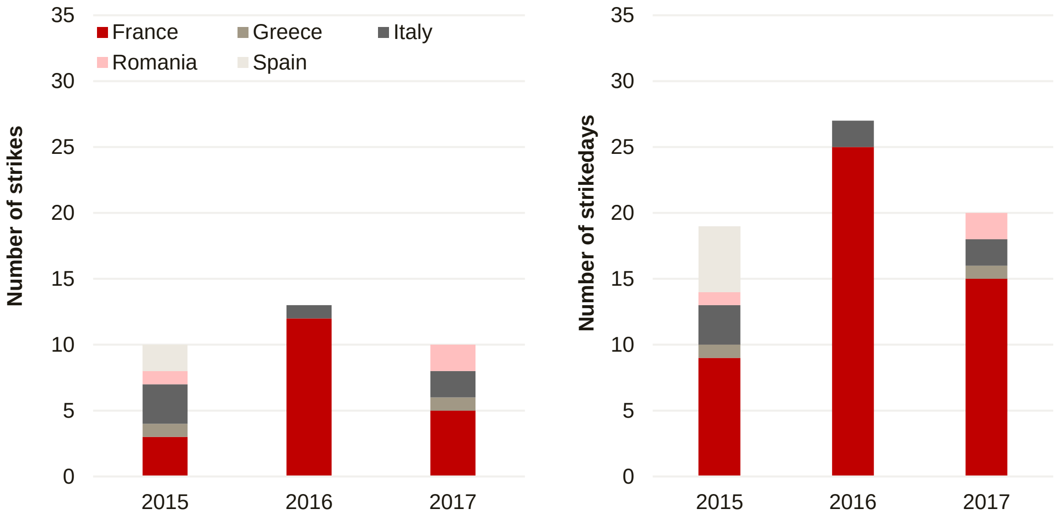
Results

Over the 2015-2017 period, traffic controllers at European ANSPs went on strike 33 times (see Figure S.1.2).[2] The French controllers at DSNA were responsible for the majority of all strikes (60%), followed by the Italian controllers (18%). The majority of the strikes in France were so-called 'solidarity strikes', supporting national labour disputes. Solidarity strikes in France were in many cases supported by DSNA staff. The strikes in Italy had to do with the privatisation of the national ANSP: ENAV.

ATC-strikes in France are normally full day strikes (midnight to midnight) and often cover multiple days, whereas strikes in other Member States, such as Italy and Greece, are generally limited to a few hours. In terms of strike days, France is therefore responsible for an even larger share (74%) than in terms of number of strikes.

2 See Appendix A for an overview of all strikes at ATC-organizations between 2015-2017.

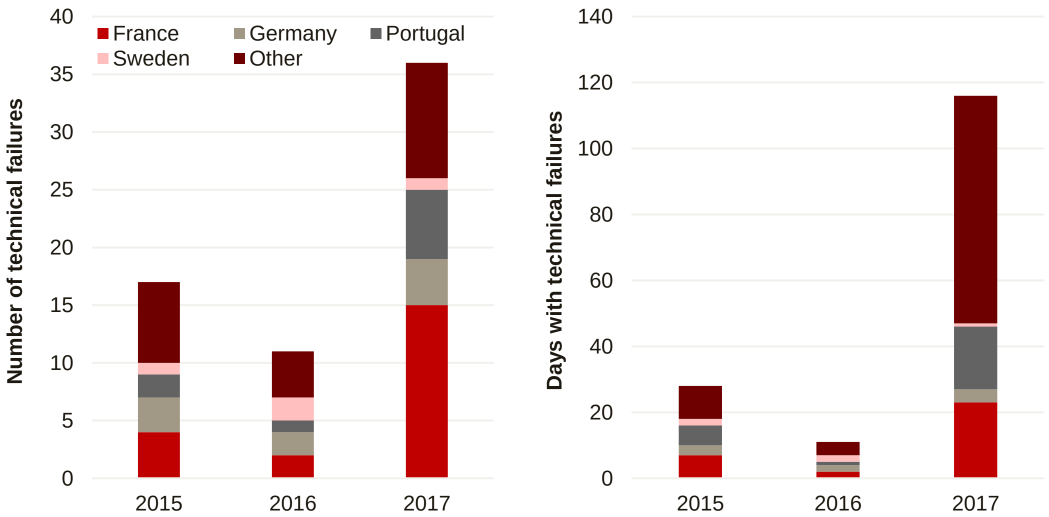
Figure S.1.2 Most ATC-strike(day)s took place at the French ANSPs between 2015 and 2017



Source: Eurocontrol (2016a, 2017c, 2018a), analysis by SEO/To70
Note: The data includes only strikes by air traffic controllers. Strikes by other categories of staff, such as ATC-technicians, are not included. Also strikes by air traffic controllers that are called on short notice may sometime be recorded as 'staffing issues' and therefore may not be included in the data.

Over the 2015-2017 period, Eurocontrol recorded 64 technical failures, more than half of which occurred in 2017. One in every three technical failures occurred at the French ANSP. Most failures were caused by radar or communication failure. Technical failures on average took 2.5 days to solve. As an exception, the Swiss ATC centres of Geneva and Zurich in 2017 experienced radar instability issues for 30 days. When we exclude these Swiss failures, the average technical failure prolongs for 1.5 days.

Figure S.1.3 Most technical failures take place at French ATC-organizations



Source: Eurocontrol (2016a, 2017c, 2018a), analysis by SEO/To70

The average number of flights affected by a disruption is 2,310. Strikes on average affected more flights (3,468) than technical failures (1,329). Differences between individual disruptions are large, ranging between 68 and 7,000 flights. French strikes generally affected a relatively large number of flights. This is explained by (1) the central location of France in Europe, (2) the fact that French strikes generally last for an entire day and (3) that not all overflights are accommodated.

During a disruption flight distances of flights through affected airspace increase by 9.8 kilometres on average. This constitutes a 0.7% increase in total flight distance. For strikes, the increase in flight distance is significantly larger (+17.1 kilometres) than for technical failures (+3.7 kilometres). Again impacts differ significantly between individual strikes and technical failures. The French strike on March 6th 2017 for instance increased the average flight distance of affected flights by 76.1 kilometres (+4.7%). There are however also cases in which disruptions led to reductions in flight distance. This may be explained by the fact that cancellation of flights reduce congestion, which allows flights that are not cancelled to follow a more optimal flight path. French strikes led to the largest increases in flight distance. This is explained by the central geographic location of France in Europe, the relatively long duration of French strikes (2 days on average) and the fact that not all overflights are accommodated.

By combining the number of affected flights with the increase in flight distance per affected flight, we estimate the total additional flight distance caused by disruptions. Table S.1 shows that strikes and technological failures at European ANSPs increased flight distances for intra-EEA flights by 4.6 million kilometres over the 2015-2017 period. Unsurprisingly, given that both the number of affected flights and the impact per affected flight is substantially higher for strikes than for technical failures, the strikes account for the majority (95%) of additional kilometres flown. On average each strike day resulted in over 70,000 additional flight kilometres; each day with a technical failure on average led to an additional 3,000 kilometres flown.

Table S.1 Strikes on average increase flight distances by 70,000 kilometres per day

Additional kilometres flown (2015-2017)	Full sample	Strikes	Technical failures
Total	4,619,788	4,377,591	242,198
Mean per disruption day	34,735	71,764	3,364
Minimum per disruption day	-16,679	-13,840	-16,679
Maximum per disruption day	314,257	314,257	51,965

Source: SEO/To70 analysis

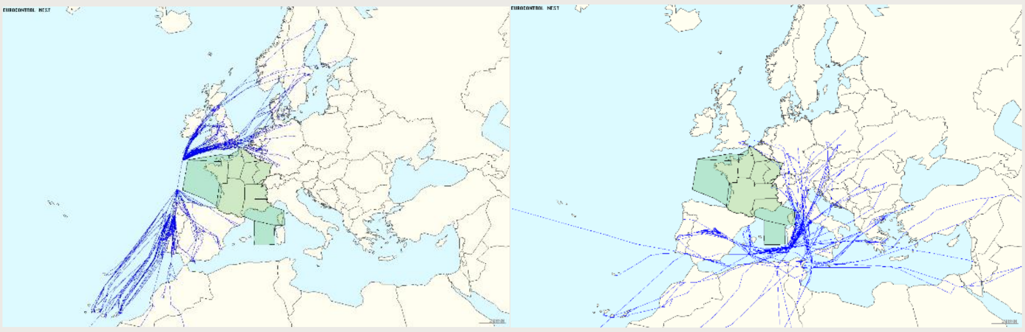
These increases in flight distance lead to additional fuel consumption and CO_2-emissions. Figure S.1.6 shows the additional consumption and CO_2-emissions caused by strikes and technical failures for intra-EEA flights over the 2015-2017 period. The grand total for the three year period adds up to 13.7 kt (kilotonnes)[3] of kerosene and 43.0 kt of CO_2. To put this into perspective, this corresponds to the fuel consumption and emissions of around 3,500 commercial passenger flights within the EEA.

3 One kiloton equals 1,000 tonnes or 1,000,000 kilograms.

Case study: French ATC strike on March 22nd 2018

Multiple trade unions in France representing public sector workers and airline personnel called for strikes on the 22 nd and 23 rd of March 2018. On the first day air traffic controllers joined the strike. On that day, 28,252 flights operated in European airspace. Of these flights, 5,405 intra-EEA operated in or near French airspace, almost 1,000 less than the week before the strike. Especially short-haul flights were less operated on the day of the strike. Over 200 flights were re-routed around French airspace, either westbound or eastbound (see Figure S.1.4). This resulted in flight extension of 14% and 21% respectively. The average route extension in the area of interest was 5.22%, an increase of 1.8% compared to the week prior to the strike.

Figure S.1.4 Re-routings around French airspace

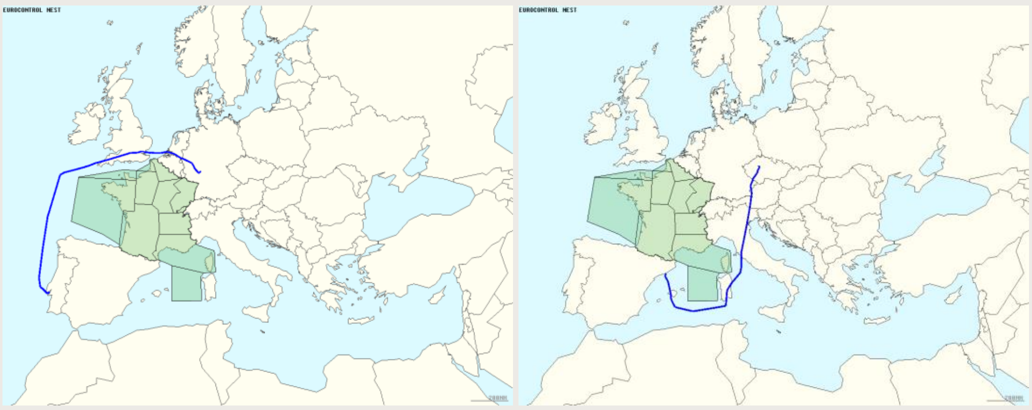


Westbound **Eastbound**

Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

For specific flights the extensions were much larger. A flight from Frankfurt to Lisbon for instance was re-rerouted westbound around France, resulting in a 637 kilometre increase in flight distance (+33%), requiring an additional 1.9 tonnes of fuel and 6.0 tonnes of CO_2 (see Figure S.1.5). A flight from Barcelona to Prague was re-routed eastbound, adding 741 kilometres to total flight distance (+56%). This required 2.7 tonnes of extra fuel and 8.6 tonnes of CO_2.

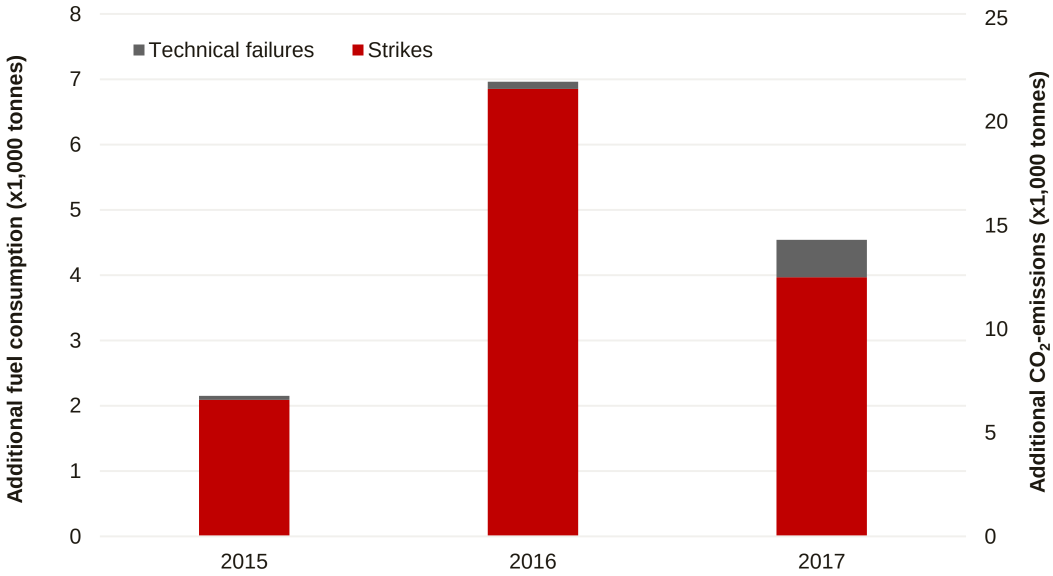
Figure S.1.5 Strikes may severely impact specific flights



Frankfurt Main to Lisbon (+637km, 33%) **Barcelona to Prague (+741km, 56%)**

Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

Figure S.1.6 Disruptions in 2016 caused most additional fuel consumption and CO_2-emissions



Source: SEO/To70 analysis

Disruptions in French airspace account for the vast majority of all additional fuel consumption and CO_2-emissions (97.6 percent). The large contribution of French disruptions to additional fuel consumption and CO_2-emissions is explained by the large number of ANSP-strikes in France and their relatively large impact. Portugal appears to be the second contributor to additional fuel consumption and CO_2-emissions, which is completely driven by equipment issues.

Case study: Understaffing at Karlsruhe UAC on 22nd December 2018

In December 2018, Karlsruhe UAC was the biggest generator of en-route delays due to understaffing (Eurocontrol, 2019d). Furthermore, Karlsruhe generated 37.4% of ATC capacity delays in the European network. Due to the staffing and capacity issues it had a limited number of sectors available in 2018, up to 10 less than required and 6 less than in 2017 (Eurocontrol, 2018b).

Eurocontrol (2019d) labelled Saturday 22nd of December 2018 as a day with high ATC understaffing and capacity issues Karlsruhe. On this day 29 regulations applied causing 18,000 minutes or delay. The causes of these delays were labelled as 'ATC staffing' (around 1,200 minutes) and 'ATC capacity' (around 16,800 minutes).[4]

In the week after[5] the 22nd of December, flights passing through the Karlsruhe airspace already showed a higher flight inefficiency (2.44%) than flights that exclusively passed through adjacent airspace (2.33%). On the 22nd of December the flight inefficiency for Karlsruhe airspace

4 As understaffing at Karlsruhe UAC has become a structural issue, operational configurations are now planned considering the staff limitations. This means that part of structural understaffing is now regulated as a capacity issue, i.e. labelled as 'ATC capacity'.

5 We did not choose the week before the 22nd, as this week was characterized by many regulations and therefore was not considered a good reference.

deteriorated by 0.14 percentage points, whereas flight inefficiency in adjacent airspace deteriorated by 0.08 percentage points.

Apart from airspace regulations, traffic scenarios can be implemented to reduce airspace complexity and therefore the workload of the understaffed ATC. Such scenarios may include level capping whereby flight level restrictions are applied to specific airspace sectors. This may lead to suboptimal vertical flight trajectories, increasing fuel consumption and CO_2-emissions. These level caps scenarios are also used in Karlsruhe. On the Dusseldorf to Munich route such caps increase fuel consumption by 120 kilograms and CO_2-emissions by 400 kilograms.

ATM-inefficiencies

Air transport came of age and grew rapidly during the fifties and sixties because of the introduction of radar technology and jet aircraft. European airspace in this period largely followed national borders and this is largely still the case. Back in the days civil air traffic routes were designed as direct routes between the largest centres of population. Military training areas were designed around the civil route network. To navigate through the route network, ground-based equipment along these routes was required. Thanks to technological development routes do not fully rely on ground equipment anymore, nevertheless these routes largely remain in use today. The fragmented airspace and original route design appears inefficient in managing current and future number of air traffic movements.

An initiative to reform the architecture of ATM was first launched by the European Commission in 1999 known as Single European Sky (SES). On the technological side, SES is supported by the Single European Sky ATM Research (SESAR) Programme launched in 2004. SESAR's high-level goals are to increase capacity, reduce delays, improve safety, reduce costs for airspace users and reduce emissions by 10%.

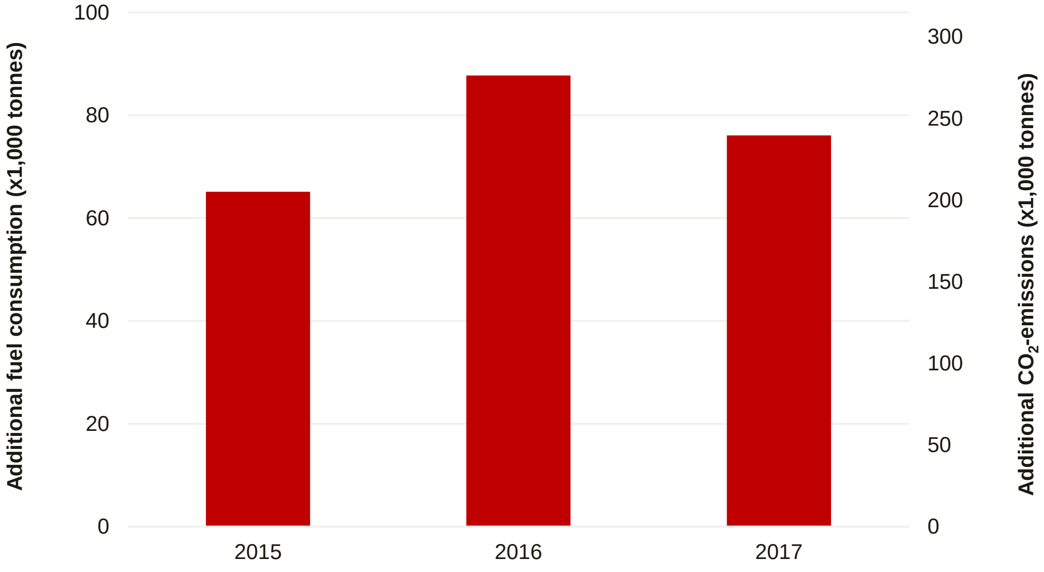
These goals should be achieved through innovative technical and operational solutions, such as Functional Airspace Blocks (FABs), Flexible Use of Airspace (FUA) and Free Route Airspace (FRA). Their of implementation status differs across Europe; general progress has been relatively low due to political, legal and technical impediments.

Methodology
Based on the performance indicators published by the Performance Review Body of the SES we estimate the inefficiencies that remain within en-route airspace due to ATM-inefficiencies. These estimates are used to assess to what extent these inefficiencies increased flight distances for intra-EEA flights over the 2015-2017 period. Finally, we calculate the associated additional fuel consumption and CO_2-emissions using our in-house emissions model.

Results
In 2015, 2016 and 2017, ATM-inefficiencies caused flight distances to be respectively 0.60%, 0.76% and 0.61% longer than technologically possible. These inefficiencies led to additional fuel consumption for intra-EEA flights ranging between 65-88 kt per year (see Figure S.1.7).

Over the entire 2015-2017 period additional fuel burn of intra-EEA flights cumulates to 229 kt, resulting in 721 kt of additional CO_2, corresponding to around 60,000 commercial passenger flights or 4 days of flying within the EEA.

Figure S.1.7 ATM-inefficiencies lead to unnecessary fuel consumption and CO_2-emissions



Source: SEO/To70 analysis

Contents

1 Introduction

The aviation industry has committed itself to reduce its impacts on the environment. Airlines continuously invest in more fuel-efficient aircraft and flight operations. Their achievements are (partly) offset by inefficiencies caused by disruptions at ANSPs and the fragmented design of Europe's airspace. This study quantifies the environmental achievements by the airline industry as well as the environmental impact of disruptions and the fragmented nature of Europe's airspace.

Climate change is one of the major challenges facing our generation. In 2015 the 196 member states of the United Nations Framework Convention on Climate Change (UNFCCC) demonstrated real commitment to reduce climate change by signing up to the Paris Agreement. The agreement aims to limit the rise in global average temperature to well below 2°C compared to pre-industrial levels.[6] The aviation industry recognizes the need to flight climate change and set itself various targets to reduce its CO_2-emissions. Airlines reduce their impact on the climate by investing in more fuel-efficient aircraft and improving flight operations.

Their achievements are (partly) offset by inefficient flight operations caused by disruptions at European ANSPs and the fragmented design of European airspace. Such inefficiencies result in suboptimal flight paths resulting in additional fuel consumption and CO_2-smissions. Previous studies have analysed the economic impacts of disruptions and the design of European airspace, few have assessed their environmental impact.

For intra-EEA flights, this study first estimates the environmental impact resulting from technical and operational measures taken by airlines over the 2015-2017 period. Second, it provides an in-depth analysis of the environmental impact caused by disruptions (strikes and technical failures) at European ANSPs. Third, it shows the environmental impact that are caused by inefficiencies in Europe's airspace design.

Reading guide

The next chapter describes the technological and operational measures that airlines have taken to improve their fuel-efficiency and quantifies their environmental impact for intra-EEA flights over the 2015-2017 period. Chapter 3 outlines which disruptions have occurred at European ANSPs over the same time period and estimates their impact on the environment. Chapter 4 presents the progress made in reforming European airspace design, the inefficiencies that remain and their impact on the environment.

[6] ICAO, the UN agency dealing with aviation is responsible for reducing the impact of international aviation on climate change.

2 Airline measures to improve efficiency

In 2009, the aviation industry set itself various goals to reduce their impact on the climate. Airlines contribute to these goals by investing in more fuel efficient technology and operations. As a result the average fuel efficiency of intra-EEA flights has increased by 1.9% per year over the last decade. Over the 2015-2017 period this translated into 3.9 Mt (Megatonnes) of fuel saved and 12.2 Mt less CO_2-emissions, corresponding to around 1 million commercial passenger flights or two months of flying within the EEA.

In 2009, the aviation industry recognized the need to address climate change and adopted a set of goals for the short-, medium- and long-term to reduce its CO_2-emissions (IATA, 2013a; 2015; 2013b; 2018a):

- Short-term (by 2020): improve fuel efficiency and CO_2 emissions by 1.5% per annum;[7]
- Medium-term (after 2020): cap emissions providing carbon-neutral growth (CNG2020);[8]
- Long-term (by 2050): reduce net CO_2 emissions by 50% compared to 2005 levels.

The goals are supposed to be achieved by a 4-pillar strategy:

1. Investment in new technology: More efficient airframe, engines and equipment, sustainable biofuels, new energy sources;[9]
2. Efficient flight operations: Drive for maximum efficiency and minimum weight;
3. Effective infrastructure: Improve air routes, air traffic management and airport procedures;
4. Positive economic measures: Carbon offsets, global emissions trading to fill the remaining emissions gap.[10]

Airlines can mainly influence the first two, i.e. invest in more fuel efficient aircraft technology and flight operations. Section 2.1 provides a literature review describing which technological and operational measures airlines have taken to improve fuel efficiency. Section 2.2 quantifies to what extent fuel-efficiency of intra-EEA has improved due to such measures. This increase in fuel-efficiency is translated into fuel and emission savings realised over the 2015-2017 period.

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7 In 2010, the EU and EFTA States agreed to work through ICAO to achieve a global annual fuel efficiency improvement of 2% and to cap the global carbon emissions of international aviation at 2020 levels (European Environment Agency et al., 2019).

8 Multiple studies have indicated that keeping aviation emissions below 2020 levels can only be achieved by a combination of these factors: technological, operational and policy measures and the use of alternative jet fuels (Hileman, et al., 2013; Dray et al., 2010; Sgouridis et al., 2011).

9 To stimulate investments in new technology, the ICAO Committee on Environmental Protection (CAEP) established a standard for aircraft CO_2 emissions (ICAO, 2016). CAEP recommends CO_2 emission standards for new aircraft designs as of 2020, as well as deliveries of in-production models by 2023. CAEP also recommends to phase-out aircraft that do not meet the new standards by 2028 (ICAO, 2016).

10 ICAO developed a global Market Based Measure (CORSIA) designed to offset emissions exceeding the 2020 level (Amizadeh et al., 2016).

2.1 Literature review

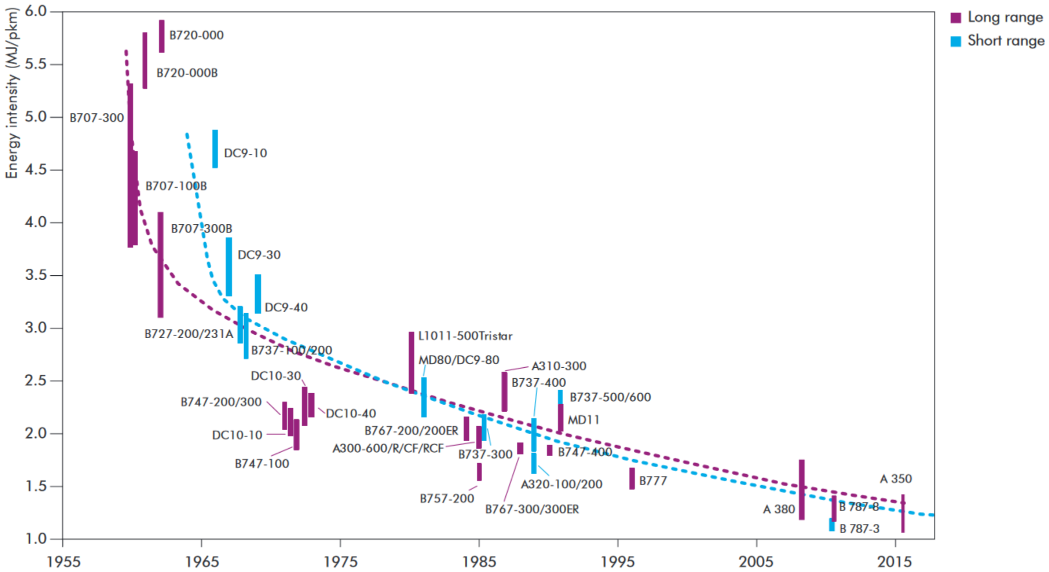
2.1.1 Technological measures

More fuel-efficient aircraft

Fuel is one of the major cost components for airlines. These costs act as a continuous incentive to reduce fuel consumption and CO_2-emissions. The recent rise in the price of ETS-allowances acts as another incentive to reduce fuel consumption and CO_2-emissions. In their quest to reduce fuel consumption and emissions, airlines demand from the aircraft manufacturers to develop ever more efficient aircraft. Of the estimated $20 billion spent each year on research by aircraft and engine manufacturers, 70% is used for measures that improve fuel efficiency (ATAG, 2014).

Figure 2.1 shows the extent to which jet aircraft have become more efficient since the 1960s. Since the 1960s fuel consumption per passenger kilometer has been reduced by 70% (Peeters and Middel, 2007; ATAG, 2014). The efficiency of aircraft has steadily and substantially improved through more fuel-efficient engines, better aerodynamics and more lightweight materials (Graham et al. 2014; Cansino and Roman, 2017; Schäfer et al., 2016).

Figure 2.1 Aircraft are still becoming more fuel-efficient



Note: Range for specific aircraft types reflect varying configurations. Dots show estimated trends for short- and long-range aircraft types

Source: International Energy Agency, 2009

Although the pace of efficiency improvements is slower than in the 1960s, aircraft are still becoming more efficient. According to Müller et al. (2018), technological improvements, such as geared turbofan and the use of composite materials allow for emission savings of up to 15% compared to previous aircraft generations. It is essential to consider that aircraft have a technical lifespan exceeding 20 years, meaning that different generation of aircraft will be operated alongside each other. The table below indicates that savings differ per aircraft type and range between 10-25%, whereby the largest savings are achieved when a new aircraft replaces a relatively old models.

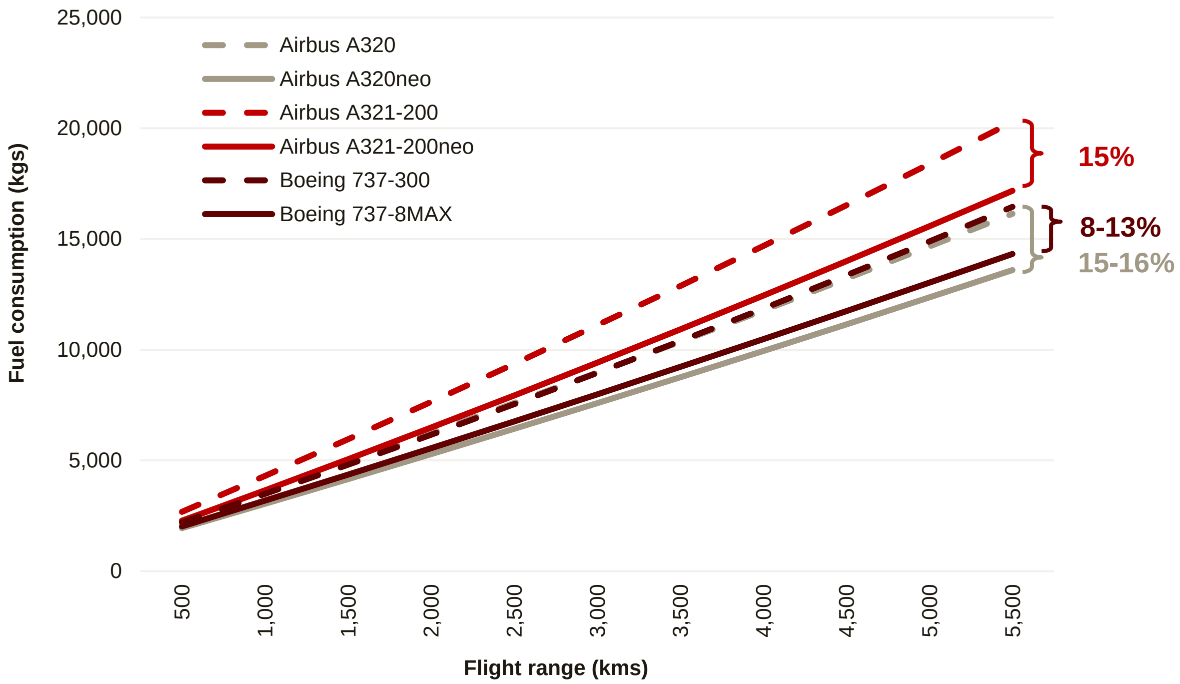
Table 2.1 New generation aircraft are 10-25% more fuel efficient than the models they replace

New generation	Introduction	Previous generation	Fuel efficiency improvement
Airbus A320neo	2016	Airbus A320	15-20%
Airbus A350XWB	2014	Airbus A340	25%
Boeing 737MAX	2017	Boeing 737NG	14%
Boeing 777X	2020	Boeing 777-300ER	13%
Boeing 787	2011	Boeing 767	20%
Embraer E190	2005	Fokker 100	10%
Airbus A220	2016	Embraer E190	20%

Sources: Airbus (2016, 2019), Lufthansa Group (2019), Boeing (2019a, 2019b, 2019c), Thomas (2008).

The efficiency improvements for the Airbus A320neo and Boeing 737MAX are confirmed by the econometric models developed by Rosskopf (2013). His models show that the Airbus A320neo and A321neo are 15-16% more fuel efficient than their predecessors. The Boeing 737MAX appears 8-13% more fuel efficient than the 737-300, depending on flight distance (see Figure 2.2).

Figure 2.2 Fuel savings of new generation narrow body aircraft compared to previous generations



Source: SEO/To70 based on Yanto and Liem (2018) and Rosskopf (2013)

Based on an analysis for 16 US airlines over the period 1995-2015, Brueckner and Abreu (2017) found that airline emissions were on average 2.2% lower for every three year reduction in the age of the fleet. The International Council on Clean Transportation (2015) analyzed the fuel efficiency of 20 airlines on the transatlantic market. Norwegian Air Shuttle was found to be the most efficient (with a fuel burn of 40 passenger kilometres per litre). This this was mainly attributable to its young fleet of Boeing 787 aircraft.

The box below describes specific measures taken by the five largest European airlines over the past decade as well as intended renewals in upcoming years.

Investments by five largest European airlines

Lufthansa Group

Since 2011 Lufthansa (2019) has been undergoing a fleet modernization that is expected to be finished by 2025. The airline currently operates over 750 aircraft and has 205 aircraft on order; the majority of which (149 in total) are A320neo's and A321neo's. Their innovative engine technology combined with the improved aerodynamics (wingtips/sharklets) reduce fuel consumption by 15% to 20% per seat kilometer, depending on the cabin configuration. Furthermore, Lufthansa replaces its Airbus A340s with A350-900s which are one of the most fuel efficient aircraft currently available. The four-engined Boeing 747-400s are replaced by the much more fuel efficient two-engined Boeing 777-9X. The fleet renewal program is expected to reduce Lufthansa's fuel consumption by 25%. In 2017, Lufthansa reduced its fuel consumption by 4.5 percent to 3.68 liters per 100 passenger kilometers.

Ryanair

Due to its young fleet (6.5 years on average), high load factors and efficient aircraft, Ryanair (2019) was found to be the most efficient in terms of fuel efficiency in 2011 (measured in pounds of CO_2 per passenger mile) by Brighter Planet in its Air Travel Carbon and Energy Efficiency Report. The fuel burn for a Ryanair aircraft is 1.9 liters per 100 passenger kilometers. Ryanair commits to further reduce its fuel consumption and emissions. It does so by (among other things), by renewing its fleet of Boeing 737-800's with Boeing 737MAX-8's. Ryanair (2018) expects that the ordered aircraft with new engines and winglets, slim line seats and aerodynamic improvements reduce fuel consumption by 16%.

IAG

By the end of 2017, IAG's (2019a) fleet was composed of 546 aircraft (72% Airbus aircraft, 24% Boeing and 4% Embraer). IAG is expecting 179 future deliveries and has 198 aircraft purchase options of the mentioned aircraft models. These consist mainly of new generation aircraft such as the Airbus A320neo, A350 and Boeing 787 Dreamliner. In 2017, 13 new aircraft joined the fleet which were at least 20% more efficient than the models they replaced (IAG, 2019b). Together with the installation of Honeywell's GoDirect Fuel Efficiency software this improved IAG's carbon efficiency by 2.6% in 2017.

By 2022, 37 new generation aircraft will enter the long-haul fleet. These aircraft are approximately 30 per cent more fuel efficient than the Boeing 747s that they replace. In addition, half of the Airbus A319s fleet is replaced by larger Airbus A320/A321neos, reducing fuel consumption and emissions per seat.

Air France-KLM

In 2017, Air France-KLM (2018) replaced three Airbus A340s by four new Boeing 787-9s and of three old generation A320s by two new Airbus A320s with sharklets. KLM added 10 B787-9 aircraft and two new B777-300 to its fleet and retired four Boeing 747-400s. HOP! replaced three ATR42/72-500s by one ATR72-600. Transavia France received four new B737-800 and KLM Cityhopper retired the last 11 Fokker 70s and replaced them with eight new Embraer 175s. Since 2011, Air France-KLM reduced its fuel consumption by 11% to 3.30 liters per 100 passenger kilometers.

easyJet

easyJet (2019) has started to replace its fleet of Airbus A319 and A320 aircraft with larger and more fuel efficient A320neo's and A321neo's. easyJet expects that its new aircraft with new engines and wingtip 'Sharklets' are 15% more fuel efficient than its current aircraft. By the end of 2022, the airline expects to operate 100 of such new generation aircraft. The new aircraft are expected to be 15% more fuel efficient than current generation aircraft. Budd and Suau-Sanchez (2016) showed that the A320neo is as fuel efficient as the smaller A319, which means that fuel consumption and CO_2 emissions per seat are reduced.

Furthermore, easyJet continues to use operational measures to reduce fuel usage and carbon emissions. These measures include the use of one engine taxiing, installation of lightweight Recaro seats, and the use of electronic devices. In 2017, easyJet reduced its carbon emissions per passenger kilometer by 1.7% (from 79.98 grams to 78.62 grams per passenger kilometre). The airline aims to reduce emissions by 10% in 2022 compared to 2016 levels.

It is expected that the trend of efficiency-gains will continue. Aircraft engines can become even more fuel-efficient by increasing temperatures and pressures[11] and applying open rotor designs. Much of the current efforts by aircraft manufacturers to reduce fuel consumption focus on weight reduction, by applying new materials and composites. Over the longer-term, improving aerodynamics will be the most effective way of reducing fuel consumption. The International Energy Agency (2009) predicts that improved aerodynamics and weight reductions could both reduce fuel consumption by 20-30% in the 2010-2030 timeframe. This constitutes a fuel efficiency improvement of 0.9-1.3% per year.

Retrofitting new technologies

New technologies can also be retrofitted to in-service aircraft. According to Müller et al. (2018) low-cost carriers and network carriers can reduce their emissions by 7-12% until 2025 by retrofitting their aircraft with blended winglets, reducing aircraft weight, installing electric taxiing systems and re-engining. This corresponds to estimations by IATA (2013a) which expects that retrofits may reduce fuel consumption by 5-12%.

Winglets / sharklets

In-service aircraft can be retrofitted with blended winglets and wingtip extensions to reduce drag. Blended winglets are angled extensions installed to the wingtip of aircraft to reduce drag over the wingtip. This yields fuel savings in the order of 1-2%. Adding small ribs to the wing surface to reduce turbulence could improve fuel consumption by another 1-2%. Whether this is sufficient for airlines to retrofit aircraft depends on the aircraft's age, as well as the price of fuel and ETS-allowances.

Boeing made winglets available as of 2001 for regional jets and the 737-800. Although the winglets increase the weight of the aircraft, the aerodynamic improvements results in a net reduction in fuel consumption of 2-4% for a Boeing 737-800 depending on the flight distance (Aviation Partners Boeing, 2017; Freitag and Schulze, 2009).

11 Increased engine pressure and temperature may however lead to increases in NO_x emissions.

Airbus introduced blended winglets under the name 'sharklets' in 2012 with the introduction of the A320ceo (current engine option). Compared to the original A320 the winglets reduced fuel consumption by 1% for flight distances of around 1,000 kilometres and 3.5% for distances over 6,500 kilometres (Cansino and Román, 2017). Airbus offers the sharklets as retrofits for the A319 and A320.

Electric taxiing
Taxi operations are the largest source of emissions in an LTO-cycle around airports (Nikoleris et al., 2011). Taxiing accounts for over 10% of total fuel consumption for very short-haul flights (up to 200 miles) and over 5% for short-haul flights (up to 600 miles) (Turgut et al., 2014).

Instead of using the aircraft's main engines to taxi around the airport, aircraft can be fitted with electric taxiing systems. These consist of electric motors powered by the auxiliary power unit (APU) to move the aircraft around airports. The APU uses less fuel during taxiing than the main engines. However, the system does add weight to the aircraft, therefore it is only efficient for short- to medium-haul aircraft. The net reduction in fuel consumption is estimated at 2.8% per flight cycle (Schäfer et al., 2016).

Re-engining
Existing aircraft can be equipped with newer more fuel efficient engines. The options are however limited as the new engines need to be of the same model. Retrofitting older aircraft types with new engine types, such as geared turbofans which offer fuel savings of of around 10-15% per flight (Jesse et al., 2012; Schäfer et al., 2016) is possibly not feasible as it requires major rework on the aircraft itself.

Weight reductions in the cabin
The weight of aircraft can not only be reduced by using light weight (composite) materials, but also by weight reductions in the cabin. Lighter trolleys, slim line seats and the replacement of paper manuals by tablets reduce weight and therefore emissions. According to Ryanair (2018), the installation of slim line seats alone reduces fuel consumption by 1%. This corresponds to reports by Flightglobal (2014) and Schäfer et al. (2016) indicating that a reduction in seat weight of one-third, would reduce fuel consumption by 1.25%. Airlines can also stimulate passengers to 'travel lighter' by implementing stricter baggage rules.

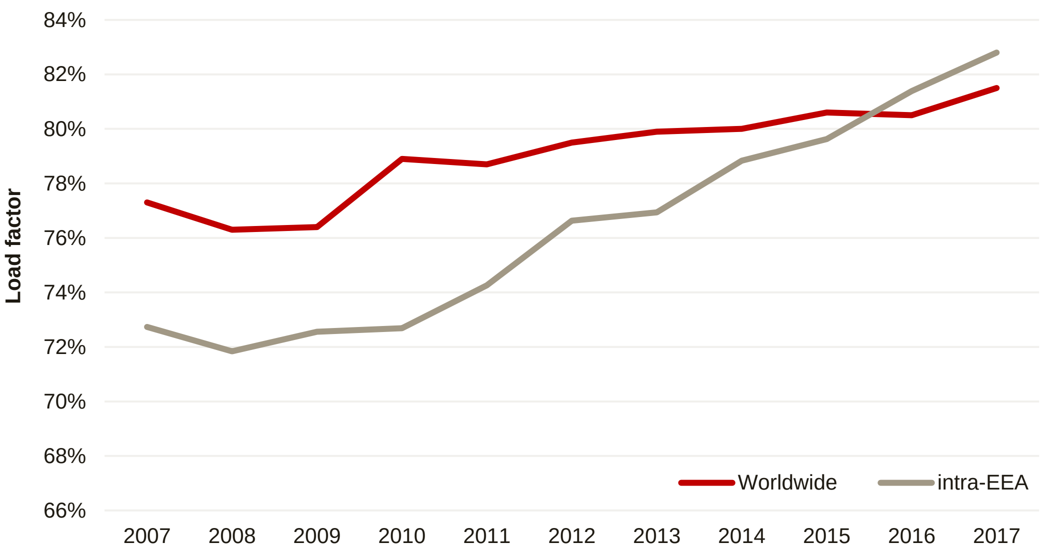
Information technology
Additionally, advances in information technology may reduce fuel consumption. IAG for instance installed Honeywell's GoDirect Fuel Efficiency software across its fleet to optimize fuel consumption by analyzing flight data and monitoring efficiency initiatives across the fleet. Air France-KLM implemented a Fuel Saving Plan which focuses on fuel policies, fuel standards, accurate planning information, route optimization, and weight reduction.

2.1.2 Operational measures

Airlines also reduce fuel consumption and emissions by taking operational measures. These include optimizing load factors, reducing cruise speeds, making optimal use of winds, electric and single-engine taxiing and the uptake of biofuels (Linke et al., 2017; Niklaß, 2017).

Although higher load factors increase the weight of an aircraft (Brueckner and Abreu, 2017), fuel consumption per passenger kilometre will reduce. Between 2007 and 2017, the average industry passenger load factor increased from 76.3% to 81.5% (IATA, 2018b). Load factors of intra-EEA flights improved even more over the same period, from 72.7% to 81.5% (Eurostat, 2018). Low-cost carriers achieve even higher load factors. Ryanair (2018) for instance increased its load factor from 83% to 94% over the past four years, which resulted in a 12% reduction in per passenger emissions (2.9% per year).

Figure 2.3 Load factors increased more within the EEA than globally, contributing to fuel efficiency



Source: SEO/To70 analysis based on Eurostat and IATA (2018b)

2.1.3 Fuel efficiency

Multiple studies have analyzed the development of aviation's fuel efficiency. Findings differ due to differences in (1) time periods analyzed, (2) regions and traffic segments included in the analysis and (3) metrics used (fuel consumption per ASK, RPK or FTK). ATAG (2018) found that global fuel efficiency improved by 2.1% per year over the 2009-2016 period. The European Environment Agency (2017) showed that average CO_2 emissions per passenger kilometer (RPK) in Europe were reduced by 18% over the 2000-2014 period. This constitutes an average reduction of 1.4% per year. To put this achievement in perspective, road transport reduced its CO_2 emissions by 10% over the same period or 0.8% per year. Amizadeh et al. (2016) estimated the reduction in CO_2 emissions for passenger and cargo traffic over the 2010-2013 period. For the EU they found that emissions per ton kilometer were reduced by 1.2%. Amizadeh et al. (2016) and Cui and Li (2016) found that fuel efficiency among European airlines improved more than the industry average.

Larsson et al. (2018) analyzed fuel aviation emissions in Sweden over the 1990-2014 period and found that average emissions (CO_2 and other emissions per passenger kilometer) were reduced by 1.9% per year around half of which (0.84%) was realized by achieving higher load factors. The remainder (1.1%) was realized by technological and ATM improvements. Developments in fuel efficiency

2.2 Analysis

This section quantifies to what extent technical and operational measures have reduce the environmental impact of intra-EEA flights over the 2015-2017 period. It presents the improvement in fuel-efficiency and the resulting fuel and emission savings. Section 2.2.1 describes the methodology used. The findings are presented in section 2.2.2.

2.2.1 Methodology

First, we determine to what extent fuel efficiency has improved over the past decade due to investments in new aircraft technology and more efficient airline operations (higher load factors). Fuel efficiency is defined as: fuel consumption per passenger kilometer. A 1% improvement in fuel efficiency means that fuel consumption per passenger kilometer is reduced by 1%. As CO_2-emissions are directly related to fuel consumption,[12] a 1% reduction in fuel consumption (and hence a 1% improvement in fuel efficiency) translates into a 1% reduction in CO_2-emissions. Second, we determine to what extent technical and operational measures have led to fuel and emission savings for intra-EEA flights over the 2015-2017 period.

Step 1: Measuring the improvement in fuel efficiency

Fuel efficiency is estimated for all scheduled passenger flights over the 2007-2017 period. Flight information, such as frequency, seats, aircraft types operated and flight distances are sourced from OAG's Schedule Analyzer. This flight information is input to our in-house aircraft emissions model. The model calculates for each aircraft operation the emissions in the various flight phases: Landing/Take-off (LTO), climb, cruise and descent. Fuel consumption for specific aircraft types is sourced from Eurocontrol's Base of Aircraft Data (BADA) for the climb, cruise and descent phases (Eurocontrol, 2017a).[13] BADA does not provide data for all aircraft types in operation, but recommends which types to use as synonyms. Fuel consumption in the LTO phase is taken from ICAO's Engine Emissions Databank (EASA, 2018). This databank contains fuel consumption data for individual engine types in the LTO phase. To each aircraft type we attach a common engine type based on the Eurocontrol ANP database. The analysis shows how fuel consumption per seat kilometer has developed over the past decade, indicating to what extent technological measures have improved fuel efficiency.

Second, we factor in the added contribution of higher load factors by calculating fuel consumption per passenger kilometer. Seat kilometers are translated into passenger kilometers by using load factor data. For intra-EEA flights we use load factors extracted from Eurostat. For other flights we use the global load factors published by IATA corrected for the intra-EEA flights.

12 Burning 1 kilogram of kerosene generates 3.15 kilograms of CO_2 (Eurocontrol, 2018e; Larsson et al., 2018).

13 BADA is used extensively in (scientific) research to estimate fuel consumption and emissions in the Climb-Cruise-Descent phase. Wasiuk et al. (2015) used the BADA model to estimate global fuel consumption and NO_x emissions over the 2005-2011 period. Schaefer (2012) used BADA to simulate flight trajectories and predict fuel consumption and emissions. Lee et al. (2005) used BADA to derive aircraft and distance specific cruise altitudes. Simone et al. (2013) developed a BADA based methodology to calculate aircraft performance and emissions. Pagoni and Psarako-Kalouptsidi (2017) used BADA to estimate fuel consumption and CO_2-emissions. BADA was also used to assess the impact of operational measures and to compute fuel consumption when actual flight data records are available (Pagoni and Psaraki-Kalouptsidi, 2017). According to Saucier et al. (2017) the latest version of BADA produces realistic fuel-flow predictions for the entire flight envelope.

Flights over very short distances are relatively inefficient in terms of fuel consumption as they spend little or no time in the cruise phase. Over the 2007-2017 period the average length of intra-EEA flights has increased from around 900 to almost 1,100 kilometers. We control for this increase in flight distance to obtain the true contributions of new aircraft technology and higher load factors on fuel efficiency. This is achieved by assuming the same distribution of flights over specific distance ranges in 2007 as in 2017. Finally, we determine the fuel efficiency improvement realized over the 2007-2017 period by comparing fuel consumption per passenger kilometer in 2007 to that in 2017.

Step 2: Calculating fuel and emission savings

We use the improvements in fuel efficiency to calculate how much fuel and CO_2 has been saved within the EEA over the 2015-2017 period through technical and operational measures taken by airlines. First, we calculate the fuel consumption over this period as described above. Next, we correct for increases in flight frequencies and changes to the composition of traffic for a fair comparison. This means estimating how much fuel would have been consumed over the 2015-2017 period when fuel efficiency had not changed since the beginning of 2015. Finally, we compare the actual fuel consumption in each year with the fuel consumption if no technological and operational measures had been takes since the beginning of 2015, to obtain the fuel savings over this period.

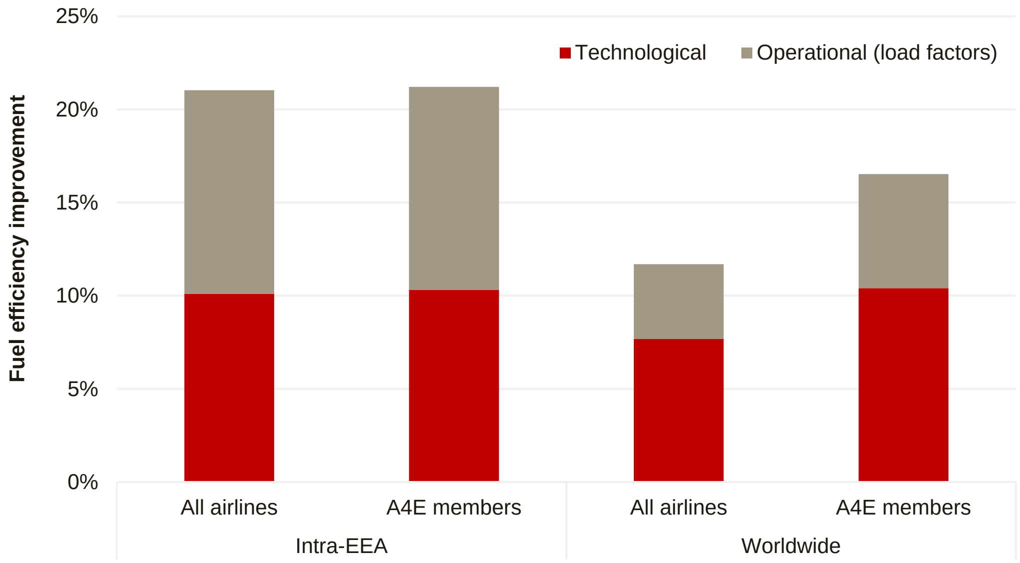
2.2.2 Results

Fuel efficiency

Figure 2.4 shows that the average fuel efficiency of intra-EEA flights improved by 21% between 2007 and 2017 (1.9% annually). Technological and operational measures both contributed to higher fuel efficiency. Technological measures led to an efficiency improvement of 10%. The remaining 11% can be ascribed to an increase in load factors. These findings correspond to the findings by Larsson et al. (2018) (see section 2.1). Fuel efficiency improvements realized by the A4E member airlines[14] were similar to the industry average.

[14] For an overview of the A4E member airlines we refer to Appendix D.

Figure 2.4 Average fuel efficiency of intra-EEA flights improved by 21% between 2007 and 2017



Source: SEO/To70 Analysis based on OAG Airline Schedules, IATA (2017, 2018b) and Eurostat

Fuel efficiency improvements within the EEA were almost twice as high as the global average (12%). This confirms the findings of Amizadeh et al. (2016) and Cui and Li (2016) (see section 2.1). The fuel efficiency of the A4E member airlines also improved more on intra-EEA flights than on extra-EEA flights. However, their efficiency improvements on extra-EEA flights still outpaced the global average.

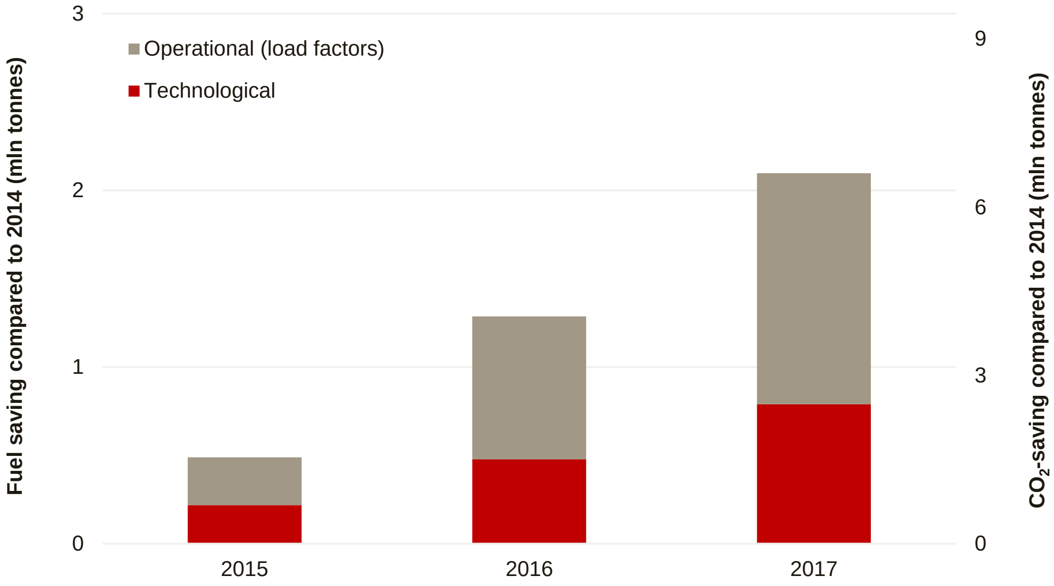
This may be explained by the fact that global load factors were already on a higher level in 2007. In 2007 global load factors were already at a higher level than the intra-EEA load. This means that less improvement in load factors was possible globally. As mentioned above (see Figure 2.3) load factors on intra-EEA flights improved more than the global average over this period, which (partly) explains why fuel efficiency improvements within the EEA were larger than globally. As load factor improvements are finite, the contribution of higher load factors to fuel efficiency is likely to decline in the future (Larsson et al., 2018).

Environmental impact

Figure 2.5 shows the fuel and emissions savings through technical and operational measures taken by airlines for intra-EEA flights in the 2015-2017 period (compared to 2014). As airlines continuously improve technological and operational measures, the fuel and emissions savings increase year by year. The cumulative fuel savings over the 2015-2017 amount to 3.9 Mt (Megatonnes)[15], translating into over 12.2 Mt of CO_2. This corresponds to the fuel consumption and emissions of around 1 million commercial passenger flights per year or two months of flying within the EEA.

15 One Megaton equals 1,000 kilotonnes or 1,000,000 tonnes.

Figure 2.5 Technological and operational measures saved over 12 Mt of CO_2



Source: SEO/To70 analysis

3 Disruptions

Strikes at Air Traffic Control (ATC) and technical failures at European Air Navigation Service Providers (ANSPs) lead to delays, flight cancellations and the rerouting of aircraft, negatively impacting passengers, airlines and the environment. Over the 2015-2017 period, Europe faced 33 ATC-strikes and 64 technical failures at ANSPs, most of which occurred in France. Strikes on average affected more flights (3,468 per day) than technical failures (1,329 per day). The impact of strikes on flight distance is also significantly larger: an average strike increases total flight distance by 70,000 kilometres per day, requiring 200 tonnes of additional fuel, whereas an average technical failure increases flight distance by 'only' 3,000 kilometres per day requiring 10 tonnes of additional fuel.
Together, ATC-strikes and technical failures increased flight distance by 4.6 million kilometres over the 2015-2017 period. As a result, fuel consumption and CO_2-emissions increased by 13.7 kt (kilotonnes) and 43.0 kt respectively. This corresponds to around 3,500 commercial passenger flights within the EEA.
Disruptions in France were responsible for almost 98% of the increases in fuel consumption and emissions. This is explained by the high number of French strikes, the central geographical location of France in Europe, the relatively long duration of French strikes (2 days on average) and the fact that not all overflights are accommodated.

Disruptions may lead to the temporary closure or limitation of available capacity in airspace sectors. A reduction of airspace capacity may lead to the rerouting of aircraft, resulting in longer flight trajectories and increased fuel consumption and emissions. This chapter quantifies the environmental impact resulting from disruptions within the EEA over the 2015-2017 period. Specifically, we estimate the impacts caused of two types of disruptions: strikes at Air Traffic Control (ATC) and technical failures at Air Navigation Service Providers (ANSPs).

Section 3.1 provides a literature review describing the type of impacts of disruptions and factors that influence their size. Furthermore, it discusses the outcomes of previous impact assessments. Section 3.2 presents the number of strikes and technical failures that occurred within Europe over the 2015-2017 period. Section 3.3 quantifies their individual and combined environmental impact. Two specific disruptions, one national strike in France and a case of understaffing at Karlsruhe ACC, are illustrated by case studies in section 3.4.

3.1 Literature review

3.1.1 Type of impacts

Strikes and technical failures at ANSPs lead to delays, flight cancellations and inefficient flight operations:

- **Delays:** Flights that pass through sectors where capacity is reduced may face delays. In addition, rerouted flights may lead to the on-loading of traffic in adjacent sectors which may also cause delays in these sectors. Furthermore, flight delays may have knock-on effects on other flights throughout the day and in subsequent days. PWC (2016) showed that on average each strike day resulted in 0.3 days with knock-on disruptions;

- **Cancellations:** Airlines may be forced to cancel flights due to (1) limitations in airspace capacity, (2) airports that are inaccessible due to airspace closures and (3) significant delays making it impossible to operate certain flights (for instance when flights are expected to arrive after the destination airport is closed or crew will exceed working time limitations);
- **Flight inefficiencies:** Capacity limitations may force airlines to reroute. Although this may allow the flight to be operated and/or delays to be minimized, the rerouted flights are generally longer in terms of distance and travel time, leading to increased fuel consumption and emissions.

Delays, cancellations and flight inefficiencies negatively affect passengers, airlines and the environment. Passengers are confronted with longer travel times disrupting their travel plans. Significant delays may lead to missed hotel bookings, missed connections and foregone attractions. Airlines are confronted with cost increases. In case of severe delays, they need to pay passengers compensation and book them on other flights. Furthermore, the rerouting of flights, generally increases flight trajectories. This not only leads to extended working times for air crews, but also results in increased fuel consumption.[16] Increased fuel consumption translates into more CO_2-emissions, which negatively impacts the environment. As pointed out above, CO_2-emissions are directly related to fuel consumption. This means that a percentage point increase in fuel consumption translates into a similar percentage point increase in CO_2-emissions.

3.1.2 Factors determining size of impacts

The size of the impacts differ between disruptions, depending on the:

1. **Number of affected airspace sectors**: the more sectors that are closed or face a capacity reduction, the more flights that are be affected. The rerouting of traffic may lead to knock-on effects on adjacent states. The French strikes for instance had a significant impact on Ireland (which controls much of the alternative 'Tango'-route between Northern Europe and Spain), Italy, Spain and the UK (Ricardo, 2017);
2. **Size of affected airspace sectors**: the larger the size of the affected airspace sectors, the larger the impacts on flight trajectories;
3. **Duration of disruptions**: the longer specific airspace sectors are closed or face a capacity reduction, the more flights that are affected. Also, strikes of short duration have a smaller impact on airlines and passengers as the airlines can plan their operations around the strike, given that the strike is announced well in advance (Ricardo, 2017);
4. **Traffic volume through the affected airspace sectors**: the more traffic that passed through the affected airspace sectors, the more flights that are affected;
5. **Advance notice of disruptions**: when airspace closures or capacity reductions are announced well in advance of a strike, airlines have time to take mitigating actions and plan around the disruptions. With technical failures this is generally not possible as these type of disruptions are unforeseen. For airlines to take appropriate mitigating actions it is also relevant to know how much capacity will be available (if any) in certain sectors;

[16] Airlines may take measures to reduce the impacts of disruptions, for instance by building additional slack into their schedules, have additional staff (crew and customer service) and aircraft on standby, increase flight speed and adjust flight plans when necessary (Filippone et al., 2016). Such measures increase resilience, but come at a costs (Kohl et al., 2007).

6. **Availability of alternative routings**: when alternative routeings are available through sectors with sufficient capacity, the impacts on flight parameters will be smaller than in a situation without such routeings. Rerouting of traffic through adjacent sectors may increase congestion and delays in these sectors however.
7. **Certainty about available capacity**: certainty about whether a strike will go ahead and how much capacity will be provided allows airlines and ANSPs responsible for adjacent airspace sectors to create contingency plans. The unpredictable nature of technical failures are by definition unplanned. Therefore airlines and ANSPs cannot anticipate on such failures.

Whether airlines are able to plan around the strike and limit the impacts for their passengers, depends on the advance notification period and certainty regarding the service level that will be provided during the strike. In some countries notification periods and minimum service levels have already been defined, whereas in other countries they have not.

In practice is it often uncertain whether strikes will go ahead. This forces airlines to make late decisions on flight cancellations. Airlines prefer to cancel flights around 24 to 48 hours before departure, as this allows them to rebook passengers onto alternative flights or to allow passengers to make other arrangements. Also there can be uncertainty about the service level provided. In France, at least 50% of all overflights should be served. Although this is intended to mitigate the impacts of the strike, it is often uncertain which overflights can be served, i.e. which sectors are open and which capacity is provided. This also leads to late decisions by airlines as to which flights to operate via which routes (Ricardo, 2017).

In its Aviation Strategy the European Commission (2015) also mentioned the importance of maintaining minimum service levels during disruption in which at least overflights should be ensured:

> *"In order to allow for continuity of air traffic management, a minimum level of service in managing European airspace should be ensured, allowing at least for the movement of overflights (flights crossing the airspace of an affected state or area) causing the least amount of disruption to the network."*

In 2017, the European Union commissioned a study into the best practices regarding the implementation of minimum notification periods (prior to a strike) and minimum service levels (during a strike). Based on an analysis of the notification periods and minimum service levels in place in certain countries, the study recommends the following best practices (Ricardo, 2017):

- Advance notification periods:
  - Initial notification on strike intentions at least 14-21 days in advance. Over this period airlines should kept up-to-date on the strike plans, the airspace sectors that will be affected and the capacity that will be available;
  - Confirmation of strike 5-7 days in advance. This allows airlines and ANSPs to work on contingency plans;
  - Specific notification of impacts 48-72 hours in advance. Confirmation on the sectors that are affected and the level of capacity that will be available. To determine how much capacity can be provided staff is required to notify their intention to strike 72 hours in advance;
- Minimum service levels:

- Maximum durations for a strike (e.g. four to eight hours) and ensuring that strikes only take place outside peak hours as is currently the case in Italy;
- Ensuring that all overflights can be served with a defined maximum level of delay;
- Providing certainty (by the ANSP) on how much traffic can be handled, either by providing a percentage or by indicating which traffic is being prioritized.

Furthermore, the study concluded that a good social dialogue between the unions and ANSPs can reduce the number of strikes. Such dialogue may prevent disputes to escalate to the point of a strike being called. In fact, in countries where the unions and ANSPs maintain an active social dialogue, strikes are largely absent. Examples of such countries are Denmark, Ireland and the UK. In Ireland the aviation authority has an agreement with its staff which requires mediation followed by a binding arbitration to resolve any issues before a strike can be called. Portuguese legislation requires a compulsory conciliation meeting and arbitration, which is generally successful and reduces the number of strikes (Ricardo, 2017).

The study also concluded that the number of 'solidarity' strikes can be reduced by separating ANSPs from the rest of a country's public service. When ANSPs are private entities it is less likely that they strike in support of a national strike. Currently the status of the European ANSPs differs between countries.

The recommendations are in line with those issued by A4E (2018a) in its 'Call for Action':

- ANSPs should actively participate in arbitration or another form of conciliatory procedure;
- Ensure all overflights while ensuring that this does not go at the expense of flights to and from the country where the strike is called;
- An advance notification period of 21 days;
- A 72 hour advance notification period of staff participating in a strike to increase the predictability of the impact of a strike;
- Implement cooperation mechanisms to minimize service disruption.

3.1.3 Previous impact assessments

In 2016, PWC assessed the economic impacts of strikes at European ANSPs. They found that in the 2010-2015 period, strikes reduced EU GDP and employment by € 10.4 billion and 143,000 jobs respectively. The majority of these impacts consist of: reduced tourism spending as passengers cancel (part of) their holiday (59%), reduced productivity as passengers have to spend more time travelling (35%) and reduced airline revenues due to cancellations (6%). Other impacts, such as on the freight industry, cost increases for airlines were not modelled due to a lack of data. The estimated economic impacts should therefore be considered as a lower bound.

Ricardo (2017) estimated that a single strike may cost airlines over € 15 million. This includes the costs of delays, additional distance flown and the costs of flight cancellations. The impacts differ between strikes, whereby the French strikes resulted in the largest increases in flight distances and airline costs. This was mainly due to (1) the central location of France in Europe whereby much traffic between Northern and Southern Europe and between the UK/Ireland and the Mediterranean passed through French airspace and (2) the treatment of overflights by France, whereby only 50% of capacity for overflights need to be provided. As it appears difficult to predict how many additional traffic controllers will show up for work, it is hard to predict how much additional capacity can be provided for overflights (Ricardo, 2017).

The study also provided a rough estimate of the impact of strikes at European ANSPs on flight distance by comparing actual distance flown on strike days to distance flown on non-strike days. It was found that the additional flight distance ranged between 0-1.8%, with the French strikes leading to the largest increases in flight distance. To our knowledge, the study by Ricardo (2017) is the only study which provides a rough estimation of ANSP-strikes on flight efficiency. The study did not estimate the impacts of technical failures at ANSPs on flight efficiency, nor did the study assess the environmental impact of disruptions.[17] This study is the first to provide an in-depth analysis of the impacts of strikes and technical failures on flight efficiency and the environment.

3.2 Disruptions between 2015-2017

ATC-strikes

Over the 2015-2017 period traffic controllers at ANSPs in Europe went on strike 33 times. The French controllers at DSNA were responsible for the majority of all strikes (60%), followed by the Italian controllers (18%). Appendix A contains a detailed overview of the strikes that occurred at the European ANSPs between 2015 and 2017.

There are two main causes for strikes at ANSPs (Ricardo, 2017):

- Disputes regarding labour conditions (salaries, working conditions, rostering, investments etc.);
- Participation of staff in national public service strikes (‘solidarity strikes’).

The majority of the strikes in France and Greece were so-called ‘solidarity strikes’, supporting national labour disputes. The French strikes in 2016 for instance were mainly due to the introduction of the ‘Loi Travail’ (a law which aimed to make labour more flexible), which caused many national strikes in France. These were in many cases supported by DSNA-staff, although the law explicitly excluded ATM. The recent strikes in Italy had to do with the privatisation of the national ANSP: ENAV.

Strikes in France are normally full day strikes (midnight to midnight) and often cover multiple days, whereas strikes in other Member States, such as Italy and Greece, are generally limited to only a few hours. In terms of strike days, France is therefore responsible for an even larger share (74%) than in terms of strikes.

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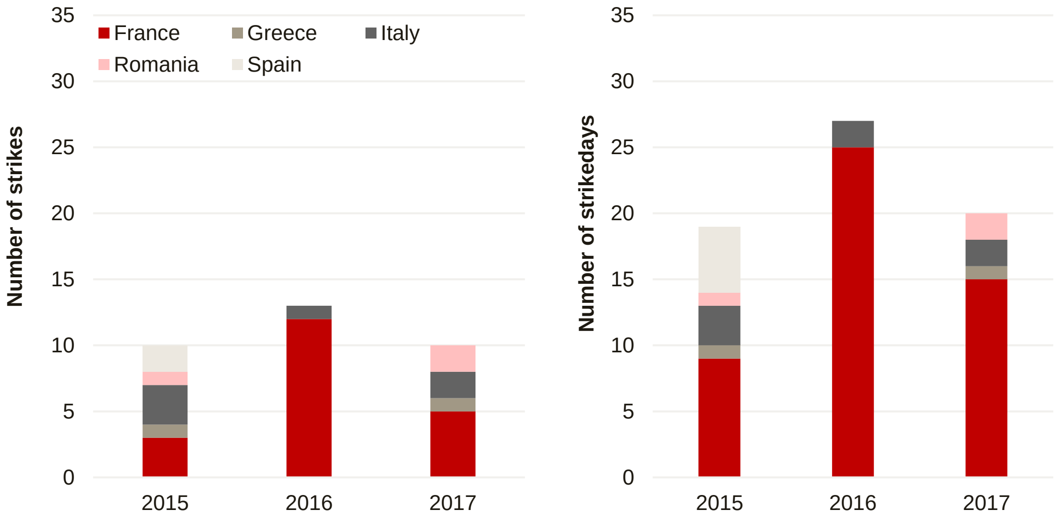
[17] Although no literature is exists on the impacts of disruptions on fuel consumption and emissions, a significant amount of literature exists on the relationship between fuel consumption and flight parameters that may be affected by disruptions (see Appendix C).

Figure 3.1 Most strikes took place at the French ANSPs between 2015 and 2017



Source: SEO/To70 analysis based on Eurocontrol (2016a, 2017c, 2018a)
Note: The data includes only strikes by air traffic controllers. Strikes by other categories of staff, such as ATC-technicians, are not included. Also strikes by air traffic controllers that are called on short notice may sometime be recorded as 'staffing issues' and therefore may not be included in the data.

In 2015, strikes at European ANSPs resulted in 600,000 minutes of delay[18], the majority (70%) of which was caused by one French strike that occurred between 8-10 April (Eurocontrol, 2016a). Brueckner and Abreu (2017) showed that when delays increase by 3 percentage points, emissions increase by 1%. Although the number of strike days increased by 40% in 2016, delays doubled to 1.2 million minutes (Eurocontrol, 2017c). This indicates that strikes may lead to very different impacts on passengers. In 2017, 800,000 minutes were lost; again the majority of the delays (85%) was caused by French strikes (Eurocontrol, 2018a). The large delays caused by the French strikes are not only the result of the large number of strikes and their relatively long duration, but also due to the geographic location of France which means that many flights pass through French airspace on a daily basis. To give an indication, 60% of Ryanair's flights use French airspace.

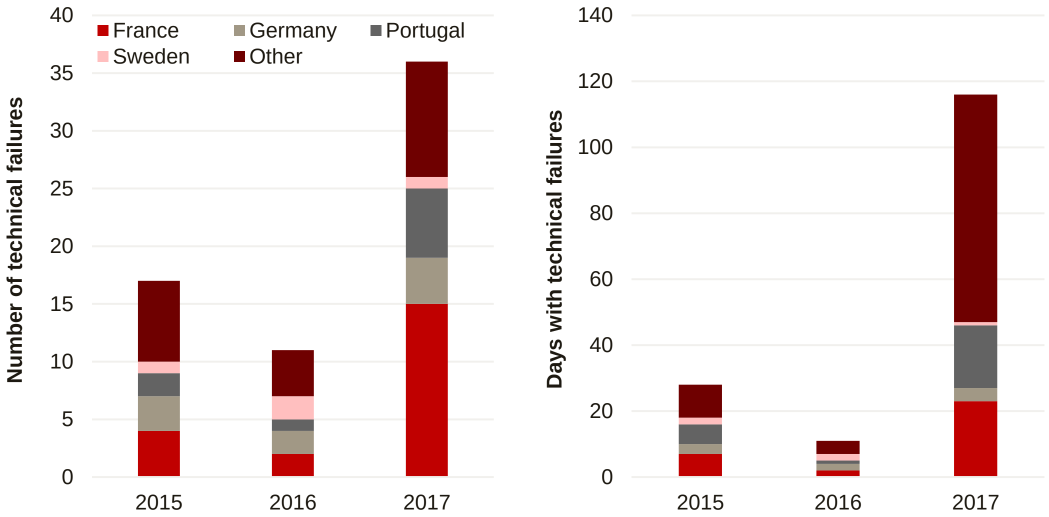
Technical failures
ANSPs provide services to flights in their designated airspace. En-route flights are controlled by integrated radar systems supplemented by voice communication systems. The failure of these technical systems may also lead to the temporary closure of airspace sectors. An important difference with strikes is that technical failures are always unexpected. Contrary to strikes, airlines and ANSPs cannot implement contingency plans for when failures occur. Planned system maintenance or the introduction of new operational concepts, like Free Route Airspace rarely cause airspace closures and therefore have a smaller impact on the environment.

Over the 2015-2017 period, Eurocontrol recorded 64 technical failures, more than half of which occurred in 2017. One in every three technical failures occurred at the French ANSP. Most failures were caused by radar or communication failure. Appendix B contains a detailed overview of all technical failures between 2015 and 2017: when and where they happened, their cause as well as their duration. Technical failures on average take 2.5 days to solve. In 2017 the Swiss ATC centres

18 Delays include indirect delays in neighbouring ANSPs due to on-loading of traffic.

of Geneva and Zurich experienced radar instability issues for 30 days. When we exclude these events, the average technical failure prolongs for 1.5 days.

Figure 3.2 Most technical failures take place at French ATC-organizations



Source: SEO/To70 analysis based on Eurocontrol (2016a, 2017c, 2018a)

3.3 Analysis

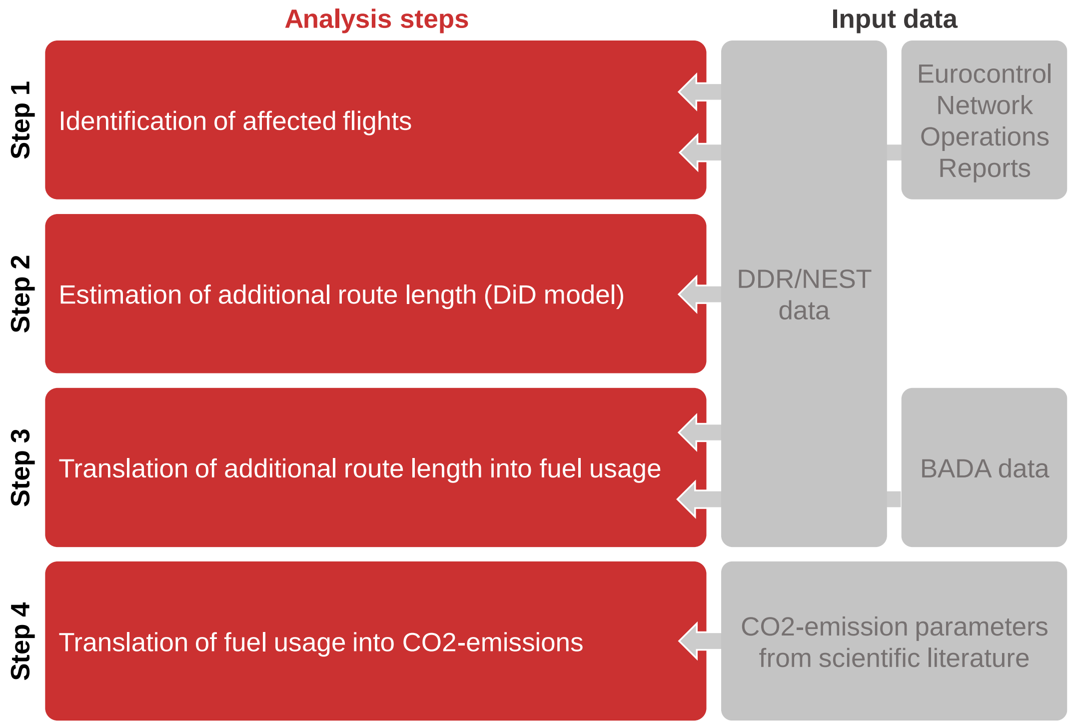
This section quantifies the environmental impact of disruptions. Specifically, we estimate the EEA-wide environmental impact caused of two types of disruptions: strikes and technical failures at ANSPs.[19] The next section describes how the impacts of strikes and technical failures have been quantified. Section 3.3.2 presents the results in terms of affected flights, additional kilometres flown, additional fuel consumption and CO_2-emissions.

3.3.1 Methodology

In this section we intuitively explain how this method calculates horizontal flight inefficiencies and how these estimates are translated into fuel consumption and CO_2-emissions. Figure 3.3 provides a schematic overview of the analysis and shows the relevant input data for each step. The main intuition behind the analysis is as follows: We compare the horizontal flight distance of affected flights on the day of the disruption, with the route length of these same flights on the day one week before the disruption.

[19] This does not mean that other types of airspace disruptions are not relevant. Indeed, other types of disruptions such as understaffing may also have an impact on flight efficiency and therefore fuel usage and CO_2-emmissions. However, because we cannot credibly identify when and where staffing issues occurred based on the available data, we are not able to provide a reliable and comprehensive assessment of the environmental impact of staffing issues at European ANSPs. In section 3.4.2 we do provide a case study regarding understaffing at Karlsruhe Upper Area Control Centre (UAC).

Figure 3.3 Approach for estimating environmental impact of airspace disruptions



Source: SEO/To70

Step 1: Identification of affected flights

To quantify the EEA-wide environmental impact of disruptions, we first identified when and where strikes and technical failures at ANSPs took place over the 2015-2017 period based on the Eurocontrol Network Operations reports. Second, we identified which airspace sectors were affected using Eurocontrol's DDR/NEST data (see box below). Third, we analysed which intra-EEA flights were affected by strikes and technical failures by determining which routes crossed the disrupted sectors *one week before the disruption actually took place*. All flights that also operated on these routes on the day of the disruption were identified as affected flights.[20] By considering the routes that crossed the disrupted sectors one week before the disruption (instead of on the day of the disruption), the list of affected flights also includes flights that were diverted around the affected airspace sector on the day of the disruption.

Eurocontrol DDR/NEST flight trajectory data

Eurocontrol's DDR/NEST data contains flight parameters for all flights executed in pan-European airspace. The dataset is made available by means of a subscription to the Demand Data Repository (DDR) website at which flight trajectory and airspace sector data can be downloaded and a desktop application, called the Network Strategic Tool (NEST), which can be used to export relevant variables from the sheer volume of available data.[21]

[20] Therefore, in this report the term 'affected flights' refers to those flights that were operated despite the airspace disruption. These include flights that were re-routed around the affected airspace or went through the affected airspace, but does not include cancelled flights. Although cancelled flights are obviously also affected by the airspace disruption, they are not affected in the terms of their flight trajectories.

[21] See: https://www.eurocontrol.int/services/nest-modelling-tool.

For each flight, the data includes among others, information on origin and destination airport, departure and arrival time, and horizontal and vertical flight distance. Some parameters, however, are only available for the flight trajectory within European airspace, causing the data to be incomplete for many intercontinental flights. For this reason, we focus our analysis on intra-EEA flights for which complete information is available in the data.[22] Moreover, although vertical flight distance is available in the data for each individual flight, but it is not possible to export this information for further analysis outside of the NEST tool. Hence, our analysis is only focussed on the horizontal flight inefficiencies caused by airspace disruptions.[23]

For some flights in this dataset the airline is unknown (i.e., ICAO code 'ZZZ'). Presumably, these flights are medical, military and private flights are other types of non-scheduled air transport. As these flights are not relevant for our analysis and could potentially obscure the calculations, we drop these flight observations from the dataset. For the same reason, we drop all flights shorter than 185.2 kilometres (100 nautical miles) and flights operated by airlines with less than 10 daily intra-EEA flights.[24]

The DDR/NEST dataset was also used to verify whether the disruptions mentioned in Eurocontrol's Network Operations Reports (see Appendix A and Appendix B) had actually led to an airspace regulation (i.e., temporary closure or limit on capacity).

Airspace disruptions usually cause a (substantial) amount of flights to be cancelled. It is important to take this into account in the analysis, because this could have an impact on the average distance flown on the day of the disruption. For instance, if the flight cancellations include predominantly flights over longer distances, then the average route length on the day of the disruption will be decreased. Note that this decrease does not mean that the stage length of individual flights has decreased; the decrease is only due to a *change in the composition* of the flights (i.e., relatively more shorter distance flights). If one would compare the stage length of all flights on the day of the disruption with the stage length of all flights one week before the disruption, one could falsely conclude that flight efficiency improved. To control for this effect, we only maintain those flights that were operated both on the day of the disruption and on the reference day (these flights are identified by looking for matches in the combination of call sign, origin and destination).

Furthermore, airlines may be more likely to cancel flights that are most affected in terms of increased flight distance. For instance, if the French national airspace is closed due to a disruption, then flights from Amsterdam to Barcelona need to incur a longer detour than flights from Brussels to Milan. As a consequence, flights from Amsterdam to Barcelona might be more likely to be cancelled. This means that we possibly only observe the flight inefficiencies for flights whose flight trajectories did not have to be changed dramatically due to the airspace disruption. Although it is possible to control for this so-called *selection effect* in the econometric model (under certain conditions), this is not a straightforward exercise. Most importantly, not controlling for this effect

22 See Appendix E for a list of EEA countries and corresponding ICAO codes.

23 Note how both these limitations, intra-EEA flights and horizontal flight inefficiencies only, may lead to an underestimation of the total environmental impact of airspace disruptions. Airspace disruption may also impact intercontinental flights that flyover European airspace and could affect vertical flight efficiencies as pilots are force to fly higher or lower than the optimal cruising height in order to circumvent disrupted airspace sectors.

24 As a robustness check we ran the complete analysis without these filters. This does not substantially alter the findings in terms of total flight inefficiencies, additional fuel consumption and CO_2-emissions caused by disruptions.

means that our estimates should be regarded as conservative estimates of the actual flight inefficiencies caused by airspace disruptions.

Step 2: Estimation of additional flight distance per affected flight

In the second step we estimate the additional horizontal flight distance of affected flights due to the airspace disruptions. For this estimation we use an econometric method called *difference-in-difference* (DiD).[25] The idea behind this methodology is that we observe the stage lengths of *two groups of flights* for *two time periods*. The groups of flights are (i) flights that are affected by the disruption and (ii) flights that are not affected by the disruption (i.e., comparable intra-EEA flights, see explanation in the next paragraph). The time periods are (i) the day exactly one week before the disruption and (ii) the day of the disruption.[26] We then compare the *difference* in route length in the group of affected flights on the day of the disruption and the day one week before the disruption, to the same *difference* for unaffected flights.

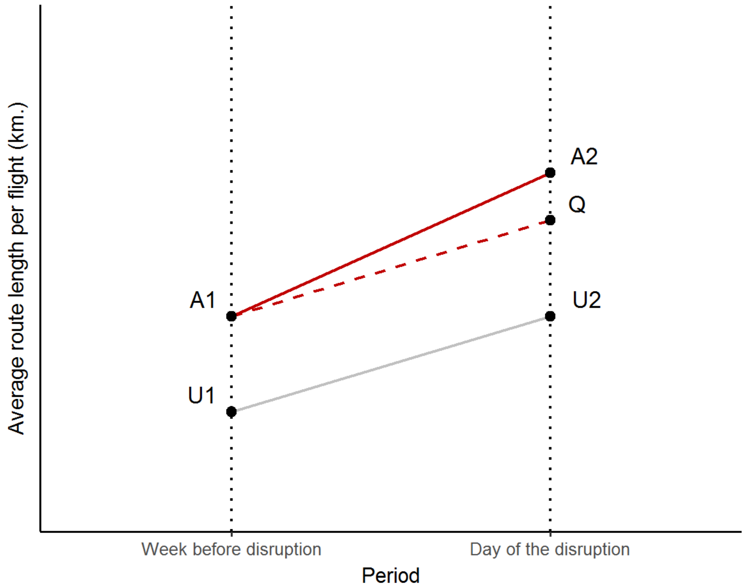
The unaffected flights on intra-EEA routes are used to control for a possible time trend. To increase the effectiveness of industrial actions, strikes may be called in peak periods. During such periods, flight efficiency may already be lower than during off-peak periods. Without correcting for such time trend, one could wrongfully ascribe peak period inefficiencies to disruptions. This leads to biased estimates of the impact of disruptions on flight parameters. Consequently, it is important to select a suitable control group that is comparable to the group of affected flights. To this end, we implement a statistical matching procedure called *nearest neighbour matching* (Rubin, 1973; 1979). This procedure matches each affected route to an unaffected route with approximately the same route length and number of daily flights flown on the route. All flights on the matched routes comprise the control group against which the affected flights are compared.

Figure 3.4 presents the logic behind this approach in a graphical manner. We compare changes in flight distance over time between flights that are affected by a disruption and flights that are not affected by the disruption. These changes over time are represented by the red solid line for the affected flights and the grey solid line for the unaffected flights. The crucial assumption of the DiD methodology is than that, if there would have been no airspace disruption, the time trend of the affected flights would have been similar to the time trend of the unaffected flights. This hypothetical time trend is represented by the dashed red line. The difference between this hypothetical flight distance (point Q) and the actual flight distance of the affected flights on the day of the disruption (point A2) provides an estimate of the additional flight distance caused by the airspace disruptions, irrespective of other factors that may influence flight distance. Simply comparing the flight distances of the affected flights on the day of the disruption (point A2) with those one week before the disruption (point A1) would overestimate the impact of the disruption.

25 The DiD methodology is a popular econometric technique for estimating causal effects (see, e.g., Bertrand et al., 2004; Hansen 2007; Wooldridge, 2012). It was originally developed by John Snow in the 1850s to study the causes of the cholera epidemic in London and was subsequently introduced in economics by Obenauer and von der Nienburg (1915) in a study on the impact of minimum wage rates. Since then it has been applied in a wide range fields, including transportation, labor markets and health economics.

26 Thus, if a disruption occurs on Friday 2015-01-16, we use Friday 2015-01-09 as the reference day. In case the day one week before a disruption was also affected by a disruption, we use the day one week after the disruption, and in case that day is also disrupted we use the day two weeks before the disruption etc. Besides, flight schedules differ significantly between the summer and winter seasons. A day in the first week of April, therefore cannot be compared to a day in last week of March. In such cases we use the day one week after the disruption as the reference day.

Figure 3.4 Isolating the additional route length caused by airspace disruptions



Source: SEO/To70

Step 3: Translation of additional flight distance into fuel consumption

In this step we translate the estimated flight inefficiencies (additional flight distances) into additional fuel consumption by using Eurocontrol's BADA Aircraft Performance Summary tables (Eurocontrol, 2017a). These tables contain fuel consumption data for various aircraft types at various altitudes.[27] For the purpose of this analysis, we make the assumption that all flight distance inefficiencies occur in the cruise phase at 31,000 feet.

From the DDR/NEST data it is clear how many flights were affected. For each of these flights the aircraft flight type is known and from step 2 the additional flight distance is known for each disruption. Combining this with the BADA data allows us to estimate the total additional fuel consumption for each individual disruption.

Step 4: Translation of additional fuel consumption into additional CO_2-emissions

As a final step, we translate the additional fuel consumption into CO_2-emissions. For this final step, we follow the guidelines set out by Eurocontrol for cost-benefit analysis (Eurocontrol, 2018e). These guidelines recommend using a value of 3.15 kg of emission released by the combustion of 1 kilogram of kerosene. This value corresponds to the factor used for CO_2-emissions for kerosene used by the Intergovernmental Panel on Climate Change (IPCC) and the value used in the scientific literature (see, e.g., Larsson et al., 2018). The limitation of this value is that it does not include the CO_2-emissions related to the production of jet fuel and other types of emissions (e.g., NO_x, H_2O, SO_2).

27 Not all aircraft types are included in the Summary tables. For those aircraft types fuel consumption of synonym aircraft is used. Eurocontrol has published a list of synonym aircraft for the types that are not included in the Summary tables.

3.3.2 Results

This section presents the results of the analysis. First we show how many intra-EEA flights were affected by disruptions over the 2015-2017 period. Secondly we show the impact of the disruptions on the efficiency of the affected flights in terms of additional kilometres flown. Finally we translate this into additional fuel consumption and environmental impact.

Affected flights

The data allowed us to analyse 133 days with disruptions over the 2015-2017 period, of which 61 related to strikes and 72 to technical failures. The average number of flights affected by a disruption is 2,310 per day. On average, strikes affected more flights (3,468 per day) than technical failures (1,329 per day). Differences between individual disruptions are large. One technical failure only affected 68 flights, whereas the most severe strike day affected over 7,000 flights (see Table 2.1).

Table 3.1 Strikes affect more flights while technical failures are more common

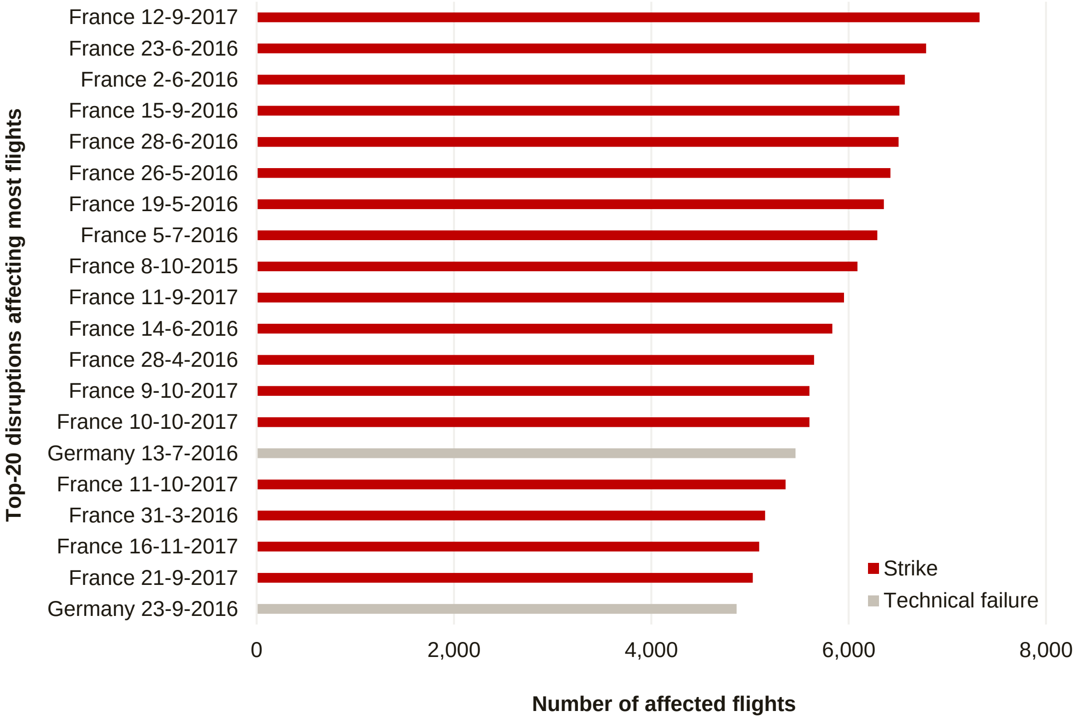
	Full sample	Strikes	Technical failures
Total number of disruptions	87	31	56
Total number of disruption days	133	61	72
Mean number of flights affected per day	2,310	3,468	1,329
Minimum number of flights affected per day	68	217	68
Maximum number of flights affected per day	7,327	7,327	5,462

Source: SEO/To70 analysis

Note: The total number of disruptions and disruption days included in the analysis is smaller than the total numbers presented in section 3.2. Specific disruptions were excluded from the analysis due to data limitations (see Appendix A and Appendix B).

Figure 3.5 shows the top-20 airspace disruptions in terms of number of flights affected. This figure clearly shows that industrial actions in French airspace affect the largest number of flights. In fact, with the exception of two technical failures in Germany, the complete top-20 consists of strikes at French ANSPs. This is consistent with the idea that strikes in France are especially impactful due to (1) the central location of France in Europe, (2) the fact that French strikes generally last for an entire day and (3) that not all overflights are accommodated. Appendix F provides a graphical representation of the number of these affected flights for all airspace disruptions in our sample.

Figure 3.5 French ANSP-strikes affect relatively many flights



Source: SEO/To70 analysis
Note: The figure shows the number of affected flights per day of disruption. Some disruptions last for multiple days (see Appendix A and Appendix B).

Flight efficiency

Table 3.2 presents summary statistics about the impact of airspace disruptions on flight efficiency *per affected flight*. The average flight inefficiency impact of airspace disruption is equal to 9.8 kilometres. This means that, on average, affected flights need to take a detour of 9.8 kilometres because of the airspace disruption. Compared to the (weighted) average route length of all affected flights on the day one week before the disruption of 1,400 kilometres, the relative impact is equal to 0.7 per cent. For strikes, the increase in flight distance is significantly larger (+17.1 kilometres) than for technical failures (+3.7 kilometres).

Table 3.2 Industrial actions have the most impact on flight efficiency

Additional route length (km) per affected flight	Full sample	Strikes	Technical failures
Mean	9.8	17.1	3.7
Minimum	-23.9	-5.1	-23.9
Maximum	76.1	76.1	57.4

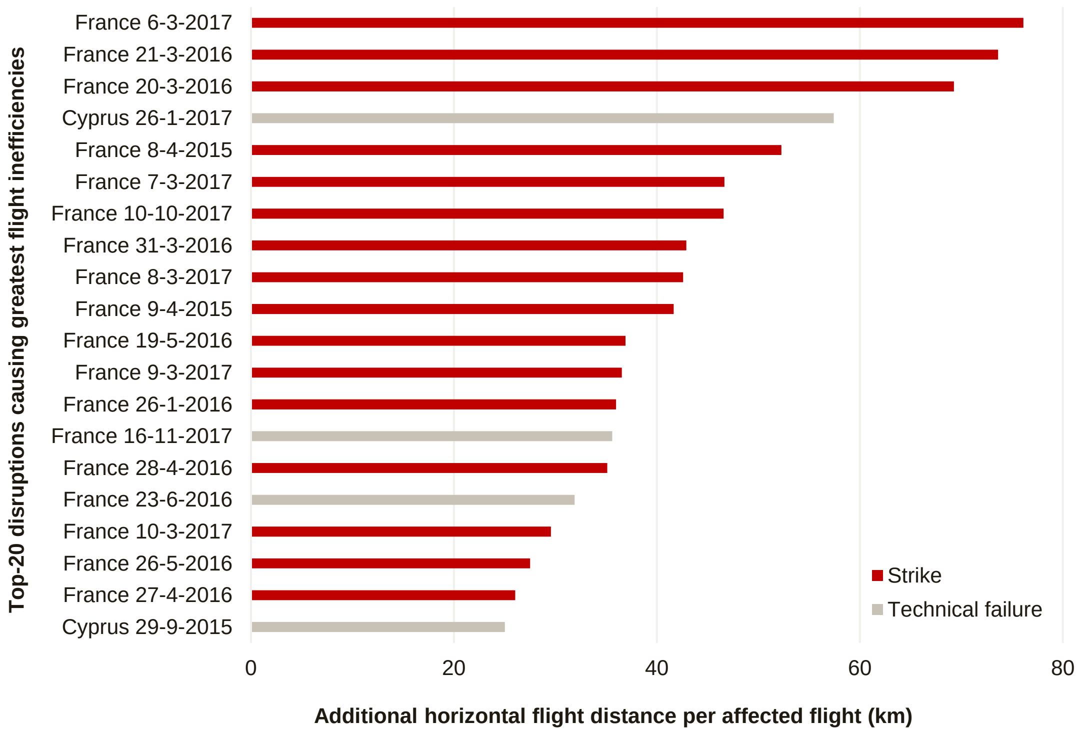
Source: SEO/To70 analysis
Note: Figures present the unweighted statistics over disruptions.

The impact of disruptions on flight efficiency however varies significantly. For instance, the disruption having the largest impact on flight efficiency (i.e., France 6-3-2017) caused average detours of 76.1 kilometres per affected flight. This equals a 4.7 percent increase in flight distance as compared to the average route length of the flights that were unaffected by the disruption. Some disruptions actually increase flight efficiency, i.e. reduce flight distances. This may be explained by the fact that cancellation of flights reduces congestion in the affected airspace sectors, which allows flights that are not cancelled to follow a more optimal flight path.

In terms of statistical significance, 110 (83 percent of all disruptions) of all estimated flight inefficiency impacts are significant at the 5 percent confidence level. Of these statistically significant impacts, 85 disruptions (65 percent of all disruptions) have a negative impact on flight efficiency – i.e., increases in flight distances. Most of the other 25 airspace disruptions (19 percent of all disruptions) that have a positive impact on flight efficiency are technical failures. The positive impact on flight efficiency of this group of disruptions is usually small.

Figure 3.6 presents the top-20 disruptions in terms of flight inefficiency. Again, the French strikes dominate the list of most impactful airspace disruptions. This is explained by France's central geographical location in Europe and the fact that only 50% of overflights is accommodated. The only non-French disruptions in the top-10 is a disruption caused by radar maintenance in Cyprus. This disruption affected a very small number of flights (68 flights) and its inefficiency impact is not statistically significant. Appendix F provides a graphical representation of the flight inefficiency impact of all disruptions in our sample.

Figure 3.6 French ANSP-strikes have a relatively large impact on horizontal flight efficiency



Source: SEO/To70 analysis

By combining the number of affected flights with the increase in flight distance per affected flight, we estimate the total additional flight distance caused by disruptions.[28] Table 3.3 shows that strikes and technological failures at European ANSPs increased flight distances for intra-EEA flights by 4.6 million kilometres. Unsurprisingly, given that both the number of affected flights and the impact per affected flight is substantially higher for strikes than for technical failures, the strikes account for the majority (95%) of additional kilometres flown. On average each strike resulted in over 70,000 additional flight kilometres per day; technical failures on average led to an additional 3,000 kilometres flown per day.

Table 3.3 Strikes on average increase flight distances by 70,000 kilometres per day

Additional kilometres flown (2015-2017)	Full sample	Strikes	Technical failures
Total	4,619,788	4,377,591	242,198
Mean per disruption day	34,735	71,764	3,364
Minimum per disruption day	-16,679	-13,840	-16,679
Maximum per disruption day	314,257	314,257	51,965

Source: SEO/To70 analysis

Environmental impact

Finally, we translate the increases in flight distance into additional fuel consumption and CO_2-emissions. Over the 2015-2017 period, disruptions caused led to an additional fuel consumption of 13.7 kt (kilotonnes)[29] (see Table 3.4) and 43.0 kt of CO_2. To put this into perspective, this corresponds to the fuel consumption and emissions of around 3,500 commercial passenger flights within the EEA.

This means that on each disruption day over 100 tonnes of extra fuel is consumed. The effect however varies significantly over disruptions; an average ATC-strike day requires over 200 tonnes of additional fuel, whereas an average day with a technical failure requires over 10 tonnes of additional fuel.

Table 3.4 Disruptions cause approximately 13.7 kt of kerosone combustion

Additional fuel consumption (tonnes)	Full sample	Strikes	Technical failures
Total	13,655	12,909	746
Mean per disruption day	103	212	10
Minimum per disruption day	-50	-41	-50
Maximum per disruption day	945	945	155

Source: SEO/To70 analysis

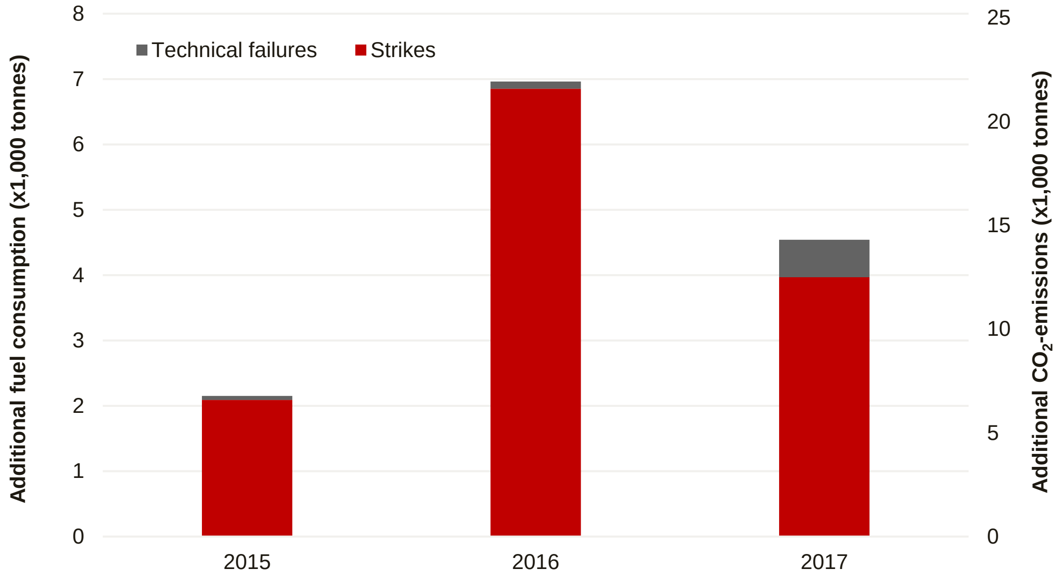
Figure 3.7 shows the additional consumption and CO_2-emissions caused by strikes and technical failures for intra-EEA flights for each year. The disruptions in 2016 caused the largest increases in fuel consumption and emissions. This is largely explained by the fact that the number of strike(day)s

28 For these calculations we use the estimates of all disruptions, including those that had a significantly negative or non-significant impact on flight inefficiencies. Using only the disruptions with statistically significant impacts results in similar figures. This is not surprising given the fact that for disruptions that have a non-significant impact on route length either the flight inefficiency impact or the number of affected flights is very small.

29 One kiloton equals 1,000 tonnes or 1,000,000 kilograms.

was significantly larger in 2016 than in the other two years (see Figure 3.1). Furthermore, the figure shows that strikes are the key driving force behind additional fuel consumption and CO_2-emissions in all three years. Nevertheless, it is noteworthy that the contribution of technical failures substantially increased in 2017, which was a year in which a lot of equipment issues occurred.

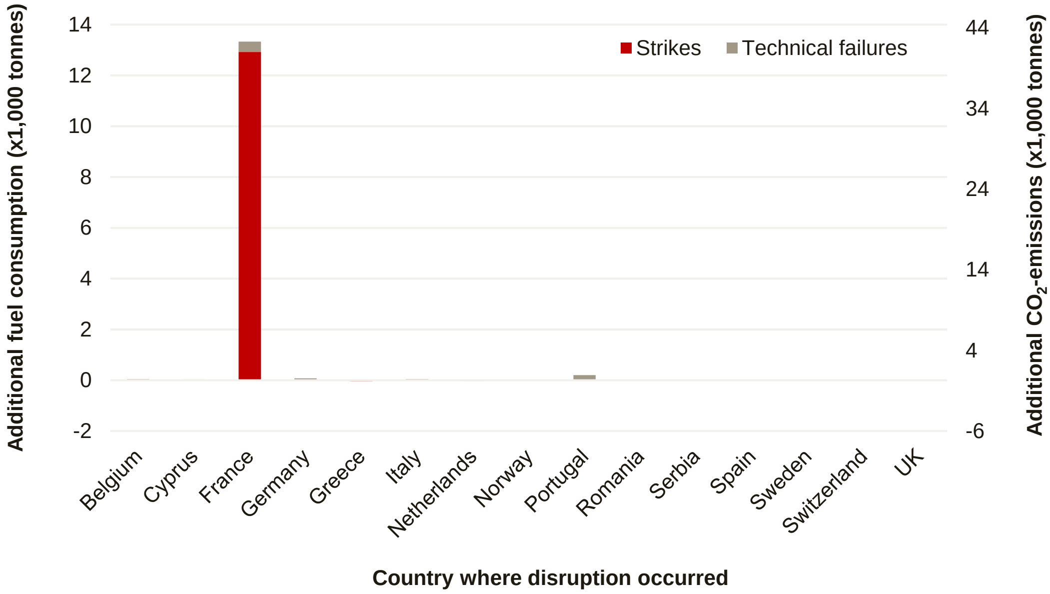
Figure 3.7 Disruptions in 2016 caused most additional fuel consumption and CO_2-emissions



Source: SEO/To70 analysis

Figure 3.8 presents the additional fuel consumption and CO_2-emissions by the country where the disruption occurred. Disruptions in French airspace account for the vast majority of all additional fuel consumption and CO_2-emissions (97.6 percent). The large contribution of French disruptions to additional fuel consumption and CO_2-emissions is explained by the large number of ANSP-strikes in France and their relatively large impact. As explained above the large impact is caused by (1) the central geographical location of France in Europe, (2) the relatively long duration of the strikes and (3) the fact that not all overflights are accommodated during a strike.

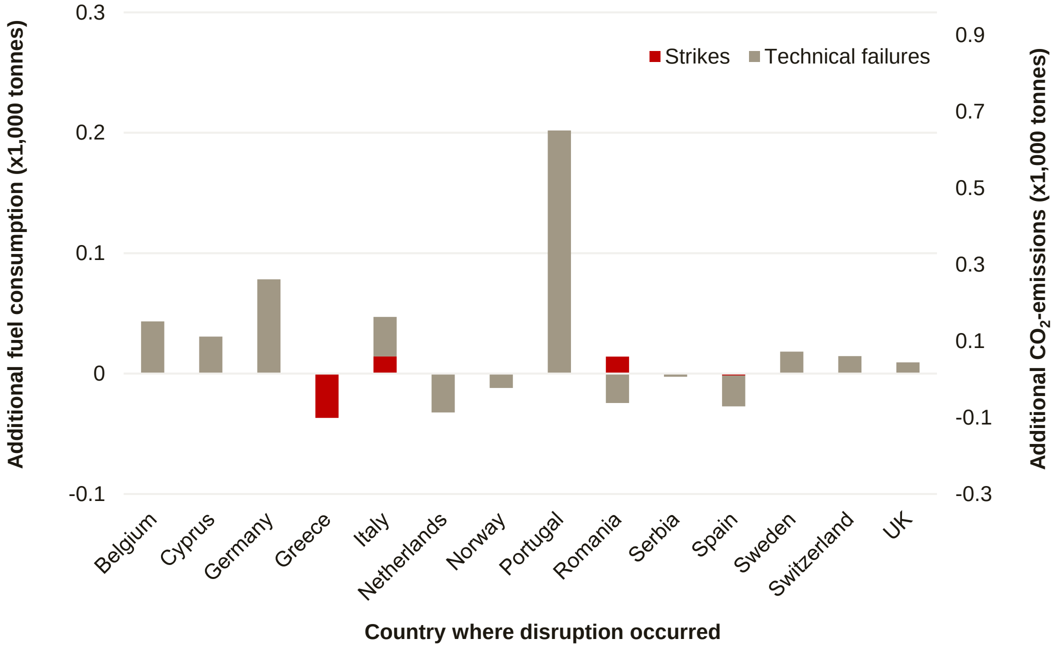
Figure 3.8 French ATC-strikes were responsible for most additional fuel burn and emissions



Source: SEO/To70 analysis

Figure 3.9 provides a plot that is similar to Figure 3.8 but without France. Portugal appears to be the second contributor to additional fuel consumption and CO_2-emissions, which is completely driven by equipment issues. It is furthermore noteworthy that disruptions in some countries have a positive impact on flight efficiency. Strikes in Greece for instance show a positive impact on fuel consumption and emissions. As mentioned above this could be due to flight cancellations which reduce congestion in the airspace and allow flights that are not cancelled to follow more optimal trajectories.

Figure 3.9 Portugal is second contributor to total additional fuel consumption and emissions



Source: SEO/To70 analysis

Given that the calculations focus on intra-EEA flights and only consider the additional fuel consumption caused by increases in *horizontal* route length of flights that had to go directly through the affected sectors, these numbers should be considered as conservative estimates. That is, if intercontinental flights, inefficiencies in vertical flight trajectories or 'knock on' effects on neighbouring sectors are taken into account, the total environmental impact could be more profound.

3.4 Case studies

The impacts of airspace disruptions are further illustrated by two case studies. The first case study focusses on a large multiple day ANSP-strike in the core area of the EEA airspace: the nation-wide strike in France on the 22nd and 23rd of March 2018. The second case study considers the impact of understaffing at the Karlsruhe Area Control Centre (ACC), a main contributor of delays in 2017.

The case studies complement the former analysis in multiple ways. First, they graphically show the impacts of disruptions on flight paths. Second, they allow us to show how individual flights are affected (whereas the former analysis provided the mean impact of disruptions. Third, the case studies allow for a more in-depth analysis of the impacts in sectors adjacent to the affected (regulated) sectors. Fourth, it allows us to assess the impact of another type of disruption: understaffing.

3.4.1 French national strike

Multiple trade unions in France representing public sector workers and airline personnel called for strikes on the 22nd and 23rd of March 2018. On the first day air traffic controllers joined the strike.

Methodology

Again, we use Eurocontrol DDR/NEST data to analyse the impacts of this strike on intra-EEA flights on the 22nd of March 2018. As in the former analysis we assess the impacts on flights that would normally (without a disruption) have passed through the affected airspace. Furthermore, we assess to what extent flights that would normally cross adjacent sectors are affected. To do so, we identified these flights by hand using expert judgement.

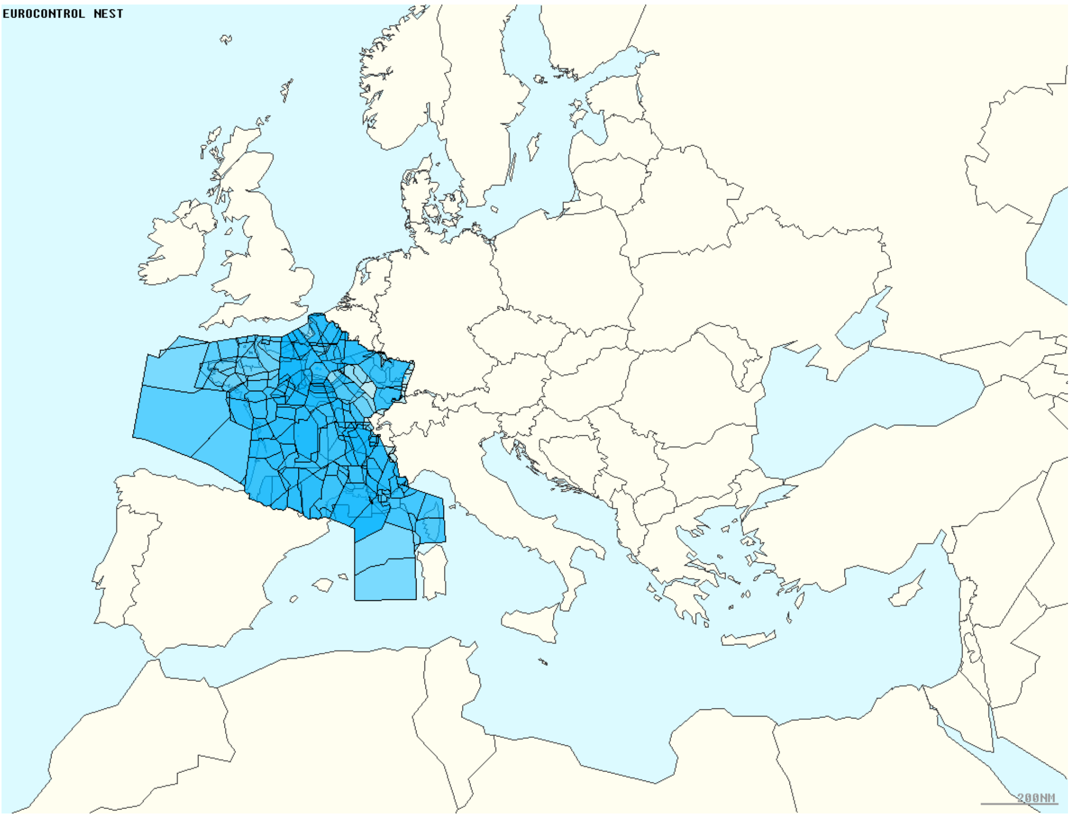
For each (potentially) affected flight, the flight distance is calculated based on the actual flight trajectory and compared to the great circle distance. This provides the route extension on the day of the disruption. The same is done for these flights one week before the disruption. The data one week before the disruption was verified for other potential disruptions.[30]

[30] It should be noted that on the day of the strike (22nd of March 2018) other regulations applied as well. The Amsterdam FIR was regulated due to bad weather conditions in the morning causing 2,227 minutes of delay. Although this regulation might have affected European network performance, it is not very likely that it affected traffic routing near France significantly, as the regulated flights were inbound Amsterdam Airport Schiphol.

Airspace regulations

Figure 3.10 depicts all applied airspace regulations on the 22nd of March 2018. In total 147 regulations with reason 'industrial action' were applied causing 99,658 minutes of delay. The regulations and declared capacities seem highly customized, strongly determined by local availability of ATC staff and actual demand. What stands out from the regulation list is that a minority of regulations limit capacity by more than 50% and only a few regulations show zero capacity. The most penalizing regulations (over 10,000 delay minutes) applied to the Brest, Marseille and Bordeaux Flight Information Regions (FIRs).

Figure 3.10 Strike on the 22nd of March 2018 restricted capacity in the entire French airspace



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

Affected flights

On that day, 28,252 flights operated in European airspace. Of these flights, 5,405 intra-EEA operated in or near French airspace. One week before the strike, 6,344 intra-EEA flights were operated within this area, of which 90% crossed French airspace.

Cancellations

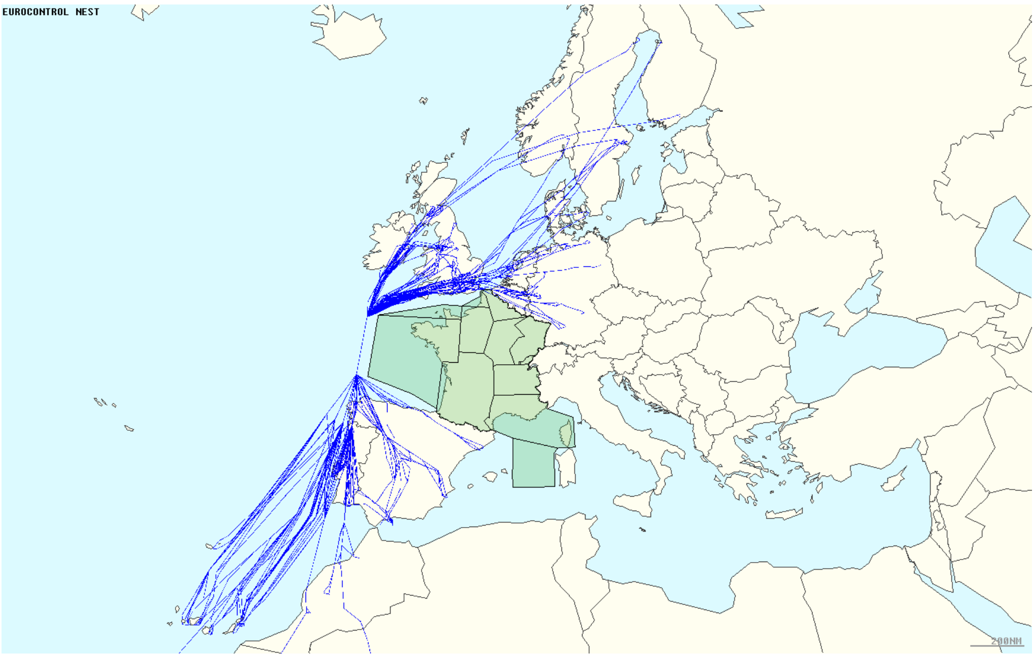
This means that almost 1,000 flights (15% of total) were operated less during the day of the strike compared to the previous week.[31] Especially short-haul flights were less operated. Of the flights

[31] This is an indication of the number of cancelled flights during the strike. We cannot say with certainty how much flights were actually cancelled, as traffic demand might have increased or decreased compared to the week before. Furthermore, airline personnel also went on strike which might have led to cancellations not related to the ANSP-strike.

with a distance between 150 and 300 nautical miles, 30% was no longer operated, whereas of the flights between 800 to 1,200 nautical miles only 2% did not operate.

Re-routings
As a consequence of the regulations airlines planned westbound and eastbound re-routings avoiding French airspace entirely. During the day, these detours had to be regulated too. The westbound routes contained within Shanwick oceanic airspace, flow traffic from the United Kingdom, Ireland, and Western Europe along a north/south axis to Spain, Portugal and the Canary Islands. Of the flights that originally crossed French airspace, 154 intra-EEA flights were re-routed along these westbound routes during the strike (see Figure 3.11).

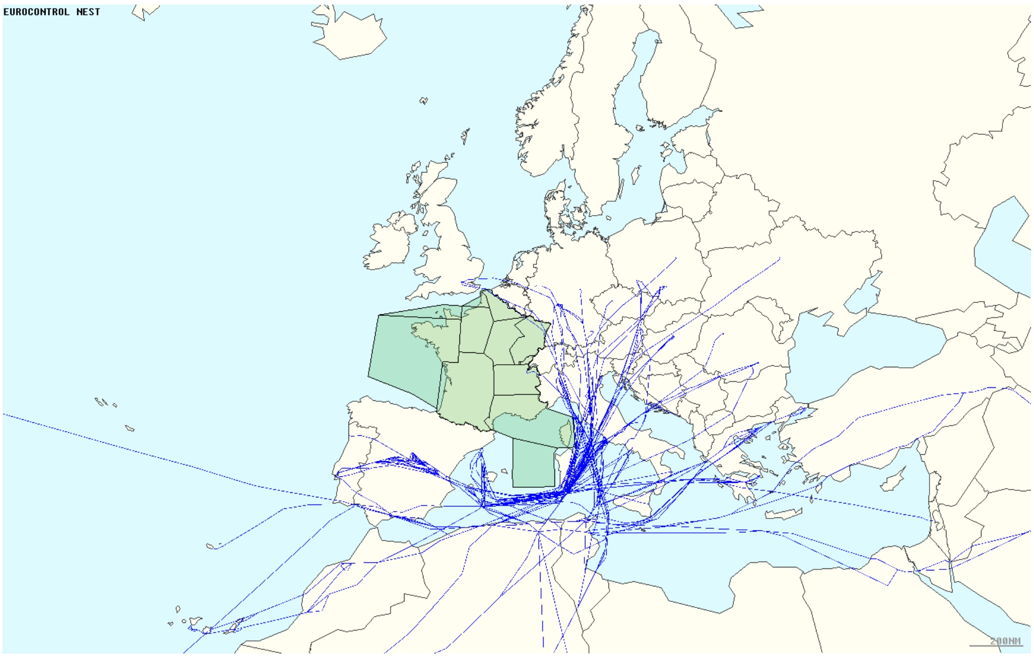
Figure 3.11 During the strike 154 intra-EEA flights were re-routed along westbound routes



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

Due to high anticipated delays in the Marseille FIR, airlines were advised by Eurocontrol to re-route flights via eastbound routes through Algerian and Tunisian FIRs. Although these airspaces do not have west-east routes, flight plans with west-east routes were temporarily accepted. During the strike 63 intra-EEA flights that originally crossed French airspace were re-routed along eastbound routes (see Figure 3.12).

Figure 3.12 During the strike 63 intra-EEA flights were re-routed along eastbound routes



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

Route extensions

The flight parameters of all flights within the area of interest are summarized in Table 3.5. One week before the strike, the average horizontal flight inefficiency within the area of interest was 3.38%. This inefficiency was similar for flights passing through French airspace and flights through adjacent airspace. During the strike the average flight inefficiency increased to 5.22%, an increase in flight distance of 1.8% on average.

Table 3.5 During the strike average flight distance increased by 1.8%

	Flights	Distance (km)		Route extension
		Route	Great circle	
During the strike	5,405	5,761,053	5,475,334	5.22%
Week before the strike	6,344	6,302,178	6,096,238	3.38%

Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

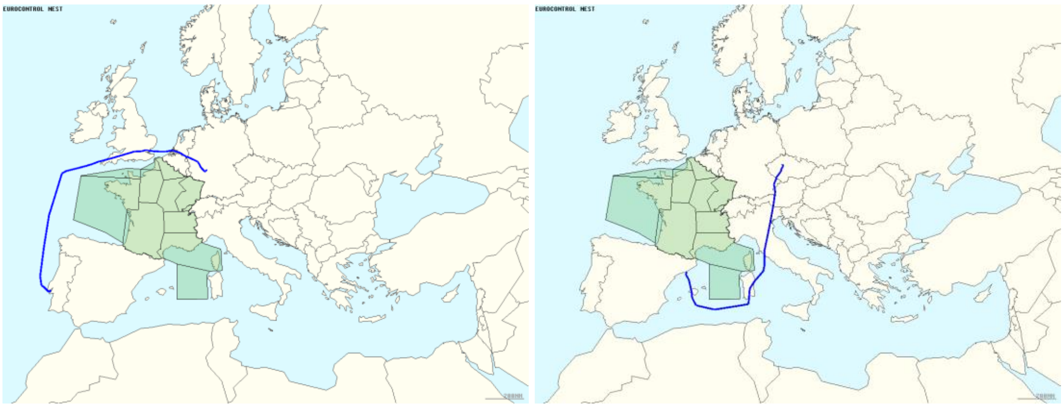
The route extension for flights that originally crossed French airspace in the week before the strike was 5.44%. The route extension for the flights that originally did not cross French airspace, but used adjacent sectors was 4.57%. This indicates that flights in adjacent sectors were also negatively impacted by the French strike, but less than the flights that originally crossed France. The route extensions were largest for the re-routed flights: 14% for the flights re-routed westbound and 21% for the flights re-routed eastbound.

Specific flights

Figure 3.13 illustrates that route extensions of individual flights may even be significantly longer. On the left side an individual flight from Frankfurt Main (FRA) to Lisbon (LIS) operated by an Airbus A320 showed a route extension of 637 kilometres (33%), requiring 1.9 tonnes of additional fuel and causing 6.0 tonnes of CO_2.

On the right side an individual flight from Barcelona to Prague operated by an Airbus A321 showed a route extension of 741 kilometres (56%), which required 2.7 tonnes of additional fuel and resulted in 8.6 tonnes of additional CO_2.

Figure 3.13 Strikes may lead to increases in flight distance of up to 60%



Frankfurt Main to Lisbon (+637km, 33%) **Barcelona to Prague (+741km, 56%)**

Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

3.4.2 Understaffing at Karlsruhe Upper Area Control Centre

The second case study provides insight into the impacts of understaffing at Karlsruhe Upper Area Control Centre (UAC). According to Eurocontrol (2019d) Karlsruhe UAC was the biggest generator of en-route delays due to understaffing. Furthermore, Karlsruhe generated 37.4% of ATC capacity delays in the European network. Due to the staffing and capacity issues it had a limited number of sectors available in 2018, up to 10 less than required and 6 less than in 2017. Eurocontrol (2019d) labelled Saturday 22nd of December 2018 as a day with high ATC understaffing and capacity issues Karlsruhe. In this case study we analyse this day in more detail.

Methodology

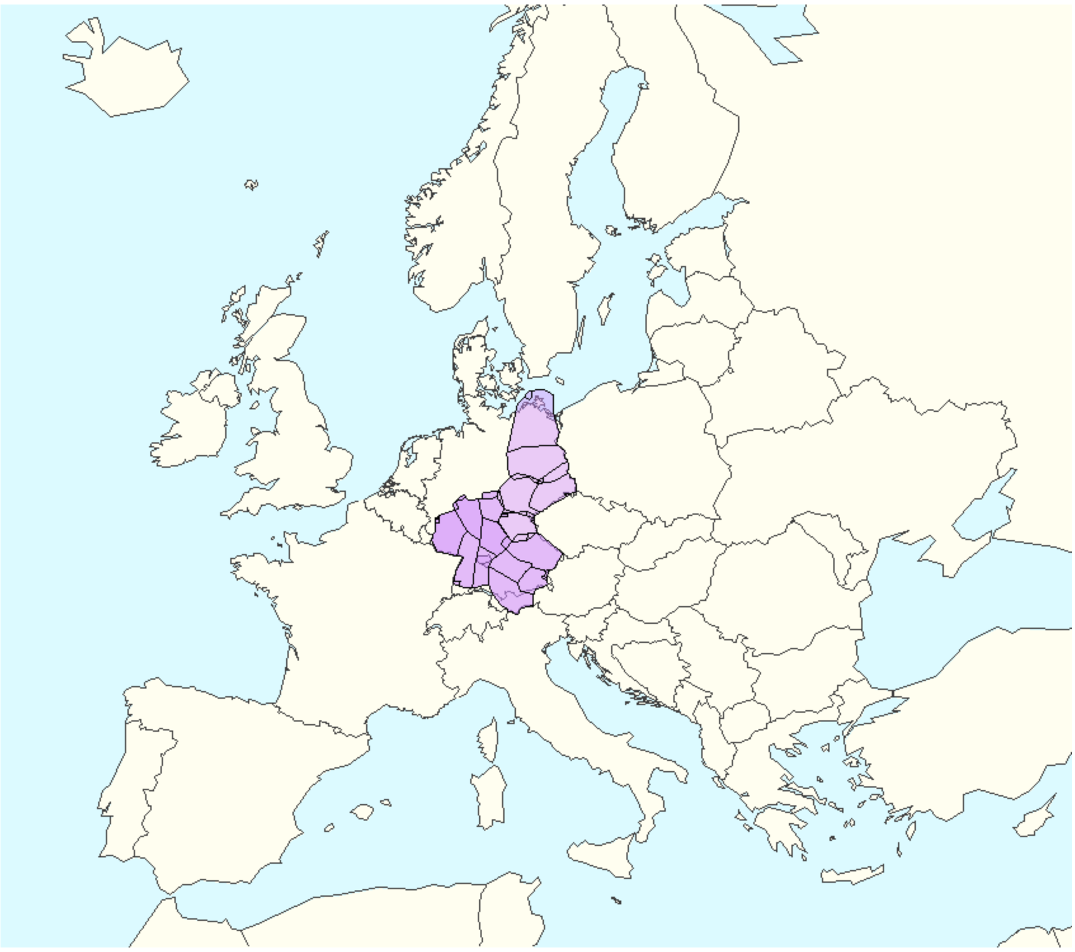
The same methodology is used as in the previous case study. Again the adjacent sectors are identified by expert judgement. It was decided to include all adjacent airspaces to Karlsruhe UAC, where possible only upper airspace:

- Maastricht Upper Area Control
- Reims Area Control
- Geneva Upper Area Control
- Zurich Upper Area Control
- Vienna Area Control
- Prague Upper Area Control
- Warsaw Area Control
- Malmo Area Control
- Copenhagen Area Control

Airspace regulations

Karlsruhe airspace covers the upper airspace in the heart of Europe, more specifically over the eastern and southern parts of Germany (see Figure 3.14). The rest of Germany as well as the entire Dutch and Belgian upper airspaces are serviced by Eurocontrol Maastricht. On the 22nd of December 2018, 29 regulations applied causing 18,000 minutes or delay. The causes of these delays were labelled as 'ATC staffing' (around 1,200 minutes) and 'ATC capacity' (around 16,800 minutes). As understaffing at Karlsruhe UAC has become a structural issue, operational configurations are now planned considering the staff limitations. This means that part of structural understaffing is now regulated as a capacity issue, i.e. labelled as 'ATC capacity'.

Figure 3.14 Karlsruhe airspace covers eastern and southern Germany



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

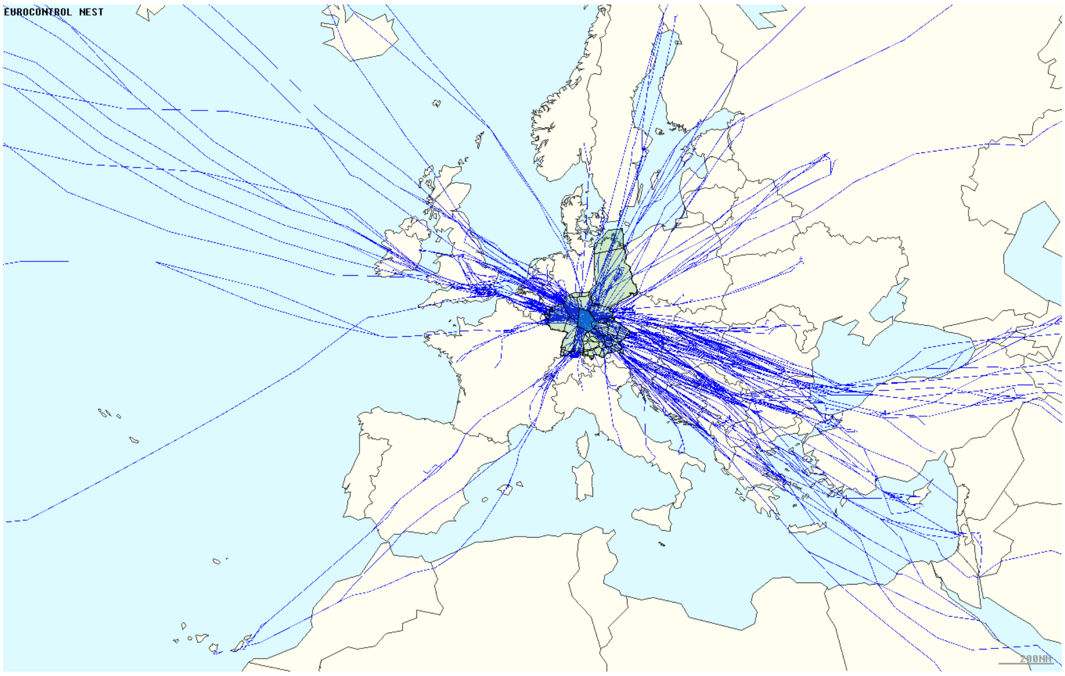
Affected flights

The number of intra-EEA flights in the case study's area of interest was 8.6% higher on December 22nd 2018 (8,514 flights) than the week after[32] (7,842 flights). The increase may have to do with the start of the Christmas holidays. The increase in the number of flights passing through Karlsruhe airspace was however smaller than the increase in adjacent sectors (+7.7% versus +9.2%). This might be an indication that the Karlsruhe airspace regulations restricted traffic through its sectors.

32 We did not choose the week before the 22nd, as this week was characterized by many regulations and therefore was not considered a good reference.

The most penalising regulation affected 445 flights and caused almost 5,000 delay minutes (see Figure 3.15).

Figure 3.15 One regulation affected 445 flights and caused 5,000 minutes of delay



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

Route extensions

One week after the severe understaffing/capacity issues at Karlsruhe UAC, the average horizontal flight inefficiency within the area of interest was 2.38%. Flights through Karlsruhe airspace already showed a higher flight inefficiency (2.44%) in this week than flights that exclusively passed through adjacent airspace (2.33%).

On the 22nd of December 2018, the overall horizontal flight efficiency in the area of interest deteriorated by 0.10 percent point to 2.48%. This could (partly) be due to the increase in traffic. Therefore we compare how the efficiency of flights passing through Karlsruhe airspace compared to the efficiency of flights passing through adjacent sectors. The route extension for flights crossing Karlsruhe airspace on December 22nd was 2.58% (+0.14 percent point increase compared to the week after). For flights not crossing Karlsruhe airspace, the route extension was 2.41% (+0.08 percent point percent point increase compared to the week after).

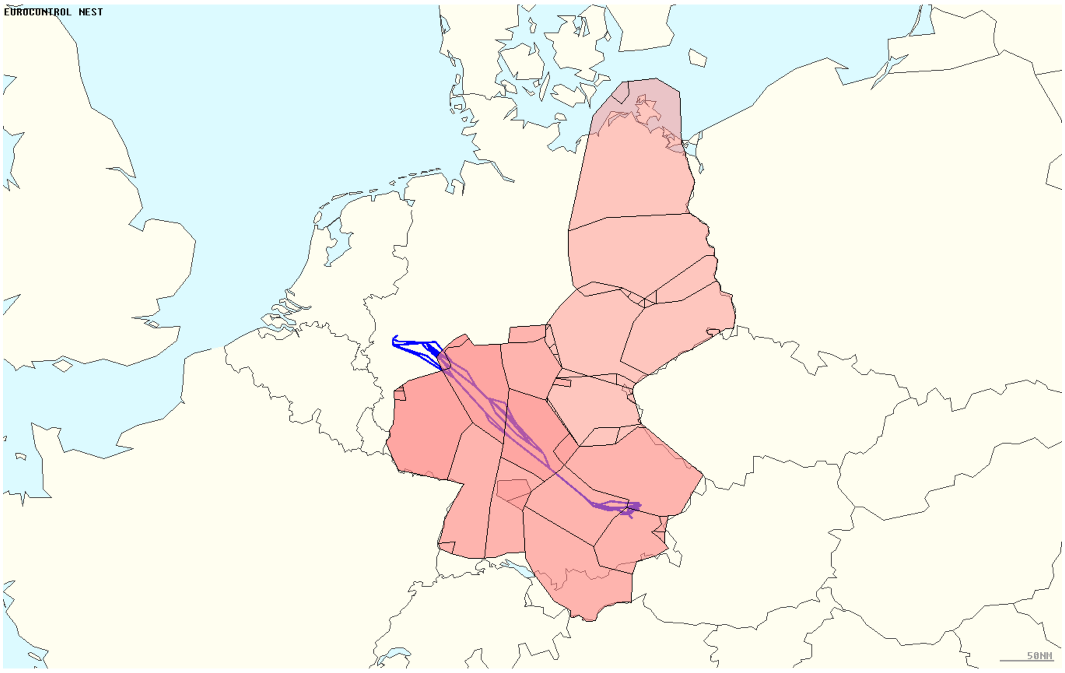
To summarize, flights passing through Karlsruhe UAC the week after the severe understaffing/capacity issues were already less efficient than those in adjacent airspace. During the understaffing/capacity issues on the 22nd of December 2018, horizontal flight efficiency deteriorated more than in adjacent sectors.

Level caps
Apart from airspace regulations, traffic scenarios can be implemented to reduce airspace complexity and therefore the workload of the understaffed ATC. Such scenarios may include level capping whereby flight level restrictions are applied to specific airspace sectors. This may lead to suboptimal vertical flight trajectories, increasing fuel consumption and CO_2-emissions. Traffic scenarios are strongly advised to airline operators to limit delays. Not adhering to the scenarios is a trade-off for the airline operator between flying the optimal vertical profile and accepting delay.

Level caps are also used to reduce the workload of ATCOs at Karlsruhe. As a result, domestic flights in Germany as well as flights to and from The Netherlands, Belgium, Luxemburg, Austria and Switzerland could not enter Karlsruhe's upper airspace but were restricted to using lower flight levels.

Specific flights
Assessing the impacts of level caps on fuel consumption and emissions requires a case-by-case approach. First, it needs to be determined which flights were affected by the cap. Second, the vertical profile of the flight needs to be analysed and compared to the vertical profile on a similar day without the cap. Third, the fuel consumption of the level capped flight needs to be compared to the fuel consumption of the same flight without the cap.

Figure 3.16 Flights from Dusseldorf to Munich affected by level caps in Karlsruhe airspace

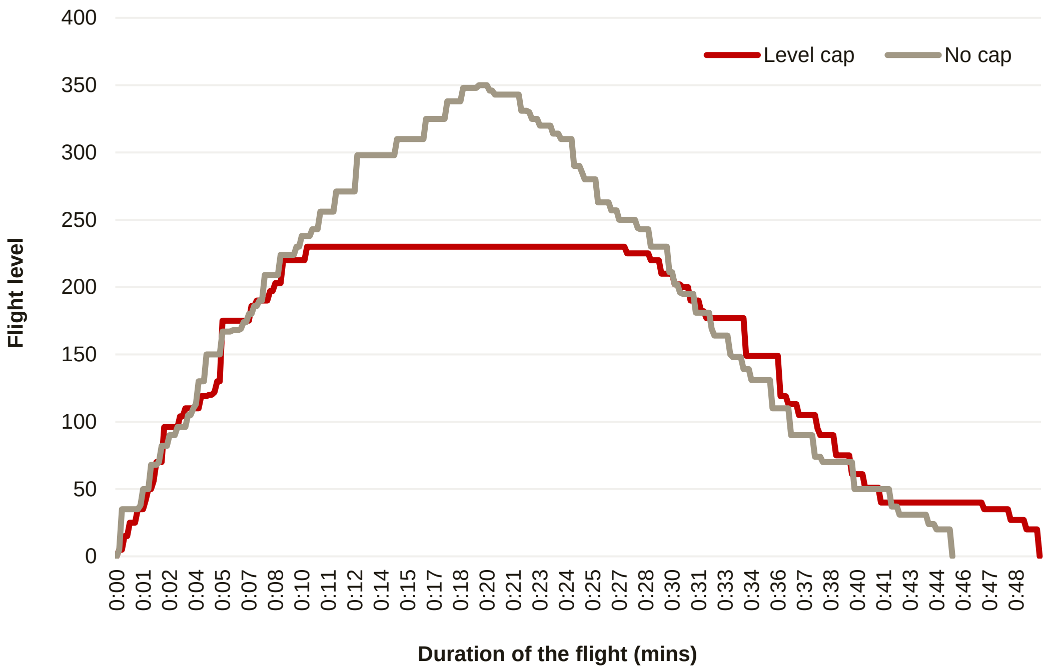


Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

For the 22nd of December 2018 we identified which flights were affected by the level cap. For the case study we selected the domestic flights from Dusseldorf to Munich. The level cap restricted the flight level to 245, below Karlsruhe airspace. Airline operators normally operate this city pair at flight levels up to 350. On the 22nd of December, 11 flights were operated on this route with A319 and A320 aircraft, out of which 6 conformed to the level cap.

Figure 3.17 shows the vertical profiles of two flights operating on the Dusseldorf to Munich route, one which is restricted to flight level 230 and one which is not restricted in terms of flight level. We use the BADA data to estimate the difference in fuel consumption for the time period in which the level capped flight reached flight level 230.[33] During the 17 minutes that the level capped flight cruises at flight level 230, it consumes 760 kilograms of fuel. During this same period, the flight which climbs to flight level 350 and then decents consumes 640 kilograms of fuel. The level capped flight therefore consumes 120 additional kilograms of fuel, which causes around 400 kilograms of CO_2.

Figure 3.17 Level capped flights remain at or below flight level 230



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST

As mentioned above, the impacts of level caps can only be assessed on a case-by-case basis. The data available does not allow for a generic analysis on the impacts of level caps.

33 We do not assess the difference in total fuel consumption as other factors may have influenced the flight profiles as well. The duration of the level capped flight for instance is 5 minutes longer. This delay was faced in the approach phase. To isolate the impact of the level cap on fuel consumption, such delay should be excluded from the analysis.

4 ATM-inefficiencies

Inefficiencies in the en-route airspace are still present. It is estimated that flight distances for intra-EEA flights over the 2015-2017 period were 0.61-0.76% longer than technologically possible due to inefficiencies in Air Traffic Management (ATM). Over this entire period, this required 229 kt of fuel, resulting in 721 kt of additional CO_2. To put this into perspective, this is equal to the fuel consumption and emissions of around 60,000 commercial passenger flights or 4 days of flying within the EEA.

Air transport came of age and grew rapidly during the fifties and sixties because of the introduction of radar technology and jet aircraft. European airspace in this period largely followed national borders and this is largely still the case. Back in the days civil air traffic routes were designed as direct routes between the largest centres of population. Military training areas were designed around the civil route network. To navigate through the route network, ground-based equipment along these routes was required. Thanks to technological development routes do not rely on ground-based anymore, nevertheless these routes largely remain in use today. The increase of population and prosperity in Europe led to an increase and shift in air traffic movements. The fragmented airspace and original route design appears inefficient in managing current and future number of air traffic movements.

This chapter quantifies the environmental impact of flight inefficiencies of European Air Traffic Management (ATM). Section 4.1 describes the efforts made to reform European ATM. Section 4.2 presents the results from our analysis.

4.1 Literature review

4.1.1 Single European Sky

The inefficiency of Europe's airspace and route network was acknowledged by the High Level Group and the Performance Review Commission (PRC) of Eurocontrol. They identified the following causes (European Commission, 2000):

- A multiplicity of national ATC centres;
- Vast differences in airspace organisation and design;
- Large amount of airspace for military purposes;
- Technological investments on the basis of national interest;
- Chronic shortage of air traffic controllers.

Furthermore, the High Level Group mentioned that defragmentation of the system would be a slow and inefficient process as it would require intergovernmental decision making. It concluded that there was a need for the European Commission to be the driving force in ATM reform. An initiative to reform the architecture of ATM was first launched by the European Commission in 1999 known as Single European Sky (SES). It proposed a legislative approach to meet future ATM challenges at a European rather than local level. The first package of legislation entered into force in 2004 and included safety, capacity, efficiency and environmental objectives.

In 2007 the European Commission published the first report on the progress of SES. It concluded that SES had not delivered the expected results in important areas, like integration of the airspace in Functional Airspace Blocks (FAB) (see below) and improvement of cost-efficiency of the European ATM network. It recommended to sharpen SES legislation.

The second legislative package, known as SES2 entered into force in 2009. It introduced a Performance Scheme, setting down EU-wide and local targets for SES as well as performance monitoring. KPI's were defined in relation to safety, capacity, efficiency and the environment. The Performance Scheme implementation and operation is realised in reference periods. The first reference period covered the calendar years 2012 to 2014 included. The second reference period covers 2015-2019[34]. The third reference period covers 2020-2024 and is currently being prepared.

4.1.2 SESAR

On the technological side, SES is supported by the Single European Sky ATM Research (SESAR) Programme launched in 2004. The SESAR European ATM Master Plan (SESAR, 2015) contains the following high-level goals:

- Enable a threefold increase in capacity which will also reduce delays both on the ground and in the air;
- Improve safety by a factor of 10;
- Enable a 10% reduction in the effects flights have on the environment;
- Provide ATM services to the airspace users at a cost of at least 50% less.

As of 2016, only a small part of the plan had actually been executed and SESAR performance ambitions were re-set for 2035, not 2020 as originally envisaged (European Court of Auditors, 2017).

4.1.3 Operational concepts

These goals should be achieved by modernising the European ATM system through innovative technical and operational solutions. With improved navigation technologies, the fixed grid of navigation points should slowly disappear to allow for smoother trajectories, so called 'business' trajectories (Bongiorno et al., 2017). Improved information exchange is also an integral part of SESAR. Currently flight operators still have little control over their trajectories while in the air (Murça, 2018). Operational concepts include to increase the efficiency of the European airspace include:

- Functional Airspace Blocks (FAB);
- Flexible Use of Airspace (FUA);
- Free Route Airspace (FRA).

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34 Regulation (EC) No 390/2013 of 3 May 2013 laying down a performance scheme for air navigation services and network functions

Functional Airspace Blocks
A Functional Airspace Block (FAB) is an airspace block based on operational requirements, reflecting the need for integrated management of the airspace regardless of national borders. By explicitly disassociating from current airspace constraints resulting from the alignment of national borders, FABs were introduced and defined through regulation.[35] FABs provide a more efficient overflight.

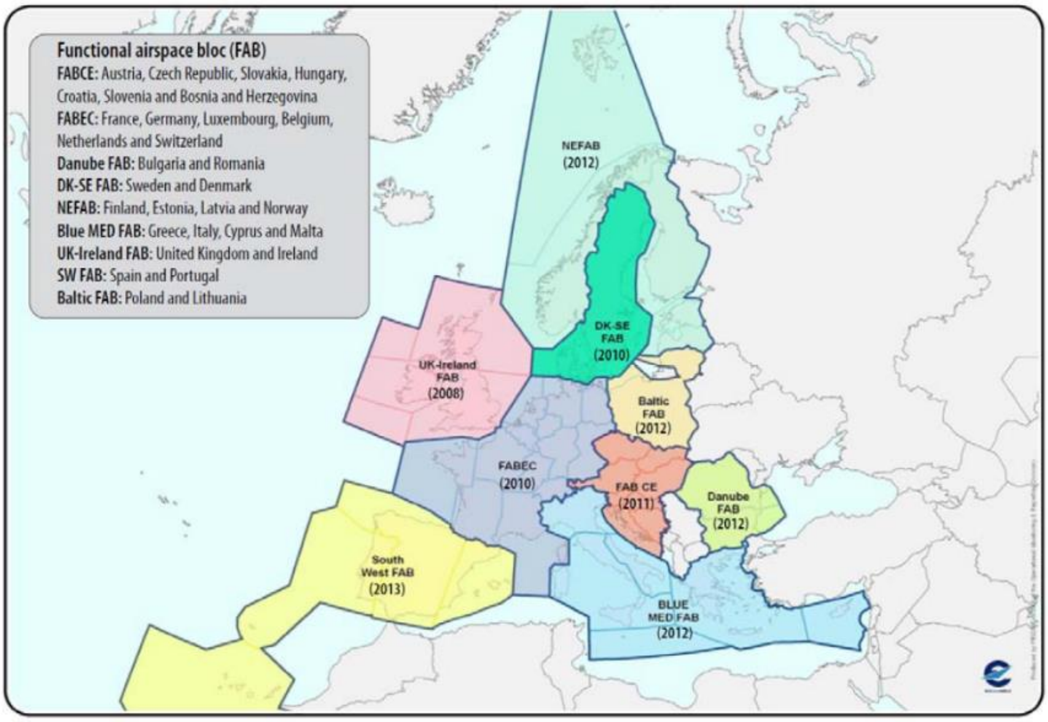
According to the Eurocontrol Performance Review Commission (2008) , one quarter of European route extension issues can only be solved through Functional Airspace Blocks (FABs) and Europe-wide. Around 11% of flight inefficiencies is attributable to the fragmentation of routes between states within each FAB and 25% is attributable to the fragmentation between FABs (ACE, 2006; Button and Neiva, 2013; Gaxiola et al., 2018).

The establishment of Functional Airspace Blocks (FABs) was defined in the first legislative package of the SES and further developed in the second legislative package. In total nine FABs have been declared, established and notified to the European Commission (see Figure 4.1):

- UK-Ireland FAB;
- Danish-Swedish FAB;
- Baltic FAB (Lithuania, Poland);
- BLUE MED FAB (Cyprus, Greece, Italy and Malta);
- Danube FAB (Bulgaria, Romania);
- FAB CE (Austria, Bosnia & Herzegovina, Croatia, Czech Republic, Hungary, Slovak Republic, Slovenia);
- FABEC (Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland);
- North European FAB (Estonia, Finland, Latvia, and Norway);
- South West FAB (Portugal, Spain).

35 Regulation (EC) No 550/2004 of the European Parliament and of the Council of 10 March 2004 on the provision of air navigation services in the Single European Sky

Figure 4.1 Functional Airspace Blocks



Source: Eurocontrol (2019a)

Implementation of the FABs is still low for almost all FABs. Defragmentation, namely through cross border service provision, merging of air traffic control centres or common charging zones, was not achieved in any of the FABs and there is a general lack of commitment to these initiatives on the part of Member States. Concerns linked with preserving sovereignty, the legacy ANSPs, their revenues and their workforce have a strong impact in the Member States preference for keeping the current status quo.

In 2017 a consultant study was performed for the European Commission to assess the organisational, operational and technical progress of FABs since their creation in 2012 (Integra, 2017). The study concluded that the implementation of the FAB concept appears to have revolved too much around the aim of ensuring formal, minimal regulatory compliance, whilst efficiency gains have been held back by political, legal and technical impediments. The European Court of Auditors (2017) concluded that the FABs proved ineffective in targeting fragmentation, whether at the levels of airspace management, service provision or procurement of technical equipment.

The most critical views were expressed by airspace users, who voiced their strong disappointment with the results of FABs and as regards FAB customer engagement. Surveys and interviews among aviation stakeholders in Europe also show that there is a concern about the implementation delays and slow progress in general due to resistance to change and the lack of economic incentivation of ANSPs (Efthymiou and Papatheodorou, 2018).

However, ANSPs already cooperated on a voluntary basis before the creation of the FABs. Current examples of such partnerships are COOPANS and iTEC in which European ANSPs make joint investments into ATM systems. In addition, the Borealis alliance is implementing Free Route

Airspace that extends beyond FAB boundaries (see box below). This shows that some benefits are also achievable through voluntary cooperation, outside any regulatory framework.

Voluntary partnerships between European ANSPs

COOPANS
COOPANS is an international partnership between the air navigation service providers (ANSPs) of Austria (Austro Control), Croatia (Croatia Control), Denmark (Naviair), Ireland (Irish Aviation Authority), Portugal (NAV Portugal) and Sweden (LFV). The partners operate a harmonized ATM system developed by Thales. The harmonization of functionalities and joint investments should translate into cost savings and an increase in airspace capacity. COOPANS was first established in April 2006 between the IAA, LFV and Naviair, with Austro Control joining in 2010, followed by Croatia Control in 2011.

iTEC
Interoperability Through European Collaboration (iTEC) is a partnership between ANSPs from Spain (ENAIRE), the UK (NATS) Germany (DFS), The Netherlands (LVNL) and Norway (AVINOR) and ATM systems provider Indra. The Polish (PANSA) and Lithuanian (ORO NAVIGACIJA) providers joined the collaboration later. The goal of the collaboration is to develop a next-generation Air Traffic Management system for busy and complex airspace. Like COOPANS, iTEC should result in cost reductions and efficiency improvements.

Borealis
Borealis is an alliance between ANSPs in the north-west of Europe: Avinor (Norway), ANS Finland (Finland), Irish Aviation Authority (Ireland), Isavia (Iceland), Lennuliiklusteeninduse AS (Estonia), Latvijas Gaisa Satiksme (Latvia), LFV (Sweden), NATS (UK) and Naviair (Denmark). The alliance is currently working on a major program to deliver Free Route Airspace (FRA) (also see below) across three FABs: NEFAB, DK/SE FAB and UK/IRE FAB, thereby covering one-third of European airspace and managing over 4 million flights (Eurocontrol, 2017c). The program will create Free Route Airspace extending from the eastern boundary of the North Atlantic to the western boundary of Russian airspace in the North of Europe (Eurocontrol, 2018b).

Flexible Use of Airspace
As mentioned above, European airspace has been designed around the needs of national civil and military stakeholders. Large parts of European airspace is permanently or temporary reserved for military activities. These Special Use Areas (SUA) for military purposes are however inactive for most of the time (especially during weekends).

The Flexible Use of Airspace (FUA) concept was developed in 1999 based on the principle of flexible and adaptive airspace structures and procedures.[36] The Eurocontrol (2019c) concept of FUA assumes:

[36] Regulation (EC) No 2150/2005 - Common Rules for the Flexible Use of Airspace (FUA)

- Airspace is no longer designated as purely civil or military, but considered as one continuum and allocated according to user requirements;
- Any necessary airspace segregation is temporary, based on real-time usage within a specific time period;
- Contiguous volumes of airspace are not constrained by national boundaries.

The Performance Review Committee (Eurocontrol, 2018) underlined that the FUA concept is an important enabler to improve capacity and flight efficiency performance. FUA benefits both civil and military parties with potential reductions in flight distance, time and fuel (Efthymiou and Papatheodorou, 2018). In addition, Vaaben and Larsen (2015) have shown that access to military airspace can reduce congestion. Furthermore it reduces navigational complexity and the workload for pilots and air traffic controllers, enhancing overall safety (Efthymiou and Papatheodorou, 2018).

Implementation of FUA requires civil/military coordination and cooperation. Three levels of coordination and cooperation can be distinguished whereby each level has an impact on the other:
- Level 1: Strategic - definition of the national airspace policy and establishment of pre-determined airspace structures;
- Level 2: Pre-tactical - day-to-day allocation of airspace according to user requirements;
- Level 3: Tactical - real-time use of airspace allowing safe Operational Air Traffic & General Air Traffic (OAT and GAT) operations.

Realizing such coordination and cooperation appears challenging in practice which has hindered the implementation of FUA. There are also inconsistencies in the coordination between the civil and military use of airspace, which makes it difficult to identify where improvements with FUA will have a significant impact. Although the concept of FUA is mandated, not every EU Member States applies it to the same extent, in other words not utilising its full potential. In many Member States, there is room for improvement.

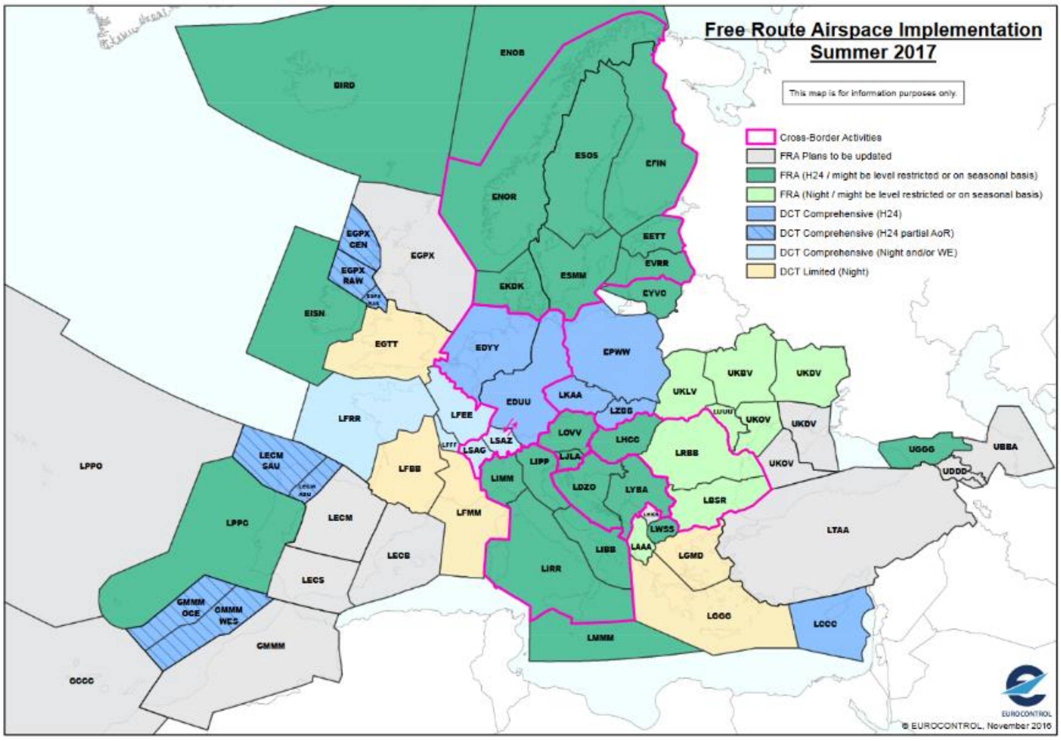
Free Route Airspace

Free Route Airspace (FRA) is a specified airspace within which users can freely plan a route between a defined entry point and a defined exit point, with the possibility of routeing via intermediate (published or unpublished) waypoints, without reference to the conventional air traffic services route network, subject of course to availability. Free route operations can be time limited, geographically limited or ultimately in a FAB environment. Within such airspace, flights remain subject to air traffic control.

In 2008, Eurocontrol initiated the coordinated development and implementation of FRA in cooperation with civil and military experts in airspace design, ECAC member states, ANSPs, airspace users, flight planning organisations and relevant international bodies. Since then, FRA has been successfully implemented across much of northern Europe, southeast, central southeast Europe. In other parts of Europe, especially FABEC, where airspace is most congested, progress is slower. This FAB is controlled by 7 civil and 5 military ANSPs and includes the major hub airports of Amsterdam, Paris and Frankfurt and military training areas for different sovereign air forces. Multilateral agreements on FRA appear rather complicated.

By the end of 2017, 51 ACCs have either fully or partially implemented FRA operations, which exceeds the target of 35 ACCs set by the Network Manager Performance plan (see Figure 4.2). The introduction of FRA has saved more than 2.6 million tons of CO_2 since 2014 (approximately 0.5% of total aviation CO_2 emissions) (EASA, 2019). With the exception of four ACCs, all ACCs in the Eurocontrol area have plans to implement FRA by 2022.

Figure 4.2 Free Route Airspace implementation summer 2017

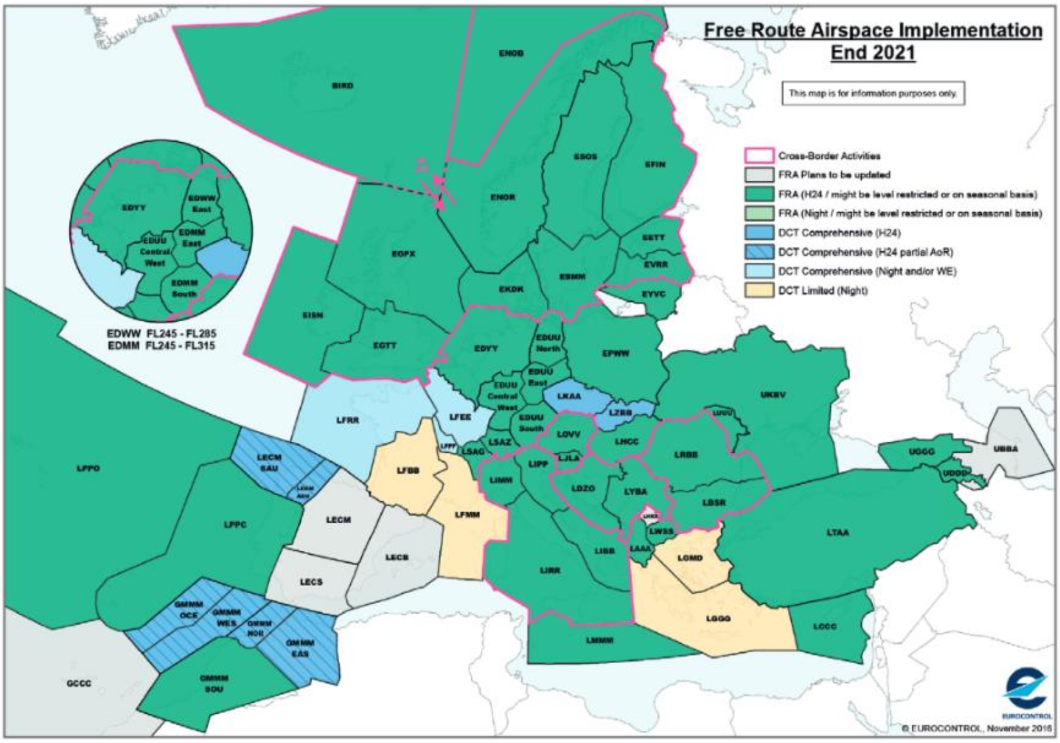


Source: Eurocontrol (2017b)

Cross-border implementation has started and is already applicable or will soon be so in many parts of Europe, namely SAXFRA (Austria/Slovenia), SEENFRA (Romania/Hungary/Bulgaria), SEAFRA (Belgrade/Zagreb ACCs), MALTA/ITALY, NEFRA (Estonia/Latvia/Finland/Sweden/Denmark/Norway). By the end of 2019, most European airspace is expected to have implemented FRA, with all airspace having this type of operations by 2021/2022[37] (see Figure 4.3).

[37] Regulation (EC) No 716/2014

Figure 4.3 Free Route Airspace Implementation End 2021



Source: Eurocontrol (2017b)

The continuous expansion of the FRA, including continuous expansion of cross-border FRA, is a major factor in the positive evolution in terms of flight efficiency, according to the Eurocontrol Network Manager (2018a). The Performance Review Body of the Single European Sky (2018a) also expects FRA to contribute towards reducing the impact of aviation on the environment through provision of an operating environment which would allow operators to both plan and fly the shortest possible routes, resulting in less less fuel consumption and emissions (Aneeka and Zhong, 2016).

Eurocontrol's Performance Review Commission (2018) indeed reported that the gap between planned and actual route is greater in States where FRA has not been fully implemented. The PRC also concluded that airspace users and their flight planning systems might not always make the best use of route design improvements including FRA, here is also still room for improvement.

Gaxiola and Barrado (2016) studied the impacts of FRA on flight distance for the Southwest FAB using traffic simulation models. Specific FRA partial deployments allowed to save 25,000 NM of flight distance per day (between 2% and 3.5%). The NEFRA led to a reduction of flight time per aircraft movement of 4%.

4.1.4 Previous impact assessments

The total annual cost of airspace fragmentation is estimated at € 4 billion (European Commission, 2015). SEO Amsterdam Economics (2016) showed that airspace modernization could lead to an average travel time reduction of 11 minutes and a fuel cost saving of over € 4 for an intra-European return trip. An average flight is 42 kilometers longer due to fragmentation inefficiencies, resulting in longer delays, higher fuel consumption and emissions (European Commission, 2012). Eurocontrol recommends to add 95 kilometers to the great circle distance for calculating fuel burn to correct for routing inefficiencies (Eurocontrol, 2016b).

Various studies have analyzed to what extent improved ATM could reduce fuel consumption and emissions. The Intergovernmental Panel on Climate Change (IPCC, 1999) and the European Union (2010a) suggested that ATM improvements could help to improve overall fuel efficiency by 6-12% per flight. The FAA and Eurocontrol (2012) compared the fuel consumed by flights in their actual trajectories against idealized trajectories. They found that significant fuel savings of 6-8% could be achieved. Edwards et al. (2016) found similar efficiency improvements are possible: a reduction in CO_2-emissions of 7% could be achieved when flying along the great circle distance compared to the regular flown distance. Arndt et al. (2007) estimated that in Europe alone additional distance flown due to non-optimal routing was 441 million kilometers, equivalent to 4% of CO_2-emissions.

Reynolds (2014) used flight data from 2008 and found that the average routes in Europe were 14% longer than the great circle trajectory. For the US this was 12% and for Africa 8%. For longer flights the relative extensions are generally smaller than for shorter flights, although in absolute terms extensions may still be significant. Airspace restrictions over parts of Russia and China may lead to relatively large extensions, both in relative and absolute terms. For an Airbus A320 on European routes, the lateral inefficiency was 13%, very similar to the European average of 14%. However the average fuel inefficiency was much greater: 23%. Around a quarter of the additional fuel burn is attributable to the route extension. The remainder is caused by suboptimal cruise altitudes and speeds. For a wide body aircraft such as the Airbus A340, the fuel inefficiency appeared only slightly larger than the lateral inefficiency, i.e. more optimal altitudes and speeds are used for long-haul flights compared to short-haul flights.

4.2 Analysis

4.2.1 Methodology

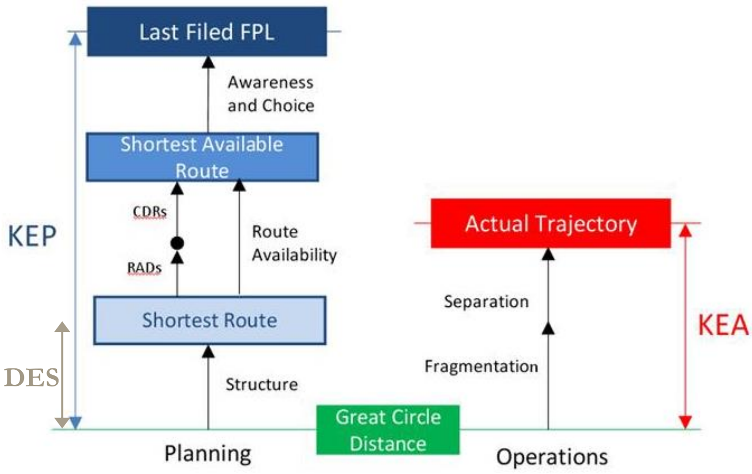
This section quantifies the environmental impact of any remaining inefficiencies in European ATM. First we assess which inefficiencies remain based on the performance indicators published by the Performance Review Body of the Single European Sky. Second, we estimate to what extent these inefficiencies lead to increased flight distances, fuel consumption and CO_2-emissions using our in-house emissions model.

Step 1: Identify remaining inefficiencies in European ATM
The European Commission drives ATM performance in cooperation with the Member States, their National Supervisory Authorities and the operational stakeholders being airline and aerodrome operators through the Performance Schemes (see above). The environmental performance indicators specified for the second reference period relate to the horizontal en-route flight efficiency of flights in the European airspace. Targets for the following indicators are defined:

- **Average horizontal en-route flight efficiency of the last filed flight plan trajectory (KEP)**: Difference between the en-route flight distance in the flight plan and the great circle distance. This indicator relates to the efficiency of flight planning. The target is set at 4.1% for 2019, i.e. the average en-route flight extension in flight plans should be no longer than 4.1%;
- **Average horizontal en-route flight efficiency of actual trajectory (KEA)**: Difference between the actual en-route flight distance and the great circle distance. This indicator relates to the efficiency of actual flight operations. The target for this indicator is set at 2.6% for 2019, i.e. the actual flight extensions should be no longer than 2.6%.[38]

Eurocontrol defined an additional performance indicator addressing the horizontal flight efficiency of airspace design (DES). This indicator measures the shortest plannable route from origin to destination compared to the great circle distance. The target is to achieve an improvement of the DES indicator by 0.57 percentage points between 2012 and 2019. Figure 4.4 shows the relations between the three described performance indicators and the great circle distance.

Figure 4.4 Performance indicators



Source: Performance Review Body of the Single European Sky (2018a)

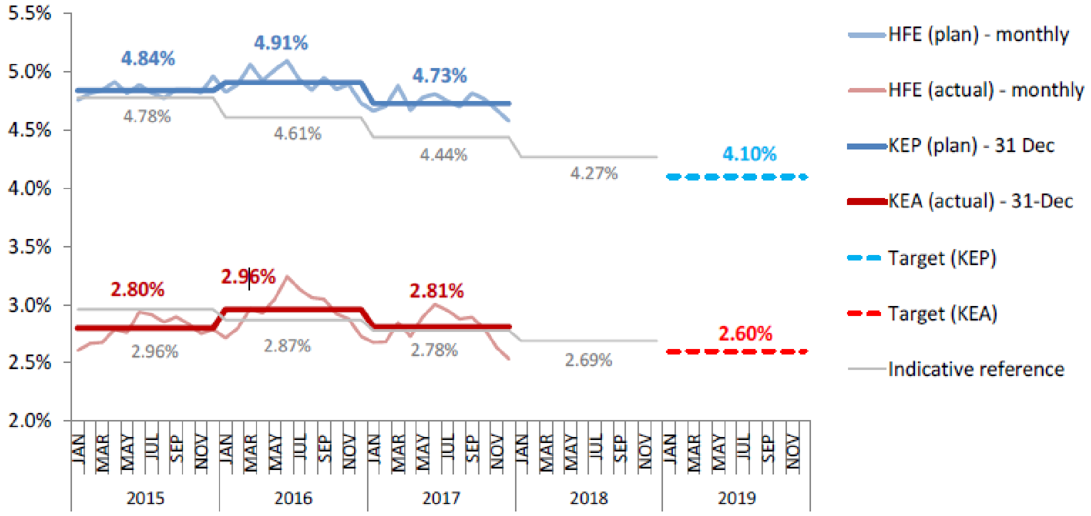
Apart from inefficient airspace design, flight extensions can also be caused by other factors, such as disruptions, congestion, weather conditions, airline economics etc. The accountability for the KPIs cannot therefore be fully allocated to individual ANSPs. Next to that, vertical flight efficiency is currently not targeted, although flight level allocation determines environmental impact.[39] The analysis is therefore limited to horizontal flight efficiency. Furthermore, we specifically assess the horizontal efficiency in the en-route phase of the flight. Inefficiencies in other phases of flight like approach procedures in terminal airspace, for instance radar vectoring, are not addressed.

38 Both performance indicators are computed on an annual basis in order to smooth out the influence of unusual events. Additionally, the ten best days and the ten worst days for each measured area are excluded from the computation. The uncorrected indicators show a much less stable progress than the formal indicators.

39 Analysis of vertical en-route flight efficiency by Eurocontrol showed that the highest level of vertical inefficiencies originated from flights on high-density airport pairs in the European core area which were restricted to enter the two Upper Area Control Centres Maastricht and Karlsruhe.

The PRB is the official body that annually reports to the European Commission about the progress with respect to the Performance and Charging Scheme. Figure 4.5 shows how the KEP and KEA indicators have developed during the second reference period. Horizontal efficiency decreased in 2016, but improved in 2017. Although target levels for the KEP and KEA were not achieved, efficiency and environmental performance have improved since 2015 through aircraft flying more direct routes.

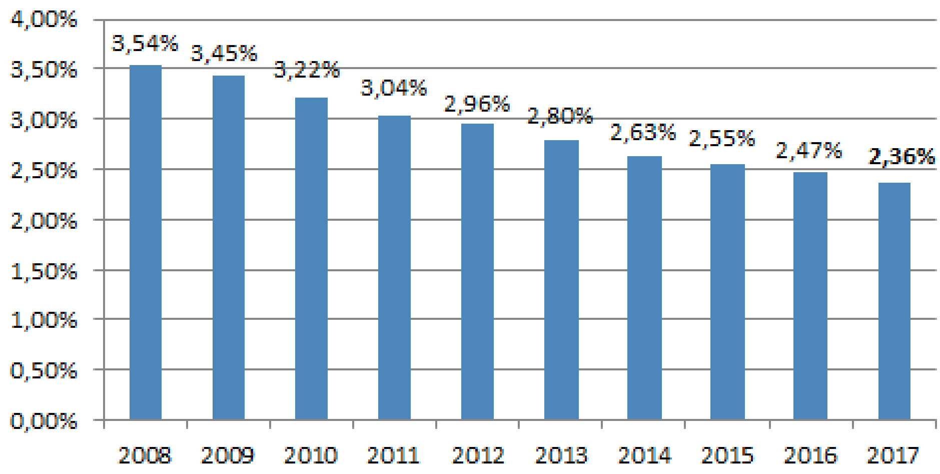
Figure 4.5 Horizontal en-route flight efficiency RP2



Source: Performance Review Body of the Single European Sky (2018c)

Eurocontrol, who was assigned with this task for RP1, still publishes an annual report showing the development of the DES indicator. The DES indicator continued its downward trend, reaching its lowest level ever in December 2017 (see Figure 4.6) (Eurocontrol, 2018a).

Figure 4.6 Route extension (DES) due to airspace design over the years



Source: Eurocontrol (2018a)

The Eurocontrol European Route Network Improvement Plan (ERNIP) (2017b) provides an overview of planned improvements aimed at delivering a safe and efficient operation of air traffic.

It is based on ANSP and FAB airspace plans until 2022 and contains, at this stage, approximately 300 packages of airspace proposals. When all the packages are fully implemented by the end of 2022, the DES indicator is expected to decrease by around 0.4 percentage points to approximately 1.9%. This implies that the KEP indicator could also be improved by another 0.4 percentage points by 2022. This assumption is based on an unconstrained scenario with no route restrictions, no capacity shortfall, no constraints due to military activity and all CDRs are permanently available. The Eurocontrol NM estimates that an improvement of 0.2 to 0.3 percentage points is feasible during this period.

The optimal KEA indicator approaches the DES indicator: 1.9%. Nonetheless, the impact of weather, staffing and capacity limitations will remain and is not likely to change significantly. The PRB assessed the contribution of weather, staffing issues and capacity on the KEA indicator. The optimal KEA indicator combined with the declared effects is 2.34%. The Performance Review Body of the Single European Sky (2018a) has therefore recommended to set the third reference period targets (2020-2024) for the KEA indicator at 2.40% and the KEP indicator at 3.90%. When FRA is fully implemented and utilized, flight efficiency in the en-route phase is largely optimized. The KEA then reaches a plateau of around 2.20%. Remaining inefficiencies are mainly in terminal airspace and ground operations.

Step 2: Quantify the environmental impact
With flight efficiency in the en-route phase optimized with a KEA of 2.20%, this means that in 2015, 2016 and 2017, flight distances in the en-route phase were respectively 0.60%, 0.76% and 0.61% longer than technologically possible.

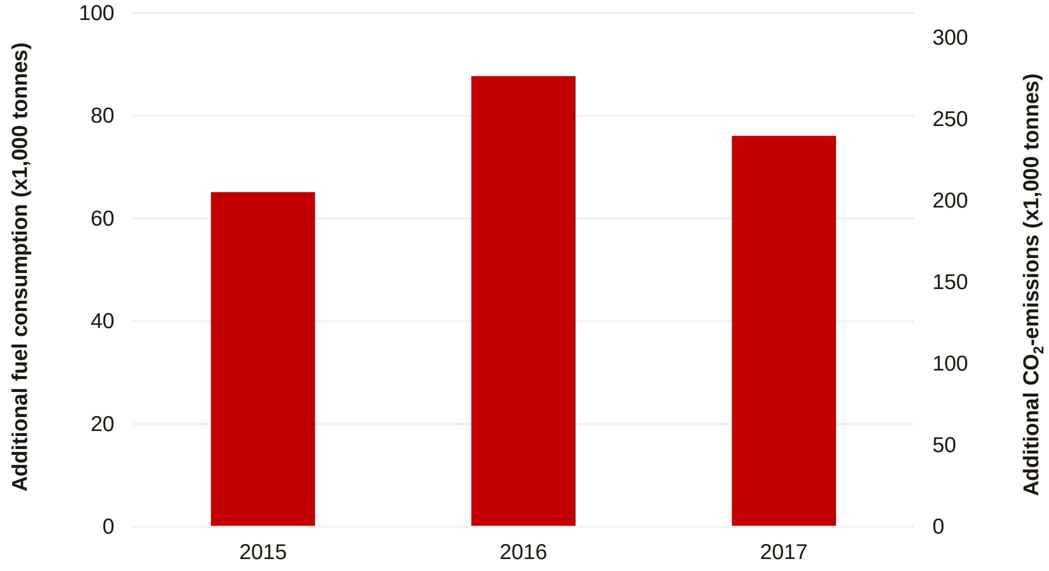
First, we use OAG Schedule Analyzer data to translate these inefficiencies into additional kilometers flown in the en-route phase by intra-EEA flights over the 2015-2017 period. Next, we use our in-house emissions model described above to estimate the additional fuel used to cover these additional kilometers. Again we note that the model differentiates between aircraft and engine types. Finally, the increases in CO_2-emissions are calculated based on the increases in fuel consumption.

4.2.2 Results

The remaining inefficiencies in European ATM lead to additional fuel consumption for intra-EEA flights ranging between 65-88 kt per year (see Figure 4.7). As the increases in fuel consumption mainly occur in the relatively fuel efficient en-route phase of the flight, the relative increase in fuel consumption and emissions is smaller (0.3-0.4%) than the relative flight inefficiency.

Over the entire 2015-2017 period additional fuel burn of intra-EEA flights cumulates to 229 kt, resulting in 721 kt of additional CO_2. To put this into perspective, this is equal to the fuel consumption and emissions of around 60,000 commercial passenger flights or 4 days of flying within the EEA.

Figure 4.7 ATM-inefficiencies lead to unnecessary fuel consumption and CO_2-emissions



Source: SEO/To70 analysis

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Appendix A ATC-strikes: 2015-2017

Table A.1 ATC-strikes at ANSPs between 2015 and 2017

Date(s)	Country	Days
16 January 2015	Italy	1
17 February 2015	Italy	1
20 March 2015	Italy	1
8-10 April 2015	France	3
11/12, 25/26 July 2015	Spain	4
15 July 2015	Romania	1
5 August 2015	Greece	1
26 September 2015	Spain	1
8 October 2015	France	1
23-27 November 2015	France	5
26 January 2016	France	1
20/21/22 March 2016	France	3
31 March 2016	France	1
27/28/29* April 2016	France	3
19 May 2016	France	1
26 May 2016	France	1
02 June 2016	France	1
13/14/15* June 2016	France	3
16*/17 June 2016	Italy	2
23/23/24 June 2016	France	3
27/28/29* June 2016	France	3
4/5/6 July 2016	France	3
14/15 September 2016	France	2
06/07/08/09/10 March 2017	France	5
20 March 2017	Italy	1
12 May 2017	Romania	1
17 May 2017	Greece	1
30 May 2017	Romania	1
11/12/13* September 2017	France	3
21 September 2017	France	1
09/10/11 October 2017	France	3
15/16/17 November 2017	France	3
15 December 2017	Italy	1

Source: Eurocontrol (2016, 2017c, 2018a)

* The following strike(day)s were excluded from the analysis (reason in brackets): 29 April 2016 (only regulations for airports), 15 and 16 June 2016 and 13 September 2017 (no regulations found in NEST), 29 June 2016 (no suitable control group found).

Appendix B Technical failures: 2015-2017

Table B.1 Technical failures at ANSPs between 2015 and 2017

Date (start)	Country	Reason	Days
15 May 2015	Italy	Radar failure	1
22-25 June 2015	Portugal	Frequency problems	4
29-30 June 2015	France	On-line Data Interchange (OLDI)/radio problems.	2
1, 9, 18 July 2015	France	On-line Data Interchange (OLDI) problems on 1 July and frequency/radar problems on 9 and 18 July	3
1 August 2015	Spain	Frequency problems	1
18 August 2015	France	Radio problems	1
27/28 August 2015	Portugal	Radar failure	2
31 August 2015	France	Radar problems	1
28-31 August 2015	Romania	FDPS problems	4
29 September 2015	Cyprus	TOPSKY ATM system upgrade	1
2 October 2015	Cyprus	ATC equipment issues	1
15 October 2015	Germany	FDPS failure	1
27 October 2015*	UK	Frequency interference issues	1
4/5 November 2015	Sweden	Radar problems due to solar activity	2
17 November 2015	Germany	Flight Data Processing System (FDPS) issues	1
18 December 2015	Belgium	Computer problems prevented the switch from night- to day-time sector configuration. Coordination between NM and Amsterdam/Schiphol, Maastricht and London ACCs mitigated delays	1
21 December 2015	Germany	Frequency and telephone problems in Langen ACC with additional delays at Frankfurt/Main airport due to lack of parking stands	1
19 May 2016	Sweden	ATC system failure	1
14 June 2016	Norway	Radar failure	1
23 June 2016	France	ATC equipment failure	1
13 July 2016	Germany	ATC equipment failure	1
28 August 2016*	Austria	Technical issues in Vienna COM Centre	1
14 September 2016	Sweden	Radar failure	1
15 September 2016	Belgium	Frequency failure	1
23 September 2016	Germany	ATC system failure	1
16 October 2016	France	Frequency failure	1
06 December 2016	Portugal	Radar and frequency failure	1
28 December 2016	UK	Communication system failure	1
06 January 2017	France	Radar and frequency failure	1
13 January 2017	France	Frequency failure	1
14 January 2017	Italy	Radar failure	1
26/27 January 2017	Cyprus	Radar maintenance	2
14 February 2017	Sweden	Non-availability of ATM back-up system due to weather phenomena	1
19-24 February 2017*	France	Frequency failure	6
23 February 2017	Germany	Frequency failure	1
11 March 2017	Switzerland	Radar failure	1
11/12/14 March 2017	Portugal	ATM system failure	3
06 April 2017	France	ATM system failure	1
10/11 April 2017	France	Communication system failure	2
17 April 2017	France	Frequency failure	1

10 May 2017	Portugal	Flight data processing system instability	1
13 May 2017	France	Frequency failure	1
23 May 2017	Portugal	Communication failure between Lisbon and Santa Maria ACC	1
01-30 May 2017*	Switzerland	Radar instability	30
01-30 May 2017*	Switzerland	Radar instability	30
06 June 2017	Belgium	ATC equipment failure	1
13 June 2017	France	FDPS failure	1
19 June 2017	France	Frequency failure	1
21 June 2017*	Ireland	Instability of telecommunication system in Gander Oceanic	1
22 June 2017	France	Frequency failure	1
25 June 2017	France	Frequency failure	1
09 July 2017	France	Frequency failure	1
10 July 2017	Serbia	Radar failure	1
15 July 2017*	Ireland	Communication failure in Ottawa Communication Center	1
21 July 2017	France	Frequency failure	1
06 August 2017	Netherlands	ATC equipment failure	1
20 August 2017	Portugal	FDPS failure	1
01 October 2017	Germany	FDPS failure	1
02 October 2017	Portugal	Surveillance system failure	1
27 October 2017	Germany	Communication system failure	1
15 November 2017	Germany	Communication system failure	1
16 November 2017	France	Frequency failure	1
19-30 December 2017*	Portugal	Frequency failure	12
09/10/11 December 2017	France	SSR code allocation issue between Madrid and Brest ACCs	3

Source: Eurocontrol (2016a, 2017c, 2018a)

* The following (days with) technical failures were excluded from the analysis (reason in brackets): 27 October 2015, 28 August 2016 and 21 June 2017 (only regulations for airports found), 19-24 February 2017 and 15 July 2017 (no regulations found in NEST), 1-30 May 2017 and 19-30 December 2017 (long duration of failure).

Appendix C Relationship between flight parameters

Disruptions may affect various flight parameters, which lead to increased fuel consumption and emissions. These flight parameters include:

- **Distance:** Re-routings may cause suboptimal flight trajectories with possibly increased flight distance, fuel consumption and emissions;
- **Air speed:** Airlines may request an increase in flight speed to make up the time lost due to the longer flight trajectories. Although this may limit delays for passengers, it leads to a suboptimal speed profile causing additional fuel consumption and emissions;
- **Flight levels:** Re-routings may force airlines to fly at suboptimal flight levels or to change flight levels more frequently which negatively impacts fuel consumption and emissions.

Distance

Fuel consumption is mainly determined by flight distance. Fuel economy is compromised on very short flights due to the fact that the aircraft is a relatively short time in the fuel-efficient cruise phase. On very long flights, fuel economy is reduced to that fact that much fuel needs to be taken on board, increasing the aircraft's weight. It is estimated that a 8,000 mile flight requires 20% more fuel than two 4,000 mile flights (Wynne, 2011). This suggests that breaking up such long flights into different flight legs requires less fuel. It however requires additional airport capacity and increases travel times. Park and O'Kelly (2014) shows that aircraft are most fuel efficient on stage lengths of 1,500-2,000 nautical miles.

However, the shortest flight trajectory (closest to the great circle distance) does not necessarily need to be the most fuel efficient. It may for instance have poor fuel economy due to suboptimal speed and altitude profiles. Also, weather conditions may lead to inefficient trajectories. Airlines may for instance choose to avoid bad weather for safety reasons or to ensure a comfortable and predictable journey. This however leads to increased flight distance. They may also take advantage of favourable wind conditions. Although this may increase total flight distance, it reduces flight time probably also fuel consumption and emissions. Furthermore, differences in navigation charges between airspace sectors may lead airlines to avoid relatively expensive airspaces, leading to increased flight distances and added fuel consumption (Reynolds, 2014).

Breguet equation

The impact of increased flight distance on fuel consumption can be estimated using the classic Breguet range equation, which is defined as follows:

$$R = \frac{V}{C_T}\frac{L}{D} ln \frac{W_i}{W_f} \qquad (1)$$

Whereby R, V and L/D refer to the range, speed and aerodynamic lift-to-drag ratio respectively. The C_T variable denotes the thrust specific fuel consumption which is defined as the fuel burned per unit of time divided by the unit thrust. This is a property of the aircraft engine. W_i and W_f are the aircraft's initial and final weight respectively. The Breguet equation is only applicable under the assumption that C_T, L/D and V are constant. Therefore it is only suitable for estimating fuel consumption during the cruise phase. When the initial flight weight W_i and flight range R are known, the equation can be used to estimate fuel consumption for this specific range.

We illustrate the Breguet equation for a 2,000 km cruise of an Airbus A320 flight. We assume a cruise velocity (V) of 460 knots or 851 km/h.[40] The thrust specific fuel consumption (C_T) and lift-to-drag ratio (L/D) for the Airbus A320 are 0.573 and 18.5 respectively (Yanto and Liem, 2018). The initial weight of the aircraft at the beginning of the cruise phase W_i is assumed to be 60,000 kilograms. Using the Breguet equation we can now calculate the aircraft's weight at the end of the 2,000 kilometers cruise phase: W_f = 55,792 kgs. This means that the aircraft has burned 4,207 kilograms of fuel during the cruise phase or 2.1 kilograms per kilometre.

Econometric models

There are also equations available showing the relationship between distance and fuel consumption for specific aircraft types. Yanto and Liem (2018) performed an econometric analysis to estimate such relationships for 40 different aircraft types controlling for the aircraft's payload. The authors first estimated fuel consumption during the cruise phase using the Breguet equation and complemented this with fuel consumption during the other phases using Eurocontrol's BADA data (Eurocontrol, 2017a). According to the estimations, an Airbus A320 for instance uses 2.3 kilograms of fuel per kilometer. This is slightly more than given by the Brequet-equation, but it should be borne in mind that the estimation with the Breguet-equation only included the cruise phase. Yanto and Liem (2018) also included the other flight phases, which include also the take-off and climbout phase during which fuel consumption is significantly higher than during the cruise phase. As disruptions often affect the cruise phases of flights, the estimations by Yanto and Liem (2018) are less suitable.

Rosskopf (2013) also used the econometric toolbox to estimate relationships between fuel consumption and distance. Relationships are given for 16 aircraft types. Fuel consumption was estimated using Eurocontrol's BADA data (Eurocontrol, 2017a), as well as the ICAO Engine Emissions Database (EASA, 2018) and the Database for Turboprop emissions. For a regular Airbus A320 the average fuel burns 2.5 kilograms of fuel for every kilometre flown. This is more than found by Yanto and Liem (2018). The difference may be caused by the fact that different input data is used and the fact that Rosskopf uses a different model specification which includes the square of the distance, but excludes payload.

Air speed

Flying at a higher speed increases air resistance or drag, which leads to increased fuel consumption. Turgut et al. (2014) performed an econometric analysis to determine how fuel consumption during the cruise phase depends on air speed and other factors using actual flight data records for domestic flights in Turkey operated by aircraft belonging to the Boeing 737 and Airbus A320 family range. They found that an airspeed increase of 1 knot increases fuel consumption by 6-8 kg per hour.

40 According to Eurocontrol's Base of Aircraft Data (BADA) the Airbus A320 cruises at 452-464 knots at flight levels 260-310 (Eurocontrol, 2017a).

Multiple studies have found that airlines often fly at speeds greater than the speed that minimizes fuel consumption (Ryerson et al., 2014; Jensen, 2013, 2014, 2015; Turgut et al., 2014). This could be due to ATM restrictions (Murrieta-Mendoza et al., 2016), but also to airline economics. Saucier et al. (2017) for instance found that the speed that minimizes airline costs (cost of fuel, crew, missed connections etc.) is slightly higher than the speed that minimizes fuel consumption. In other words, the savings of flying at a higher speeds outweigh the increased cost of fuel. Lovegren and Hansman (2011) estimate that flying at optimal speeds could reduce fuel consumption by 2.4%.

Altitude

Air density decreases with altitude, which means that resistance or drag is lower at higher altitudes. Fuel consumption therefore also decreases with altitude. However, climbing to a higher altitude leads to increased fuel consumption. Whether it is cost-efficient to climb to a higher altitude depends on the time that can be spent at the higher altitude. Also it should be born in mind that heavy aircraft (carrying a large amount of fuel) cannot always climb to a higher flight level, as the engines provide insufficient thrust to carry the aircraft to a higher level.

The aforementioned study by Turgut et al. (2014) also estimated the relationship between altitude and fuel consumption. The authors found that a 1,000ft increase in the cruise altitude reduces fuel consumption by 21-25 kg per hour for aircraft belonging to the Boeing 737 and Airbus A320 family range.

Pagoni and Psarako-Kalouptsidi (2017) found that an Airbus A321 consumes 4.4% less fuel when cruising at 35,000ft compared to cruising at 33,000ft. At 37,000ft fuel consumption is 3.6% lower than when cruising at 35,000 feet. This means that fuel efficiency increases with altitude although at a decreasing rate. On average, total fuel consumption during the Climb-Cruise-Descent phase decreases by 2.6-4.8% for every 2,000 foot increase in cruise altitude depending on the aircraft type.

Lovegren and Hansman (2011) found that flying at optimal altitudes could reduce fuel consumption by 1.5% on average.

Turgut et al. (2012) found that during descent fuel economy is improved when maintaining a higher altitude for as long as possible. Continuous Descent Approaches (CDAs) for instance minimize low level flights, thereby reducing fuel consumption and consequently emissions. Numerous studies have demonstrated the benefits of CDAs (Clarke et al., 2004; Coppenbarger et al., 2009; Shresta et al., 2009). However, the success of the concept depends heavily on air traffic volume (Turgut et al., 2014).

Specific models have been developed to estimate fuel consumption, ranging from very simple to highly sophisticated (see the box below).

Aircraft performance data and models

- **ICAO reference method**. This allows for the calculation of fuel consumption and emissions during the Landing/Take-Off (LTO) cycle (below 3,000ft). It uses engine specific fuel consumption and emission data;

- **Base of Aircraft Data (BADA)** (Eurocontrol, 2017a). BADA is a mathematical model developed by Eurocontrol to estimate the performance of a wide range of aircraft types. It includes databases with operating parameters for each aircraft type. BADA characterizes fuel flow for the phases of climb, cruise and descent with respect to different altitude, true air speed (TAS) and mass. BADA also contains Performance Summary Tables for each aircraft type which shows the air speeds and fuel consumption at various flight levels during the climb, cruise and descent phases;
- **Small Emitters Tool (SET)** (2016b). Since the 1st of January 2010 the European Commission (2009) requires from aircraft operators to monitor and report their annual CO_2-emissions. To reduce the administrative burden for airlines operating a limited amount of flights or with little CO_2-emissions, they are allowed to use a simplified tool to estimate their fuel consumption developed by EUROCONTROL. The tool estimates fuel consumption during all flight phases as well as the taxiing phase based on distance for the most common aircraft types (European Commission, 2010b);
- **EMEP/EEA air pollutant emission inventory guidebook** (formerly: EMEP CORINAIR). This database provides emissions data for various industries, including the aviation industry. It is used by European Member States to calculate national emission inventories. To estimate aviation emissions, it uses fuel burn data based on 4D-trajectories and the BADA database;
- **P3T3 method**. This method takes the combustion inlet pressure (P3) and temperature (T3) as well as the engine fuel flow into account when estimating fuel consumption. It is commonly used by engine manufacturers (Schaefer and Bartosch, 2013), yet it requires the knowledge of internal engine parameters which are difficult to measure or compute (Chen et al., 2016);
- **Boeing Fuel Flow Method 2 (BFFM2)**. This method explicitly takes power settings and atmospheric conditions at different altitudes into account when estimating fuel consumption;
- **Piano X**. The Piano X model estimates fuel consumption based on a range of flight parameters.

The amount of fuel consumed during a flight depends on a large range of factors, such as airframe design, engine type, flight trajectory, atmospheric conditions (temperature, air density, pressure) as well as airline economics.

Simple models, such as the ICAO reference method, the Small Emitters Tool (SET) and the EMEP/EEA air pollutant emission inventory guidebook either, only consider fuel consumption certain flight phases or under specific assumptions regarding the actual trajectory and atmosphere. More sophisticated models such as the BADA model or Boeing Fuel Flow Method 2 take actual flight trajectories and atmospheric conditions into account.

Yanto and Liem (2018) have shown that the simplest models yield unpredictable results. Although the sophisticated models are the most accurate, they require vast amounts of data and computational time. This makes them unsuitable for large scale studies covering a large amount of flights. This shows that there is a trade-off between model accuracy and computational time/data requirements.

Appendix D A4E member airlines

Table D.1 A4E member airlines

A4E member	Airlines	IATA code
Aegean	Aegean	A3
	Olympic Air	OA
Air Baltic	Air Baltic	BT
Air France-KLM	Air France	AF
	HOP!	A5
	Joon	JN
	KLM & KLM Cargo	KL
	KLM Cityhopper	WA
	Martinair	MP
	Transavia	HV
	Transavia France	TO
Cargolux	Cargolux	CV
	Cargolux Italia	C8
easyJet	easyJet Europe	EC
	easyJet Switzerland	DS
	easyJet UK	U2
Finnair	Finnair & Finnair Cargo	AY
	Nordic Regional Airlines	N7
IAG	Aer Lingus & Aer Lingus regional	EI
	Anisec Luftfahrt	VK
	BA Cityflyer	CJ
	British Airways & British Airways Shuttle	BA
	Iberia	IB
	Iberia Express	I2
	Iberia Regional / Air Nostrum	YW
	LEVEL	LV
	Vueling	VY
	Comair	MN
	Sun-Air of Scandinavia	EZ
	IAG Cargo	
Icelandair	Icelandair & Icelandair Cargo	FI
	Air Iceland Connect	NY
Jet2com	Jet2.com & Jet2holidays	LS
Lufthansa Group	Air Dolomiti	EN
	Austrian Airlines	OS
	Brussels Airlines	SN
	Edelweiss Air	WK
	Eurowings	EW
	Eurowings Europe	E2
	Luftfahrtgesellschaft Walter	HE
	Lufthansa & Lufthansa Cargo	LH
	Lufthansa Cityline	CL
	SWISS	LX
	Aerologic	3S
	Germanwings	4U
	SunExpress	XQ
Norwegian	Norwegian Air Argentina	DN
	Norwegian Air International	D8
	Norwegian Air Shuttle	DY
	Norwegian Air UK	DI
	Norwegian Long Haul	DU

Ryanair	Laudamotion	OE
	Ryanair	FR
	Ryanair Sun	RR
Smartwings	Czech Airlines	OK
	Smartwings	QS
	Travel Service Hungary	7O
	Travel Service Polska	3Z
	Travel Service Slovakia	6D
TAP	TAP & TAP Express	TP
Volotea	Volotea	V7

Appendix E EEA countries and ICAO codes

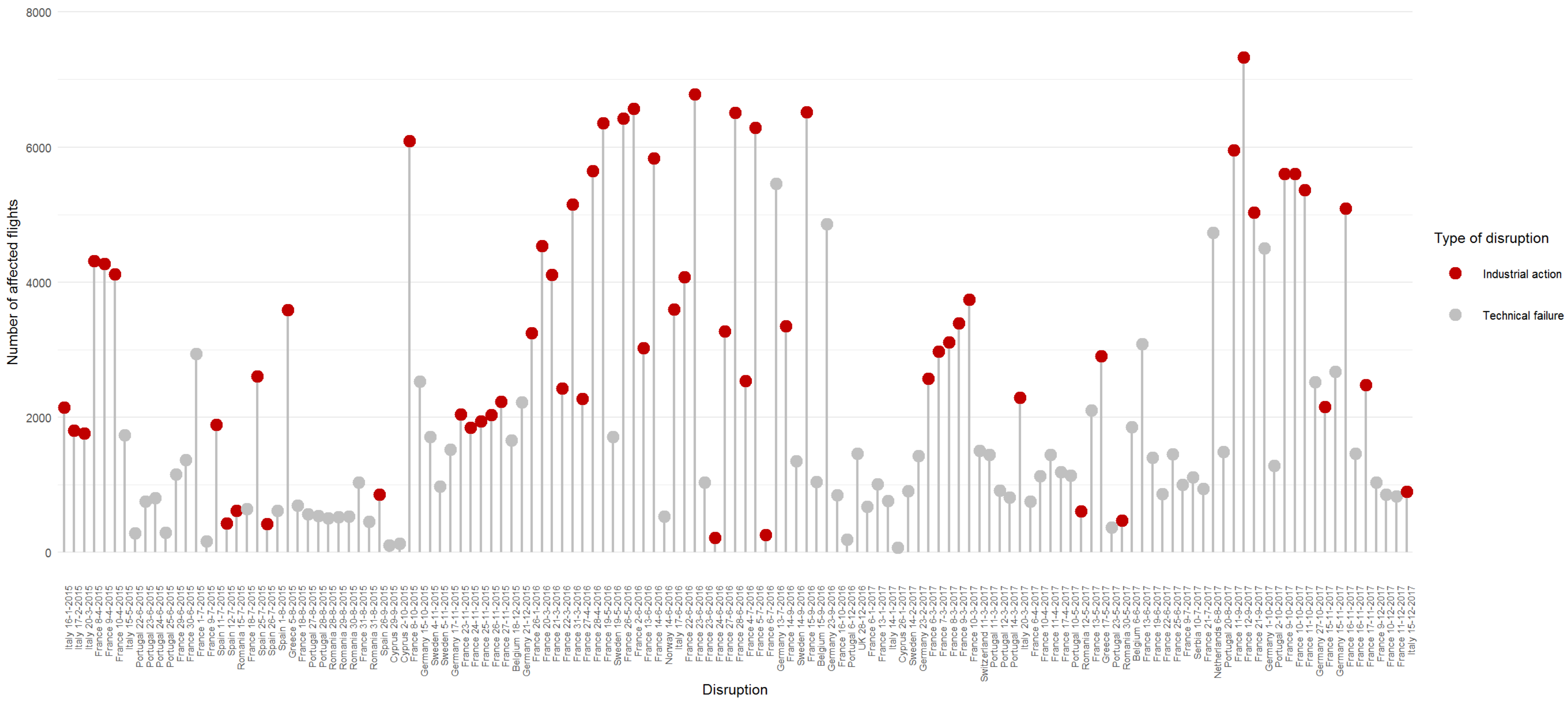
Table E.1 EEA countries and ICAO codes

Country	ICAO code	Country	ICAO code
Austria	LO	Lithuania	EY
Belgium	EB	Luxembourg	EL
Bulgaria	LB	Malta	LM
Croatia	LD	Netherlands	EH
Cyprus	LC	Poland	EP
Czech	LK	Portugal	LP
Denmark	EK	Romania	LR
Estonia	EE	Slovakia	LZ
Finland	EF	Slovenia	LJ
France	LF	Spain	LE
Germany	ED	Sweden	ES
Greece	LG	United Kingdom	EG
Hungary	LH	Iceland	BI
Ireland	EI	Liechtenstein	LIE
Italy	LI	Norway	EN
Latvia	EV	Switzerland	LS

* Switzerland is neither an EU nor EEA member but is an EFTA member and is part of the single market and therefore included in the analysis.

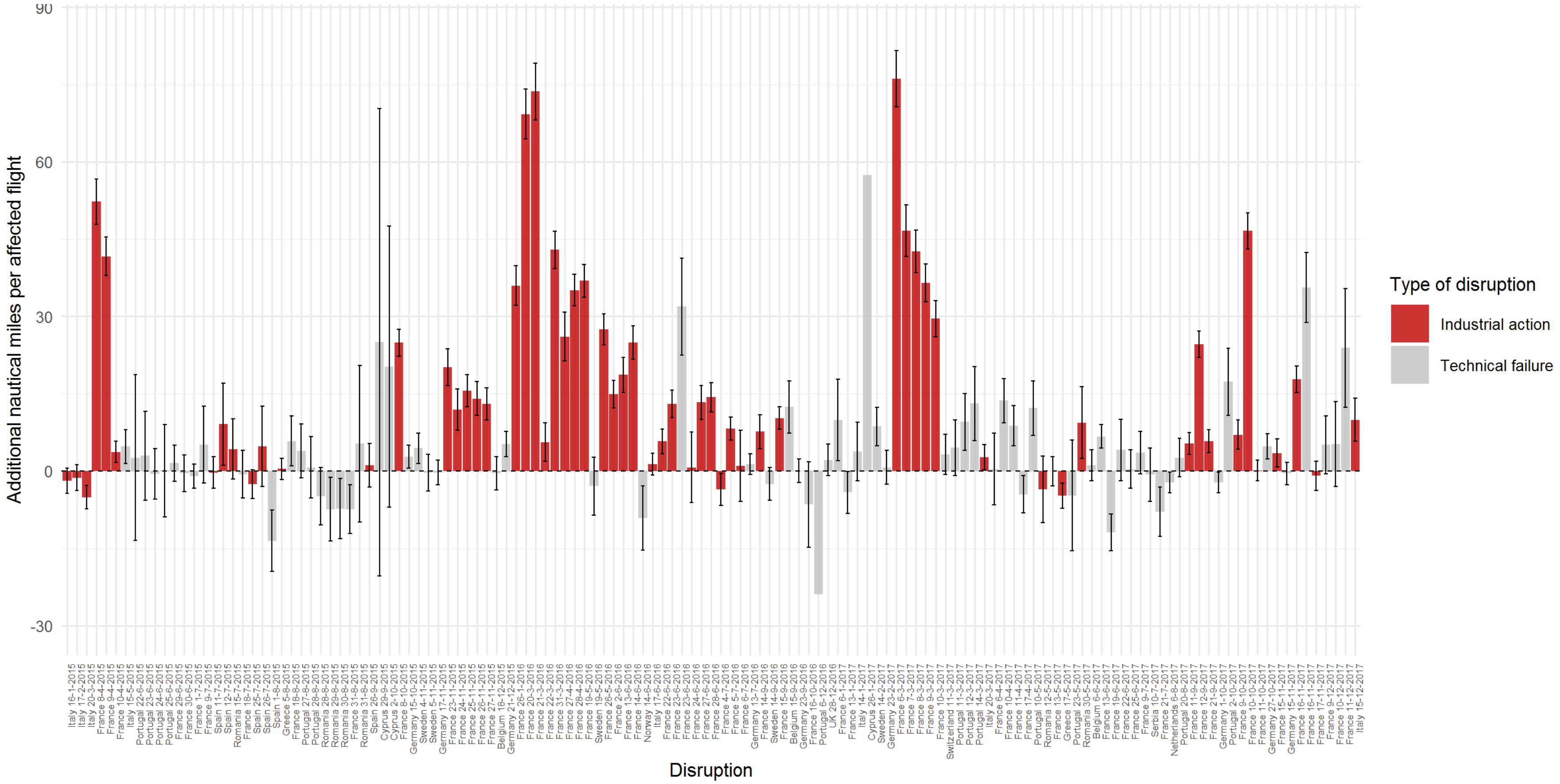
Appendix F Affected flights by disruption

Figure 5.1 Number of affected flights per disruption day, 2015-2017



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST data

Figure 5.2 Additional nautical miles per affected flight for each disruption day, 2015-2017



Source: SEO/To70 analysis based on Eurocontrol DDR/NEST data