

# Statistical evaluation of fuel values

A Walter<sup>1,2</sup>, S Kubica<sup>1</sup> and V Rocco<sup>2</sup>

<sup>1</sup> Faculty of Business, Computing and Law, Technical University of Applied Sciences Wildau, Hochschulring 1, 15745 Wildau, Germany

<sup>2</sup> Department of Industrial Engineering, University "Tor Vergata", Via del Politecnico 1, 00133 Roma, Italy

E-mail: [walter.andreas@students.uniroma2.eu](mailto:walter.andreas@students.uniroma2.eu), [stefan.kubica@th-wildau.de](mailto:stefan.kubica@th-wildau.de), [rocco@uniroma2.it](mailto:rocco@uniroma2.it)

**Abstract.** Aviation emissions, domestic and international, account for approximately 2 % of total global CO<sub>2</sub> emissions. Fuel consumption for a given route, excluding other factors such as wind, depends largely on the weight of the aircraft. To minimise fuel consumption, it is often most economical to carry only the minimum weight required for the sector. Within the framework of a dissertation, possibilities to reduce the final reserve fuel and thus the amount of fuel required are being researched and evaluated. This paper shows part of the results, as reliability and accuracy of flight planning and actual operations are a necessary basis for a possible reduction. The level of safety in aviation must always be taken into account. To prove this, fuel values are recorded and statistically evaluated, based on real flight and fuel data provided. Analysis, systematization and generalization were used to conduct the study. As a statistical background, extensive fuel data of an airline from a period of about five years were examined. The focus of this paper is on the results for taxi and trip fuel. The result shows that the current requirements for flight planning and the subsequent execution of flights are very reliable and highly accurate today. The results of the study can be used as a basis for a performance-based approach to reduce the final reserve fuel while maintaining the necessary safety level. Reducing the final reserve has a significant impact on reducing overall fuel consumption and emissions. Further research and studies are needed to determine performance indicators.

## 1. Introduction

Fuel, which is required for the daily operation of thousands of flights worldwide, is one of the most important cost factors in the airline business. The associated emissions of air traffic have an impact on the climate that is increasingly coming into focus. In 2020, almost every commercial aircraft is still equipped with a fossil fuel-based propulsion system. Emissions from aircraft are greenhouse gases and noise. Main emissions from aviation published by IPCC [1] are CO<sub>2</sub> emissions, which account for approximately 2 per cent of the global man-made CO<sub>2</sub> emissions. They are expected to increase by 3 to 4 per cent annually. Besides CO<sub>2</sub>, water vapor H<sub>2</sub>O is another products of jet fuel combustion. Their emission indices are 3.15 kg/kg fuel burned and 1.26 kg/kg fuel respectively [1]. NO<sub>x</sub> constitutes the next most abundant engine emission [1]. Mitigation of emissions from the aviation sector potentially can come from improved fuel efficiency. This is although in the financial interest of the operators, see e.g. in the documents published by Airbus [2] or IATA [3]. However, such improvements are expected



to only in part offset the growth of aviation CO<sub>2</sub> emissions [4]. For this reason, correspondingly great efforts are being made in various areas to reduce emission.

As the area of fuel economy and emissions reduction becomes more prominent, a wide range of research is being conducted. Singh and Sharma have found that the number of articles published has increased since 2000 compared to three decades before [5]. Here are a few examples, representing the broad spectrum: Kaiser et al. presented a jet performance model for prediction of optimized four-dimensional aircraft trajectories to allow better prediction of fuel flow and thus give a base for airborne and ground flight optimisation [6]. Trajectory optimization, in regard of better use of Flight Management Systems, was done by Patrón, Berrou and Botez. They presented an algorithm for a complete trajectory optimization, from climb to descent using real flight information [7]. Benefits of improved cruise speed and altitude profiles were investigated by Lovegren and Hansman [8]. Ryerson, Hansen and Bonn highlighted the role of the air traffic management in fuel saving improvements [9]. These examples represent only a small part of the comprehensive optimisation efforts.

Aircraft manufactures try to improve their respective models in terms of efficiency. Weight saving is a crucial point here [2]. Capoccitti, Khare and Mildenerger [10] show that a saving of just 1 % in fuel consumption for a medium-sized aircraft could offer savings of around 100 tonnes of fuel per year, resulting in an annual cost reduction of around EUR 38 000 per aircraft [11].

Opportunities to reduce costs and emissions are often associated with newer aircraft, which are claimed to perform better. Efforts have already been made in recent decades to introduce new aircraft models. To further reduce fuel consumption in the long term, revolutionary aircraft technologies are needed, such as the double-bubble fuselage, blended wing body or the box-wing aircraft. The development of evolutionary and revolutionary aircraft technologies is a medium to long-term task.

Regulators are also taking into account the development of emissions reduction and fuel economy. ICAO published document 10013 - Operational Opportunities to Reduce Fuel Burn and Emissions. It provides civil aviation stakeholders with operational opportunities and techniques to reduce fuel burn and therefore emissions. Doc 10013 assumes that the most effective way to minimise emissions is through the amount of fuel consumed [4].

Many efforts are being made in the area of research and development to make aviation more efficient. Weight reduction, engine consumption and aerodynamics are the fundamental pillars here. An instant reduction of weight through saved transported fuel promises quick results. For a given route, fuel consumption under constant environmental conditions such as weather or routing depends on the weight of the aircraft. The specific range at given altitude, temperature and speed depends on the mass of the aircraft. The heavier the aircraft, the higher the fuel consumption. To minimise fuel consumption, it is most economical to carry only as much fuel as is required for the sector in question. Lighter aircraft have performance advantages during take-off and landing and reduced wear, e.g. on the brakes. In addition, fuel can be saved in climb, as the lighter aircraft reaches its optimum flight altitude earlier [12]. The primary focus was to explore and evaluate ways to reduce the final reserve fuel (FRF) carried by aircraft with turbine engines and thus the amount of fuel needed. Final reserve fuel is the fuel required for a 30-minute flight at holding speed at an altitude of 1500 feet (450 m) above the aerodrome under standard conditions, calculated with the estimated mass on arrival at the destination alternate aerodrome or the destination aerodrome if no destination alternate aerodrome is required. Normally, this proportion of fuel is not required as a landing had already taken place beforehand. This paper specifies a relevant part and a step towards achieving a possible reduction in FRF: the correlation between flight planning fuel figures and actual in-flight fuel consumption as a basis for assessing the reliability of fuel planning and flight execution.

The European Union Aviation Safety Agency (EASA) has published Notice of Proposed Amendment (NPA) 2016-06, which takes a performance-based approach by updating regulatory

requirements for fuel planning, selection of aerodromes and in-flight fuel management to improve operational efficiency and deliver cost and environmental benefits [13]. The NPA 2016-06 also introduces the concept of individual fuel schemes, which is already included in Regulation (EU) No 965/2012 with the flight time specification schemes. Those operators who demonstrate certain capabilities will be able to use individual fuel schemes in the future. Recently, the associated new EASA fuel management rules were published as part of the regulatory package consisting of Regulation (EU) 2021/1296 and Decision 2022/005/R of the European Parliament and Council - applicable from autumn 2022.

However, due to the special nature of air traffic, considerations regarding fuel planning and the execution of flights are always linked to corresponding safety considerations. A corresponding safety level, which must be demonstrated by the operator, is the prerequisite for the approval of the individual fuel schemes. In order to achieve a certain safety level, Drees et al. therefore recommend on the other hand a higher final reserve fuel value [14]. In the same context, Gregor also researched the probability of landing at the airport with less than final reserve fuel or running out of usable fuel, along with corresponding risk assessments for today's commercial turbine aircraft operations. The safety assessment focused on the risk of attaining low usable fuel levels during flight due to insufficient planning, loss of fuel or inability to use remaining fuel [15]. Based on Gregor's work, Mazaris went on to estimate the probabilities of rare events for several operational scenarios related to the issue of fuel planning and management, together with quantification of risks. Landing below FRF probability and fuel exhaustion were simulated [16]. The 60 million simulated flights represent almost twice the actual number of flights worldwide [17]. As a result, Mazaris obtained probabilities in the range of  $10^{-6}$  for the different below FRF scenarios investigated. For fuel exhaustion the probabilities were significantly lower [16].

The EASA Member States accident rate for the year 2011-2014 had an average value of 0.0235 accidents per 10 000 flight hours, or  $2.35 * 10^{-6}$ . The 4-year period (2011-2014) fatal accident rate was as low as 0.0004 per 10 000 flight hours, or  $4 * 10^{-8}$  [18]. This high level of safety forms the basis for the introduction of performance-based regulations.

## 2. Methods

The possible adjustment of the different fuel values is to be done according to a performance-based approach. A risk assessment is part of the process. In order to obtain the necessary information, among other things, the statistical evaluation of fuel data has to be taken into account. To explore a statistical background, the fuel data of an airline were examined for a period of about five years, from March 2016 to the end of December 2020. The airline operates Boeing B777-200 aircraft in a freighter version. The route network it operates includes both major airports and some local airports. The route network offers a mix of short-, medium- and long-haul flights.

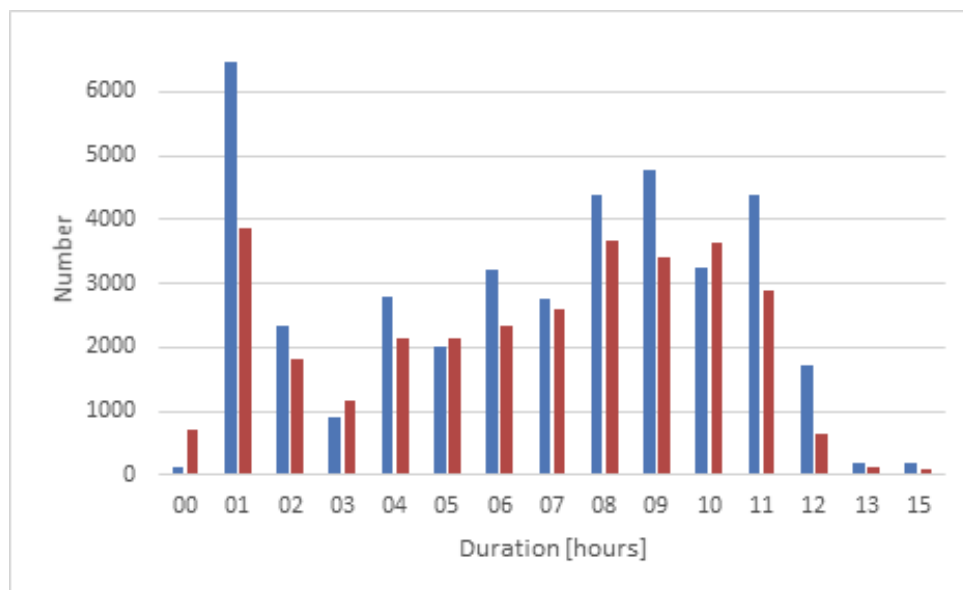
For the data period provided, multiple flight information, available via various reports, is fed back into the airline data management system used. The system collects and provides a variety of facts in different areas of interest, such as aircraft information, airport statistics, cosmic radiation, crew details, on-time performance and so on. Flight information such as tracking of auto lands, city pair information, de-icing reports, delay reports, etc. are also available. The information from the data system is used, among other things, to provide fuel planning information and statistics to the flight crew via an Electronic Flight Back (EFB) application. Thus, specific fuel and flight information is available via 5 different reports:

- Fuel Data Validation, contained 40 166 flights
- Dynamic Flight List, 43 113 flights
- Fuel Analyzer Reference List, contains information for 31 315 flights

- Fuel Analyzer App Data
- Flight List Uld Detail Load

Examination of the 5 reports revealed that they contain different amounts of data records or information for the same period - as the first three entries above illustrate. Missing data, incorrect data or erroneous entries lead to differences in the reports. Missing data can lead to a flight not being included in one report, while the same flight is still included in another report that has a different focus or filter. Missing or incorrect data may result from connectivity problems of the Aircraft Communications Addressing and Reporting System (ACARS) used, miscalculations, e.g. due to missing data, accidental operation of the ACARS system, diversion of an associated flight or simply missing information. Missing information that may lead to the rejection of a record may include: previous fuel, fuel uplift, density, off or on block time, shutdown fuel. The varying number of records in the reports did not allow the information to be combined into a single report.

Various reports were evaluated to verify the information, depending on the information needed and available in each case. Presented here is mainly the Fuel Data Validation Report. It contains planned (p), actual (a) and corrected (c) information. While planned figures are self-explanatory, such as a planned departure time, actual figures are the reality figures, such as the actual departure time. Actual numbers describe the numbers returned by the aircraft. The report also contains corrected figures. The corrected figures describe the difference between the planned figures and the figures returned, based on the true fuel decision and payload of the flight.



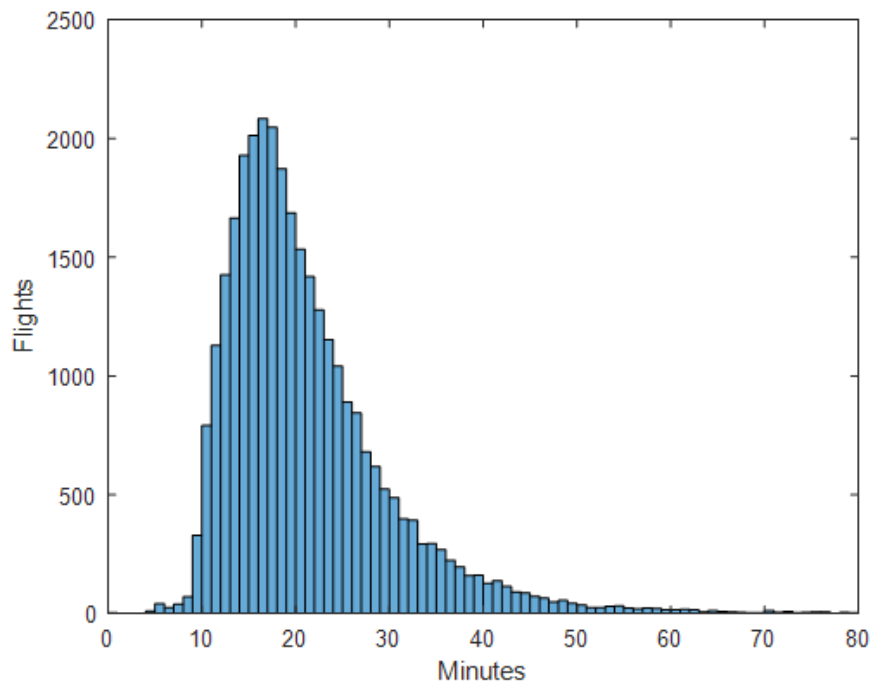
**Figure 1.** Distribution of flight times.

To start a flight, here with the push-back at the gate, the so-called off-block fuel is on board. The off-block fuel could be evaluated in the fuel data validation report. For 39 928 flights, the average was 61 650 kg, with a minimum of 8 200 kg and a maximum of 142 300 kg. The mean was 63 800 kg, the deviation 28 800.6 kg and the variance 829 474 303.09 kg. The 25 percent quantile is 38 500 kg and the 75 percent quantile is 85 300 kg. The ratio of mean value and deviation together with the quantile limits shows the broad distribution of the discrete off-block fuel values. This reflects the distribution of flight times, as shown in figure 1, different routings, different payload and consideration of weather for the sectors flown.

For the evaluation of planned and real figures, within the framework of the overall consideration for the dissertation, all parts of the required fuel quantity were evaluated. As an example, only the results for taxi fuel and travel fuel are presented below. Figure 4 shows information on average values of other fuel information.

*2.1. Taxi Fuel*

Taxi fuel could be analysed in the Fuel Analyzer App Reference List report as planned (p) and actual (a) value. For the 31 315 flights, the average taxi out fuel was 724 kg (a) and 670 kg (p). The maximum values were 64 000 kg (a) and 2 000 kg (p). The minima were -98 700 kg (a) and, for 16 cases, 0 kg (p). These values are considered unrealistic or erroneous, as they may be due to incorrect inputs or calculations. Mean values are 700 kg (a) and 600 kg (p), the standard error of the mean is 4.97 (a) and 0.78 (p). The 25 percent quantiles are 500 kg (a) and 600 kg (p), the 75 percent quantiles are 900 kg (a) and 733 kg (p), respectively. As shown above, the actual taxi fuel required was on average 54 kg higher than planned. On the other hand, this corresponds to a deviation of only 0.08 % in relation to the average 61 500 kg off-block fuel. It should be noted that the deviation in taxi fuel was calculated from 31 315 flights. The average off-block fuel was calculated from 39 928 flights.



**Figure 2.** Taxi out times.

As can be seen in figure 2, the upward deviations of taxi fuel are explained by taxi times of 30 minutes and more.

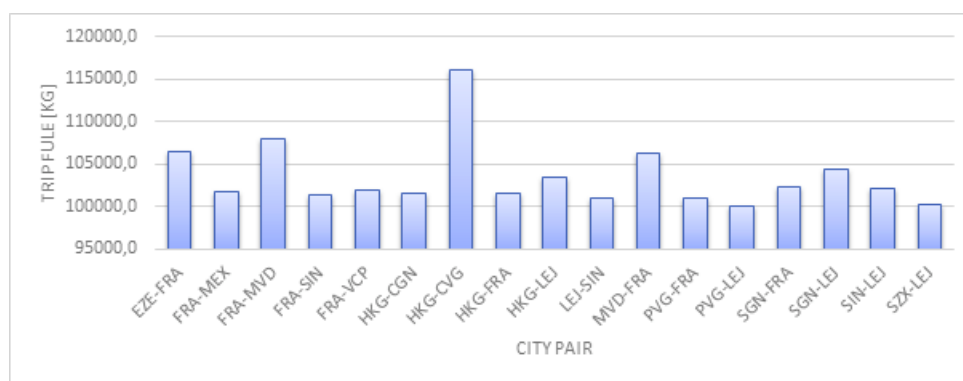
*2.2. Trip Fuel*

Trip fuel\* values are tracked in the Fuel Analyzer App Reference List. As described above, planned, actual and corrected values are available. All of these values are close to each other, as shown in the overview for the average Trip Fuel\* value:

- Actual trip fuel\* 50.382,00 kg
- Trip fuel\* corrected 50.442,96 kg
- Trip fuel\* planned 50.353,70 kg
- Trip fuel\* planned corrected 50.414,66

It is worth mentioning that the definition of trip fuel\* in the Fuel Analyzer App and the Fuel Analyzer App Reference List includes taxi out fuel. This differs from the definition according to Regulation (EU) No 965/2012 [19]. Therefore, the marking with a \* was chosen. However, it is possible to calculate the actual trip fuel as trip fuel\* minus actual and planned taxi fuel to obtain the value that complies with Regulation (EU) No 965/2012. The trip fuel planned (trip fuel\* planned – taxi out fuel planned) is the value listed in the operational flight plan (OFP) for that flight. The actual trip fuel (trip fuel\* – actual taxi out fuel) is the value reported back via the aircraft system.

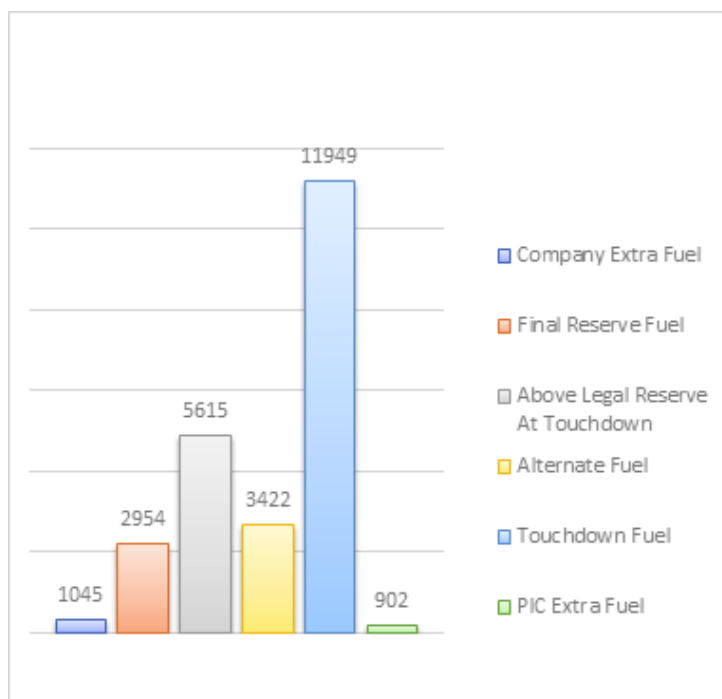
The average planned trip fuel for 31 315 flights in the Fuel Analyzer App Reference List report was 49 683 kg. The actual average was 49 658 kg. The 25 percent quantiles are 23 895 kg (p) and 24 300 kg (a), the 75 percent quantiles are 73.431 kg (p) and 73.600 kg (a), respectively. This shows that the planned and actual fuel consumption correspond to a large extent.



**Figure 3.** Trip Fuel more than 100 tonnes.

Most trip fuel was consumed on the Hong Kong – Cincinnati route, compare figure 3. Due to the long distance, long flight time and high load, the largest amounts of fuel were refuelled and consumed on this route. This pair of cities was flown to 177 times. In an exceptional flight, 123 400 kg of travel fuel was consumed, compared to 124 131 kg planned. About 300 kg more fuel was consumed on this flight, which in this case corresponds to a difference of 0.24 %. However, such differences between planned and actual circumstances are covered through contingency fuel. A total of 344 flights with a planned en-route fuel of more than 100 tonnes could be identified. This correspond to 1 % of 31 315 flights. These are therefore relatively rare cases of high cruise fuel volumes, with correspondingly little buffer for additional extra fuel.

The comparison between the average planned 50 353 kg and the actual fuel quantity of 50 382 kg showed that in fact slightly more fuel was needed than planned. In the corrected figures, the values were 50 414 kg and 50 442 kg respectively. The difference determined was less than 30 kg in both cases. On the one hand, this indicates exact planning, and on the other hand, it can be explained by the fact that the fuel consumption was slightly higher than planned due to extra fuel added by the crew. At this point it should be mentioned that extra fuel that is not planned but added by the crew during flight preparation leads to extra consumption due to the fuel penalty factor. As can be seen in figure 4, the average value of the additional fuel required by the commander over all flights from the Fuel Analyser reports is about 900 kg - this leads to additional consumption.



**Figure 4.** Average Fuel values.

Figure 4 also shows other fuel components and values that could be evaluated from the various reports, e.g. alternate fuel. These components are not evaluated in depth in this paper. The investigated components taxi and trip fuel are deliberately not shown in the figure, as they are significantly smaller and significantly larger, respectively.

### 3. Results

The above assessment was carried out on the basis of statistical data for a period of almost five years. The analysis of the fuel data has shown that the planned and actual figures for taxi and trip fuel are very close. The planning and in-flight management processes are mature. Even extraordinary events, such as the eruption of a volcano, did not result in a situation where fuel values, as required per legal regulations, were not met or in danger. Planned figures and real consumption were close together. The planning process thus proves to be very reliable. By checking the reliability of the planning and execution of the flights, a first step was taken towards a performance-based approach to fuel planning. As a result, a reduction of the fuel portions not needed in normal cases can be considered. The conclusion of the single value observation of all fuel values showed that planned and actual consumption are on a high and reliable level. It can therefore be assumed that the planned and actual fuel values on board can be considered reliable and almost consistent.

It was determined that an adjustment of the Final reserve fuel figures in terms of reduction is possible. A reduction in fuel (weight) has an impact on overall fuel and emissions. Between 3 and 4 % difference in fuel consumption per kg and flight hour for additional weight can be taken as a basis for the savings potential.

A reduction in transported fuel by a value equivalent to 5 minutes of flight time corresponds to e.g. to ~ 600kg less fuel carried, corresponding to the examined aircraft type B777-200. Based on the average 16 flight hours, this would mean a daily saving of ~ 270 kg less fuel consumed. This in turn would save approx. 850 kg CO<sub>2</sub> and 340 kg H<sub>2</sub>O per aircraft per day

for this aircraft type and operation. The potential savings for a fleet of 20 Boeing B 777 aircraft amount to 6 209 000 kg CO<sub>2</sub> and 1 973 000 kg fuel per year – corresponding to the average daily flight hours of 16 hours or more. On this basis, airline operators are recommended to evaluate their operational procedures, management and safety systems in preparation for the introduction of reduced fuel.

#### 4. Discussion

For evaluation, the actual development of fuel consumption and supply over real flights is recommended. In particular, extreme values should be taken into account. Inaccuracies in displays and systems are also low today compared to the early days of aviation and are at a high and reliable level in modern aircraft. Nevertheless, investigation of this area should be carried out to avoid inaccuracies, even if only in a small range.

Further research is needed to identify performance indicators. The above assessment has focused only on two fuel components. A more in-depth assessment of total fuel numbers is recommended, as well as consideration of other factors such as aircraft system reliability, the influence of weather or airfield processes. Based on these investigations, a risk assessment can be made to further consider the reduction of the fuel.

#### ORCID iDs

V Rocco <https://orcid.org/0000-0001-8030-2452>

A Walter <https://orcid.org/0000-0001-5043-4833>

#### References

- [1] Penner J E, Lister D H, Griggs D J, Dokken D J and McFarland M (eds) 1999 *Aviation and the Global Atmosphere* (Cambridge: Cambridge University Press) URL <https://archive.ipcc.ch/ipccreports/sres/aviation/index.php?idp=0>
- [2] Airbus 2008 *Getting to grips with A320 Family Performance Retention and Fuel Saving (Flight Operations Support & Services no 2)* (Blagnac Cedex: AIRBUS S.A.S.) URL <https://www.cockpitseeker.com/wp-content/uploads/goodies/ac/a320/pdf/data/GTGA320PerfoRetentionIssue2.pdf>
- [3] IATA 2020 Jet Fuel Price Monitor URL <https://www.iata.org/en/publications/economics/fuel-monitor/>
- [4] ICAO 2014 *Doc 10013 – Operational Opportunities to Reduce Fuel Burn and Emissions* 1st ed (*Doc vol 10011-AN/506*) (Montréal: International Civil Aviation Organization) ISBN 978-92-9249-563-3
- [5] Singh V and Sharma S K 2015 *European Transport Research Review* **7** 12 ISSN 1867-0717 URL <https://doi.org/10.1007/s12544-015-0160-x>
- [6] Kaiser M, Schultz M and Fricke H 2011 Enhanced Jet Performance Model for High Precision 4D Flight Path Prediction *Proceedings of the 1st International Conference on Application and Theory of Automation in Command and Control Systems ATACCS '11* (Toulouse, FRA: IRIT Press) p 33–40 ISBN 9781450315067 URL <https://doi.org/10.5555/2248467.2248472>
- [7] Patrón R S F, Berrou Y and Botez R M 2015 *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* **229** 1853–1867 URL <https://doi.org/10.1177/0954410014561772>
- [8] Lovegren J and Hansman R J 2011 Estimation of potential aircraft fuel burn reduction in cruise via speed and altitude optimization strategies Tech. Rep. ICAT-2011-03 MIT International Center for Air Transportation (ICAT) Cambridge URL <http://hdl.handle.net/1721.1/62196>
- [9] Ryerson M S, Hansen M and Bonn J 2014 *Transportation Research Part A: Policy and Practice* **69** 286–298 ISSN 0965-8564 URL <https://doi.org/10.1016/j.tra.2014.08.024>
- [10] Capocritti S, Khare A and Mildenerger U 2010 *Journal of technology management & innovation* **5** 66–75 URL <https://doi.org/10.4067/S0718-27242010000200006>
- [11] Ayra E S, Insua D R and Cano J 2014 *Journal of the American Statistical Association* **109** 465–476 URL <https://doi.org/10.1080/01621459.2013.879060>
- [12] Airbus 2004 *Getting to grips with fuel economy (Flight Operations Support & Services no 4)* (Blagnac Cedex: AIRBUS S.A.S.) URL <https://ansperformance.eu/library/airbus-fuel-economy.pdf>
- [13] European Aviation Safety Agency 2016 Notice of Proposed Amendment 2016-06 (A): Fuel planning and management URL <https://www.easa.europa.eu/downloads/21129/en>



- [14] Drees L, Mueller M, Schmidt-Moll C, Gontar P, Zwirgmaier K, Wang C, Bengler K, Holzapfel F and Straub D 2017 *Journal of Air Transport Management* **65** 1–10 ISSN 0969-6997 URL <https://doi.org/10.1016/j.jairtraman.2017.07.003>
- [15] Gregor V 2015 *Safety Risk Assessment for Aircraft Fuel Management* Master thesis Comenius University in Bratislava URL <http://www.iam.fmph.uniba.sk/studium/efm/diplomovky/2015/gregor/diplomovka.pdf>
- [16] Mazaris S 2020 *Safety Risk Assessment in Aircraft Fuel Planning and Management* Master of Science thesis Delft University of Technology URL <http://resolver.tudelft.nl/uuid:4a863318-3a6b-4d60-9402-d4864229ecd8>
- [17] ICAO 2019 Annual Report 2019: Presentation of 2019 Air Transport statistical results URL [https://www.icao.int/annual-report-2019/Documents/ARC\\_2019\\_Air%20Transport%20Statistics.pdf](https://www.icao.int/annual-report-2019/Documents/ARC_2019_Air%20Transport%20Statistics.pdf)
- [18] European Aviation Safety Agency 2019 The European Plan for Aviation Safety (EPAS 2020-2024) URL <https://www.easa.europa.eu/document-library/general-publications/european-plan-aviation-safety-2020-2024>
- [19] European Aviation Safety Agency 2019 Easy Access Rules for Air Operations (Regulation (EU) No 965/2012) URL [https://www.srvsop.aero/site/wp-content/uploads/2020/06/7-EasyAccessRules\\_for\\_AirOperations-Oct2019-EASA.pdf](https://www.srvsop.aero/site/wp-content/uploads/2020/06/7-EasyAccessRules_for_AirOperations-Oct2019-EASA.pdf)