Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol

Ellerbroek, Joost; Inaad, Mazin; Hoekstra, Jacco

Publication date
2018

Document Version
Accepted author manuscript

Published in
2018 International Conference on Research in Air Transportation

Citation (APA)
Ellerbroek, J., Inaad, M., & Hoekstra, J. (2018). Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol. In *2018 International Conference on Research in Air Transportation: Barcelona, Spain, 2018*

Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol

Joost Ellerbroek, Mazin Inaad, and Jacco M. Hoekstra
Faculty of Aerospace Engineering, Delft University of Technology
Kluyverweg 1, 2629 HS, Delft, The Netherlands

Abstract—**This paper presents an analysis of the potential fuel and emission benefits of implementing Continuous Descent Operations at Schiphol International Airport, from cruise altitude to the final approach fix, for a large scope of aircraft types. Using historical data from on-board sources and ADS-B, fuel-optimal continuous descents are simulated using the total-energy model. By comparing the fuel consumption between historical flights and the simulated continuous descent flights, fuel benefits are found. CO_2 emissions are then calculated linearly from the fuel benefits. The results show average savings of 92kg up to 500 kg of fuel per flight. For Schiphol, this results in a total of 39 million kg of fuel savings per, year leading to more than 123 thousand tonnes of CO_2 savings per year.**

Keywords—**Continuous Descent Operations (CDO), data analysis, ADS-B, simulation**

I. INTRODUCTION

To mitigate the climate impact of air transportation, Continuous Descent Operations (CDO) are seen as an way to reduce greenhouse gas emmissions per flight. Eurocontrol defines a CDO as an operation in which an "*aircraft descends from an optimal position with minimum thrust and avoids level flight segments*" [1]. With a linear relationship between fuel burn and emissions, [2], the emission benefits of continuous descents are clear.

Previous studies have shown that CDOs can have beneficial effects on fuel consumption when compared to conventional approaches as they are predominantly flown at the moment. In 2000, Wubben and Busink performed flight experiments with Boeing 747-400 and Boeing 737-300 aircraft, in which a CDO procedure was implemented from 7,000 ft until the Instrument Landing System (ILS) intercept point [3]. Using on-board fuel flow data, fuel benefits of 161 - 407 kg for Boeing 747-400 aircraft, and 43 - 55 kg for Boeing 737-300/400 aircraft were found on average. Clarke et al. performed CDO flight experiments using Boeing 767-300 aircraft in 2004 [4]. Here, flight recorder data revealed that when flying a CDO from an altitude of 11,000 ft, aircraft consumed 181-226 kg of fuel less than aircraft flying a conventional approach. And in 2010, Turgut, Usanmaz, Canarslanlar and Sahin implemented partial CDO procedures in which the level flight segments during the approach phase were still there, but at a higher altitude [5]. By moving level segments from 3,000 ft to 8,000 ft, FMS data from a Boeing 757 showed fuel benefits of up to 44 kg. These studies had the resources to fly conventional approaches and CDOs and to compare FMS data from both flights to determine fuel savings.

However, performing flight experiments is an expensive process, and results from individual aircraft types do not necessarily extrapolate to other aircraft. In the flight experiments performed by Sprong, Klein, Shiotsuki, Arrighi and Liu in 2008, FMS data was not available and thus the fuel benefits of implementing a CDO procedure needed to be calculated [6]. Using recorded radar track data of non-CDOs and of CDO demonstration flights, the fuel burn was modeled using Eurocontrol's Base of Aircraft Data (BADA) 3.5. The study estimated fuel benefits of 114 kg per flight for Boeing 767 aircraft and 146 kg per flight for Boeing 757 and Boeing 737-800 aircraft. And finally Cao, DeLaurentis and Sun used radar track data to simulate CDOs using the NASA Future ATM Concepts Evaluation Tool (FACET) and estimated fuel burn using a corrected thrust-specific fuel consumption (TSFC) model which is based on BADA 3.9 [7]. Cao et al. used the ground tracks from radar data, and changed the vertical profiles to create comparable CDOs per flight to find average fuel benefits of 160 kg per flight.

The aim of the current paper is to investigate the potential benefits of 100% CDO operations at Schiphol International Airport, by comparing historical flight data to simulated continuous descents of those same flights for an entire year. Similar analyses have been performed previously for (constrained) continuous descents [8], [9], and for en-route speed absorption [10]. The analysis is done for the year 2015. For this year, Aircraft Condition Monitoring System (ACMS) on-board data was made available by the Royal Dutch Airline KLM, for several aircraft types whose flights make up a large portion of the arrivals at Schiphol in this year. To analyze flights for which this data was not available, ADS-B data was collected. For flights that are not available from either source, statistics from the Schiphol annual traffic review [11] will be used to extrapolate results to all flights.

The remainder of this paper is structured as follows: First, Sec. II describes how fuel usage is calculated using BADA. Sec. III describes the simulation set-up, and results are presented in Sec. IV. The paper concludes with a discussion and conclusions.

II. CALCULATING FUEL CONSUMPTION

In this study, CDOs are not actually flown but simulated based on historical flights. For these flights, as well as for the ADS-B-based historical flights, fuel consumption will have to be calculated. Similar to previous studies such as Sprong et al. [6] and Cao et al. [7], fuel consumption will be determined by integrating fuel flow over time, using aircraft performance coefficients from Base of Aircraft Data (BADA) 3.12 [12], [13]. Here, fuel flow is calculated as a function of thrust:

$$\begin{aligned} f &= \eta \cdot Thr \\ \eta &= C_{f1}\left(1+\frac{V_{TAS}}{C_{f2}}\right), \end{aligned}$$

where η is the thrust-specific fuel consumption, which in turn is specified as a function of true airspeed V_{TAS} and BADA fuel coefficients C_{f1} and C_{f2}. Thrust is obtained by integrating the total energy equation:

$$Thr = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{d}t} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{d}t} + D$$

Here, m is aircraft mass, $g_0 = 9.80665 m/s^2$ is the gravitational acceleration, h is aircraft altitude, and D is aircraft aerodynamic drag, which can also be calculated using aircraft coefficients provided by BADA. For KLM aircraft where on-board data is available, ACMS data is used, which provides the required true airspeed, aircraft mass, and actual atmospheric conditions. For ADS-B-based historical flights, BADA's reference mass is used, ISA conditions are assumed, and true airspeed is considered to be equal to groundspeed.

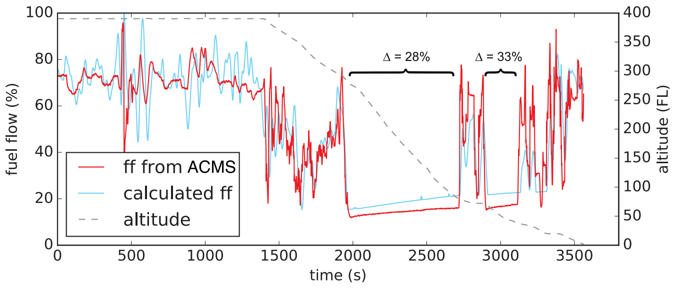

Fig. 1. Original BADA vs ACMS fuel flow.

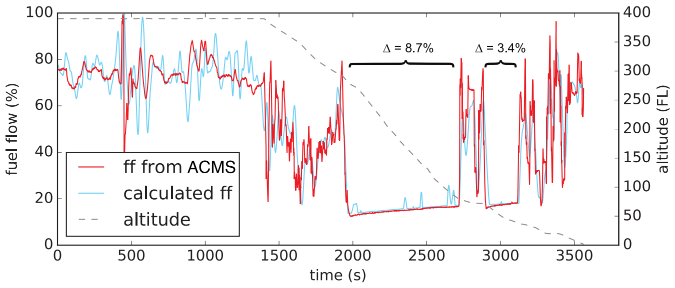

Fig. 2. Calibrated BADA vs ACMS fuel flow.

For flights where ACMS data is available, calculated fuel consumption can be validated, and BADA coefficients can be adjusted to increase the accuracy of the fuel consumption calculations for the simulated CDOs. To illustrate, Figures 1 and 2 show an example of measured and calculated fuel flow for the original and corrected coefficients, respectively. In Figure 1 it can be seen that for the fuel flow simulated with the unmodified BADA coefficients, the instantaneous error increases up to 28% and 33% of the actual fuel flow. To adjust the coefficients per flight, a calibration is done by calculating the error between the BADA fuel flow calculations and the actual fuel flow. This error is minimized using a GRG non-linear solver [14] to calibrate the BADA coefficients. With the corrected coefficients, the average fuel flow error is reduced to $< 4\%$. For ADS-B flights, unmodified BADA coefficients are used.

III. SIMULATION SET-UP

To analyze the fuel and emission benefits for a year of arrivals at Schiphol airport, a comparison is made between recorded historical flights, and a series of simulated CDO profiles for each flight. CDOs are considered as idle descents, with a fixed Flight Path Angle (FPA).

A. Data

From the Schiphol Traffic Review 2015 [11], the number of arrivals per aircraft type can be determined for Schiphol in 2015, see Table I. For these arrivals, two types of historical data are used in this study. For KLM aircraft where on-board data is available, ACMS data is used. For other aircraft, ADS-B data is used. Two aircraft types from the Schiphol traffic review are excluded during the study. The Dash 8-400 is the only aircraft with propeller engines and no data was available for the McDonnell Douglas MD-11 which lead to their exclusion. For the remaining flights without data, average results are extrapolated to obtain annual fuel saving results for Schiphol.

B. Approach

In this study, 25 CDO profiles are determined per historical flight with FPA values varying linearly from $-4°$ to $-1.6°$. The CDO profile with the maximum fuel benefit is stored as the fuel-optimal CDO flight for the corresponding historical flight. This fuel-optimal CDO flight is then compared against the actual flight in terms of fuel consumption[1]. This process is visualized in Figure 3. As can be seen in this figure, fuel consumption is calculated for both the historical flight and the simulated CDO flight. For the historical flights for which ACMS data is available the actual fuel consumption is known, however the fuel consumption is calculated for these flights as well to account for any bias produced by the fuel consumption calculations. The difference in fuel consumption between the actual approach and the fuel-optimal CDO for the same flight is used to calculate fuel and emission benefits.

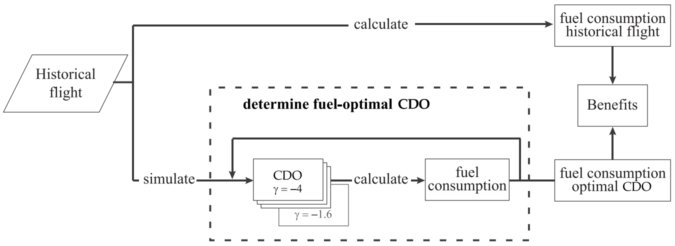

Fig. 3. Fuel benefit calculation

In order to obtain annual fuel saving results for Schiphol, average fuel savings per aircraft type from the available historical flights are used to determine an estimate of the total fuel savings per aircraft type. This estimate is done by extrapolating these averages with the total descents per aircraft type at Schiphol as given by the Schiphol Traffic Review 2015 [11]. In this extrapolation, the aircraft types analyzed in this study account for 98% of the arrivals at Schiphol in 2015. 45% of the arrivals are aircraft types for which ACMS data is available and for 53% of the arrivals are aircraft types for which ADS-B data is available.

---

[1] Note that the true optimal idle descent can be one where the flight-path angle is not constant. The difference, however, is small, and for operational reasons constant flight-path angle descents are often preferred.

TABLE I
NUMBER OF DESCENTS AT SCHIPHOL IN 2015 AND NUMBER OF HISTORICAL FLIGHTS ANALYZED

Aircraft type	**# Total**	**# Analyzed**
ACMS flights		
Airbus A330-200	5264	1543
Airbus A330-300	4952	1045
Boeing 737-700	20257	10839
Boeing 737-800	45139	9995
Boeing 737-900	4746	2207
Boeing 747-400	9443	4372
Boeing 777-200	7756	3274
Boeing 777-300	4160	1739
ADS-B flights		
Airbus A300	465	173
Airbus A318	646	107
Airbus A319	15836	2473
Airbus A320	23664	4327
Airbus A321	4913	1009
Airbus A340-300	541	135
Airbus A380	494	180
Bae 146/AVRO RJ	2521	509
Boeing 737-300	1269	272
Boeing 737-400	265	40
Boeing 737-500	755	191
Boeing 737-600	392	88
Boeing 747-8	736	220
Boeing 757-200	1302	235
Boeing 767-300	2757	745
Boeing 767-400	856	255
Boeing 787-8	1157	219
Bombardier CRJ 700/900/1000	1985	554
Embraer 170/175	3383	730
Embraer 190/195	34157	4591
Embraer EMB 120	198	31
Embraer ERJ 145	1663	295
Fokker 100	1103	147
Fokker 70	17616	2328

C. Metrics

The main output of the simulations are the *fuel benefits from fuel-optimal CDOs*. The size of the fuel benefits depends on the efficiency of each historical flight. If the historical flight has many level segments with high fuel consumption after Top of Descent (ToD), the amount of fuel saved by the fuel-optimal CDO with respect to the historical flight will be high. On the other hand, if the historical flight has an efficient descent, the amount of fuel saved by the fuel-optimal CDO will be small. Fuel benefits of optimal CDOs are also compared to a reference three-degree CDO. In addition, the optimal descent angle is determined per aircraft type. Flight duration offset is determined as a metric for the possible planning penalty of flying a CDO, and to investigate the operational feasibility of flying 100% fuel-optimal CDOs.

IV. RESULTS

Results are presented in terms of fuel savings of the optimal CDO profile per observed aircraft type, with corresponding flight path angles, and additional time flown. In addition, the fuel-optimal CDOs are compared to a reference, three degree (idle) descent. To conclude, the yearly fuel and emission benefits are presented.

A. Fuel-optimal CDO profiles

Fuel benefits are calculated per aircraft type, by simulating 25 constant-FPA idle descent profiles, and selecting the fuel-optimal CDO, and comparing that to each original flight. Figures 4 and 5 give two examples of fuel-optimal CDO profiles.

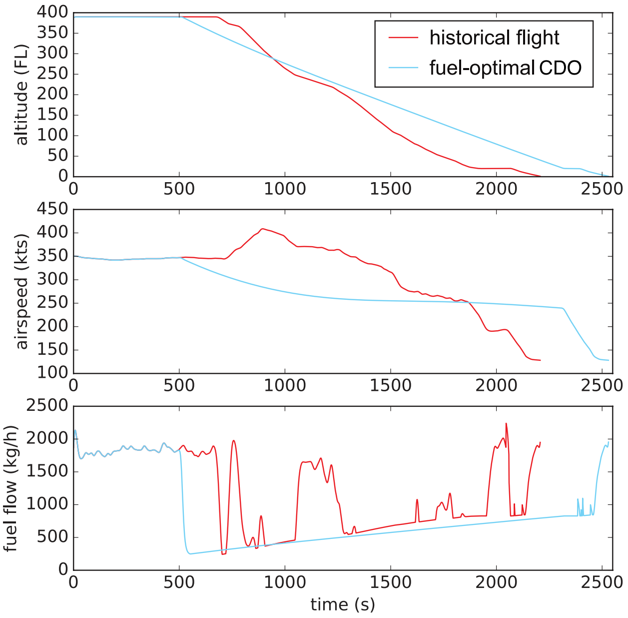

Fig. 4. Fuel-optimal CDO vs historical flight with CDO top of descent before historical top of descent

As can be seen in Figure 4, for this particular flight the CDO top of descent is located at an earlier moment than the original top of descent. For the flight shown in Figure 5 however, the top of descent is located after the original top of descent. This difference with previous studies is caused by the fact that CDOs selected for fuel optimality employ shallower descent angles, and as such, can result in earlier descents than the original flight. The shift in top of descent also depends on the number of level segments, i.e., the inefficiency of the historical flight. If there are a lot of level segments in the historical flight, even if the FPA of the fuel-optimal CDO is shallower than the FPA of the descent segments of the conventional approach, the CDO top of descent will be located after the historical top of descent.

For both flights, the CDO flight duration is longer than the historical flight duration. The extra flight time is caused by a reduced average airspeed after top of descent, resulting from the shallow descent angle in combination with idle thrust. In the CDO flights it is clearly visible that from top of descent onwards, the fuel flow remains at a minimum until the aircraft reaches the Final Approach Fix (FAF). From there on the fuel flow is exactly the same as the original fuel flow. In the

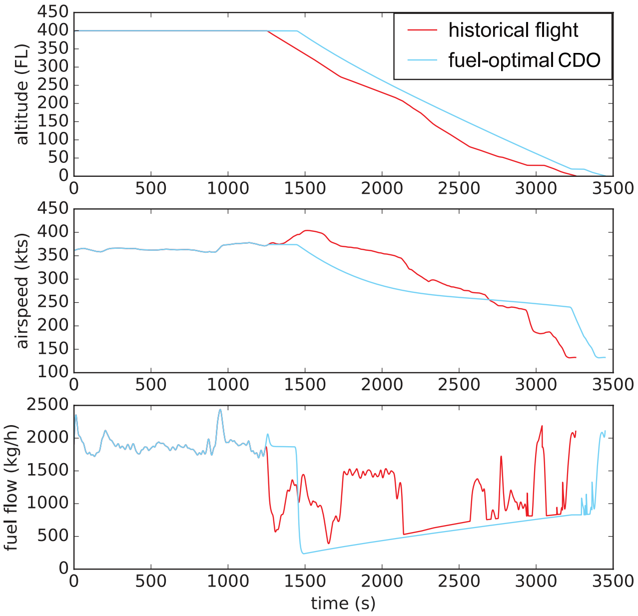

Fig. 5. Fuel-optimal CDO vs historical flight with CDO top of descent after historical top of descent

historical flight, there are some small level segments after top of descent, where the fuel flow is high as can be seen from the peaks in the historical fuel flow values. Therefore, even though the CDO flight has a longer flight duration compared to the historical flight, the CDO flight still has a lower fuel consumption at the end of the flight. The CDO flights in Figures 4 and 5 respectively save 144kg and 141kg of fuel per flight.

B. FPAs of fuel-optimal CDOs

As shown in Figure 3, 25 CDOs using different FPAs are simulated for each flight. The CDO flight with the maximum fuel benefits is saved as the fuel-optimal CDO flight. The FPAs for the fuel-optimal CDOs per aircraft type are given in Figures 6 and 7. Here, it can be observed that for some aircraft types, the lower quartile, the median and the upper quartile fall together. This is the case for several aircraft types, and indicates that at least 50% of the flights for these aircraft types have a fuel-optimal CDO with the same FPA. And for some of these aircraft types, the quartiles and medians fall together with the maximum FPA for the aircraft type. This means that at least 75% of the flights for these aircraft types have a fuel-optimal CDO with the same FPA. Another observation is that for nearly all aircraft types, the fuel-optimal CDO has an FPA which is smaller than the reference 3° FPA. Only for the B747-400, the lower quartile and the median FPA value is precisely 3°, which is the steepest fuel-optimal FPA of all aircraft types.

C. Flight duration

Since the speed profile of the original flight is adapted to a fuel-optimal profile the flight duration of the fuel-optimal CDO is not the same as the flight duration of the original flight. In the examples given in Section IV-A, the durations of the CDO flights are longer than the durations of the original flights. The flight durations from the CDO flights relative to historical flights can be found in Figures 8 and 9 per aircraft type.

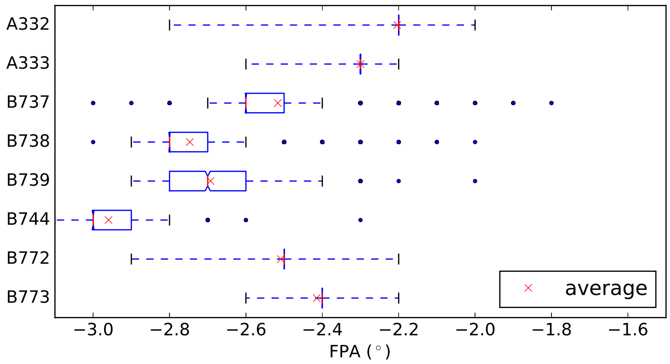

Fig. 6. Fuel-optimal CDO FPAs per ACMS aircraft type

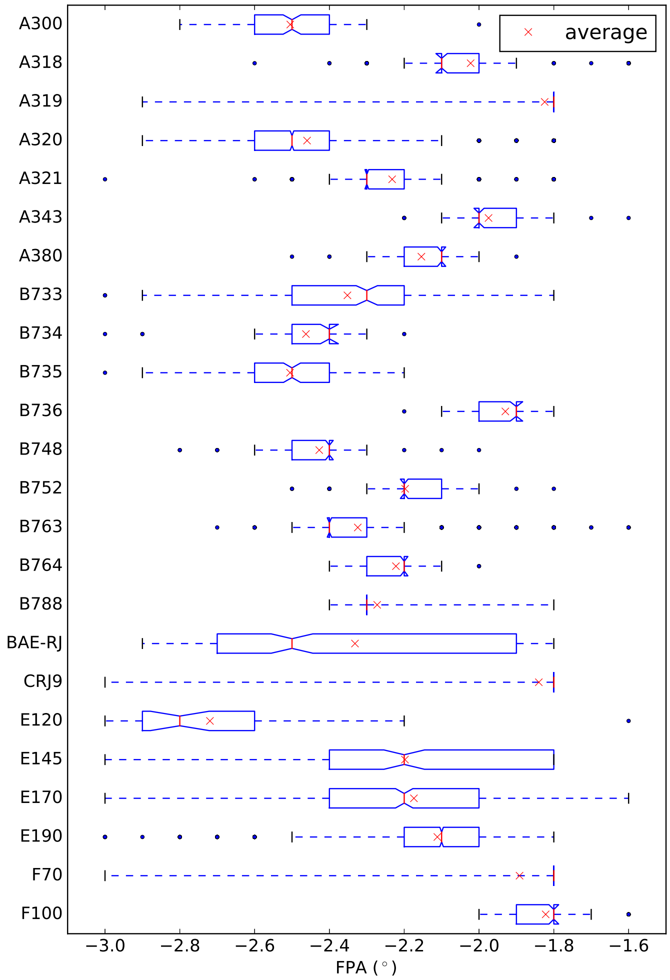

Fig. 7. Fuel-optimal CDO FPAs per ADS-B aircraft type

As can be seen from these results, not all CDO flights have a longer flight duration. However the majority of the CDO flights do require a longer flight time compared to the original flight. For all aircraft, the flight duration of the fuel-optimal CDO varies from 5 minutes less than the original flight to over 12 minutes more than the original flight. The majority of the simulations using ACMS data result in fuel-optimal CDOs that are a minute faster to 5 minutes slower than the original flight. The relative flight duration averages of fuel-

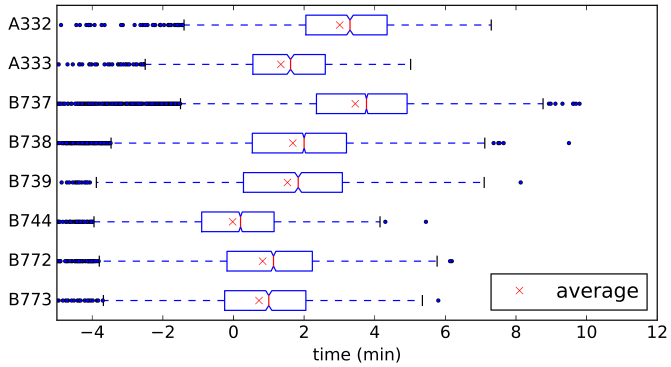

Fig. 8. CDO flight duration relative to historical flights per ACMS aircraft type

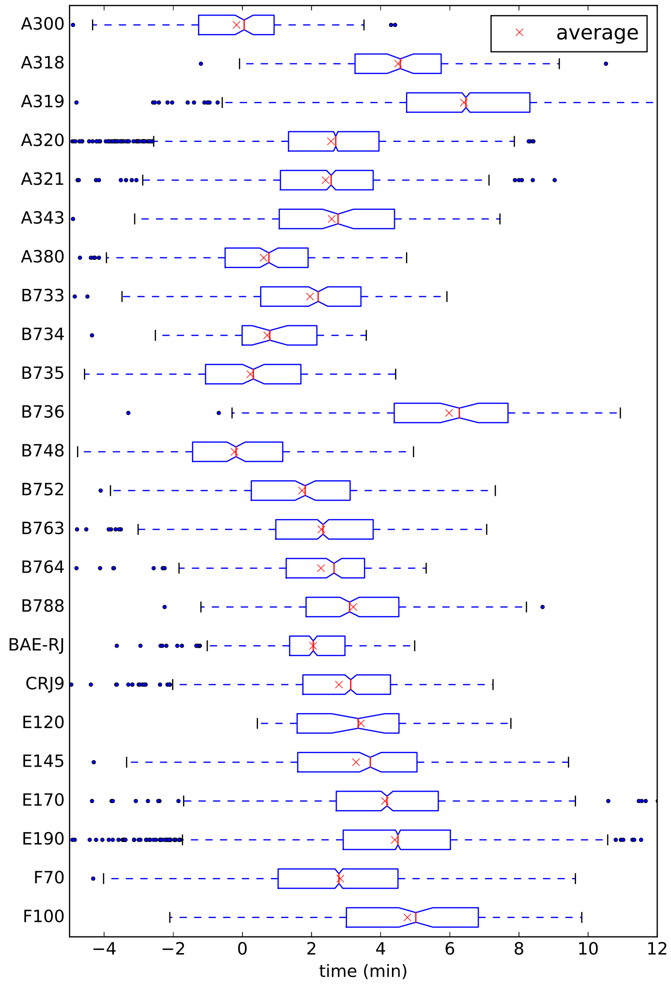

Fig. 9. CDO flight duration relative to historical flights per ADS-B aircraft type

optimal CDOs for all aircraft are between 14 seconds faster and 6.4 minutes slower. For fuel-optimal CDO flights where the flight duration was shorter than the historical flight, the original flights contained large level segments at a relatively low speed. In these cases, the fuel-optimal CDO profile has a longer cruise phase, maintaining a higher airspeed for a longer time, resulting in a faster, and thus shorter, flight.

Figures 8 and 9 also show differences between aircraft types in CDO flight duration relative to historical flights. The differences between different aircraft models can be explained by the fact that each aircraft type has a different FPA for their respective fuel-optimal CDO. The different FPAs result directly in longer or shorter descents. Furthermore, each aircraft type has different optimal cruise altitudes and speeds and different FAF speeds. Due to these differences in initial conditions and final conditions between aircraft types, the shift in flight duration is different for each aircraft type as well.

D. *Fuel benefits from fuel-optimal CDOs*

The fuel benefits per flight from the fuel-optimal CDOs relative to historical flights, sorted per aircraft type can be found in Figures 10 and 11. Here, it is clear that the medians are shifted slightly to the left of the average. The medians are shifted, because the averages include the outliers visible in the boxplots in Figures 10 and 11. The results thus have a skewed distribution. This is due to the fact that the fuel savings per flight depend on multiple factors such as cruise altitude, cruise speed, FAF speed, mass and of course the efficiency of the descent in the historical flight itself, i.e., whether or not the historical flight had large segments of level flight with high fuel flow. This also explains the difference in fuel savings between aircraft types seen in the figures. This is influenced by the same factors and additionally also the fact that different aircraft types have different aerodynamic properties. Furthermore, large aircraft types require more thrust than small aircraft types, therefore the absolute savings for larger aircraft types will also be larger. Due to these influences, the results for the aircraft types using ACMS data are expected to be more accurate than the results for the aircraft types using ADS-B data. However, when comparing the fuel savings results of the Boeing 737s between the ACMS aircraft types and the ADS-B aircraft types it can be seen that the results are quite comparable: the ACMS Boeing 737s have average savings between 123 - 139 kg, and the ADS-B Boeing 737s have savings between 122 - 172 kg, which indicates that the ADS-B fuel savings for the B737s are quite accurate as well. The same goes for the Boeing 747s. For the aircraft types that were analyzed using ACMS data, the smallest relative savings are found for the Boeing 737 aircraft, specifically the 737-900. The savings vary from 2 - 253 kg with a median of 123 kg per flight. The largest savings are found for the Boeing 747-400 aircraft with savings between 79 and 1023 kg with a median of 486 kg. For the aircraft types which were analyzed using ADS-B data, the smallest relative savings are found for the Bae 146/AVRO RJ aircraft, with savings varying between 39 - 165 kg with a median of 83 kg per flight. The largest savings are found for the Airbus A380, with savings varying from 402 - 1430 kg with a median of 951 kg.

E. *Comparison to the reference CDO*

Besides the fuel benefits from the fuel-optimal CDOs, the simulation also generates fuel benefits for a 3° CDO. The fuel benefits relative to the historical flights for the fuel-optimal CDO and the 3° reference CDO for the Boeing 737-700 are depicted in Figure 12.

Figure 12 shows generally the same distribution of fuel benefits for all the CDOs. However, the 3° CDO clearly results in lower fuel benefits than the fuel-optimal CDO. This is to be

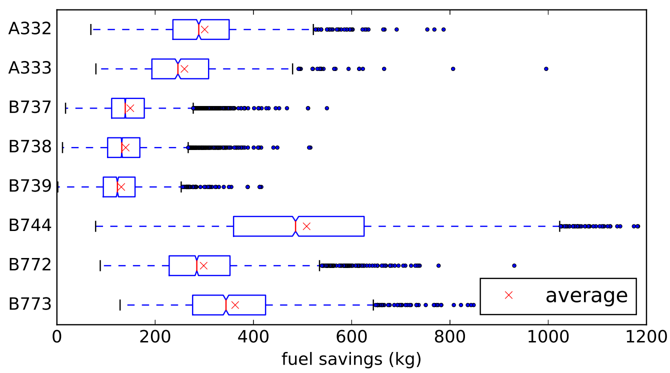

Fig. 10. Fuel benefits for fuel-optimal CDOs relative to historical flights per ACMS aircraft type

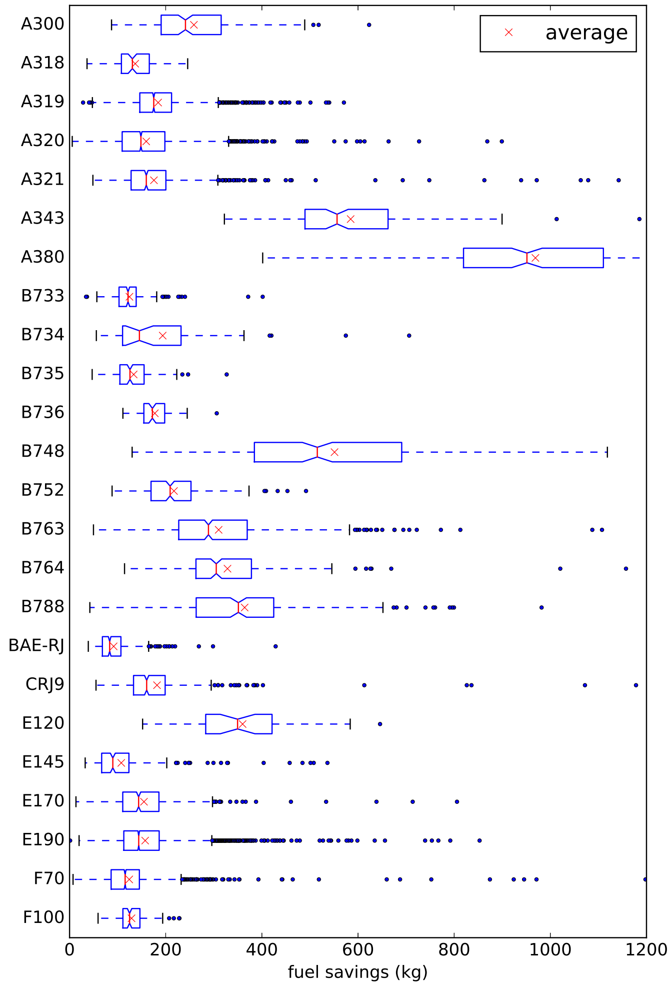

Fig. 11. Fuel benefits for fuel-optimal CDOs relative to historical flights per ADS-B aircraft type

expected since the FPAs for the fuel-optimal CDOs of nearly all aircraft types are shallower than 3°. This automatically means that the 3° CDO will thus result in lower fuel benefits for all aircraft types since the 3° FPA is included in in the fuel-optimal CDO simulation, as explained in Figure 3, but has apparently been rejected as the most fuel saving CDO.

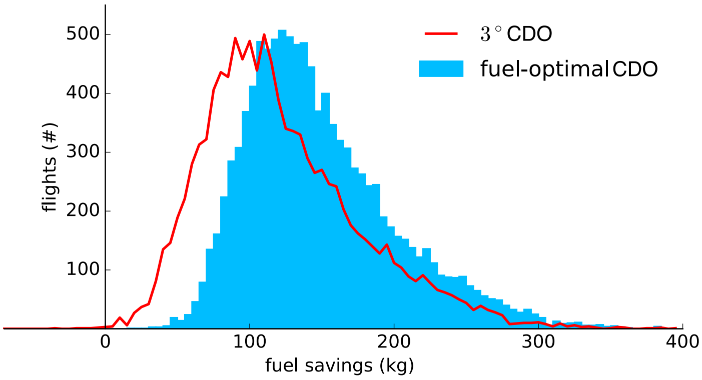

Fig. 12. Fuel benefits for B737 relative to historical flights

For the B747-400 the fuel benefits of the fuel-optimal CDO are nearly equal to the fuel benefits of the 3° CDO, as can be seen in Figure 13. This is due to the fact that most fuel-optimal CDOs for the B747-400 have a 3° FPA as seen in Figure 6.

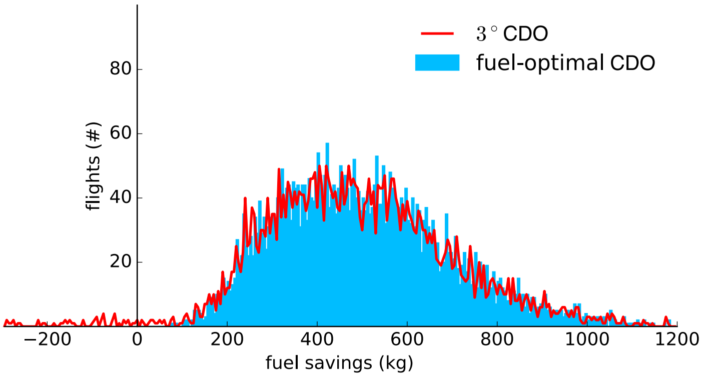

Fig. 13. Fuel benefits for B744 relative to historical flights

F. *Yearly fuel and emission benefits for Schiphol*

Table II presents the total fuel benefits per aircraft type for the year 2015. This value is calculated by multiplying the number of descents per aircraft type given in Table I with the median of the fuel benefits per aircraft type.

In the ACMS data, the fuel consumption of the entire flight is available. This allows the benefits to be expressed in percentages or in how many flights the benefits equate to. The Airbus A330s are long range aircraft with fuel consumption values per flight between $28 \cdot 10^3$ kg and $60 \cdot 10^3$ kg. The fuel benefits of the Airbus A330s alone account for 2.7 million kg. This corresponds to a fuel consumption reduction of 0.45% - 0.96% which equates to 46 - 98 A330 flights per year. The Boeing 737s are short range aircraft with fuel consumption values per flight between 1200 and 9600 kg. The fuel benefits of all the Boeing 737s from ACMS data sum up to 9.4 million kg. This would mean a fuel consumption reduction between 1.4% and 11% which equates to 975 - 7802 B737 flights. In the same manner the Boeing 777s result in 0.3% to 1.3% fuel consumption reduction which equates to 33 - 152 flights. And finally the Boeing 747-400 has a fuel consumption reduction of 0.12% - 1.6% which equates to 12 - 153 flights worth of B744 flights.

If the yearly benefits per aircraft type are all added up, the fuel benefits for 98% of the aircraft landing at Schiphol

TABLE II
EXTRAPOLATED YEARLY FUEL BENEFITS PER AIRCRAFT TYPE

Aircraft type	**yearly fuel benefits** (10^6**kg**)
ACMS flights	
Airbus A330-200	1.52
Airbus A330-300	1.22
Boeing 737-700	2.82
Boeing 737-800	5.96
Boeing 737-900	0.58
Boeing 747-400	4.59
Boeing 777-200	2.21
Boeing 777-300	1.43
ADS-B flights	
Airbus A300	0.11
Airbus A318	0.08
Airbus A319	2.77
Airbus A320	3.51
Airbus A321	0.78
Airbus A340-300	0.30
Airbus A380	0.47
Bae 146/AVRO RJ	0.21
Boeing 737-300	0.15
Boeing 737-400	0.04
Boeing 737-500	0.09
Boeing 737-600	0.07
Boeing 747-8	0.38
Boeing 757-200	0.27
Boeing 767-300	0.80
Boeing 767-400	0.26
Boeing 787-8	0.41
Bombardier CRJ	0.32
Embraer 170/175	0.49
Embraer 190/195	4.91
Embraer EMB 120	0.07
Embraer ERJ 145	0.15
Fokker 100	0.14
Fokker 70	2.04

International Airport for the year 2015 are found. Adding up all the savings per aircraft type results in fuel benefits of $39.2 \cdot 10^6$ kg, which corresponds to $1.23 \cdot 10^5$ metric tonnes of CO_2 . That is 338 tonnes of CO_2 per day that can be saved. With 58.2 million passengers in 2015 [11], this results in 2.12 kg of CO_2 savings per passenger.

V. DISCUSSION AND CONCLUSIONS

The aim of this study is to investigate the benefits in terms of fuel and emission savings of a hypothetical scenario of 100% continuous descent operations at Schiphol airport. A comparison was made between historical flights for the entire year 2015, with a set of different idle descents with varying descent angles. When compared with previous studies, it can be seen that on average, the findings of this study are in agreement with previous observations. The differences that do exist can be explained by the differences in the CDO implementations. First, in the previous studies, CDOs are either limited to start between 7,000 and 11,000 ft, whereas in the current study CDOs are not limited, and start at cruise altitude. Also, in previous work, CDOs could be performed with non-idle thrust from cruise altitude, whereas the current study only analyzes idle thrust CDOs. It is therefore to be expected that the savings found in this study are larger than the savings found in previous studies. This is the case for all aircraft types except for the B738 + B757 combination from Sprong et al. [6]. This can be explained by the fact that the savings found by Sprong et al. are combined savings, where the B738 has smaller savings on average than the B757. Nevertheless, for this study it should be noted that a comparison was made against historical data, which also contains a proportion of idle descents. Because of this, the benefits presented in this study would come on top of the improvements already achieved by the (night time) continuous descent operations.

In this study, a fuel-optimal flight path angle (FPA) was selected for each continuous descent. As a result, descent profiles for most aircraft were relatively shallow, and added flight time could be significant. In practice, these delays also have a cost for airliners, and in addition will have an impact on the predictability of the flights, and the capacity of the runway. A more realistic scenario could for instance be to implement a common, and possibly steeper CDO such as the reference 3° CDO that was used in this paper. In previous studies there is some variability with regard to the steepness of the descent. Some studies [3] [7] adopted a 3° glideslope, and Clarke et al. [4] chose a 2° FPA. These, and other efficiency and also safety-related aspects will have to be taken into consideration when CDO's are to be implemented on a large scale.

For this study the influence of the lateral path of the flight is neglected. For all aircraft analyzed in this study only the altitude and speed profiles vs. along track distance to the runway are analyzed. This makes it possible to compare all aircraft landing at all runways at Schiphol. However, this also means that even though the actual approach may include extra horizontal segments, the CDO profile will also follow this prolongated lateral path. This will have consequences for the feasibility of the CDO. For future studies it is recommended to analyze whether a shorter lateral path would have been possible and whether this might have allowed the CDO flight to arrive at the same time as the original flight without creating new conflicts.

To put the potential environmental benefit of 100% CDO into perspective; the Environmental Sciences Division of the Oak Ridge National Laboratory [15] states that the world CO_2 output amounts to $35.849 \cdot 10^9$ tonnes and the CO_2 output from the Netherlands $169.97 \cdot 10^6$ tonnes. The CO_2 savings found in this study thus account for 0.07% of the total CO_2 output of the Netherlands. The Environmental Sciences Division [15] also states that the transport section in the Netherlands accounts for 20.4% of its total CO_2 output. This brings the CO_2 savings of this study to 0.36% of the CO_2 emissions from the transport sector. For 2020, the Dutch government has targeted to have 16% less CO_2 emissions compared to the year 2005 [16]. This equates to about $13 \cdot 10^6$ tonnes of CO_2 reduction. By implementing CDOs at Schiphol, 0.9% of this reduction could be achieved.

REFERENCES

[1] Eurocontrol, IATA, CANSO, and ACI, "Continuous descent - a guide to implementing continuous descent," Brussel, 2011. [Online]. Available:

http://www.eurocontrol.int/articles/continuous-descent-operations-cdo

[2] D. J. Sutkus, S. L. Baughcum, and D. P. DuBois, "Scheduled civil aircraft emission inventories for 1999: Database development and analysis," National Aeronautics and Space Administration, Technical Report NASA/CR-2001-211216, Oct 2001. [Online]. Available: http://ntrs.nasa.gov/search.jsp?R=20020012699

[3] F. J. M. Wubben and J. J. Busink, "Environmental benefits of continuous descent approaches at schiphol airport compared with conventional approach procedures," *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, vol. 2000, no. 8, pp. 1355–1361, 2000. [Online]. Available: http://ince.publisher.ingentaconnect.com

[4] J. P. B. Clarke, N. T. Ho, L. L. Ren, J. A. Brown, K. R. Elmer, K. O. Tong, and J. K. Wat, "Continuous descent approach: Design and flight test for louisville international airport," *Journal of Aircraft*, vol. 41, no. 5, pp. 1054–1066, 2004.

[5] E. T. Turgut, O. Usanmaz, A. O. Canarslanlar, and O. Sahin, "Energy and emission assessments of continuous descent approach," *Aircraft Engineering and Aerospace Technology*, vol. 82, no. 1, pp. 32–38, 2010.

[6] K. R. Sprong, K. A. Klein, C. Shiotsuki, J. Arrighi, and S. Liu, "Analysis of aire continuous descent arrival operations at atlanta and miami," *Dasc: 2008 Ieee/Aiaa 27th Digital Avionics Systems Conference, Vols 1 and 2*, pp. 486–498, 2008.

[7] Y. Cao, D. DeLaurentis, and D. F. Sun, "Benefit and trade-off analysis of continuous descent approach in normal traffic conditions," *Transportation Research Record*, no. 2325, pp. 22–33, 2013.

[8] P. Melby and R. Mayer, "Benefit potential of continuous climb and descent operations," in *The 26th Congress of ICAS and 8th AIAA ATIO*, 2008.

[9] J. E. I. Robinson and M. Kamgarpour, "Benefits of continuous descent operations in high-density terminal airspace considering scheduling constraints," in *Proceedings of the 10th AIAA aviation technology, integration, and operations (ATIO) conference*. AIAA, 2010, Conference Paper.

[10] D. Knorr, X. Chen, M. Rose, J. Gulding, P. Enaud, and H. Hegendoerfer, "Estimating atm efficiency pools in the descent phase of flight," in *Proceedings of the Ninth USA/Europe Air Traffic Management Research and Development Seminar*, Berlin, Germany.

[11] B. V. Schiphol Nederland, "Traffic review 2015," Report, Feb 2016. [Online]. Available: http://www.schiphol.nl/SchipholGroup/Company1/Statistics.htm

[12] A. Nuic, D. Poles, and V. Mouillet, "Bada: An advanced aircraft performance model for present and future atm systems," *International Journal of Adaptive Control and Signal Processing*, vol. 24, no. 10, pp. 850–866, 2010.

[13] A. Nuic, "User manual for the base of aircraft data (bada) revision 3.12," EUROCONTROL Experimental Centre, EEC Technical/Scientific Report 14/04/24-44, Aug 2014.

[14] L. S. Lasdon, R. L. Fox, and M. W. Ratner, "Nonlinear optimization using the generalized reduced gradient method," *Revue française d'automatique, d'informatique et de recherche opérationnelle. Recherche opérationnelle*, vol. 8, no. 3, pp. 73–103, 1974. [Online]. Available: http://www.numdam.org/item?id=RO_1974__8_3_73_0

[15] Carbon Dioxide Information Analysis Center, "Co2 emissions," 7 Nov 2016. [Online]. Available: http://data.worldbank.org/indicator/EN.ATM.CO2E.KT

[16] J. Atsma, "Kabinetsaanpak klimaatbeleid op weg naar 2020," 2011. [Online]. Available: https://www.rijksoverheid.nl/onderwerpen/klimaatverandering/documen-ten/kamerstukken/2011/06/08/kabinetsaanpak-klimaatbeleid-op-weg-naar-2020