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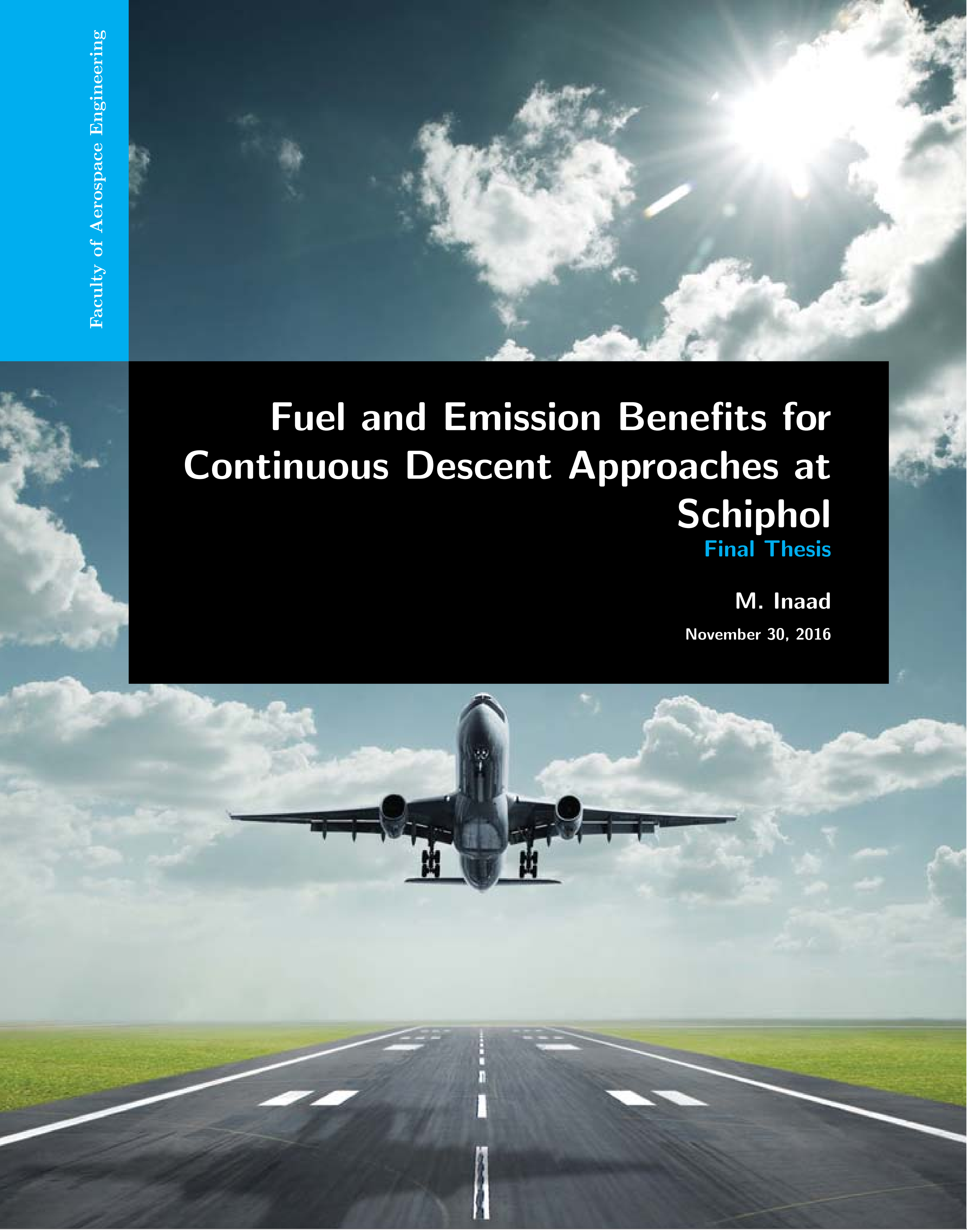

Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol

Final Thesis

M. Inaad

November 30, 2016

TU Delft
Delft University of Technology

Challenge the future

Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol

Final Thesis

Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering
at Delft University of Technology

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol"** by **M. Inaad** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Chapter 1

Introduction

Today, more people have taken to the skies than ever before. Meanwhile, governments have become more and more aware of the urgencies of climate change. In 2015 the 21'st Climate Change Conference, COP 21, was held. The main focus of this conference was to reduce the global greenhouse gas emissions. Just in October of 2016, during the ICAO gathering, the aviation industry agreed to reduce the CO_2 emissions of aircraft and to compensate for CO_2 emissions (Luchtvaartniews, 2016; Duursma, 2016) And so, as the skies around Amsterdam Schiphol Airport fill up, the Netherlands needs to decrease its greenhouse gas emissions.

Since the demand for air transportation is only expected to increase in the coming years (International Air Transport Association, 2013), solutions to decrease the greenhouse gas emissions are necessary for all stakeholders. One possible solution to reduce greenhouse gas emissions is to perform continuous descent operations (CDOs). The term CDO is interchangeable with continuous descent approach (CDA). "*Continuous Descent Approach is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and air traffic control (ATC) instructions*" (Eurocontrol, IATA, CANSO, & ACI, 2011). Figure 1-1 visualizes the difference between a CDA and a conventional approach.

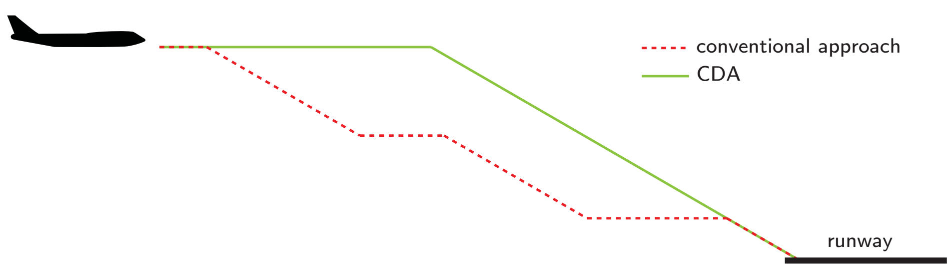

Figure 1-1: CDA vs conventional approach

In the past, CDA research was focused on noise abatement (Alders, 2013), however in recent years the focus has slowly shifted towards fuel and emission reduction research. These studies, however, were limited to certain aircraft types and to a small number of flights. For example, Wubben and Busink (2000) investigated CDAs at Schiphol airport with a focus on noise abatement. In their study the CDA procedure was started from an initial approach fix (IAF). Wubben's study shows promising results for fuel consumption reduction. And since emissions can be calculated as a linear function of fuel burn (Sutkus, Baughcum, & DuBois, 2001), fuel consumption reduction means emission reduction. So even though the number of flights per year increases, if the fuel consumption per flight can be reduced, the total emissions for a year need not increase at the same rate. Furthermore if the relative fuel consumption reduction is higher than the relative increase of number of flights, the absolute emission increase during descent to Schiphol Airport could be zero or even less, i.e. a decrease in emissions in areas around airports.

This project investigates the potential benefits of 100% CDA operations at Schiphol International Airport. At the moment only partial CDA operations are implemented which are limited to the night hours when the air traffic density is low. This is due to several factors. For example, each aircraft type has a different ideal CDA profile, there is a large dispersion of aircraft approach speeds (Wubben & Busink, 2000) and it is difficult for ATC to predict the aircraft behavior during CDAs. Due to this, aircraft are spaced further apart during CDA operations which decreases the capacity at an airport. However, several studies have been and are still being done to investigate how CDAs can be implemented during high traffic hours as well. This project only focuses on how much benefit there is to be obtained from CDA operations.

This is done by comparing the total fuel burned from cruise altitude or top of descent (ToD) to touchdown between aircraft flying a CDA and aircraft flying a conventional approach. In this study this is done for different aircraft types. An ideal CDA profile is calculated for historical flights by analyzing the total-energy model (TEM) provided by Base of Aircraft Data (BADA) 3.12. In order to simulate CDA profiles using historical data, this study has collected flight management system (FMS) data for a limited amount of aircraft types and Automatic Dependent Surveillance-Broadcast (ADS-B) data for the other aircraft types involved in this study. ADS-B is an on-board avionics function that automatically transmits, among other information, aircraft position data from the on-board navigation system, via a digital data link (Kayton & Fried, 1997). The transmitted data can be picked up by an ADS-B receiver. For this study ADS-B data was obtained by scraping data from Flightradar24 (Flightradar24, 2012-2016).

The results can be extrapolated to all aircraft landing at Schiphol airport for a whole year by using Schiphol Traffic Review (Schiphol Nederland, 2016). The results of this project may well influence the political decisions for Schiphol, since the impact of emission benefits are of utmost concern at the moment. At the least the Netherlands will have quantitative data on how much fuel and emissions can be saved by implementing CDAs at Schiphol.

This report is divided into three parts. The first part presents the main report of this study in the form of a paper. The second part presents the entire preliminary report. And finally the third part consists of appendices to the paper.

Part I

Paper

Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol

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Abstract

As the demand for air transportation increases, it becomes more and more challenging for the aviation industry to reduce its CO_2 impact. This paper presents the potential fuel and emission benefits of implementing continuous descent approaches (CDA) at Schiphol International Airport, from cruise altitude to the final approach fix, for a large scope of aircraft types. Using historical data from FMS and ADS-B, fuel-optimal CDAs are simulated using the total-energy model from BADA. By comparing the fuel consumption between the historical flight and the simulated CDA flight, 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.

I. INTRODUCTION

Today, more people have taken to the skies than ever before. Meanwhile, governments have become more and more aware of the urgencies of climate change. Since the demand for air transportation is only expected to increase in the coming years [1], solutions to decrease greenhouse gas emissions per flight are necessary for all stakeholders. One possible solution to reduce greenhouse gas emissions is to perform Continuous Descent Approaches (CDAs). Eurocontrol defines a CDA as an operation in which an "*aircraft descends from an optimal position with minimum thrust and avoids level flight segments*" [2]. Since emissions can be calculated as a linear function of fuel burn [3], fuel consumption reduction means emission reduction. So even though the number of flights per year increases, if the fuel consumption per flight can be reduced, the total emissions for a year need not increase, or at least not at the same rate. In this paper the fuel benefits of implementing CDAs are presented which are then used to calculate the emission benefits as described by Sutkus et al. [3].

Previous studies have shown that CDAs can have beneficial effects on fuel consumption when compared to the conventional approach as flown at the moment. In 2000, Wubben and Busink performed flight experiments with Boeing 747-400 and Boeing 737-300 aircraft in which a CDA procedure was implemented from 7000 ft until the Instrument Landing System (ILS) intercept point [4]. Using fuel flow data from the operational flight management system (FMS) data provided by Koninklijke Luchtvaart Maatschappij (KLM), 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 CDA flight experiments using Boeing 767-300 aircraft in 2004 [5]. The flight recorder data revealed that when flying CDA from an altitude of 11,000 ft, aircraft consumed 181-226 kg of fuel less than aircraft flying the conventional approach. And in 2010 Turgut, Usanmaz, Canarslanlar and Sahin implemented partial CDA procedures in which the level flight segments during the approach phase were still there, but at a higher altitude [6]. By moving the level segment from 3000 ft to 8000 ft, the FMS data from a Boeing 757 showed fuel benefits of up to 44 kg. These studies had the resources to fly conventional approaches and CDAs and to compare the FMS data from both flights to determine the fuel savings.

However, performing flight experiments is an expensive process and FMS data is not easily available. 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 CDA procedure needed to be calculated [7]. Using recorded radar track data of non-CDAs and of CDA 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 CDAs 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 [8]. Cao et al. used the ground tracks from the radar data and changed the vertical profiles to create comparable CDAs per flight to find average fuel benefits of 160 kg per flight. The results from previous studies are summarized in Table I.

TABLE I. RESULTS FROM PREVIOUS STUDIES

Study	Experiment	Fuel calculation method	Aircraft	Fuel benefits
Wubben et al. [4]	Flight experiments: CDA from 7000 ft	FMS data	Boeing 747-400 Boeing 737-300	161-407 kg 43-55 kg
Clarke et al. [5]	Flight experiments: CDA from 11,000 ft	FMS data	Boeing 767-300	181-226 kg
Turgut et al. [6]	Flight experiments: raise level segment from 3000 ft to 8000 ft	FMS data	Boeing 757	44 kg
Sprong et al. [7]	Flight experiments: CDA from ToD with non-idle descent segments to honor waypoint constraints	BADA using radar data	Boeing 767 40% Boeing 757 60% Boeing 737-800	114 kg 146 kg
Cao et al. [8]	Simulation using FACET: Optimized vertical profiles along same radar ground track	TSFC based on BADA using radar data	10,407 flights	160.22 ± 18.27 kg

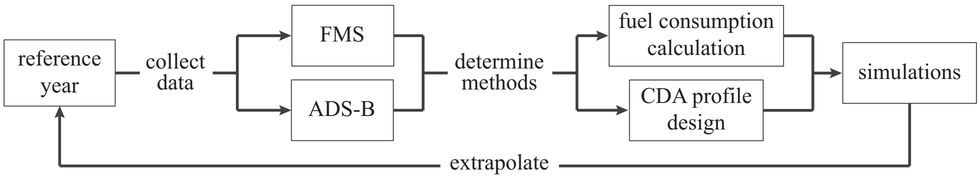

Fig. 1. Study set-up

This paper presents the results of investigating the potential fuel and emission benefits of 100% CDA operations at Schiphol International Airport. The goal of this paper is to contribute to the decision of implementing CDAs by determining how much fuel and emissions can be saved on a yearly basis if all aircraft arriving at Schiphol would implement CDAs. In order to reach this goal, two main questions need to be answered:

- What is the difference in fuel consumption between the conventional approach and CDA?
- What is a fuel saving CDA for aircraft arriving at Schiphol?

Figure 1 illustrates the steps taken to reach the goal of this study. To answer the main questions, the fuel consumption of aircraft needs to be calculated and a fuel saving CDA has to be designed. This paper presents how the BADA total-energy model is used to calculate the fuel consumption in Section II. Section III presents a CDA profile design method, which also uses the BADA total-energy model. Contrary to previous studies, the CDA presented in this paper is not limited and is implemented from cruise altitude. To calculate the fuel and emission benefit on a yearly basis, data is needed for a whole year. If data for a whole year is not available, the results need to be extrapolated for a whole year. The extrapolation is further discussed in Section IV. For this study, 2015 is chosen as its reference year for which the fuel and emission benefits are to be calculated. This has two reasons; first, 2015 is the last year for which Schiphol has released its yearly traffic review at the time of this study. This traffic review [9] will form the basis of the extrapolation for this study since data is not available for every flight landing at Schiphol. Second, FMS data is available for some aircraft types for a large portion of the historical flights from 2015. Contrary to most previous work, this study analyzes the benefits of implementing CDAs for multiple aircraft types. Therefore, to account for the aircraft types for which FMS data is not available, ADS-B data is collected.

II. Calculating fuel consumption

In this study, the CDAs are not actually flown but simulated based on historical flights. Therefore, accurate fuel consumption calculation is important for the significance of the results presented in this paper. The accuracy of fuel consumption calculation is limited by the data which is available for this study. ADS-B data only provides altitude, speed and time data whereas FMS data also provides mass, aircraft configuration and actual fuel consumption data. Base of Aircraft Data (BADA) provides a method with which the fuel consumption can be calculated for both data types used in this study. In many previous studies, such as those of Sprong et al. [7] and Cao et al. [8], fuel consumption is also calculated using BADA.

This section first describes the BADA fuel consumption calculations which are based on a kinetic approach to aircraft performance modeling [10]. This study uses BADA 3.12, which provides a set of ASCII files containing performance coefficients used to calculate thrust, drag and fuel flow [10], [11]. However, the BADA fuel calculation method also has some limitations due to assumptions made in the method. Therefore, this section ends with a discussion on the accuracy of the fuel consumption calculations.

A. Fuel consumption using BADA

The fuel consumption of a flight is calculated by integrating the fuel flow f of the aircraft over time. For jet engine aircraft, f depends on thrust. BADA uses a Total-Energy Model (TEM) which "*equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy*" [11]. This TEM can be used to calculate the thrust as given in Equation 1.

$$Thr = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{dt}} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} + D \tag{1}$$

$$\begin{aligned} Thr &= \text{thrust} \\ m &= \text{aircraft mass} \\ g_0 &= \text{gravitational acceleration} \\ V_{TAS} &= \text{true airspeed} \\ h &= \text{altitude} \\ \frac{\mathrm{d}}{\mathrm{dt}} &= \text{time derivative} \\ D &= \text{drag} \end{aligned}$$

For Equation 1, the aircraft mass is available when using FMS data. However, since this information is not available when using ADS-B data, the reference mass per aircraft type provided by BADA is used for these aircraft types. The gravitational acceleration is 9.80665 m/s^2. True airspeed is available in the FMS data. However, in the ADS-B data, ground speed is available instead of true airspeed. For the purposes of this study it is assumed that the ground speed is equal to true airspeed when using ADS-B data, i.e., it is assumed that there is no wind. Both data types provide altitude and time data. The values for $\frac{\mathrm{d}h}{\mathrm{dt}}$ and $\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}}$ are determined using the finite difference method and coefficients provided by Fornberg [12]. The only remaining unknown at this point is drag, which can be calculated using Equations 2 to 4 as a function of speed and altitude.

$$D = C_d \cdot \tfrac{1}{2}\rho V_{TAS}^2 \cdot S \tag{2}$$

$$\begin{aligned} C_d &= \text{drag coefficient} \\ \rho &= \text{air density} \\ S &= \text{wing reference area} \end{aligned}$$

The air density is calculated as a function of the altitude using an atmospheric model provided by BADA and the wing reference area is provided by BADA per aircraft type. Which only leaves the drag coefficient to be calculated using Equation 3.

$$C_d = C_{d_0} + k \cdot C_l^2 \tag{3}$$

C_{d_0} = zero lift drag coefficient
k = induced drag coefficient
C_l = lift coefficient

The values for the zero lift drag coefficient and the induced drag coefficient depend on the aircraft configuration. BADA provides these coefficients per aircraft configuration. Finally, the lift coefficient is then calculated as a function of mass, gravitational acceleration, air density, true airspeed and wing surface area using Equation 4.

$$C_l = \frac{m \cdot g_0}{\frac{1}{2}\rho V_{TAS}^2 \cdot S} \tag{4}$$

As mentioned before, for jet engine aircraft, the fuel flow f depends on thrust. In order to calculate the fuel flow, first the Thrust-Specific Fuel Consumption (TSFC), which depends on the airspeed as given in Equation 5, needs to be calculated.

$$\eta = C_{f1}\left(1 + \frac{V_{TAS}}{C_{f2}}\right) \tag{5}$$

η = thrust-specific fuel consumption
C_{f1} = TSFC coefficient 1
C_{f2} = TSFC coefficient 2

Here, C_{f1} and C_{f2} are coefficients provided by BADA. Fuel flow is a linear function of the TSFC value and thrust as given by Equation 6. BADA also defines a minimum fuel flow as a function of the height. In Equation 7, C_{f3} and C_{f4} are coefficients provided by BADA.

$$f = \eta \cdot Thr \tag{6}$$

$$f_{min} = C_{f3}\left(1 - \frac{h}{C_{f4}}\right) \tag{7}$$

f = fuel flow
f_{min} = minimal fuel flow
C_{f3} = fuel flow coefficient 1
C_{f4} = fuel flow coefficient 2

The fuel consumption during the flight is then calculated by integrating the fuel flow, calculated by Equations 6 and 7, over time.

B. Accuracy of calculations

BADA family 3 is limited by its "*requirement to keep the model algorithms simple because of limited computing capabilities*" and depends on the availability of high quality aircraft performance reference data [13]. Due to this, some assumptions are made to simplify the model algorithms. Alternative methods to calculate the fuel consumption would include working with non-linear tables or to use complete, non-linear, simulation models of aircraft types. However, non-linear tables and complete simulation models of aircraft types are not easily available and are quite costly. The BADA 4 family has a more complex model than the BADA 3 family, and also results in more accurate fuel consumption calculations [13]. However, at the moment BADA 4 only covers major airliners and is subject to strict licensing. So, despite its limitations, since this study aims to analyze many different aircraft types and multiple flights per aircraft type, BADA 3.12 offers the best method to calculate the fuel consumption for this study. But what is the effect of the limitations of BADA on the accuracy of the calculations? Since a large set of FMS data is available for this study, this provides essential insight into the accuracy of the calculations described in Section II-A. The FMS data can also be used to improve the accuracy of the calculations by calibrating the BADA coefficients.

Figure 2 shows the FMS data plotted alongside the results from the BADA calculations for an Airbus A330-200. For the A330-200, the fuel flow calculated with BADA has an average error of $< 9\%$. As can be seen in Figure 2, the BADA results follow the trend of the FMS fuel data, but has some inaccuracies especially in the minimal fuel flow values, where the error increases to 28% and 33% for the areas indicated in the figure. However since FMS data is available, the coefficients provided by BADA can be calibrated so as to minimize the error between the BADA calculations and the actual fuel flow value. The calibration is done by calculating the error between the BADA fuel flow calculations and the actual fuel flow value from the FMS. This error is minimized using a GRG non-linear solver [14] to calibrate the BADA coefficients. The results with the improved BADA coefficients can be found in Figure 3. The average fuel flow error is now $< 4\%$ and, as can also be seen in the figure, the inaccuracies in minimal fuel flow have now decreased from 28% and 33% to 8.7% and 3.4% respectively. By integrating the fuel flow over time, the fuel consumption (fburn) is found. The difference in fuel consumption error between the original BADA coefficients and the calibrated BADA coefficients for the A330-200 flight shown in Figures 2 and 3 can be found in Table II.

TABLE II. FUEL CONSUMPTION ERROR FOR ORIGINAL AND CORRECTED BADA COEFFICIENTS

	Original fburn error			**Corrected** fburn error		
A330-200	-38.5kg	±	26.0	-8.8kg	±	8.5
	-.074%	±	.050	-.017%	±	.016
B737-900	139kg	±	64.1	.65kg	±	3.73
	1.15%	±	0.51	.006%	±	.03

For other aircraft types, the original BADA coefficients have comparable results for the average fuel flow error as for the A330-200. This can be seen for example for the Boeing 737-900 shown in Figure 4 where the average fuel flow error is approximately 9%. In this case however, the error is mainly seen in the cruise phase where there is a constant offset between the actual fuel flow and the estimated fuel flow with an average error of nearly 14%. Again this can be corrected since the actual FMS data is available. By calibrating the coefficients, as explained for the A330-200, the error is significantly reduced to an average $< 2\%$ over the entire flight and approximately 0.2% during cruise as can be seen in Figure 5. This also affects the fuel consumption error as can be seen in Table II.

From Figures 2 to 5 it is clear that the BADA TEM provides accurate fuel flow results. Even though there are some small inaccuracies, the general trend of the fuel flow coincides with the actual fuel flow of the flight. For this reason, all fuel consumption calculations for this study are performed with the BADA TEM. For the aircraft types for which FMS data is

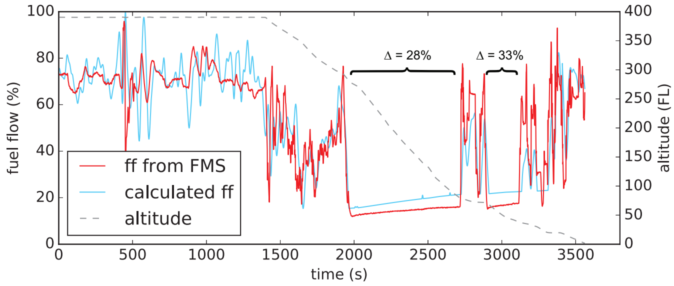

Fig. 2. Original BADA vs FMS fuel flow for Airbus A330-200

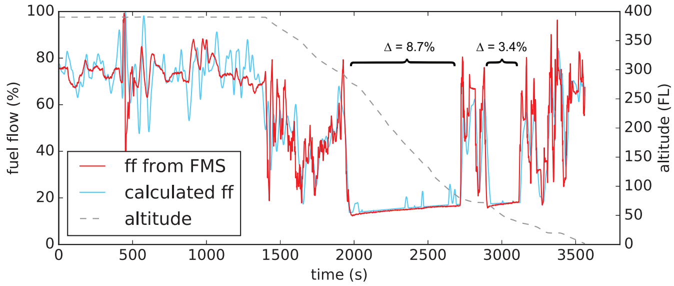

Fig. 3. Calibrated BADA vs FMS fuel flow for Airbus A330-200

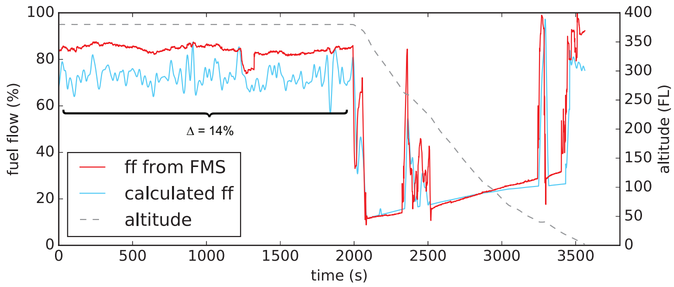

Fig. 4. Original BADA vs FMS fuel flow for Boeing 737-900

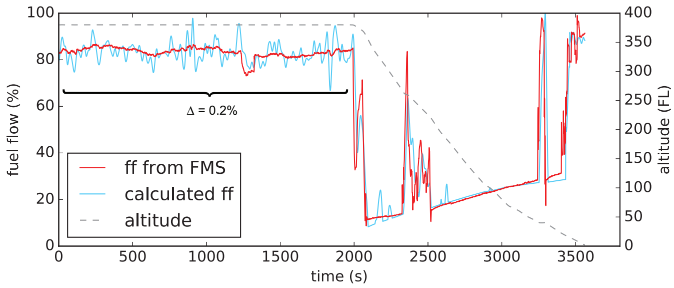

Fig. 5. Calibrated BADA vs FMS fuel flow for Boeing 737-900

available, the BADA coefficients are calibrated as explained in Section II-B and for the aircraft types for which ADS-B data is used, the original BADA coefficients are used.

III. Designing the CDA profile

In Section I, a definition for CDAs was given. For the purpose of this study, a fuel-optimal CDA is defined as *a procedure which reduces or eliminates level flight segments after Top of Descent (ToD), conducted at idle throttle settings, flying a fuel-optimal vertical and speed profile*. The main difference with the original definition in Section I is that the fuel-optimal CDA strives to minimize the fuel consumption during descent. Using this definition, fuel-optimal CDA profiles need to be determined for each historical flight. This section shows that the design of the fuel-optimal CDA can be reduced to depend on two variables: flight path angle (FPA) and acceleration.

Using an analytical approach, a fuel-optimal CDA profile is determined by analyzing the TEM provided by BADA. The fuel-optimal CDA profile is built by first analyzing the historical flight data. Starting with the altitude and speed from the Top of Descent (ToD) of the historical flight at time i, $\dot{V}_{TAS}$ and $\dot{h}$ are calculated to define V_{TAS} and h at time $i+1$. This is then repeated until the V_{TAS} and h correspond with the values at the Final Approach Fix (FAF) which is assumed to be at an altitude of 2000 ft. This is illustrated in Figure 6.

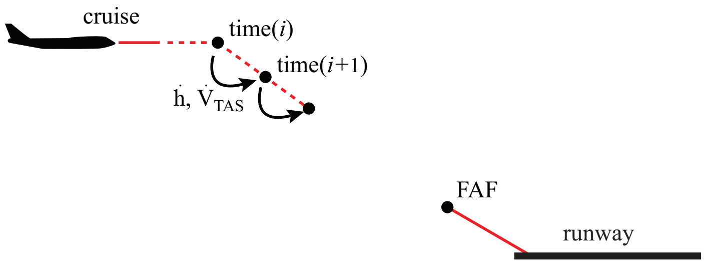

Fig. 6. Building CDA profile between ToD and FAF conditions

Since the speed and altitude at the ToD are known, time $i = 0$ is set with these values for V_{TAS} and h. The fuel-optimal CDA is defined to be conducted at idle throttle settings after ToD. Therefore, the thrust that equates to idle throttle settings needs to be calculated. It is assumed that the minimal thrust corresponds to the minimal fuel flow as given by Equation 8.

$$Thr_{min} = \frac{f_{min}}{\eta} \tag{8}$$

Thr_{min} = minimal thrust for idle throttle

The minimal fuel flow for Equation 8 is calculated using Equation 7 as given in Section II-A using the altitude at time i. The TSFC value is calculated using Equation 5 also as given in Section II-A, but now using the airspeed at time i. Next, the minimal thrust, that can now be calculated using Equation 8, is inserted into the TEM. As explained in Figure 6, the airspeed and altitude at time $i+1$, can be calculated from the airspeed and altitude at time i if the values for $\dot{V}_{TAS}$ and $\dot{h}$ can be calculated. Therefore the TEM is rewritten to Equation 9.

$$\frac{Thr_{min} - D}{m} = g_0 \cdot \frac{\dot{h}}{V_{TAS}} + \dot{V}_{TAS} \tag{9}$$

Here, drag is calculated with Equations 2 to 4 from Section II-A. As can be seen from these Equations, drag depends on altitude, airspeed and the aircraft configuration. The altitude and airspeed at time i are known, but the aircraft configuration needs to be determined. For the fuel-optimal CDA profiles, the aircraft configuration is defined as a function of airspeed. For the FMS data aircrafts, the lower speed limits for each flap configuration per aircraft type is determined by analyzing the historical flights. For the ADS-B data, the lower speed limits for the flap configurations are set slightly higher than the stall speeds per configuration provided by BADA. In this manner the configurations with smaller drag are flown as long as possible, and the switch to higher flaps occurs as late as possible. Less drag from cleaner configurations reduces the fuel consumption and thus contributes to a better fuel-optimal CDA. That concludes the drag calculation. The mass of the aircraft for Equation 9 at time $i = 0$ is defined as the mass of the historical flight at ToD. With this, the left side of Equation 9 can be calculated. On the right side, the gravitational acceleration is known and the airspeed at time i is also known. This leaves two free variables: $\dot{V}_{TAS}$ and $\dot{h}$. These are the values needed to move from time i to time $i+1$. So, a choice needs to be made for either $\dot{V}_{TAS}$ or $\dot{h}$. Choosing a value for one variable automatically determines the value of the second variable. When flying, it is more common to fly with set FPAs than with rate of descents $\dot{h}$. Furthermore $\dot{h}$ also depends on the airspeed of the aircraft. And in previous studies, constant FPAs have been proven to provide positive results [5] [15]. For these reasons $\dot{h}$ is replaced with the FPA, as is shown in Equation 10.

$$\frac{Thr - D}{m} = g_0 \cdot \sin\gamma + \dot{V}_{TAS} \tag{10}$$

γ = flight path angle (FPA)

Using Equation 10 the altitude and speed profiles for the fuel-optimal CDA can be constructed. Once the FPA or $\dot{V}_{TAS}$ is known, the other value is calculated using Equation 10. By varying the values for the FPA and $\dot{V}_{TAS}$ from Equation 10, different scenarios are tested. CDAs using constant values for $\dot{V}_{TAS}$ ranging from $-.35$ to $-.15$ $\frac{ft}{s^2}$ and constant values for FPA ranging from $-4°$ to $-1.6°$ are created. However, during the simulations it became clear that the majority of the maximum savings were obtained for constant flight path angles. After further analysis it became clear that the CDAs with maximum savings for constant decelerations had comparable maximum savings for constant FPAs. For this reason the simulations are performed with constant FPAs only, in order to save computation time. But there are other reasons to choose a constant FPA over constant deceleration as well. First of all, constant FPA descents can easily be implemented into the FMS or VNAV. Furthermore, studies have shown that flying constant FPAs during descent increases the predictability of the aircraft which increases the feasibility of implementation [15] [16]. Some studies have shown that a constant FPA approach of 3°, the three-degree deceleration approach, results in a runway capacity of 90% of the theoretical maximum [17] [18] and can reach a runway throughput of up to 98% of the capacity of a conventional approach [19]. For this reason three-degree CDAs are also simulated in this study to compare with the fuel-optimal CDAs in terms of fuel savings. Finally, a $\left(\frac{C_l}{C_d}\right)_{max}$ CDA is also simulated. Since $\left(\frac{C_l}{C_d}\right)_{max}$ corresponds to the maximum glide ratio of the aircraft it is to be expected that this should result in fuel savings as well. For this CDA, the FPA will not remain constant during the entire descent, but will depend on the aircraft configuration.

Once the FPA is set, the values for $\dot{V}_{TAS}$ and $\dot{h}$ are calculated using Equations 11 and 12 to move from time i to time $i+1$.

$$\dot{V}_{TAS} = \frac{Thr - D}{m} - g_0 \cdot \sin\gamma \tag{11}$$

$$\dot{h} = \sin\gamma \cdot V_{TAS} \tag{12}$$

Once the CDA profile has been determined from ToD altitude and speed down to FAF altitude and speed, the location of the CDA ToD is determined by backward integration of the CDA V_{TAS} over time, starting from the FAF location and moving backwards, towards the ToD. This along track distance is compared to the original along track distance. If the CDA ToD has moved closer to the runway, the altitude and speed is kept constant for the CDA profile until the along track distance of the CDA coincides with the along track distance of the original ToD. From that point on the original flight values are copied to the CDA flight.

IV. Simulation design

In this section the fuel consumption calculation method presented in Section II and the CDA profile determination method presented in Section III are combined to form the strategy in Section IV-A. This section also discusses the different data types, and which historical flights are used in this study in Section IV-B. Section IV-C then explains how the limited number of historical flights are used to calculate the fuel and emission benefits for a full year. Finally, the output parameters of the simulation which will be analyzed in Section V are stated in Section IV-D.

A. Strategy

In this study, 25 CDA profiles are determined per historical flight with FPA values varying linearly from $-4°$ to $-1.6°$. The CDA profile with the maximum fuel benefit is stored as the fuel-optimal CDA flight for the corresponding historical flight. This fuel-optimal CDA flight is then compared against the actual flight in terms of fuel consumption. This process is visualized in Figure 7. As can be seen in this figure, the fuel consumption is calculated for both the historical flight and the simulated CDA flight. For the historical flights for which FMS 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 CDA for the same flight results directly in fuel and emission benefits.

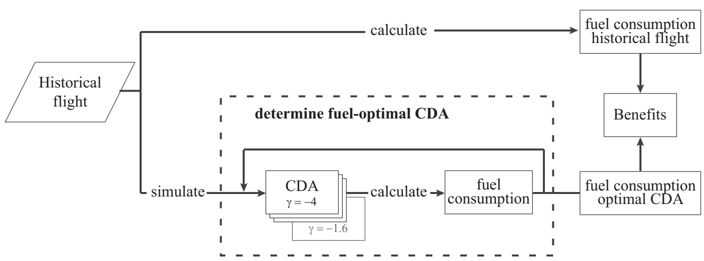

Fig. 7. Fuel benefit calculation

B. Data

Two types of historical data are used in this study. For certain aircraft types, FMS data is used. For the aircraft types for which FMS data is not available, ADS-B data from FlightRadar24 [20] is used. Tables III and IV list the aircraft types per data type. These tables are composed using the Schiphol Traffic Review 2015 [9]. 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 aircraft types for which FMS data is available, a number of historical flights from January to December of the year 2015 are available. ADS-B data is available for its aircraft types for the months July, August and September of 2016.

TABLE III. FMS AIRCRAFT TYPES: NUMBER OF DESCENTS AT SCHIPHOL IN 2015 AND NUMBER OF HISTORICAL FLIGHTS ANALYZED

Aircraft type	# Descents 2015	# Analyzed
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

TABLE IV. ADS-B AIRCRAFT TYPES: NUMBER OF DESCENTS AT SCHIPHOL IN 2015 AND NUMBER OF HISTORICAL FLIGHTS ANALYZED

Aircraft type	# Descents 2015	# Analyzed
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. *Extrapolation*

Tables III and IV list the number of historical flights that are analyzed per aircraft type. These are not all the flights for a full year. In order to extrapolate the results of this study to a full year, Tables III and IV also list the number of flights that landed at Schiphol during 2015 according to the Schiphol Traffic Review [9]. By calculating the average fuel savings per aircraft type for the available historical flights, the fuel savings for a whole year are estimated by extrapolating these averages with the total descents per aircraft type at Schiphol as listed in Tables III and IV. With 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 FMS data is available and for 53% of the arrivals are aircraft types for which ADS-B data is available.

D. *Simulation output*

The main output of the simulations are the *fuel benefits from fuel-optimal CDAs*. The amount of fuel benefits depends on the efficiency of the historical flight. If the historical flight has more level segments with high fuel consumption after ToD, the amount of fuel saved by the fuel-optimal CDA with respect to the historical flight will be larger. On the other hand, if the historical flight has an efficient descent, the amount of fuel saved by the fuel-optimal CDA will be small. The *fuel-optimal CDA profile* itself along with the *FPAs of the fuel-optimal CDAs* are also outputs of the simulation. The fuel-optimal CDA profile characteristics will help explain why this profile saves fuel with respect to the historical flight. The simulation also compares the fuel-optimal CDA with the historical flight to calculate the *flight duration* difference between both flights. The difference in flight duration can be used as a measure for the feasibility of 100% CDAs. Finally, the *fuel benefits from reference CDAs* are also outputs of the simulation. As explained in Section III two reference CDAs are used, one CDA with a constant FPA of 3° and one CDA with FPAs corresponding to $\left(\frac{C_l}{C_d}\right)_{max}$.

V. RESULTS

The steps described in Section IV lead to the results presented in this Section. First, Section V-A presents some examples of fuel-optimal CDA profiles that have been simulated in order to calculate the fuel and emission benefits. In Section V-B, the FPAs that lead to the fuel-optimal CDAs are presented. The difference in flight time duration between the fuel-optimal CDA and the historical flight is then presented in Section V-C. Next, the fuel benefits per aircraft type are presented in Section V-D for the fuel-optimal CDA and Section V-E presents the difference in fuel benefits between the fuel-optimal CDA and the reference CDAs. Finally, the main findings of this study, the yearly fuel and emission benefits, are presented in Section V-F.

A. *Fuel-optimal CDA profiles*

The fuel and emission benefits are calculated by simulating fuel-optimal CDA flights for the historical flights as explained in Sections III and IV. This section presents some examples of these fuel-optimal CDA simulations for historical flights. Two examples of fuel-optimal CDA profiles are found in Figures 8 and 9.

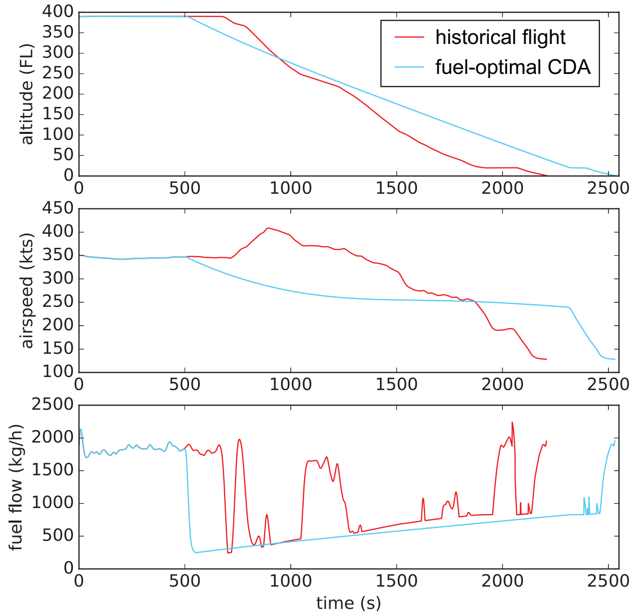

Fig. 8. Fuel-optimal CDA vs historical flight with CDA ToD before historical ToD

As can be seen in Figure 8, for this particular flight the CDA ToD is located at an earlier moment than the original ToD. For the flight shown in Figure 9 however, the ToD is located after the original ToD. In previous studies, it has been

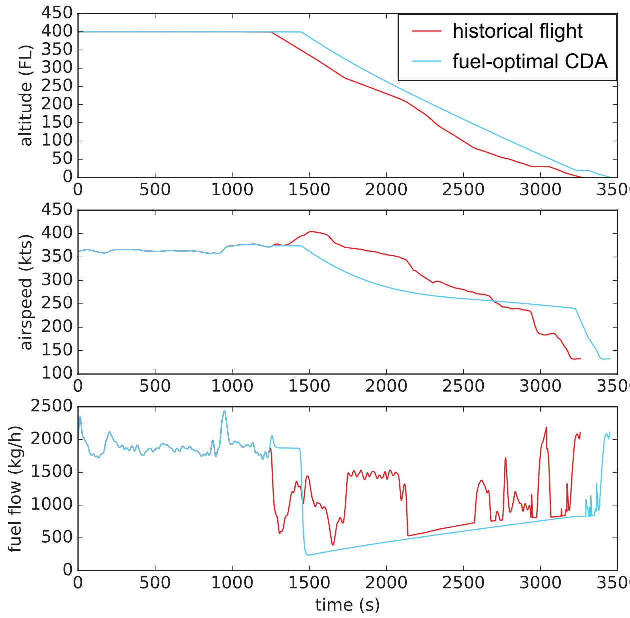

Fig. 9. Fuel-optimal CDA vs historical flight with CDA ToD after historical ToD

shown that the ToD of a CDA is mostly located after the ToD of the original flight [8] [21]. However, the fuel-optimal CDA simulation results show that in this study the ToD of the CDA can also be located before the ToD of the historical flight. This is due to the fact that the FPAs for which fuel-optimal CDAs are found in this study are often shallower than the FPAs of the descent segments of the conventional approach from the historical flight. The shift in ToD also depends on the amount of level segments, i.e., 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 CDA is shallower than the FPA of the descent segments of the conventional approach, the CDA ToD will be located after the historical ToD.

For both flights, the CDA flight duration is longer than the historical flight duration. The extra flight time can be explained by the fact that the airspeed of the CDA flight immediately reduces after ToD and is lower than the airspeed of the historical flight for a large portion of the descent.

In the CDA flights it is clearly visible that from ToD onwards, the fuel flow remains at a minimum until the aircraft reaches the FAF. From there on the fuel flow is exactly the same as the original fuel flow. In the historical flight, there are some small level segments after ToD, where the fuel flow is high as can be seen from the peaks in the historical fuel flow values. Therefore, even though the CDA flight has a longer flight duration compared to the historical flight, the CDA flight still has a lower fuel consumption at the end of the flight. The CDA flights in Figures 8 and 9 respectively save 144kg and 141kg of fuel per flight.

B. FPAs of fuel-optimal CDAs

As shown in Figure 7 of Section IV, 25 CDAs using different FPAs are simulated for each flight. The CDA flight with the maximum fuel benefits is saved as the fuel-optimal CDA flight. The FPAs for the fuel-optimal CDAs per aircraft type are given in Figures 10 and 11. Interesting to note here is that for some aircraft types, the lower quartile, the median and the upper quartile fall together. This is the case for the several aircraft types. This means that at least 50% of the flights for these aircraft types have a fuel-optimal CDA 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 CDA with the same FPA.

Another interesting point is that for nearly all aircraft types, the fuel-optimal CDA has an FPA which is smaller than the 3° FPA explained in Section III. For the B747-400, the lower quartile and the median FPA value is precisely 3°. With this, the B747-400 has the steepest fuel-optimal FPA of all aircraft types.

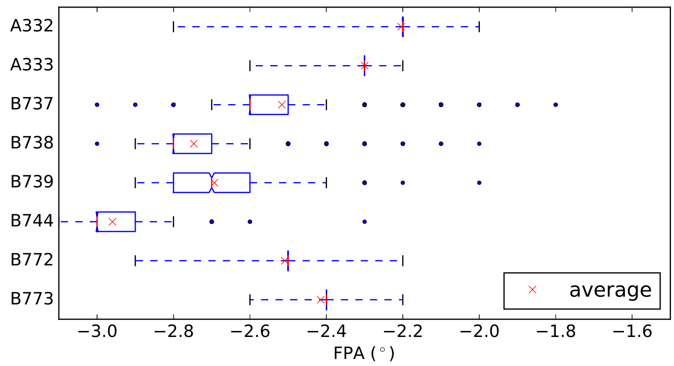

Fig. 10. Fuel-optimal CDA FPAs per FMS a/c type

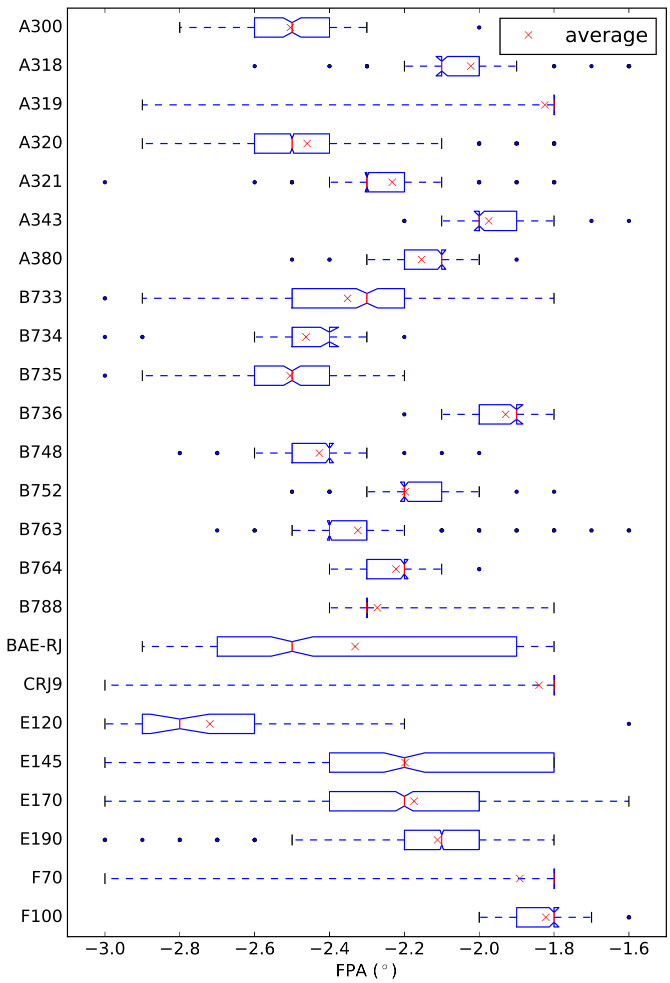

Fig. 11. Fuel-optimal CDA FPAs per ADS-B a/c type

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 CDA is not the same as the flight duration of the original flight. In the examples given in Section V-A, the durations of the CDA flights are longer than the durations of the original flights. The flight durations from the CDA flights relative to historical flights can be found in Figures 12 and 13 per aircraft type.

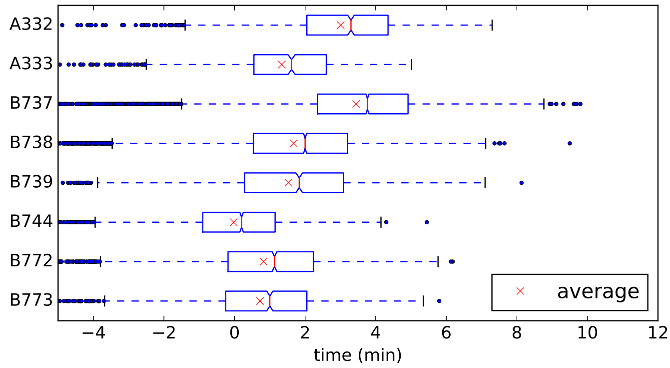

Fig. 12. CDA flight duration relative to historical flights per FMS a/c type

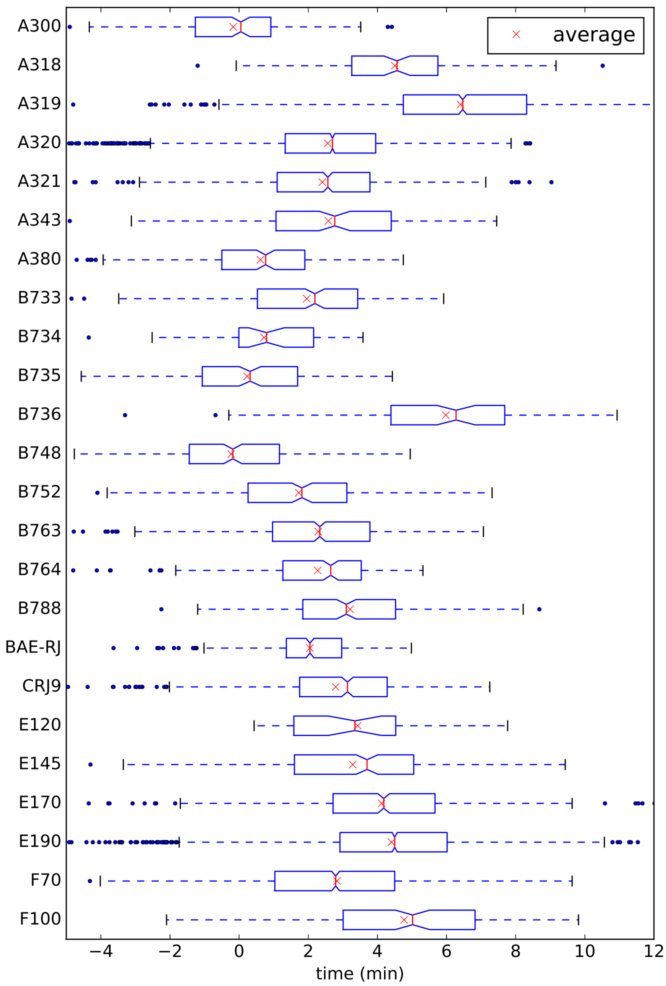

Fig. 13. CDA flight duration relative to historical flights per ADS-B a/c type

As can be seen from these results not all CDA flights have a longer flight duration. However the majority of the CDA flights do require a longer flight time compared to the original flight. For all aircraft, the flight duration of the fuel-optimal CDA varies from 5 minutes less than the original flight to over 12 minutes more than the original flight. The majority of the simulations using FMS data result in fuel-optimal CDAs that are a minute faster to 5 minutes slower than the original flight. The relative flight duration averages of fuel-optimal CDAs for all aircraft are between 14 seconds faster and 6.4 minutes slower. The longer flight duration is due to the fact that during the fuel-optimal CDA, less thrust is used during descent, which results in a slower flight. Due to this slower flight, the flight duration is longer for the fuel-optimal CDA. However, for some of the fuel-optimal CDA flights, the flight duration was shorter than the historical flight. These are the historical flight with large level segments which have flown a rather inefficient descent. In these cases, the fuel-optimal CDA profile has a longer cruise phase with high thrust before the throttle is set to idle. In this high thrust cruise phase, the airspeed of the CDA profile is higher than airspeed of the historical flight at the same location, therefore resulting in a faster, and thus shorter, flight.

Figures 12 and 13 also show differences between aircraft types in CDA 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 fuel-optimal CDA. 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 CDAs

The fuel benefits per flight from the fuel-optimal CDAs relative to historical flights, sorted per aircraft type can be found in Figures 14 and 15. 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 14 and 15. The results thus have a skewed distribution. This is due to the fact that the fuel savings per flight depends 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 or not. This also explains the difference in fuel savings between aircraft type 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 FMS 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 FMS aircraft types and the ADS-B aircraft types it can be seen that the results are quite comparable: the FMS 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 FMS data, the smallest relative savings

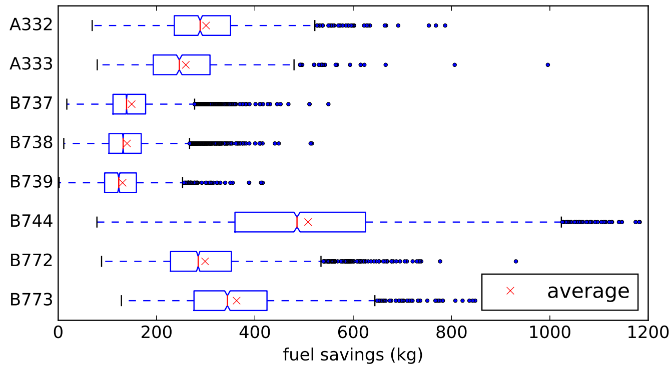

Fig. 14. Fuel benefits for fuel-optimal CDAs relative to historical flights per FMS a/c type

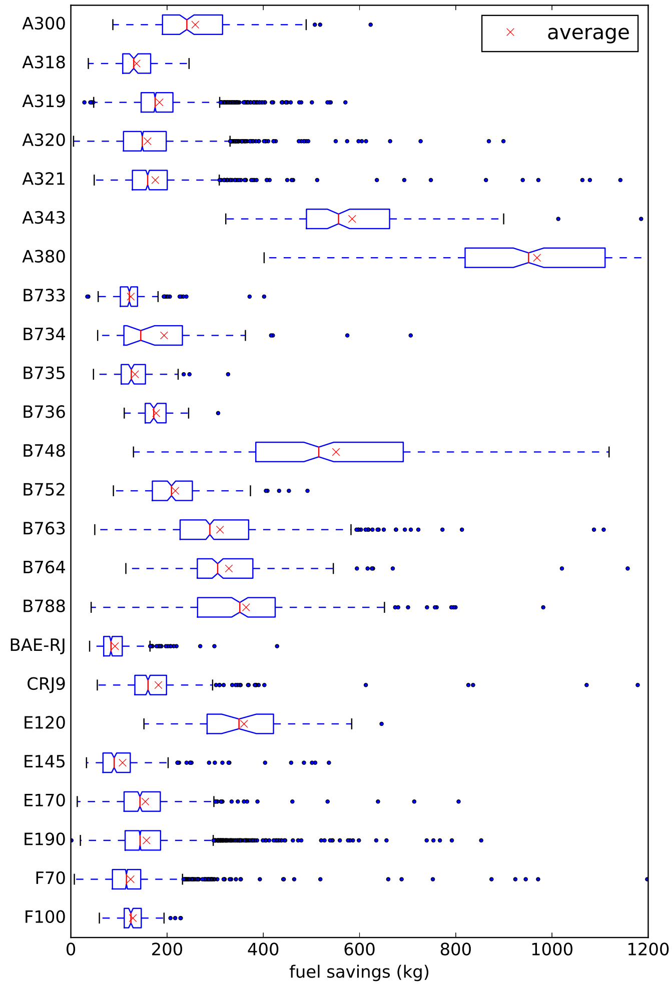

Fig. 15. Fuel benefits for fuel-optimal CDAs relative to historical flights per ADS-B a/c type

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. Fuel benefits from reference CDAs

Besides the fuel benefits from the fuel-optimal CDAs, the simulation also generates fuel benefits for a 3° CDA and a $(C_l/C_d)_{max}$ CDA. The fuel benefits relative to the historical flights for the fuel-optimal CDA, the 3° reference CDA and the $(C_l/C_d)_{max}$ CDA for the Boeing 737-700 are depicted in Figure 16.

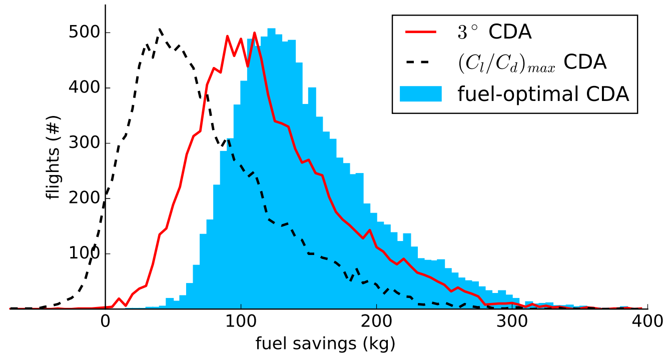

Fig. 16. Fuel benefits for B737 relative to historical flights

Figure 16 shows generally the same distribution of fuel benefits for all the CDAs. However, the 3° CDA and the $(C_l/C_d)_{max}$ CDA clearly result in lower fuel benefits than the fuel-optimal CDA. This is to be expected since the FPAs for the fuel-optimal CDAs of nearly all aircraft types are shallower than 3°. This automatically means that the 3° CDA will thus result in lower fuel benefits for all aircraft types since the 3° FPA is included in in the fuel-optimal CDA simulation, as explained in Figure 7, but has apparently been rejected as the most fuel saving CDA. For the B747-400 the fuel benefits of the fuel-optimal CDA are nearly equal to the fuel benefits of the 3° CDA, as can be seen in Figure 17. This is due to the fact that most fuel-optimal CDAs for the B747-400 have a 3° FPA as seen in Figure 10.

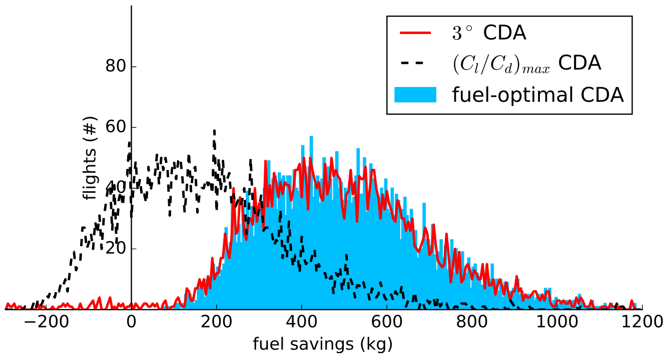

Fig. 17. Fuel benefits for B744 relative to historical flights

However, the fuel benefit from the $(C_l/C_d)_{max}$ is still lower than the fuel benefits from the other CDAs. This is due to the fact that the $(C_l/C_d)_{max}$ FPAs are not equal to the fuel-optimal FPAs. Tables V and VI give the cruise configuration FPAs for the $(C_l/C_d)_{max}$ CDAs. This cruise configuration is flown for the most part of the descent until the airspeed becomes too low for the cruise configuration. From that point on the $(C_l/C_d)_{max}$ CDA occurs at an even steeper FPA. From Tables V and VI it is clear that the FPA for the cruise configuration is already steeper than the FPA of the fuel-optimal CDA for all aircraft types. Hence, the $(C_l/C_d)_{max}$ CDA is always less beneficial than the fuel-optimal CDA.

TABLE V. $(C_l/C_d)_{max}$ CRUISE CONFIGURATION FPAS PER FMS A/C TYPE

Aircraft type	$(C_l/C_d)_{max}$ FPA ($^\circ$)
Airbus A330-200	-2.9
Airbus A330-300	-2.9
Boeing 737-700	-3.4
Boeing 737-800	-3.5
Boeing 737-900	-3.4
Boeing 747-400	-3.6
Boeing 777-200	-3.3
Boeing 777-300	-3.3

TABLE VI. $(C_l/C_d)_{max}$ CRUISE CONFIGURATION FPAS PER ADS-B A/C TYPE

Aircraft type	$(C_l/C_d)_{max}$ FPA ($^\circ$)
Airbus A300	-3.7
Airbus A318	-3.6
Airbus A319	-3.0
Airbus A320	-3.7
Airbus A321	-3.5
Airbus A340-300	-3.0
Airbus A380	-3.2
Bae 146/AVRO RJ	-4.3
Boeing 737-300	-3.7
Boeing 737-400	-3.9
Boeing 737-500	-3.7
Boeing 737-600	-3.2
Boeing 747-8	-3.6
Boeing 757-200	-3.3
Boeing 767-300	-3.4
Boeing 767-400	-3.3
Boeing 787-8	-3.2
Bombardier CRJ 700/900/1000	-3.2
Embraer 170/175	-4.1
Embraer 190/195	-3.7
Embraer EMB 120	-3.9
Embraer ERJ 145	-4.6
Fokker 100	-3.6
Fokker 70	-3.3

F. *Yearly fuel and emission benefits for Schiphol*

Tables VII and VIII present 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 Tables III and IV with the median of the fuel benefits per aircraft type.

TABLE VII. EXTRAPOLATED YEARLY FUEL BENEFITS PER FMS A/C TYPE

Aircraft type	yearly fuel benefits (10^6kg)
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

In the FMS 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 FMS data sum up to 9.4 million

TABLE VIII. EXTRAPOLATED YEARLY FUEL BENEFITS PER ADS-B A/C TYPE

Aircraft type	yearly fuel savings (10^6kg)
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

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 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 [9], this results in 2.12 kg of CO_2 savings per passenger.

VI. DISCUSSION

A. *Fuel-optimal CDA profiles*

In the simulated CDA profiles, the continuous descent with the constant flight path angle (FPA) is clearly visible from the ToD onwards. However, in the altitude profile there is still a level segment visible at the end of the CDA. The fuel flow is still at a minimum during this level segment, which results in a deceleration of the aircraft. The level segment is actually required to decelerate to the FAF speed. Since the fuel flow stays low during this level segment, this still qualifies as a fuel optimal CDA.

B. *FPAs of fuel-optimal CDAs*

It is difficult to compare the fuel-optimal CDA FPAs to other FPAs from literature. Some studies [4] [8] only mention the 3° glideslope. Clarke et al. [5] choose a 2° FPA for the B767-300 since this "*provides the most aggressive deceleration during the initial segment*". However this is not based on fuel consumption reduction. Other studies either do not mention the FPA used during CDA or choose a set FPA for all CDAs assuming that this is an optimal FPA [6] [7].

In the FPAs of fuel-optimal CDAs, differences are found between aircraft types. The differences in fuel-optimal CDA

FPAs between aircraft types can be explained by the different aerodynamic properties of the aircraft types. The B747-400 has the steepest fuel-optimal CDA and the A330's have the shallowest fuel-optimal CDA from the FMS aircraft types. In Table V, the differences in $(C_l/C_d)_{max}$ FPAs between FMS aircraft types is given. The same shift in FPAs found for the fuel-optimal CDAs between aircraft types, can also be found for the FPAs in Table V. This indicates that the aircraft with highest drag to lift ratio also has the steepest fuel-optimal CDA. The same correlation can also be found for the ADS-B aircraft types using Table VI.

C. Flight duration

For the majority of the historical flights that were analyzed, a longer flight duration is required when implementing CDAs. One might argue that this would lead to capacity issues or conflict issues when flying a CDA. However since all the aircraft types have more or less the same shift in flight duration this might be an indication that conflict issues need not be that large. And that since the CDA path can be determined during the planning of the flight, the extra time that it takes to fly the CDA can also be taken into account during the planning phase of the flight. However, the flexibility for air traffic control to implement level segments for aircraft in order to space aircraft during arrival is lost if 100% CDAs are implemented. The only way to analyze the extra conflicts and the feasibility of 100% fuel-optimal CDAs is to perform a full airspace simulation. However, this is outside the scope of this study.

D. Fuel benefits from fuel-optimal CDAs

Here the savings per aircraft type are compared with the savings that have been found in previous studies as mentioned in Section I. Table IX lists the savings from previous studies and the setup of these studies.

TABLE IX. RESULTS FROM PREVIOUS STUDIES

Aircraft type	Experiment	savings (kg)	source
B733	CDA from 7000 ft	43-55	Wubben [4]
B738 + B757	non-idle CDA from ToD	146	Sprong [7]
B744	CDA from 7000 ft	161-407	Wubben [4]
B757	CDA from 8000 ft	44	Turgut [6]
B763	CDA from 11,000 ft	181-226	Clarke [5]
B767	non-idle CDA from ToD	114	Sprong [7]

Even though there are some (small) differences between the fuel savings found in this study and the fuel savings found in previous studies, the numbers are quite comparable. Furthermore, all the differences in fuel savings can be explained by the differences in the CDA implementations. In the previous studies the CDAs are either limited to start between 7000 and 11,000 ft, whereas in the current study the CDAs are not limited and start at cruise altitude, or the CDA is performed with non-idle thrust from cruise altitude, whereas the current study only analyzes idle thrust CDAs. 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 [7]. This can be explained by the fact that the savings found by [7] is a combined saving where the B738 has a smaller saving on average than the B757.

E. Fuel benefits from reference CDAs

The 3° reference CDA fuel benefits will at most be equal to the fuel benefits from the fuel-optimal CDA. This is due to the fact that during the simulation a 3° FPA is already tested to check whether this is the most fuel saving CDA or not. If another FPA has a higher fuel saving the 3° is rejected as fuel-optimal FPA. The $(C_l/C_d)_{max}$ CDA fuel savings were expected to have promising results as this corresponds to the maximum glide ratio of the aircraft. However, $(C_l/C_d)_{max}$ calculation assumes a zero-thrust flight. Due to the fact that idle thrust settings is not equal to zero-thrust, the glide ratio calculated using $(C_l/C_d)_{max}$ is no longer the maximum glide ratio.

F. Yearly fuel and emission benefits for Schiphol

The Environmental Sciences Division of the Oak Ridge National Laboratory in Tennessee [22] states that the world CO_2 output is about $35.849 \cdot 10^9$ tonnes and the CO_2 output from the Netherlands is about $169.97 \cdot 10^6$ 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 [22] 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. However, for 2020 the Dutch government has targeted to have 16% less CO_2 emissions compared to the year 2005 [23]. This equates to about $13 \cdot 10^6$ tonnes of CO_2 reduction. By implementing CDAs at Schiphol, 0.9% of this reduction is already achieved.

VII. RECOMMENDATIONS

For this study the influence of the lateral path of the flight is neglected. For all aircrafts analyzed in this study only the altitude and speed profiles vs. along track distance to 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 due to holding patterns, i.e. prolongation of the lateral path, the CDA profile will also follow this prolongated lateral path. Figure 18 shows that the calculated CDA follows the exact lateral path while it might have been possible to fly a shorter distance. This means that the results of this project could be conservative. For future studies it is recommended to analyze whether a shorter lateral path would have been possible and whether this might have allowed the CDA flight to arrive at the same time as the original flight without creating new conflicts.

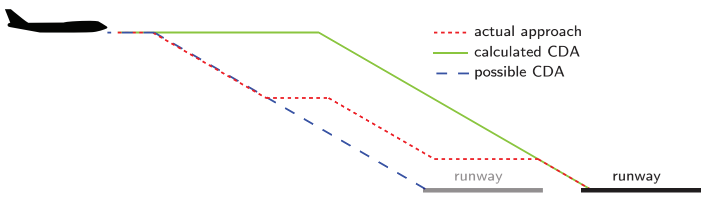

Fig. 18. CDA calculated along the lateral path of the original flight

In future studies, FMS data would be the recommended data type, since it allows for accuracy correction. However if ADS-B data is to be used, it is recommended to analyze the exact same flights using ADS-B data and FMS data to establish the accuracy of the ADS-B calculations. This was unfortunately not possible during the current study. And finally, for future studies it is recommended to also analyze varying flight path angles during descent instead of constant flight path angles, because this might further increase the fuel benefits.

VIII. Conclusions

In order to determine how much fuel and emissions can be saved on a yearly basis if all aircraft arriving at Schiphol would implement continuous descent approaches (CDAs), two questions were posed. This paper has shown that fuel consumption calculations based on the Base of Aircraft Data (BADA) total-energy model (TEM) are considered accurate. For aircraft types for which FMS data was available, this accuracy was increased by calibrating the BADA coefficients. This paper has also shown that a fuel-optimal CDA profile can be found per flight with a fixed flight path angle (FPA) depending on the aircraft type, mass, cruise speed, cruise altitude and final approach fix (FAF) speed. The Top of Descent (ToD) location of the fuel-optimal CDA profile is not necessarily the same as the historical ToD location. The fuel-optimal CDA profile found has a minimal fuel flow between ToD and the FAF. A level segment can occur at the end of the fuel-optimal CDA profile, with minimal fuel flow, in order to decelerate to meet the FAF speed limit.

This paper concludes that by implementing fuel-optimal CDAs, the fuel consumption per flight is reduced. With a total of $39.15 \cdot 10^6$ kg of fuel benefits for 225 thousand descents, the fuel consumption is reduced with 174 kg per flight on average. This paper has discussed how many extra flights can be flown, before the total emissions increase, showing that even though the number of flights per year increases, the total emissions for a year need not increase, or at least not at the same rate.

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Part II

Prelim Report

Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol

Draft Preliminary Thesis

Preliminary Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

M. Inaad

July 8, 2016

Faculty of Aerospace Engineering · Delft University of Technology

Acronyms

ADS-B Automatic Dependent Surveillance-Broadcast
AIRE Atlantic Interoperability Initiative to Reduce Emissions
ATC air traffic control
ATL Hartsfield-Jackson Atlanta International Airport
BADA Base of Aircraft Data
BCOP Boeing Climbout Program
CDA continuous descent approach
CDO continuous descent operation
ECAC European Civil Aviation Conference
FACET Future ATM Concepts Evaluation Tool
FAF final approach fix
FMS flight management system
FPA flight path angle
IAF initial approach fix
ILS instrument landing system
MIA Miami International Airport
TAAM Total Airspace & Airport Modeler
TEM total-energy model
ToD top of descent
TSFC thrust-specific fuel consumption

Contents

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Chapter 1

Introduction

In this fast modernizing world, more people have taken to the skies than ever before. Meanwhile, governments have become more and more aware of the urgencies of climate change. In 2015 the 21'st Climate Change Conference, COP 21, was held. The main focus of this conference was to reduce the global greenhouse gas emissions. And so, as the skies around Amsterdam Schiphol Airport fill up, the Netherlands needs to decrease its greenhouse gas emissions.

Since the demand for air transportation is only expected to increase in the coming years (International Air Transport Association, 2013), solutions to decrease the greenhouse gas emissions are necessary for all stakeholders. One possible solution to reducing greenhouse gas emissions is to perform continuous descent operations (CDOs). The term CDO is interchangeable with continuous descent approach (CDA). "*Continuous Descent Approach is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and air traffic control (ATC) instructions*" (Eurocontrol, IATA, CANSO, & ACI, 2011). Figure 1-1 visualizes the difference between a CDA and a conventional approach.

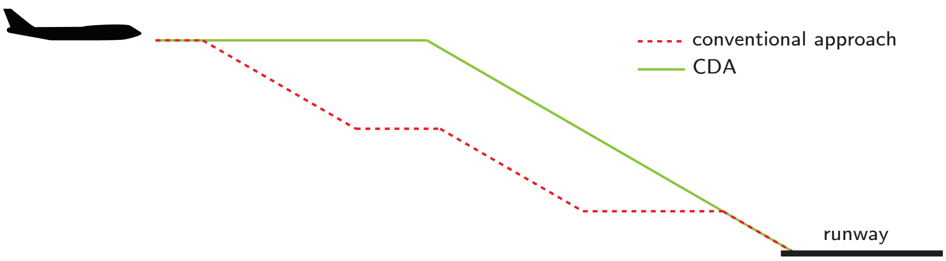


Figure 1-1: CDA vs conventional approach

In the past, CDA research was focused on noise abatement (Alders, 2013), however in recent years the focus has slowly been shifting towards fuel and emission reduction research. These studies, however, were limited to certain aircraft types and to a small number of flights.

Wubben and Busink (2000) investigated CDAs at Schiphol airport, with a focus on noise abatement. In their study the CDA procedure was started from an initial approach fix (IAF). Wubben's study shows promising results for fuel consumption reduction. And since emissions can be calculated as a linear function of fuel burn (Sutkus, Baughcum, & DuBois, 2001), fuel consumption reduction means emission reduction. So even though the number of flights per year increases, if the fuel consumption per flight can be reduced, the total emissions for a year need not increase as much as the number of flights. Furthermore if the relative fuel consumption reduction is higher than the relative increase of number of flights, the absolute emission increase during descent to Schiphol Airport could be zero or even less, i.e. a decrease in emissions in areas around airports.

This project investigates the potential benefits of 100% CDA operations at Schiphol International Airport. This will be done firstly by comparing the total fuel burned from cruise altitude or top of descent (ToD) to touchdown between aircraft flying a CDA and aircraft flying a conventional approach. In this study this will be done for different aircraft types, using actual flight data supplied by Koninklijke Luchtvaart Maatschappij (KLM) Royal Dutch Airlines. If no CDA flight data is available for a certain aircraft type a theoretical CDA profile can be calculated by analyzing the most common glide path angle during descent for that specific aircraft type.

From the real flight data the results can be extrapolated to all aircraft landing at Schiphol airport for a whole year. Using Automatic Dependent Surveillance-Broadcast (ADS-B) and Schiphol Traffic Review (Schiphol Nederland, 2016) nearly all non-KLM flights can be estimated. ADS-B is an on-board avionics function that automatically transmits, among other information, aircraft position data from the on-board navigation system, via a digital data link (Kayton & Fried, 1997). The transmitted data can be picked up by an ADS-B receiver. Decoded ADS-B data is available from the TU Delft server (Sun, 2015-2016) and Flightradar24 (Flightradar24, 2012-2016). Readers interested in decrypting ADS-B data can find information on-line (Sun, 2015).

The biggest challenges for this project will be to find a reliable manner to determine (theoretical) ideal CDA profiles and to extrapolate the calculations from real flight data to all flights landing at Schiphol International Airport for a whole year.

The results of this project may well influence the political decisions for Schiphol, since the impact of emission benefits are of utmost concern at the moment. At the least the Netherlands will have quantitative data on how much fuel and emissions can be saved by implementing CDAs at Schiphol.

Chapter 2

Literature Review

In this chapter a summary of the literature review carried out for this project can be found. First an overview is given of results of previous studies on the fuel benefits of continuous descent approaches. The results of the studies discussed in this chapter have been converted to kilograms of fuel saved per aircraft type where possible. This first section concludes by placing the current study in relation to previous studies. The second section discusses the possible reasons for the beneficial effects of CDAs. And finally the last section of this chapter states some disadvantages of implementing CDAs.

There are different methods to study the fuel benefits of implementing CDAs. The most accurate way is to use flight recorder data to determine the fuel consumption between different approach procedures. However since flight recorder data is often sensitive data, it is not easily obtainable. The next best way to determine these benefits is to calculate the fuel benefits using ADS-B or radar data. ADS-B/radar data is less sensitive and thus easier to obtain than flight recorder data. With this method, however, an accurate fuel consumption calculation method is necessary to determine the benefits. Finally, some studies have calculated fuel benefits without using any actual flight data, but by running simulations of arrivals. These three categories of studies are distinguished in this chapter.

2-1 CDA benefits

Initial studies on CDAs were aimed at solving noise issues. This is reflected in the experiments summarized in this chapter. However, in the last couple of years the focus of CDA studies has shifted toward fuel and emission benefits as well. This section will introduce some of the studies on CDA benefits and present the results of these studies.

2-1-1 Experiments with FMS data

For the 29^{th} International Congress and Exhibition on Noise Control Engineering, Wubben and Busink (2000) performed a study to quantitatively calculate the "*Environmental benefits of continuous descent approaches at Schiphol Airport compared with conventional approach procedures*". In Wubben and Busink's experiment a CDA procedure is implemented in which the aircraft starts at an IAF at 7000 ft and descends with (near) idle power settings to the instrument landing system (ILS) intercept point at 2500 ft. Using fuel flow data from the operational flight management system (FMS) data provided by KLM, fuel savings of 161 - 407 kg for Boeing 747-400 aircraft and 43 - 55 kg for Boeing 737-300/400 aircraft were found.

In another effort to reduce the impact of noise in communities close to airports, a study led by MIT with members from Boeing, FAA, NASA, RAA of Louisville and Jefferson County and UPS designed a CDA procedure for runway 17R at Louisville International Airport (Clarke et al., 2004). Clarke et al. initially designed a two-segment CDA with a constant flight path angle (FPA) initial segment from 7000 ft and a 3-deg ILS glide slope second segment. But because analysis showed that the procedure could be initiated at a higher altitude with no aircraft performance penalty or additional workload for controllers, Clarke et al. removed the initial level flight segment at 7000 ft and extended the flight path to coincide with an existing waypoint for Louisville International Airport with an altitude restriction of "at 11,000 ft". Clarke et al. go on to suggest that with some minor improvements to the current FMS systems, aircraft would be able to perform CDAs from ToD without reverting to level flight. The flight recorder data from Clarke et al.'s experiment revealed that the Boeing 767-300 aircraft flying CDA consumed 400-500 lb (181-226 kg) of fuel less than the aircraft flying the conventional approach.

Turgut, Usanmaz, Canarslanlar, and Sahin (2010) conducted a study which focused "*on the potential abatement of energy consumption and emission while implementing CDA procedures*". The study implements partial CDA procedures at International Istanbul Ataturk Airport. The main objective of the experimental approach procedure is to have the level flight segments during the approach phase at the highest possible altitude. This means that there are still level segments during the approach phase. Instead of a level segment at 3000 ft, the procedure calls for that same level segment to be at 8000 ft. This can be seen in Figure 2-1. Using flight recorder data from a Boeing 757, Turgut et al. found fuel savings of up to 44 kg per flight.

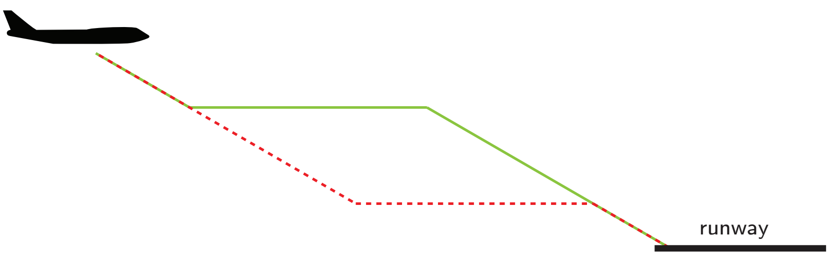


Figure 2-1: Horizontal segment at a higher altitude during approach

2-1-2 Fuel calculations using Radar/ADS-B data

As part of the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) program, Sprong, Klein, Shiotsuki, Arrighi, and Liu (2008) developed and demonstrated CDA operations at Hartsfield-Jackson Atlanta International Airport (ATL) and Miami International Airport (MIA) in 2008. The procedures were designed to overlay the conventional routes into the respective airports typically used by flights arriving from Europe. Using recorded radar track data of non-CDAs and of the CDA demonstration flights, the fuel burn was modeled using Eurocontrol's Base of Aircraft Data (BADA) 3.5. Using the aircraft position, speed, acceleration/deceleration, descent rate and aircraft performance parameters supplied by BADA, the fuel flow for the recorded radar track history could be estimated. Sprong et al. also estimate the CO_2 emissions as "*a linear multiple of the amount of fuel burned according to the methodology*" described by Sutkus et al. (2001). Fuel savings of 37 gallons (114 kg) corresponding to 360 kg of CO_2 savings were estimated per flight at ATL using data from Boeing 767 aircraft. Fuel savings of 49 gallons (146 kg) corresponding to 460 kg of CO_2 savings were estimated per flight at MIA using data from Boeing 757 and Boeing 737-800 aircraft.

Cao, DeLaurentis, and Sun (2013) performed a benefit and trade-off study of implementing continuous descent approachs (CDAs) in normal traffic conditions in which the CDA arrival traffic was simulated using the NASA Future ATM Concepts Evaluation Tool (FACET) with radar track data as input. The fuel burn was estimated using a corrected thrust-specific fuel consumption (TSFC) model which is based on BADA 3.9. Cao et al. used the ground tracks from the radar data and changed the vertical profiles to create comparable CDAs per flight. This method ensures that only the optimized vertical profiles and speed profiles influence the difference in fuel consumption. After analyzing inbound traffic flying into Hartsfield-Jackson Atlanta International Airport (ATL) during a two week period, average fuel savings of 160 kg per flight was found.

2-1-3 Simulations

Wilson and Hafner (2005) ran a series of simulations using the Total Airspace & Airport Modeler (TAAM) Fast-time simulation tool (Jeppesen, n.d.) to analyze the fuel benefits of CDAs also at Hartsfield-Jackson Atlanta International Airport (ATL). In this experiment about 2,800 flights were simulated, both arriving and departing, based on a timetable of actual operations at ATL. The simulation results showed daily fuel savings that could reach $80 thousand at ATL. However this number is based not only on CDAs but also on simulations in which the aircraft have lateral freedom to determine their own path to the runway. For the simulations in which they only had altitude freedom (CDA) fuel savings were estimated to reach $30 thousand. Taking into account the price of Jet fuel in October of 2004, this corresponds to about 19.7 thousand gallons of Jet fuel (Barrientos & Soria, 2016). This results in a total fuel saving of about 59 thousand kilograms for the 2,800 flights. Assuming that fuel savings are equal during departure and arrival this results in fuel savings of 21 kg per flight on average.

In an attempt to make the implementation of CDAs in medium to high traffic conditions possible, Tong, Schoemig, Boyle, Scharl, and Haraldsdottir (2007) studied the fuel benefits of "*partially powered, low thrust CDA along a geometric vertical path*". In order to achieve this Tong et al. redefines CDA procedures in their study as "*any descent procedure that minimizes or even eliminates high thrust level flight segments during descent and still supports the required traffic flow*". Using the Boeing Climbout Program (BCOP) for simulations on Boeing 737-700 and Boeing 777-200 aircraft, fuel benefits are calculated for CDA, partical CDA, and conventional descents. All the descents simulated by Tong et al. start at 33,000 ft from a fixed location and end in another fixed location at 11,000 ft. The CDA profile can be seen as the solid green line in Figure 2-1 where the aircraft performs a level flight at 33,000 ft and descends to 11,000 ft. The conventional profile is the dashed red line in which the aircraft first descends to 11,000 ft and then performs a level flight at 11,000 ft. BCOP analysis predicted 24.2% fuel burn savings for the B737 and 19.4% fuel burn savings for the B777 aircraft. Since no other numbers are mentioned in the paper, the absolute fuel savings in kg can not be calculated.

2-1-4 Results and relation to current study

The methods and results discussed up to now are summarized in Table 2-1. Note the different fuel savings results listed in the table. These differences can be explained by the different aircraft types that have been studied and by the the different experiment methods. No aircraft type has been studied twice in the studies listed in Table 2-1 or the type specification is missing. Sprong et al. state the use of a Boeing 767 but does not state whether it is a B767-200, B767-300 or a B767-400 which makes it difficult to compare with Clarke et al.'s Boeing 767-300. Turgut et al. and Sprong et al. state the use of Boeing 757 without specifying the specific type either. This makes it difficult to compare the studies with each other.

The current study will make use of flight management system (FMS) data provided by Koninklijke Luchtvaart Maatschappij (KLM) to study descents at Schiphol International Airport which is comparable to Wubben and Busink (2000). However, in contrary to Wubben and Busink's study, no flight experiments will be carried out with pre-designed procedures for the current study. The historical data provided by KLM will be used to determine the fuel consumption of conventional approaches, validate the fuel consumption calculation method for the current study (Section 4-1-2), determine ideal CDA profiles per aircraft type (Section 4-2) and to create optimal vertical and speed profiles per flight along the same ground track. This means that for the current study, no expensive flight tests have to be performed. Furthermore, in contrary to most previous studies, the current study will not focus on select aircraft types, but aims to include all (major) aircraft types descending at Schiphol airport as addressed in the Schiphol Traffic Review found in Table B-2. This aligns the current study with Cao et al. (2013). Where Cao et al.'s study used radar data to optimize the vertical profile along the same ground track, the current study will use the FMS data to optimize the vertical profile and the speed profile along the same ground track.

Table 2-1: Results from previous studies

Study	Experiment	Fuel calculation method	Aircraft	Fuel savings
Wubben and Busink (2000)	Flight experiments: CDA from 7000 ft	FMS data	Boeing 747-400	161-407 kg
			Boeing 737-300	43-55 kg
Clarke et al. (2004)	Flight experiments: CDA from 11,000 ft	FMS data	Boeing 767-300	181-226 kg
Wilson and Hafner (2005)	Simulation using TAAM: CDA by removing altitude restrictions on conventional approach from IAF	TAAM departures and arrivals	2,800 flights	21 kg
Tong et al. (2007)	Simulation using BCOP: CDA vs conventional between fixed point at 33,000 and fixed point at 11,000 ft	BCOP	Boeing 737-700	24.2%
			Boeing 777-200	19.4%
Sprong et al. (2008)	Flight experiments: CDA from ToD with non-idle descent segments to honor waypoint constraints	BADA using radar data	Boeing 767	114 kg
			40% Boeing 757 60% Boeing 737-800	146 kg
Turgut et al. (2010)	Flight experiments: raise level segment from 3000 ft to 8000 ft	FMS data	Boeing 757	44 kg
Cao et al. (2013)	Simulation using FACET: Optimized vertical profiles along same radar ground track	TSFC based on BADA using radar data	10,407 flights	160.22 ± 18.27 kg

2-2 Why is CDA beneficial?

The previous section states the benefits of implementing CDA procedures at different airports using actual (flight) data and/or simulations. This section focuses on the causes for these benefits.

Wubben and Busink (2000) conclude that the differences in fuel burn between conventional approach and CDA are due "*to the presence of a horizontal segment in conventional approaches*". This coincides with the conclusions drawn by Sprong et al. (2008). In Sprong et al.'s study, level flight is reduced by 92% when implementing CDA which results in lower fuel consumption. Sprong et al. underline that even though initially more fuel is burned due to the extended cruise portion (see Figure 1-1), the fuel benefits during the rest of the descent phase, which is "*conducted at idle or near-idle settings, more than compensates for increases seen at cruising altitude*".

Clarke et al. (2004) explain that fuel benefits from implementing CDAs occurred in their study due to lower thrust. The lower thrust results from different flap settings between the two approaches. During the continuous descent approach in Clarke et al.'s study the flaps were extended closer to the runway compared to the conventional approach. Less thrust is needed because in the CDA procedure, the flaps are extended closer to the runway threshold which results in a smaller drag during the rest of the approach.

Turgut et al. (2010) conclude that the fuel savings due to implementing CDAs result mainly from flying at higher altitudes. At higher altitudes the aircraft experiences less drag due to lower air density. Turgut et al. also state the fuel can be saved due to reduction of descent time when implementing CDAs. When flying at higher altitudes, aircraft can also fly at higher speeds, with the same thrust settings, which result in time saving. This coincides with the conclusions drawn by Tong et al. (2007) who state that during level flight, aircraft "*burn more fuel and have longer flight time when flying at lower altitudes*". Sprong et al. (2008)'s study also resulted in flight time savings, which also result in fuel savings. Sprong et al. explain the time savings as a result of the reduction of level flight segments and of a more favorable groundspeed profile.

Jin, Cao, and Sun (2013) performed a theoretical analysis on the influence of approach procedure on fuel consumption using BADA 3.9. Jin et al. explain that implementing CDA moves the speed profile closer to the fuel-optimal speed profile which is consistent with Sprong et al.'s findings. By analyzing the influence of speed on fuel consumption, Jin et al. argue that speed influences the fuel consumption as significantly as, if not more than, altitude.

2-3 Disadvantages of CDA

So far it has been established that implementing CDAs can be quite beneficial in terms of fuel and emission savings. So why has CDA not been embraced yet by the aircraft community? Why is it not implemented at all airports? Apparently there are also disadvantages to implementing CDAs. This section will discuss some of these disadvantages.

Weitz, Hurtado, and Bussink (2005) explain that CDAs diminish aircraft deceleration capabilites. During level flight, an aircraft can reduce speed by reducing power. However, during

CDA operations, the thrust is (near) idle already. Weitz et al. state that this "*can only be achieved using drag devices like flaps and landing gear*" and "*if the aircraft is above the speed threshold for different flap configurations, spoilers can be used to increase drag*". Due to this inability to swiftly decelerate during continuous descent, CDA aircraft are spaced further apart to ensure separation limits. Note that during CDA aircraft can decelerate swiftly by pulling up, but this results in a non-optimal vertical profile which means that the aircraft is no longer flying a CDA. Wubben and Busink (2000) state that in order to guarantee sufficient spacing between aircraft during the final approach segment, the landing interval for Schiphol airport has to be increased from 1.8 to 4 minutes on average referring to Mohleji (1999). Wubben and Busink also argue that the increase in landing interval is necessary due to the large dispersion of aircraft approach speeds. Tong et al. (2007) show in their study that there are vast differences in deceleration capability between different aircraft types. This means that the ideal CDA vertical profile and speed profile will differ per aircraft type.

Increasing the landing interval from 1.8 to 4 minutes has a significant impact on the airport capacity. Due to this, CDA operations are implemented during low traffic hours (mostly at night). Cao et al. (2013) explains that the spacing buffer increases the flight time of aircraft which needs to be absorbed during descent or during the cruise phase, and that it "*partially offsets the fuel efficiency attributed to the optimized vertical profile*". This results in a lower fuel efficiency. Cao et al.'s findings show a reduction of 12 kg per flight in fuel savings on average due to delay absorption. Wubben and Busink also state that in conventional approaches, the arrival route can be easily lengthened by air traffic control by extending the flight path as illustrated in Figure 2-2, which results in (longer) horizontal segments.

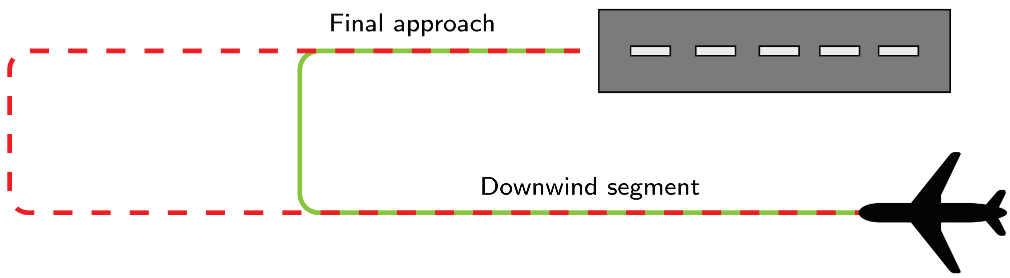


Figure 2-2: Lengthening of arrival route

This is done for delay absorption purposes. If the arrival route is extended during CDA, and results in a horizontal segment or high thrust segment in the arrival path, it would mean that the approach is by definition no longer a continuous descent approach. This means that delay absorption is quite difficult during a CDA operation. A possible solution would be to implement partial CDAs as explained by Tong et al. in which a descent is performed with non-idle thrust settings which is still beneficial compared to conventional approaches. This is also visualized in Figure 2-3. In the partial CDA the aircraft can have a different vertical profile and speed profile which might be more favorable for delay absorption. The area enclosed between the ideal CDA profile and the conventional approach profile in Figure 2-3 is the scope in which a partial CDA can be performed.

Due to the large impact of fuel and emission benefits of implementing CDAs, quite some studies have been done to investigate how CDAs can be implemented during high traffic hours as well. Tong et al. (2007)'s study is an example of such a study. Another example

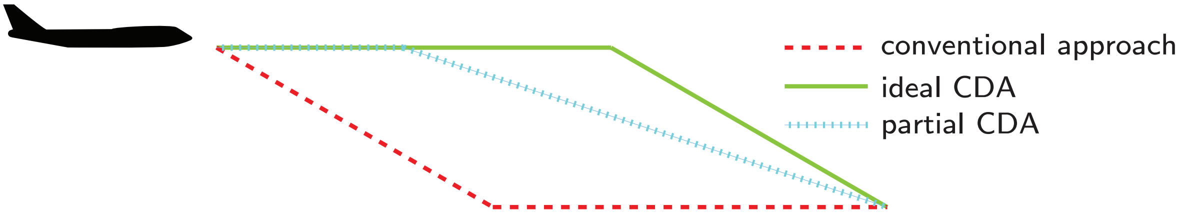


Figure 2-3: Possible partial CDA with different thrust settings

is Ledesma, Navarro, and Figlar (2007) which presents a vertical guidance law for CDAs to improve the predictability of arrival times and ground velocity. Robinson III and Kamgarpour (2010) investigated the "*prioritization of airspace, procedure and technology changes needed to achieve use of continuous descents during all traffic conditions*". However the study of counteracting the disadvantages of CDAs falls outside the scope of the current study.

2-4 Conclusion

The literature review has established for select aircraft types that CDAs can be beneficial in terms of fuel consumption. Looking at the different causes for these benefits a definition for CDAs can be stated as

a descent procedure which reduces or eliminates level flight segments after ToD conducted at (near) idle or low throttle settings flying a fuel-optimal vertical profile with a fuel-optimal speed profile.

In other words, a descent procedure where an aircraft flies as far as possible at its optimal cruise height and descends at its most optimal glide path at its optimal speed.

Disadvantages of implementing CDAs is that aircraft have to be spaced further apart to ensure separation limits. This is due to the vast difference in optimal vertical and speed profiles between aircraft type, which makes it difficult for ATC to predict the flight paths. Delay absorption is a problem as well when implementing ideal CDAs since the intervention of ATC during descent would directly deviate the aircraft from its ideal CDA. However, the current study will not focus on solving these disadvantages.

The current study aims to contribute to the body of knowledge by providing a method to calculate ideal and practical fuel-optimal vertical profiles and fuel-optimal speed profiles for all (major) aircraft types. The next chapter discusses all the steps to be taken in order to do this.

Chapter 3

Research Plan

The research objective for this project is

to contribute to the decision of implementing CDAs at Schiphol Airport by performing a fuel and emission benefit analysis using data mining, performance calculations and off-line simulations.

In order to achieve this objective several steps are necessary. This chapter shortly discusses the steps to be taken in order to complete this project. Chapter 4 discusses the methodology of the steps to be taken in more detail. In this chapter first the research questions are formulated and then all the steps to be taken for this project are discussed.

3-1 Research questions

From the research objective stated in this chapter, a set of research questions can be formulated. In order to contribute to the decision of implementing CDAs at Schiphol Airport, the main question that this project aims to answer is: "*How much fuel and emissions can be saved on a yearly basis if all aircraft arriving at Schiphol Airport would implement CDAs?*" In order to answer this question the following subset of research questions are formulated.

- What is the ideal CDA for aircraft arriving at Schiphol Airport?
  - How can fuel-optimal vertical and speed profiles be calculated?
  - What are fuel-optimal vertical and speed profiles per aircraft type?
  - What is the effect of initial altitude and speed on the fuel-optimal vertical and speed profiles?
- What is the difference in fuel consumption between conventional approach and CDA?
  - Can fuel consumption be calculated from vertical and speed profiles?
  - Does the calculated fuel consumption correspond to the actual fuel consumption from FMS data?

3-2 Strategy

In order to answer the research questions posed in Section 3-1, several steps have to be taken. These steps can be subdivided into two stages. The first stage determines **how** to calculate everything necessary for this project which will allow the second stage to actually **do** the calculations in order to find the benefits of implementing CDAs.

One of the steps in the first stage is to determine how to calculate fuel consumption. Details on the fuel calculation method can be found in Section 4-1. In order to determine whether this fuel calculation method is reliable it needs to be validated. Using the actual fuel consumption data from the FMS data the fuel calculations can be validated.

Another step during the first stage is to determine the CDA profile. A theoretical approach will lead to an ideal CDA. In the ideal CDA profile, it is expected that the top of descent (ToD) location will be different than the ToD location of most flights. This ideal CDA might not be feasible (at the moment) at Schiphol airport due to practical reasons, but will give an indication of the amount of fuel and emission benefits that could be achieved in the future. Since this ideal CDA might not be feasible, a practical CDA for Schiphol airport will also be determined. With the FMS data provided by KLM, the aircraft types flown by KLM can be analyzed and practical CDAs can be established for Schiphol airport. In this practical CDA analysis, the ToD of the actual flight location will not be changed and the speed restrictions imposed by Schiphol ATC will be enforced. Since FMS data is not available for all aircraft types, practical CDAs for those aircraft types will need to be determined by using ADS-B data. Details on how to determine CDA profiles can be found in Section 4-2. It is to be expected that the CDA profiles will differ per aircraft type. But it might also differ depending on initial altitude and speed. This means that it might be necessary to determine a CDA per flight. Figure 3-1 shows the steps from the first stage schematically.

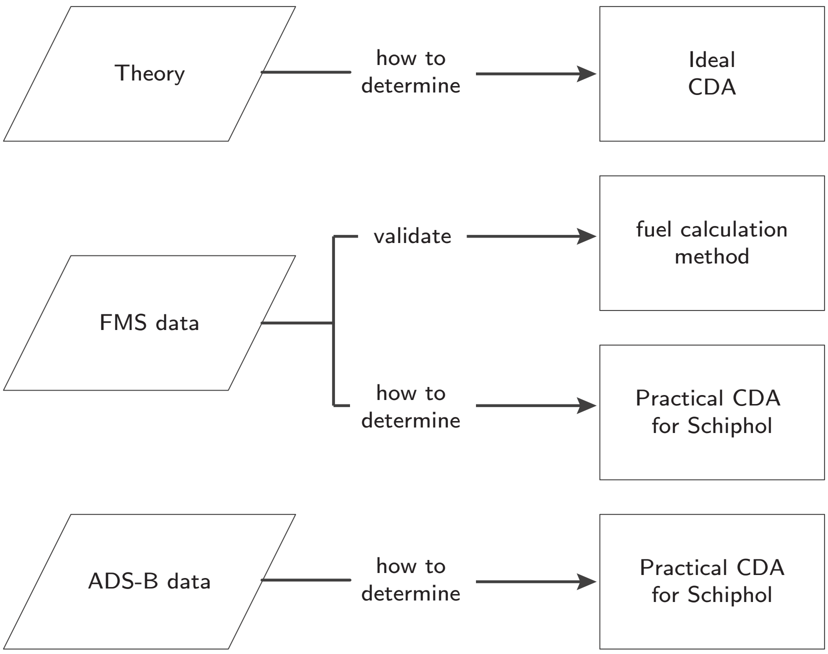


Figure 3-1: Stage I: setting up fuel calculation method and determining CDA profiles

Once the **how to** has been dealt with, it will be possible to perform fuel consumption calculations on CDA flights and to compare the fuel consumption of the CDA flights with the actual flight. This is the second stage of the project. The calculation of the benefits in the second stage using FMS data is visualized in Figure 3-2.

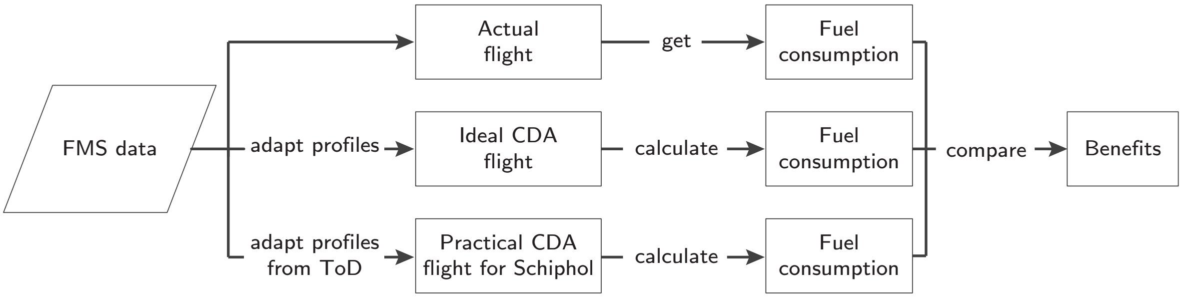


Figure 3-2: Stage II: calculating benefits using FMS data

This project aims to analyze all KLM flights landing at Schiphol airport using FMS data provided by KLM, if possible for a whole year. Since KLM flights account for roughly 65% of the movements at Schiphol Airport (Schiphol Nederland, 2016) this should provide a good representation of how much fuel and emissions can be saved by implementing CDAs. However, FMS data cannot be retrieved for all aircraft types landing at Schiphol Airport. In order to analyze the benefits of these aircraft types ADS-B data can be used where available. The calculation of the benefits in the second stage using ADS-B data is visualized in Figure 3-3.

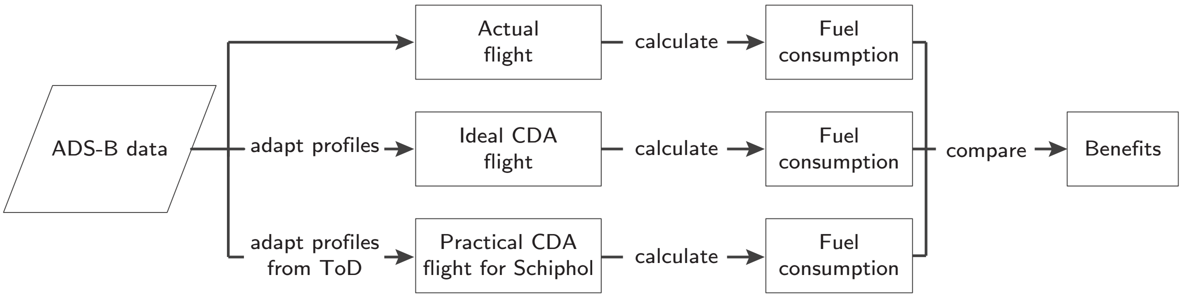


Figure 3-3: Stage II: calculating benefits using ADS-B data

3-3 Data

As mentioned in Section 3-2 this project intends to make use of two different data sources; flight management system (FMS) data provided by KLM and ADS-B data. This section discusses which data is available per source and whether any pre-processing needs to be done before the data can be used.

3-3-1 FMS data

The FMS data is provided by KLM in a `.csv` format. This data has been saved directly from the on-board computers. Table 3-1 shows an overview of the different computers which have logged the FMS data. Analysis of some data sets showed that the GPS logging sometimes logged a `zero` instead of the GPS value for either Latitude or Longitude. Using Visual Basic coding to pre-process the `csv` data, these `zero` values are filled by interpolating the values surrounding them. Most of the data is logged per second. However some data such as weight is not logged every second, but every four seconds. When loading the data into `Python` the data is pre-processed such that the gaps are filled with the last known value.

As can be seen in Figure 3-2, FMS data has fuel consumption information, which means that this will not need to be calculated. Furthermore, when using FMS data, information such as weight and configuration is available which will be helpful when determining the practical CDA flights. This information will also lead to more accurate fuel consumption results than when using ADS-B data.

Table 3-1: FMS data sources

Data	**Source**
Altitude	Air Data Computer
True Airspeed	Air Data Computer
Fuel Burn	Engine Interface and Vibration Monitoring Unit
Fuel Flow	Engine Interface and Vibration Monitoring Unit
Gross Weight	Fuel Control and Monitoring Computer
Latitude	GPS
Longitude	GPS
Roll angle	Inertial Reference Unit
Landing gear	Landing Gear Control Interface Unit
Configuration	Slat Flap Control Computer

3-3-2 ADS-B data

The ADS-B data from the TU Delft server provides time, latitude, longitude, altitude, ICAO code and ground speed data. Using the ICAO code the aircraft type can be determined. A disadvantage of ADS-B data is that the intervals between data points can differ quite a bit. This provides a challenge when using this data. One way to tackle this issue would be to interpolate the data. Another possibility is to use ADS-B data from another source. It is possible to “scrape” data from Flightradar24. By doing this every second or every two seconds a steadier flow of data is guaranteed and no pre-processing is necessary before using the data. Another disadvantage of ADS-B is that weight and configuration data is not available. This means that a reference weight will need to be used which will lead to less accurate fuel consumption results.

3-4 Limitations

For this project the influence of the lateral path of the flight is neglected. For all aircrafts analyzed in this project only the altitude and speed profiles vs. along track distance to runway will be 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 due to holding patterns, i.e. prolongation of the lateral path, the CDA profile will also follow this prolongated lateral path. Figure 3-4 shows that the calculated CDA follows the exact lateral path while it might have been possible to fly a shorter distance. This means that the results of this project will be conservative.

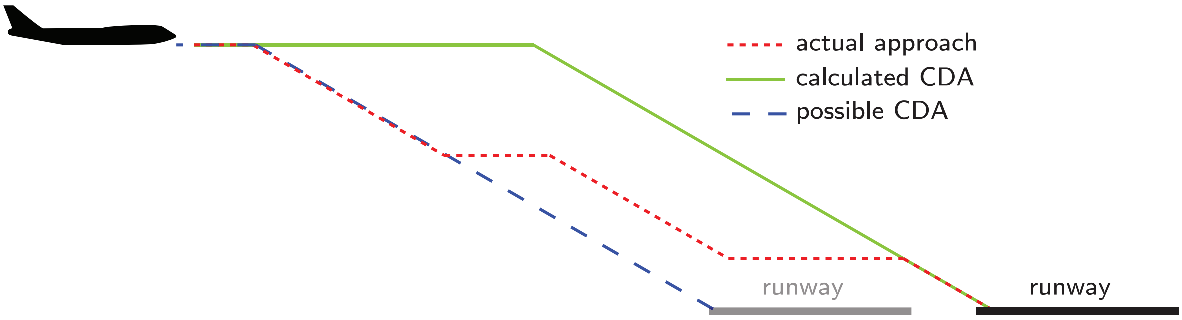


Figure 3-4: CDA calculated along the lateral path of the original flight

Chapter 4

Methodology

This chapter dives into the details on how to calculate fuel consumption and determine CDA profiles. First, a method to calculate the fuel consumption will be discussed in Section 4-1. This is an important component for this project. This section will also set the first steps toward validating the fuel calculation method using FMS data provided by KLM. The second section will discuss different methods to determine the CDA profile per aircraft type.

4-1 Fuel consumption

Accurate fuel consumption calculation is an important component for this project. If the fuel consumption cannot be calculated accurately, the results of this project will have no significance. This section discusses a fuel consumption method and sets the first steps in validating this fuel consumption method using actual flight data so that it can be used for fuel calculation once the CDA profiles have been determined.

Fuel consumption can be calculated using performance calculations from Base of Aircraft Data (BADA). BADA is an aircraft performance model, which has been developed and is maintained by EUROCONTROL with the cooperation of aircraft manufacturers and operating airlines, based on a kinetic approach to aircraft performance modeling (Nuic, Poles, & Mouillet, 2010). TU Delft has access to BADA 3.12 which "*provides a set of ASCII files containing performance operating procedure coefficients for 438 different aircraft types. The coefficients include those used to calculate thrust, drag and fuel flow*" (Nuic, 2014). This covers close to 100% of aircraft types in the European Civil Aviation Conference (ECAC) area (Eurocontrol, n.d.). 166 of these aircraft types have their own coefficient files and are referred to as original aircraft models. The other 272 aircraft types were identified as 'equivalent' to original aircraft models and make use of one of the coefficient files from the 166 original aircraft models.

4-1-1 Method

In order to calculate aircraft performance, BADA uses a total-energy model (TEM) which "*equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy*" (Nuic, 2014). Equation 4-1 represents the TEM. The fuel flow of an aircraft can be calculated from the thrust-specific fuel consumption (TSFC) value η [kg/(min·kN)] which depends on the true airspeed in knots. Fuel flow is a linear function of the TSFC value η and thrust. Thrust can be calculated using Equation 4-2. BADA also defines a minimum fuel flow as a function of the height.

$$(Thr - D) \cdot V_{TAS} = mg_0 \frac{\mathrm{d}h}{\mathrm{dt}} + mV_{TAS} \frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} \tag{4-1}$$

In Equation 4-1 Thr stands for Thrust [N], D is drag [N], m is aircraft mass [kg], h is altitude [m], g_0 is the gravitational acceleration [m/s^2], V_{TAS} is true airspeed [m/s] and $\frac{\mathrm{d}}{\mathrm{dt}}$ the time derivative. In order to calculate the Thrust, Equation 4-1 can be rewritten to:

$$Thr = \frac{mg_0}{V_{TAS}} \frac{\mathrm{d}h}{\mathrm{dt}} + m \frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} + D \tag{4-2}$$

Speed and height data for Equation 4-2 can be obtained from FMS data provided by KLM or from ADS-B data. The height and speed data along with time information can be used to determine $\frac{\mathrm{d}h}{\mathrm{dt}}$ and $\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}}$. The values for $\frac{\mathrm{d}h}{\mathrm{dt}}$ and $\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}}$ can be determined using the finite difference method and coefficients provided by Fornberg (1988). Since mass is unknown when using ADS-B data, BADA provides a reference mass per aircraft type. Then, only drag remains, which can be calculated using Equation 4-3.

$$D = \frac{C_d \cdot \rho \cdot V_{TAS}^2 \cdot S}{2} \tag{4-3}$$

In Equation 4-3 S is the wing reference area [m^2] which is provided by BADA per aircraft type, ρ is the air density [kg/m^3] which can be calculated as a function of the height using an atmospheric model provided by BADA and finally C_d stands for the drag coefficient which is a function of the lift coefficient C_l and depends on the aircraft configuration. For cruise, approach and landing configurations, BADA provides different coefficients for C_d calculations. The lift coefficient C_l can be calculated as a function of mass, g_0, air density, true airspeed, wing surface area and bank angle using Equation 4-4. When using FMS data the bank angle is available, however when using ADS-B data, the bank angle is not available and will thus be neglected in fuel consumption calculations. Since bank angles are small and occur for short periods of time during descent, this should not have a large influence on the results when using ADS-B data.

$$C_l = \frac{2 \cdot m \cdot g_0}{\rho \cdot V_{TAS}^2 \cdot S \cdot \cos\phi} \tag{4-4}$$

Now that the thrust can be calculated, the fuel flow can be calculated from thrust and η.

4-1-2 Validation

Using FMS data from different KLM aircraft types, the fuel calculation method described in Section 4-1 can be validated. This section will describe the first steps taken toward validating the fuel calculation method using an anonymized sample from the FMS of an Airbus A330-200. In this short sample the A330-200 is descending from a height of 29,824 ft and changes its descent rate after about a minute into the sample. The height profile for this sample can be seen in Figure 4-1.

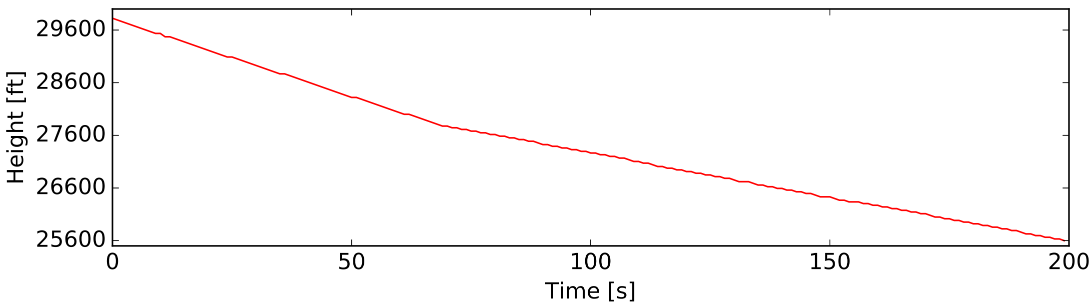
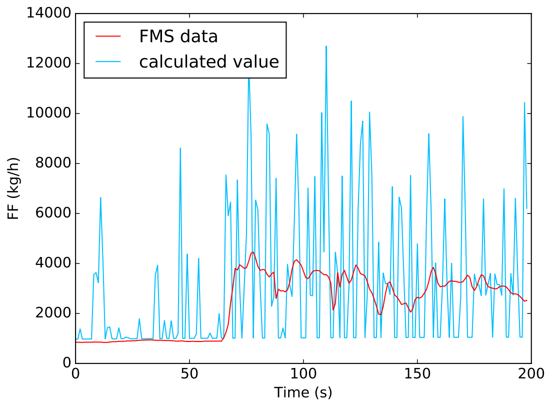
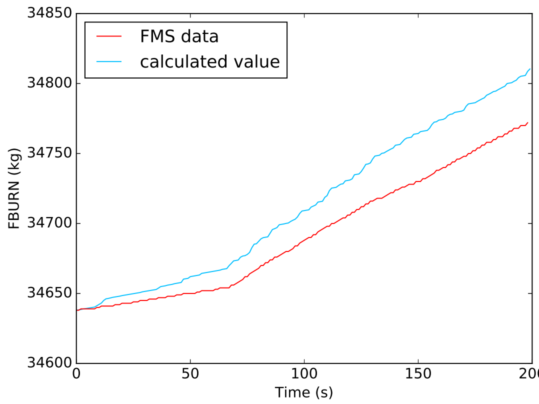


Figure 4-1: Height profile for KLM flight sample

As explained in Section 4-1, $\frac{dh}{dt}$ and $\frac{dV_{TAS}}{dt}$ can be determined using the finite difference method. The results of applying the method from Section 4-1 to calculate the fuel flow can be seen in Figure 4-2. By integrating the fuel flow, the fuel burn can also be calculated. The fuel burn is also given in Figure 4-2.



(a) Fuel flow



(b) Fuel burn

Figure 4-2: FMS data vs BADA estimates with finite difference method

Figure 4-2a shows highly fluctuating fuel flow results from the calculations. This indicates a lot of noise or fluctuation in the data. Analysis showed that the fluctuations are caused by the discrete height and speed data. To remove these large fluctuations, a Gaussian filter can be applied to the height and speed data before implementing the finite difference method to calculate the derivatives. The next step then is to determine how large the Gaussian filter should be. For this more research needs to be done on what the best fitting filter would be with a larger data sample. Appendix C shows the results of applying different Gaussian filters on the data.

Another interesting phenomenon in Figure 4-2b is that the calculated fuel burn is higher than the actual fuel burn. This is due to the fact that a minimum fuel flow has been defined and the fluctuations are thus cut off in the lower regions. Once the fuel flow fluctuations are dealt with, the overestimation is expected to disappear.

Once a proper filter has been determined, the fuel calculation method can be validated by analyzing several flights per aircraft type. If the error between the actual data and the calculated data is small enough the method can be accepted and applied for the rest of this project. How large the error may be before acceptance still needs to be determined.

4-2 CDA profiles

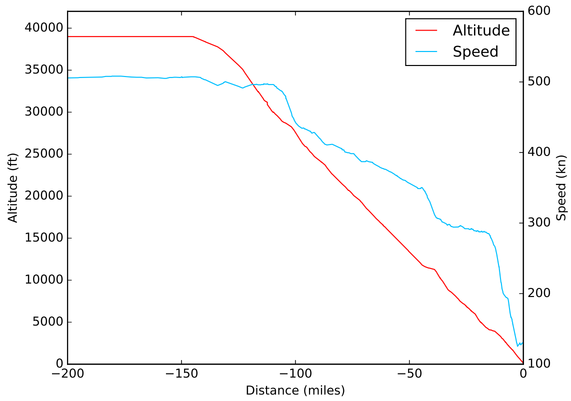
The literature review in Chapter 2 defined CDA as "*a descent procedure which reduces or eliminates level flight segments after ToD conducted at (near) idle or low throttle settings flying a fuel-optimal vertical profile with a fuel-optimal speed profile*". This means that in order to determine a CDA profile, a fuel-optimal vertical profile and fuel-optimal speed profile needs to be generated from cruise level. This needs to be done per aircraft type since each aircraft type has different performance characteristics. But since different flights with the same aircraft can occur at different cruise altitudes and speeds, it might be necessary to determine a CDA profile per flight. This section presents some possible methods to determine a CDA profile. First the theoretical approach as explained in Section 3-2 is specified. Then the possibilities of determining CDA profiles using FMS data is discussed. And finally some possibilities on how to determine CDA profiles using ADS-B data is discussed.

4-2-1 Characteristics of a fuel-optimal CDA

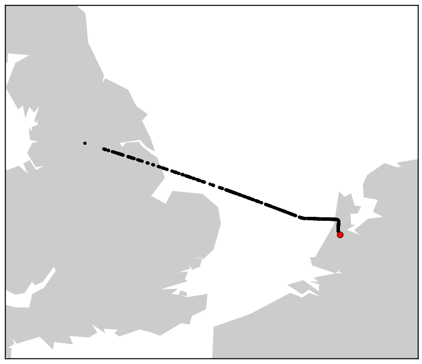
Before CDA profiles can be determined, some characteristics of a fuel-optimal CDA needs to be discussed. This project defines the following characteristics:

- no horizontal flight segments after ToD
- no acceleration after ToD
- minimal constant speed segments
- minimal divergence from shortest flight path

Figure 4-3 shows an example of a possible CDA flight of an Airbus A330-200 aircraft retrieved via ADS-B. In this figure, the A330-200 descends gradually from a cruise altitude of 39,000 ft without any horizontal flight segments. As can be seen by the speed profile, there are also no accelerations after ToD and barely any constant speed segments. As can be seen on the map in Figure 4-3b the aircraft flies in nearly a straight line over England to Schiphol airport. However, around 28,000 ft and 11,000 ft a slight pull-up maneuver can be seen in Figure 4-3a which can be interpreted as a small near horizontal segment. Since the aircraft is still slightly descending at these points it is not really a horizontal segment and the affect of these points is that the speed drops drastically. These small pull-up maneuvers can be used for deceleration purposes as explained in Section 2-3.



(a) Vertical and speed profile



(b) Flight path

Figure 4-3: Example of possible CDA flight of an A330-200

4-2-2 Ideal CDA

Using a theoretical approach, an ideal CDA can be determined by analyzing the Total-energy model (TEM) used by BADA. Section 4-1-1 explained that fuel flow is a function of thrust. If Equation 4-2 for thrust can be rewritten as a function of rate of descent, airspeed and acceleration only, the thrust can be minimized by analyzing the influence of the descent rate, airspeed and acceleration. Equation 4-2 for thrust was given in Section 4-1-1 as:

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

Using Equations 4-3 and 4-4 and the definition for C_d given by BADA, Equation 4-2 can be rewritten to Equation 4-5.

$$Thr = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{dt}} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} + C_d \cdot \frac{\rho \cdot V_{TAS}^2 \cdot S}{2}$$

$$Thr = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{dt}} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} + \left[c1 + c2 \cdot (C_l)^2\right] \cdot \frac{\rho \cdot V_{TAS}^2 \cdot S}{2}$$

$$Thr = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{dt}} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} + \left[c1 + c2 \cdot \left(\frac{2 \cdot m \cdot g_0}{\rho \cdot V_{TAS}^2 \cdot S \cdot \cos\phi}\right)^2\right] \cdot \frac{\rho \cdot V_{TAS}^2 \cdot S}{2}$$

$$Thr = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{d}t} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{d}t} + c1 \cdot \frac{\rho \cdot V_{TAS}^2 \cdot S}{2} + c2 \cdot \frac{4 \cdot m^2 \cdot g_0^2}{\rho^2 \cdot V_{TAS}^4 \cdot S^2 \cdot \cos^2\phi} \cdot \frac{\rho \cdot V_{TAS}^2 \cdot S}{2}$$

$$Thr = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{d}t} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{d}t} + c1\frac{\rho \cdot V_{TAS}^2 \cdot S}{2} + c2\frac{2 \cdot m^2 \cdot g_0^2}{\rho \cdot V_{TAS}^2 \cdot S \cdot \cos^2\phi} \tag{4-5}$$

In Equation 4-5, m is assumed constant (during a CDA descent the change in mass is assumed to be small enough to neglect), g_0 is assumed constant, $c1$ and $c2$ are constants which depend on the configuration of the aircraft and S is constant per aircraft type. Fur the purposes of analyzing the optimal vertical en speed profiles, the bank angle is assumed to be zero. This reduces Equation 4-5 to:

$$Thr = K_1\frac{\dot{h}}{V} + K_2\dot{V} + K_3\rho V^2 + K_4\frac{1}{\rho V^2} \tag{4-6}$$

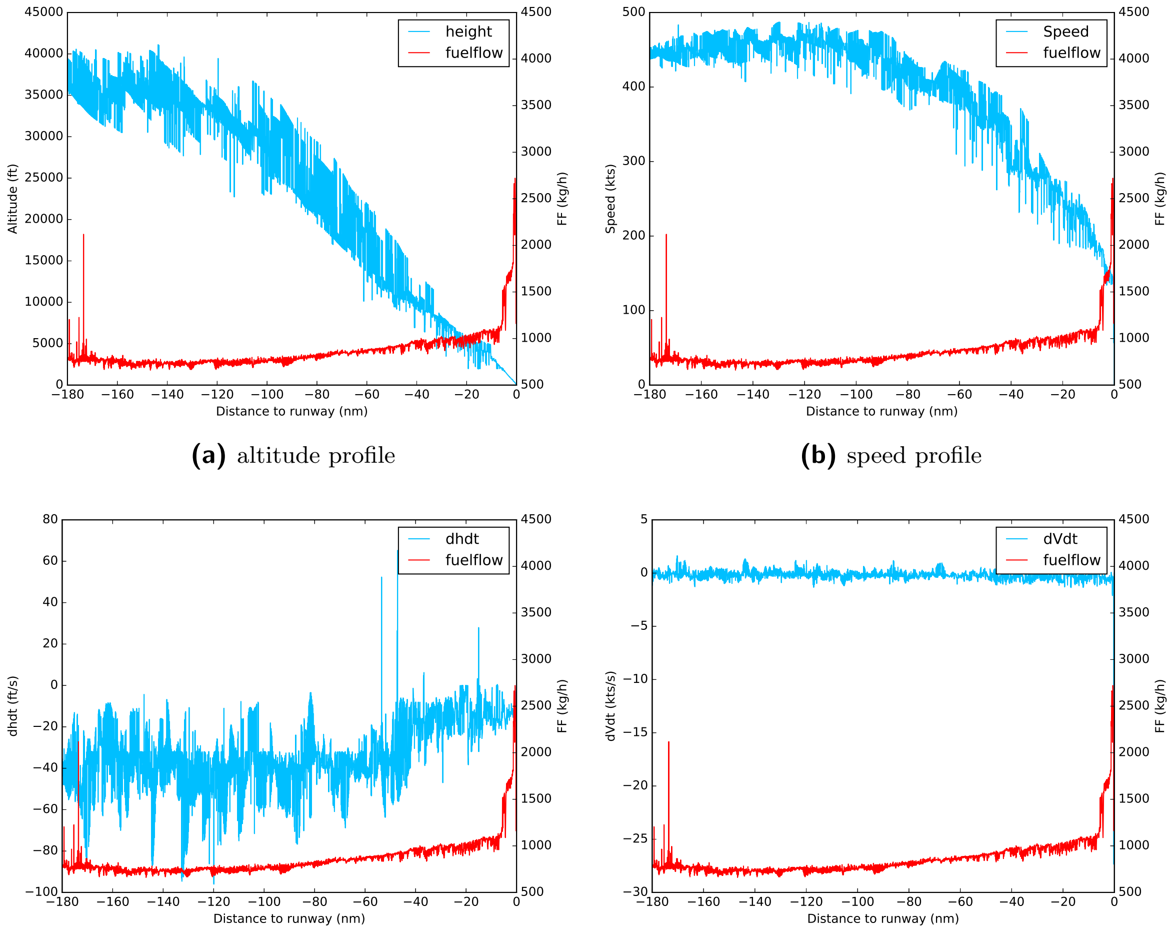
in which K_{1-4} are constants, $\dot{h}$ is $\frac{\mathrm{d}h}{\mathrm{d}t}$, $\dot{V}$ is $\frac{\mathrm{d}V_{TAS}}{\mathrm{d}t}$ and ρ is a function of height. Thus Equation 4-6 for thrust is a function of height, rate of descent, speed and acceleration. These are exactly the variables needed for the optimal vertical and speed profiles. For each flight the initial height and speed is known. Which means that only the rate of descent and acceleration needs to be determined. By running simulations for different rates of descent and accelerations, the values which result in the least fuel consumption can be determined. It is to be expected that the rate of descent corresponding with maximum glide ratio will be most fuel efficient. But since this will be a slow and long flight it might have the lowest fuel flow, but in the end a higher total fuel consumption. By running simulations the profile with the least total fuel consumption needs to be determined. This will then result in an ideal CDA.

4-2-3 Practical CDA for Schiphol

Since the theoretical CDA calculated in the previous section might not be feasible at Schiphol airport due to practical reasons such as speed, time and altitude restrictions, a practical CDA will also be developed which will comply with the restrictions. This can be done by adjusting the theoretical model to include the restrictions and by analyzing the FMS and ADS-B data of flights landing at Schiphol to get an idea of the practical characteristics during approach.

Minimal fuel flow properties

Using a big data approach to analyze multiple flights, the flight properties with minimal fuel flow can be analyzed. Since the flight path and position data is known for each flight, the distance to runway can be calculated for each flight. By subdividing the distance to runway into small intervals and analyzing the flight properties at each interval for as many flights as possible, it might be possible to define a minimal fuel flow vertical and speed profile. For each interval, the flight properties of the flight with the least fuel flow according to the FMS data or fuel calculations of the ADS-B data can be saved. The results of analyzing 166 A330-200 aircraft is shown in Figure 4-4.



(a) altitude profile

(b) speed profile

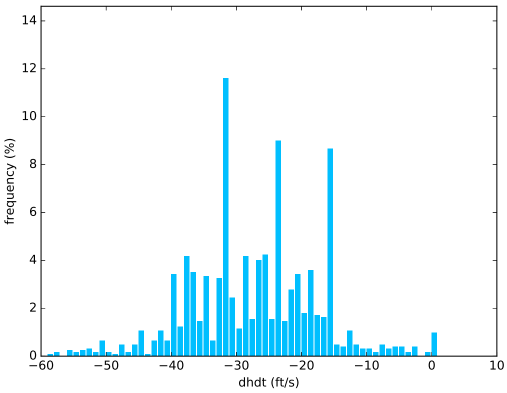
(c) rate of descent

(d) acceleration

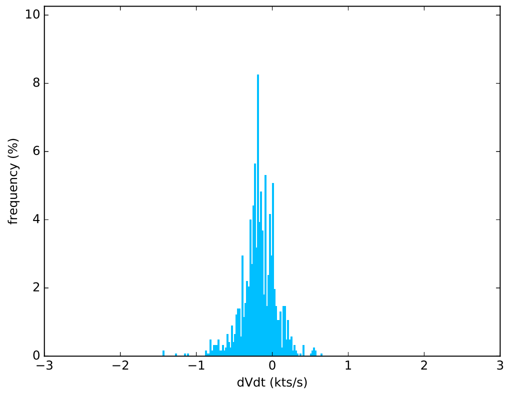
Figure 4-4: CDA profiles for minimal fuel flow

Most common properties

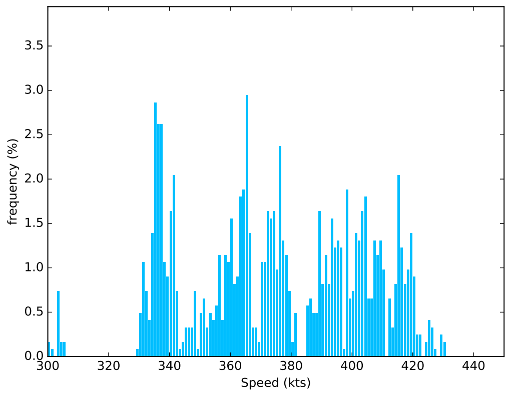
Another possibility is to analyze the most common rate of descent, speed and acceleration at each altitude. By combining the most common values for each altitude a vertical and speed profile can than be obtained which might be the optimal profiles. The idea behind this method is the assumption that when examining a lot of descents, the most occurring descent rate, speed and acceleration per altitude will be the ideal settings for the aircraft type selected by the FMS. The results of analyzing 166 A330-200 aircraft for their most common flight properties at a height of 20,000 ft is shown in Figure 4-5.



(a) rate of descent



(b) acceleration



(c) speed

Figure 4-5: Most common properties at FL200

Appendix A

Definitions

CDA "Continuous Descent Approach is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and ATC instructions." (Eurocontrol et al., 2011)

Thrust transient Significant but short duration increases in thrust

Top of descent Transition point from cruise phase to descent phase

Track distance Distance from aircraft to runway threshold

Appendix B

Schiphol Traffic Review 2015

Table B-1: Monthly air transport movement totals for 2015 (Schiphol Nederland, 2016)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
32,032	30,607	34,599	37,602	41,072	40,070	42,494	42,341	40,558	40,241	34,454	34,609

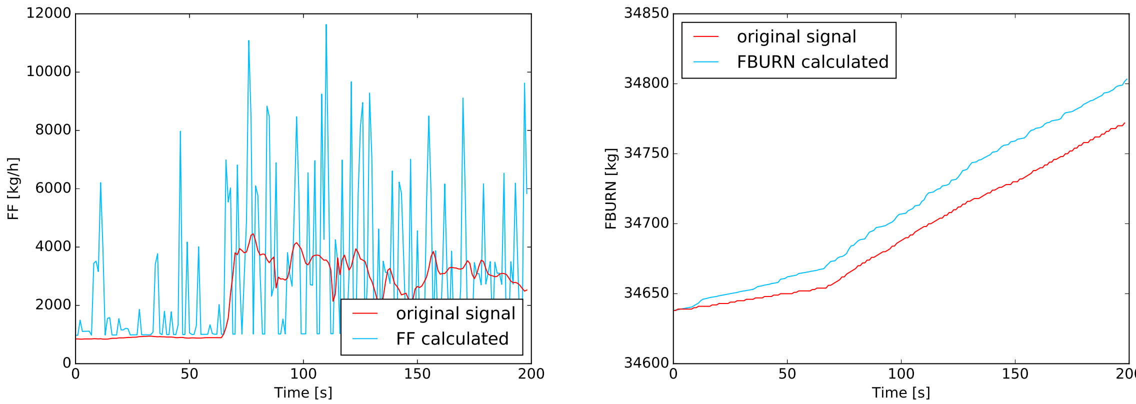
Table B-2: Aircraft types and movements at Schiphol for 2015 with average maximum take off weight (MTOW) in tonnes and number of flight movements (Schiphol Nederland, 2016)

Type	Average MTOW	Movements
Boeing 737-800	74	90,277
Embraer 190/195	46	68,314
Airbus A320	75	47,328
Boeing 737-700	62	40,513
Fokker 70	37	35,231
Airbus A319	66	31,672
Boeing 747-400	395	12,669
Airbus A330-200	229	10,287
Boeing 777-200	298	10,095
Airbus A330-300	233	9,885
Airbus A321	86	9,826
Boeing 737-900	78	9,492
Boeing 777-300	351	8,320
Embraer 170/175	38	6,766
Dash 8-400	30	6,419
Boeing 767-300	184	5,484
Bae 146/AVRO RJ	42	5,042
Bombardier CRJ 700/900/1000	37	3,970
Embraer ERJ 145	20	3,326
Boeing 737-300	61	2,476
Boeing 787-8	228	2,313
Fokker 100	45	2,205
Boeing 757-200	113	2,175
Boeing 767-400	205	1,712
Boeing 737-500	57	1,509
Airbus A318	61	1,292
Airbus A340-300	269	1,082
Airbus A380	529	988
Boeing 737-600	60	784
Boeing 737-400	66	459

Appendix C

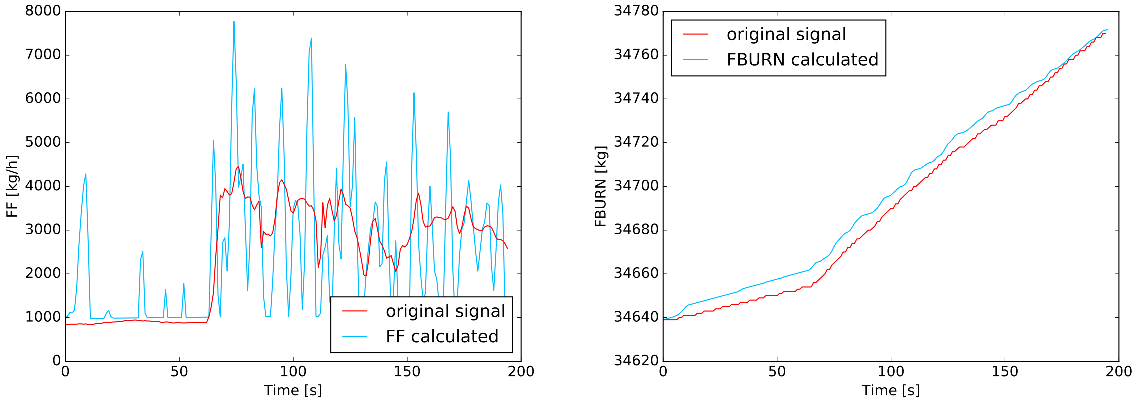
Fuel consumption results

This appendix shows the fuel flow and fuel burn calculation results using the method described in Chapter 4 when different Gaussian filters have been applied to the height and speed data. The results vary with the width of the Gaussian filter. As expected a wider filter results in less variation of the signal.



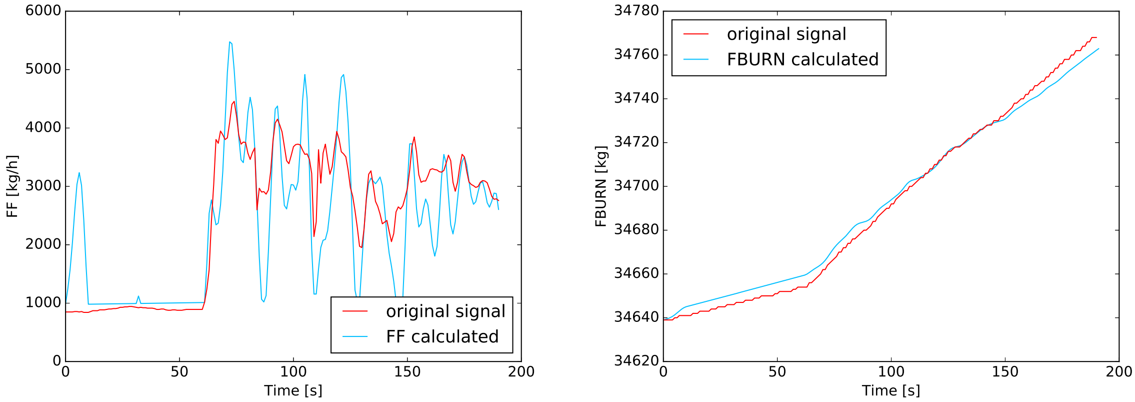
(a) Fuel flow **(b)** Fuel burn

Figure C-1: FMS data vs BADA estimates without filter



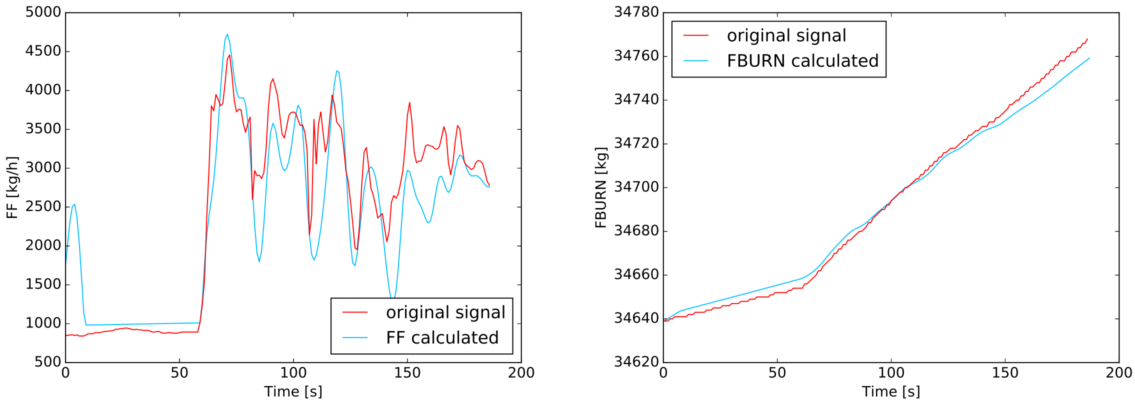
(a) Fuel flow **(b)** Fuel burn

Figure C-2: FMS data vs BADA estimates with Guassian filter sample size one



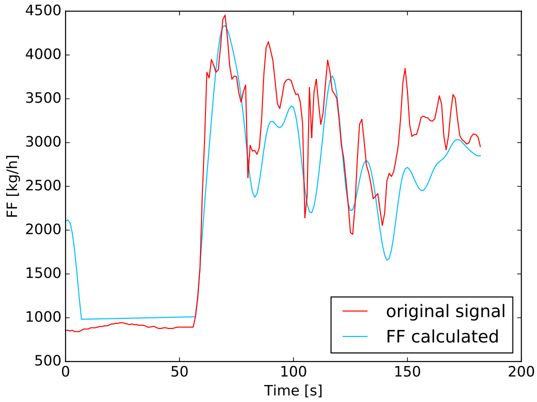
(a) Fuel flow **(b)** Fuel burn

Figure C-3: FMS data vs BADA estimates with Guassian filter sample size two

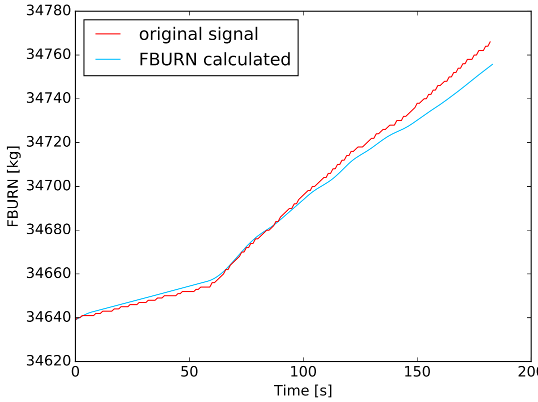


(a) Fuel flow **(b)** Fuel burn

Figure C-4: FMS data vs BADA estimates with Guassian filter sample size three

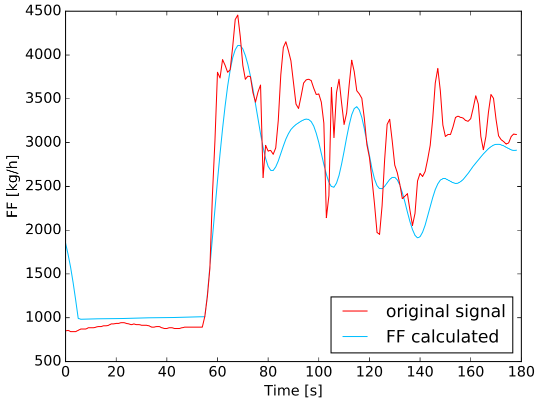


(a) Fuel flow

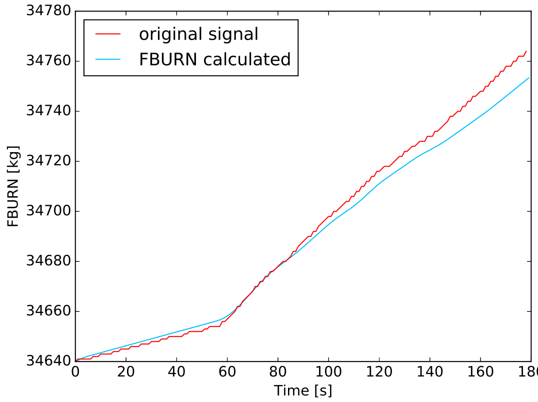


(b) Fuel burn

Figure C-5: FMS data vs BADA estimates with Guassian filter sample size four

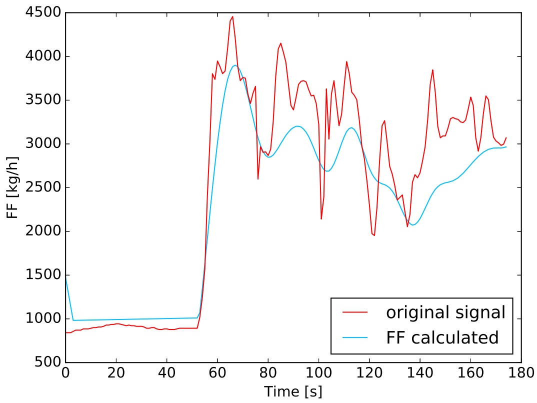


(a) Fuel flow

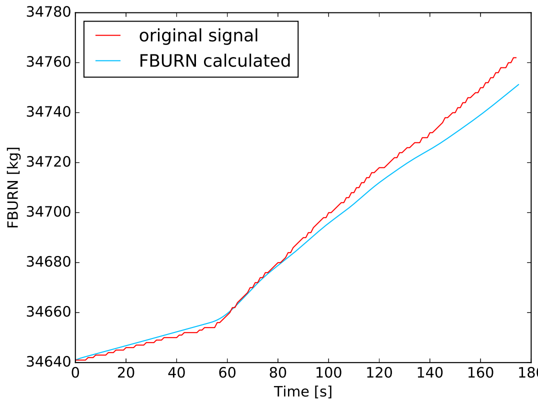


(b) Fuel burn

Figure C-6: FMS data vs BADA estimates with Guassian filter sample size five



(a) Fuel flow



(b) Fuel burn

Figure C-7: FMS data vs BADA estimates with Guassian filter sample size six

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Part III

Appendices

Appendix A

Data

Two types of historical data is used in this study; flight management system (FMS) data and ADS-B data. This section discusses which data is available per data type and whether any pre-processing needs to be done before the data can be used.

A-1 FMS data

The FMS data is provided in a `.csv` format. This data has been saved directly from the on-board computers. Using Visual Basic coding to pre-process the `csv` data, incomplete datasets (where the data stops before the aircraft reaches final approach fix (FAF) altitude) and erroneous datasets are removed. Furthermore, the datasets are processed such that only data from cruise altitude up to the landing is available. Most of the data is logged per second. However some data such as weight is not logged every second, but every four seconds. When loading the data into `Python` the data is pre-processed such that the gaps are filled with the last known value.

When using FMS data, information such as weight and configuration is available which is used to set up the CDA profile determination. The information can be used for example to determine at which speed the flap configuration needs to change.

A-2 ADS-B data

The TU Delft has an ADS-B receiver (Sun, 2015-2016). However during the study it became clear that not all flights were registered by this receiver. A solution is found in Flightradar24 (2012-2016) which has a network of more than 10,000 ADS-B receivers and also implements Multilateration (MLAT) to calculate positions and speeds of non-ADS-B equipped aircraft which use an older ModeS-transponder. It is however not possible to simply download historical flight data from Flightradar24, and so a server was set up which "scraped" data from Flightradar24 for a couple of months.

A disadvantage of ADS-B data is that the intervals between data points can differ quite a bit. This problem is solved by interpolating the data. Another disadvantage of ADS-B is that aircraft mass and configuration data is not available. This means that a reference mass will need to be used which will lead to less accurate fuel consumption results. For this study the reference mass provided by BADA is used and the configuration is set to be dependent on the stall speeds per configuration which is also provided by BADA.

Appendix B

Programming code

For this project, two programming languages are used. `Python` is the main language and `Visual basic` code is used for some of the FMS data processes since this allows easy interaction with the csv files.

B-1 Pre-processing

B-1-1 FMS data

The FMS data is available in `.csv` format. The FMS data is mainly preprocessed using visualbasic code found in `Data_correction.xlsm`. The `Height` module removes data from the data file after the aircraft has landed (to make sure that divide by 0 cannot occur due to zero speed) and also removes the climbing phase of the flight before cruise. The `DataCheck` module then runs the data files through several different checks, such as: if the data file smaller than 300 data points the data file is deleted or if the data stops before the aircraft has reached FAF altitude a warning is printed.

Next the BADA coefficients are calibrated. This is done in two phases. First only the cruise coefficients are calibrated. After that the other coefficients are calibrated. In order to do this, the `csvwriter.py` file writes a csv file using multiple flights with only the cruise configuration data points or with the rest of the configuration data points and prints out the initial coefficients. Next the `BADA` module in `Data_correction.xlsm` prepares the csv files for calibration. Finally using the GRG-nonlinear solver in Excel the coefficients are then calibrated.

Finally, using `Configuration.py` the airspeeds at which the configurations have to be changed are determined.

B-1-2 ADS-B data

The ADS-B data is stored in a MongoDB format. First all the data is restored using the standard restore function of `mongodb` in collections per month. Next the `extract_flights_fr24.py` is run to sort the data per flight. This extraction is based on previous work done by Junzi Sun. Since the database is now very large and it takes time to go through all the flights, the database is reduces using `remove_flights.py` which removes flights which do not land at Schiphol. Finaly, the `ADSB_id.py` file returns the flight numbers of all flights corresponding to an aircraft type in the database.

B-2 Simulation

Figure B-1 shows the relations between the different python files and the most important functions per file for the FMS data simulations. The structure for the ADS-B simulations is comparable.

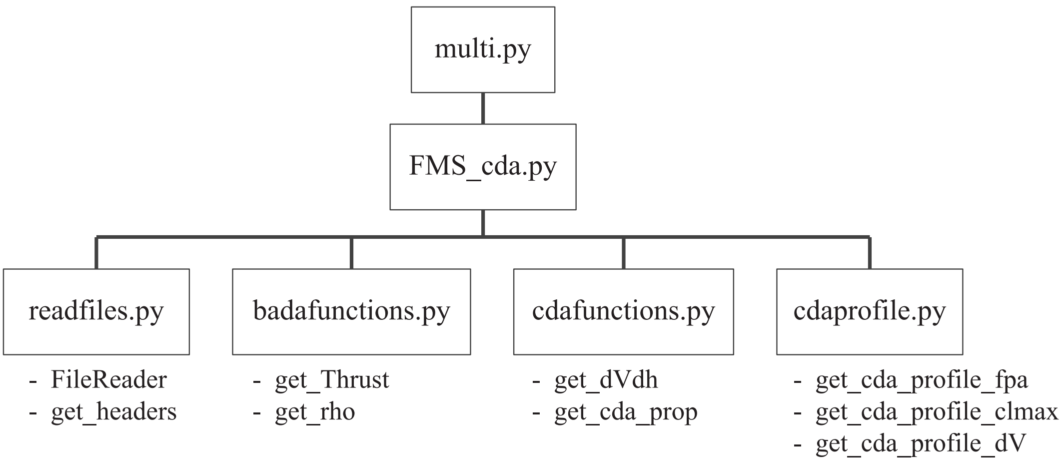

Figure B-1: Simulation structure python files

`readfiles.py`

`FileReader` uses a python csv reader to read in the FMS data files and to store in a dictionary format. Since not all variables are logged each second, the last known value of each variable is held until a new value is found for that variable. Each aircraft type has a different name for the altitude variable and landinggear variable. The function `get_headers` links the names of these variables to aircraft types. It also stores the airspeed at which the configuration of the aircraft should be switched per aircraft type.

`badafunctions.py`

This file has important functions such as the calculation of air density and calculation of thrust as explained in the BADA manual. It also imports the BADACoefficients file from BlueSky which is used to read the BADA coefficient files per aircraft type.

`cdafunctions.py`

This file has the function `get_cda_prop` which returns the indexes of the ToD and FAF of the original flight. It also has the function `get_dVdh` which returns the time derivations of speed and altitude using the finite difference method and coefficients provided by Fornberg (1988).

`cdaprofile.py` and `adsb_cdaprofile.py`

These files have the functions that actually build the cda profile. Depending on whether constant fpa, constant deceleration or cl/cd max is used, the corresponding function can be called upon.

`FMS_cda.py`

This is the main calculations file. This file imports `readfiles.py`, `badafunctions.py`, `cdafunctions.py` and `cdaprofile.py`. Once the FMS data is imported, the variables are converted to SI units. The fuelflow is calculated using a `for-loop` for the entire historical flight. The configuration of the FMS aircraft types are listed in `Data_correction.xlsm`. The fuel consumption is then found by crudely integrating the fuel flow over time. In the same manner the fuel consumption of all the CDA profiles are determined and at the end of the simulation, the CDA profile with the maximum fuel benefit is returned.

`ADSB_cda.py`

The main difference with `FMS_cda.py` is that this file opens the `mongodb` database and also interpolates the data to a time rate of 1 Hz.

`multi.py`

The `multi.py` file allows multiprocessing of the different flights to save computation time.

B-3 Results

The `badaA330.py` file generates the images used to show the accuracy of the BADA calulations in Section II-B of the paper. `A330_cda.py` generates the example CDA profiles shown in the Results Section V-A. `Boxplots.py` creates all the boxplots per aircraft type found in the Results of the paper and `Histograms.py` creates all the histograms found in the Results section of the paper.

Appendix C

Acknowledgements

This report is the result of my Master thesis for the Control and Simulation track of Aerospace Engineering. In choosing my thesis subject, I was looking for a project with a lot of programming work. When Jacco mentioned the fact that the benefits of CDAs were being disputed and that this thesis would include analyzing large amounts of data, I was instantly attracted to it. In the first place because I thought that CDAs would definitely have beneficial effects on fuel and emissions, and secondly because I liked the challenge of analyzing multiple flights of multiple aircraft types. Automating the simulation process was something that I really looked forward to.

This thesis would not have been possible without the help of KLM, and for that I would first like to thank Ceriel Janssen for the possibilities he created to work together towards this goal. I would also like to thank Roberto Hofman for all his help in obtaining the proper data, and his willingness to answer all my questions with regard to the data and different KLM aircraft types.

I would especially like to thank Joost and Jacco. Joost, thank you for your patience in reading multiple versions of my report and providing essential and critical feedback to improve it. Jacco, thank you for your enthusiasm and motivation. Whenever I hit a wall, you motivated me to keep going.

I would also like to thank my fellow students, friends and family for their support and motivation to finally finish my study. And last, but not least I would like to thank Marit for all her support during the entire process and for the substantive discussions about my thesis that kept me going whenever I did not know how to proceed.

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Nijmegen, the Netherlands
November 30, 2016

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