TÉCNICO LISBOA

Calculation and replication of several In Flight Performance scenarios from the Quick Reference Handbook

Development of a Computational Methodology

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Statement

I declare that this document is an original work of my own and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

Nos últimos tempos, as tecnologias de informação têm assumido um papel fundamental na evolução das operações na aviação comercial. Os constantes avanços tecnológicos e o consequente aumento do poder de computação dos dispositivos permitem a digitalização de processos e publicações até então baseados em papel.

Os pilotos têm ao seu dispor uma ferramenta informática denominada Programa de Gestão Eletrónica de Dados (EFB). Este dispositivo permite efetuar cálculos complexos de desempenho em tempo real e consultar diversa documentação relacionada com a operação das aeronaves. A introdução do EFB nos *cockpits* tem permitido aumentar a segurança e eficiência das companhias aéreas.

Este trabalho toma como ponto de partida o Manual de Referência Rápida (QRH), um manual que contém dados de desempenho de aeronaves referentes a diversos cenários de voo. Este projeto foi motivado pela intenção da Airbus de remover alguns desses cenários da versão impressa do QRH. O objetivo deste trabalho consiste na replicação desses cenários em formato digital, para a frota atual da TAP.

Esta tese acompanha o processo de replicação para um tipo específico de aeronave, o Airbus A320neo. É dado especial enfoque aos métodos usados na obtenção de dados para os cenários a replicar, e na sua inclusão numa estrutura de base de dados. De seguida, os resultados obtidos são aplicados a dois casos concretos e comparados com os valores correspondentes que constam no QRH, discutindo-se as eventuais diferenças. Por fim, são avaliados os possíveis desenvolvimentos futuros para a solução apresentada, nomeadamente a sua inclusão no EFB da TAP.

Palavras-chave: Desempenho de Aeronaves, Manual de Referência Rápida, Programa de Gestão Eletrónica de Dados, *Airbus Performance Engineer's Programs*

Abstract

In recent times, information technology has assumed a key role in the transformation of airlines' operations. Constant technological advances and the consequent increase of the devices' computing power allow for the digital transformation of paper-based processes and publications.

Pilots have at their disposal a computer tool called Electronic Flight Bag (EFB). This device allows them to perform complex performance calculations in real-time and consult various aircraft operations-related publications. The introduction of EFBs into the cockpits has increased the operational safety and efficiency of airlines.

This work's foundation is the Quick Reference Handbook (QRH), a printed manual that contains aircraft performance data regarding various flight scenarios. This project was motivated by Airbus' planned removal of some of these scenarios from the printed version of the QRH. The objective of this work is the replication of said scenarios in digital format, for TAP's current fleet.

This thesis covers the entire replication process for a specific type of aircraft, the Airbus A320neo. Special focus is placed on the data retrieval methods for the various scenarios to be replicated, and their subsequent inclusion into a database structure. The obtained results are then applied to two specific cases and compared with the corresponding values in the QRH. Eventual discrepancies between the two data sets are then discussed. Finally, the prospective developments for the presented solution are evaluated, namely its inclusion into TAP's EFB.

Keywords: Aircraft Performance, Quick Reference Handbook, Electronic Flight Bag, Airbus Performance Engineer's Programs

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Nomenclature

A/C Air Conditioning

AC Advisory Circular

AE Absolute Error

AI Anti Ice

AMC Acceptable Means of Compliance

API Application Programming Interface

APM Aircraft Performance Monitoring

BLT Boeing Laptop Tool

c-PED Controlled Portable Electronic Device

CAS Calibrated Air Speed

ceo Current Engine Option

CG Center of Gravity

CL Climb

COTS Commercial Off-The-Shelf

CSV Comma-Separated Values

DB Database

EASA European Union Aviation Safety Agency

EAS Equivalent Air Speed

ECAM Electronic Centralized Aircraft Monitor

EFB Electronic Flight Bag

EF Entity Framework

EKB Electronic Kit Bag

eOps e-Operations

EU European Union

FAA Federal Aviation Administration

FCOM Flight Crew Operating Manual

FLIP Flight Planning

FL Flight Level

FMS Flight Management System

FM Flight Manual

FOT Flight Operations Transmission

FTP Fuel Temperature Prediction

GA General Aviation

GD Green Dot

GPS Global Positioning System

GS Ground Speed

GUI Graphical User Interface

GW Gross Weight

HSP High Speed Performance

IAP Instrument Approach Plate

IAS Indicated Air Speed

ICAO International Civil Aviation Organization

IDE Integrated Development Environment

IFP In Flight Performance

IFR Instrument Flight Rules

ILS Instrument Landing System

IMC Instrument Meteorological Conditions

ISA International Standard Atmosphere

JAR Joint Aviation Requirement

LRC Long Range Cruise

MAC Mean Aerodynamic Chord

MCT Maximum Continuous Thrust

MEL Minimum Equipment List

MR Maximum Range

MSL Mean Sea Level

NAA National Aviation Authority

neo New Engine Option

NOTAM Notice To Airmen

O/RM Object-Relational Mapping

OAT Outside Air Temperature

OEB Operations Engineering Bulletin

OEI One Engine Inoperative

OFP Operational Flight Plan

OLB Operational Library Browser

OM Operations Manual

OPT Onboard Performance Tool

OS Operating System

PC Personal Computer

PDA Personal Digital Assistant

PED Personal Electronic Device

PEP Performance Engineer's Programs

pp percentage point

QRH Quick Reference Handbook

R&D Research & Development

RE Relative Error

SQL Structured Query Language

TAP *Transportes Aéreos Portugueses*

TAS True Air Speed

TLO Takeoff and Landing Optimization

TLP Takeoff and Landing Performance

TO/GA Take-Off/Go-Around

USD United States Dollar

VB Visual Basic

VMC Visual Meteorological Conditions

WS Wind Speed

α Angle of attack

γ Ratio of specific heats; Climb angle

ρ Density

σ Relative air density

θ Pitch angle

a Atmospheric lapse rate

$\mathbf{C_D}$ Drag coefficient

$\mathbf{C_L}$ Lift coefficient

g Gravitational constant

h Altitude

M Mach number

m Mass

n Load factor

p Pressure

R Gas constant

T Temperature

V Speed

Chapter 1

Introduction

The project described in this thesis was developed as the result of an internship at the Innovation and Technical Support Department of TAP[1] Air Portugal, in the e-Operations (eOps) group. TAP Air Portugal is the Portuguese flag air carrier and the largest in the country, having carried in 2019 a total of 17 million passengers on 137 000 flights to 95 destinations [1]. As of November 2020, TAP mainline fleet comprises a total of 84 aircraft manufactured by the European aerospace consortium Airbus. These are all twin-engine jets from two families of airliners: 59 from the A320 narrow-body family and 25 from the A330 wide-body type [2]. This fleet is further detailed in Table 1.1:

Table 1.1: TAP Air Portugal's mainline fleet composition (adapted from [2]).

Family	Model	Generation	Type	Quantity
A320F	A319	ceo[2]	-111	12
			-112	2
	A320	ceo	-214	11
			-214J	7
		neo[3]	-251	8
	A321	ceo	-211	3
		neo	-251	16
A330F	A330	ceo	-202	5
			-203	1
		neo	-941	19

1.1 Motivation

The implementation of information technology devices provides benefits to a great number of industries. In particular, the introduction of such devices in the commercial aviation sector enables an increase of operational efficiency and safety, which translates into major economical gains.

[1] TAP: *Transportes Aéreos Portugueses*
[2] ceo: Current Engine Option
[3] neo: New Engine Option

The present work is especially motivated by Airbus' decision of removing specific performance sections from the paper-based versions of several flight manuals. One of the manuals that is affected by this decision is the Quick Reference Handbook (QRH). By doing so, Airbus expects to promote the airlines' transition into an Electronic Flight Bag (EFB)-based operation.

To provide airlines with an alternative to the QRH, Airbus developed the *eQRH*[2] application. This product can either be purchased as a separate application or as part of *Flysmart+*, Airbus' own EFB solution [3]. However, TAP has decided not to purchase *eQRH* and instead develop its own, alternative tool that covers the functionalities that were previously contained in the paper-based QRH. The company's goal is to integrate that tool into its in-house developed EFB solution, which would ultimately provide additional flexibility to its operations. This project aims to be a relevant contribution to achieve TAP's goal regarding this new tool.

1.2 Objectives

The present work aims to develop a High Speed Performance (HSP) module, database (DB) and application to calculate and replicate several flight scenarios that are part of the HSP chapter of the QRH. Furthermore, this thesis analyses the methods and procedures involved in replicating the following scenarios from said chapter:

- One Engine Inoperative (OEI):
  - Ceilings;
  - Gross Flight Path Descent at Green Dot (GD) Speed;
  - Cruise at Long Range Cruise (LRC) Speed;
  - In Cruise Quick Check Long Range.
- Flight Without Cabin Pressurization:
  - In Cruise Quick Check Flight Level (FL) 100 Long Range.
- Climb Gradient:
  - Maximum Climb Gradient:
    - Maximum Climb Gradient - ISA[3]+10 & below;
    - Maximum Climb Gradient - ISA+20.
  - Approach Climb Gradient:
    - Approach Climb Gradient - ISA+10 & below;
    - Approach Climb Gradient - ISA+20.

The proposed solution targets not only the replication of the aforementioned QRH's flight scenarios, but also the execution of accurate performance data calculations for the aircraft's real-time flight conditions and on-board systems settings (such as Air Conditioning (A/C) and Anti Ice(AI)). This functionality eliminates the need for interpolations and corrections, which ultimately reduces the flight crew's

[2]eQRH: Electronic Quick Reference Handbook
[3]ISA: International Standard Atmosphere

workload, improves the aircraft's performance and provides economical gains. By mitigating the risk of errors occurring during the interpolation process, this tool plays an important role in further increasing operational safety during flight.

Following a recommendation from Airbus, the data that is incorporated into the developed application is retrieved from the manufacturer's aircraft-specific performance DBs. To access said DBs, the project makes use of Airbus' proprietary *Performance Engineer's Programs* (PEP) software. Moreover, the project resorts to PEP's Flight Manual (FM) and In Flight Performance (IFP) modules.

The solution that results from this project covers all the aircraft types that are part of TAP Air Portugal's fleet, and that are listed above in Table 1.1. However, for the sake of conciseness, this report solely focuses on a single aircraft type, the Airbus A320-251, also known as A320neo. This aircraft is Airbus' most recent upgrade to the A320 family, and it incorporates several innovations, such as new wingtip devices and a range of more fuel-efficient engines. These enhancements provide a 20% reduction in fuel consumption per seat, when compared to the previous generation of the A320 (A320ceo) [4].

Despite the approach of focusing on a single aircraft type, it is worth noting that the procedures that are carried out for the remainder of the fleet are analogous to the ones presented in the current work.

Airlines are constantly seeking ways to reduce fuel consumption, which allows them to improve their operational efficiency. One of the main strategies consists in replacing older aircraft models in their fleets with newer, more efficient ones as they are launched into the market. Therefore, airline fleets tend to evolve with time. To account for this variability, the present solution not only computes performance data for TAP's current fleet (listed above in Table 1.1), but also allows the user to include different aircraft types to the list, whenever necessary.

1.3 Thesis Outline

The Thesis is organized into a total of eight chapters.

Chapter 2 provides an overview of EFB systems and the inherent benefits and drawbacks of its introduction into airlines' flight operations.

In Chapter 3, the author introduces a series of relevant concepts concerning aircraft performance, explaining in detail the notions that are relevant to the scope of this work.

Chapter 4 explores the QRH flight manual and presents its structure and contents. The Operational Manual (OM), in which the QRH is integrated, is briefly covered as well by this Chapter.

In Chapter 5, each of the QRH's flight scenarios that are replicated during this project are thoroughly analysed. Whenever necessary, additional performance concepts are also clarified.

Chapter 6 guides the reader through the project's computational process and analyses each of its stages in detail.

In Chapter 7, the author presents and discusses the results that are obtained for the several QRH's scenarios. The computational tool that is described in Chapter 6 is also tested in a simulated scenario.

Chapter 8 performs a balance of the achieved goals during this project and elaborates on some final remarks.

Chapter 2

The Electronic Flight Bag

This chapter provides a comprehensive approach to the field of Electronic Flight Bags (EFBs). As previously mentioned, this is the underlying technology upon which the present work is developed. The impacts of such systems on airlines' operational ecosystems are discussed throughout the following sections. Section 2.1 starts off with a concise introduction to the concept of EFBs. Then, the history and evolution of these devices is analysed in Section 2.2. The different types of EFB's classification systems are presented in Section 2.3. Section 2.4 weighs in the benefits and drawbacks introduced by EFB solutions. Finally, Section 2.5 focuses on the practical aspects of the solution developed and implemented by TAP Air Portugal.

2.1 Initial approach: what is an Electronic Flight Bag?

AMC[1] 20-25, a document published by the European Union Aviation Safety Agency (EASA), defines the EFB as "An information system for flight deck crew members which allows storing, updating, delivering, displaying, and/or computing digital data to support flight operations or duties" [5].

The EFB is a tool that intends to gradually replace the traditional flight bag. As the name suggests, the latter is a bag that contains all the manuals, navigational charts and other document resources that are useful to the flight crew, on paper format. Examples of both a flight bag and an EFB that are used by TAP Air Portugal are illustrated in Figures 2.1(a) and 2.1(b), respectively.

Initially, the role of the EFB was to simply adapt the aforementioned documentation into a paperless environment, thus covering an alternative method of storing and retrieving relevant information. However, the technical developments in the field of Personal Electronic Devices (PEDs) potentiated the integration of more powerful software applications into the EFB [5]. The in-flight performance calculation solution developed in the present work aims to be integrated into an application that fits into this category.

[1] AMC: Acceptable Means of Compliance

(a) Traditional flight bag (approx. 480 mm × 380 mm × 280 mm).

(b) Electronic Flight Bag (approx. 305 mm × 225 mm × 9 mm).

Figure 2.1: TAP's different flight bag solutions[2].

2.2 Evolution of the EFB

The inception of the EFB concept can't be accurately traced back to a specific time frame. Since the early stages of aviation that paper has been the primary support for in-flight information. However, since the second half of last century that technological improvements have enabled the incorporation of an ever-increasing number of electronic devices into the cockpit.

One of the first tools of its kind was the Global Positioning System (GPS). On February 16, 1994, the Federal Aviation Administration (FAA) certified the first GPS unit designed for General Aviation (GA) aircraft in Instrument Flight Rules (IFR) conditions, the Garmin GPS 155 TSO, illustrated in Fig. 2.2 [6]. Later on, additional features such as Very High Frequency (VHF) radio transmitter/receivers and weather information systems were integrated into the GPS units.

Figure 2.2: Garmin GPS 155 TSO prototype [6].

The introduction of electronic approach and aerodrome charts was possible because Jeppesen, a global provider of Instrument Approach Plates (IAPs) and navigational charts, made their products available in electronic format [7]. From this point onwards, EFBs began replacing a considerable amount of paper documents in the cockpit.

[2]The two photos that are presented in Figure 2.1 were kindly provided by Eng. Pedro Gonçalves.

The first iterations of EFB devices consisted of regular Commercial Off-The-Shelf (COTS) laptops that pilots simply carried to the cockpit and were capable of performing very basic performance calculations. However, the first dedicated solution designed to replace the entire pilot's flight bag, the Electronic Kit Bag (EKB), was developed by former American Airlines pilot Angela Masson. Its patent dates back to 1999 [8]. A schematic of such device can be found in Figure 2.3:

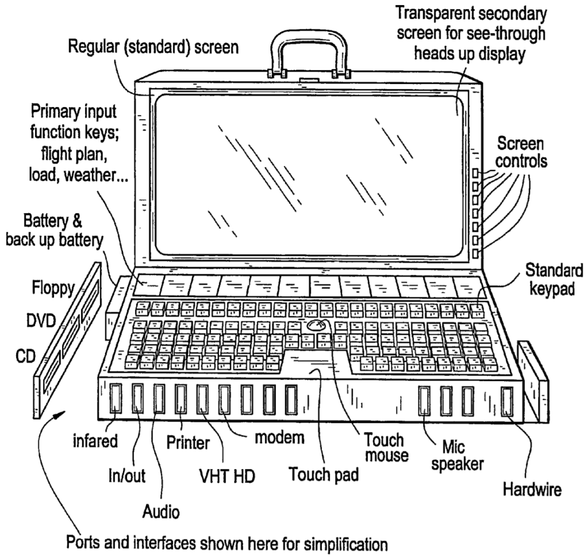


Figure 2.3: "Super Lap-Top Plus" Electronic Kit Bag schematic [8].

At the time, FAA enforced a lesser degree of regulations to business jet operators on the subject of EFBs, when compared to commercial airlines. This contributed to a faster implementation of EFB infrastructures by this group of operators. Flight Options, a US-based fractional jet operator, was among the first operators to equip its entire fleet of 88 business jets with EFBs, back in the Summer of 2000. From that point onwards, airlines became more interested in adopting this technology [7].

In response to this transition, FAA began regulating this sector more rigorously and published the AC[3] 120-76A, *Guidelines for the Certification, Airworthiness and Operational Approval of Electronic Flight Bags* in March 2003. The most recent update to this document is the AC 120-76D, published in October 2017 [9].

To comply with market demand, aircraft manufacturers introduced their first EFB solutions. Boeing rolled out the Boeing Laptop Tool (BLT) and started to include it in their commercial aircraft as standard equipment. This Windows-based software incorporated several flight operations manuals, Minimum Equipment Lists (MELs) and training documents. Furthermore, BLT contained a takeoff and landing performance and weight and balance calculators, which allowed the flight crew to optimize the aircraft's payload. Additionally, it also included Jeppesen's JeppView FliteDeck software for displaying electronic aerodrome, approach and en-route charts [7].

Since then, commercial airlines started to proactively introduce EFB-based solutions, either outsourced or in-house developed, into their operations. Following recommendations and guidelines from

[3]AC: Advisory Circular

EASA and FAA, cockpits were populated with a wide range of c-PEDs[4], laptops and PDAs[5]. One of the most popular devices at the time was the Fujitsu LT P-600, a pen-tablet Personal Computer (PC). This device, depicted in Figure 2.4, had an average retail price of 3600 USD[6] [10].

Figure 2.4: Fujitsu Stylistic LT P-600 [10].

Developments in tablet technology over the last decade made this the leading device in current EFB applications. Manufacturers are now investing in integrated tools that run exclusively on these devices. For example Jeppesen, now part of Boeing, offers the Onboard Performance Tool (OPT), an evolution of the BLT that is now compatible with Apple iPad and Windows-based mobile devices [11]. The iPad version of this tool is illustrated in Figure 2.5. Likewise, Airbus' subsidiary NAVBLUE offers the Flysmart+, a solution that sports the same compatibility features as Boeing's OPT [3]. Both these tools provide access to powerful performance data calculators and to all the important flight manuals and documents such as the Flight Crew Operating Manual (FCOM) and the QRH. These innovations represent a key milestone towards a paper-free cockpit environment.

Figure 2.5: Boeing Onboard Performance Tool for iPad [12]

[4]c-PED: Controlled Portable Electronic Device
[5]PDA: Personal Digital Assistant
[6]USD: United States Dollar(s)

The evolution of the EFB concept to this day proves that airlines will constantly seek solutions to improve operational efficiency and safety. In the future, technological breakthroughs in this field are expected to further enhance the interaction between the flight crew and EFBs, which will ultimately improve these metrics.

2.3 Classification of EFB solutions

From the point of view of implementation logistics, EFB solutions are classified as either aircraft or pilot-attached. An aircraft-attached system requires two devices for every aircraft in the operator's fleet, plus a fixed percentage of devices to serve as replacement units. In contrast, a pilot-attached infrastructure assigns one EFB unit to every flight crew member of the airline's workforce.

Moreover, regulatory authorities' classification systems focus on software and hardware attributes, and are the subject of the following subsections.

2.3.1 Software

Regarding the applications incorporated into the EFB, AMC 20-25 states that these can be from one of three types [5]:

- **Type A:** this type of app consists of a fixed presentation of data that is currently available on the paper version of the Flight Bag. Therefore, this type of software apps don't require any type of certification approval. May a failure in an app of this kind occur, safety is not compromised [9].
- **Type B:** software from this category can, for instance, execute performance data calculations and display electronic checklists, aeronautical charts or weather information. Its malfunction would be limited to a minor failure condition (i.e., "[a failure condition] which would not significantly reduce aeroplane safety, and would involve crew actions that are well within their capabilities." [5]). These applications are exempted from airworthiness approval, but still require an operational assessment performed by the aircraft operator.
- **Miscellaneous:** these applications support functionalities that are not directly related to the operations performed by the flight crew, and therefore are considered to be non-EFB apps. Applications of this type must run independently from the remaining EFB software, and must boot from a dedicated hard drive partition. This software category includes web browsers and e-mail clients, among other functionalities.

By EASA and FAA's policies, software that does not belong to any of these categories requires full airworthiness approval from these regulatory authorities [9].

2.3.2 Hardware

In terms of hardware, the AC 120-76B, published by the FAA, categorizes EFBs into 3 classes [9, 13]:

- **Class 1:** The equipment of this class consists of a COTS PED and does not require any design or installation approvals from the National Aviation Authorities (NAAs). Its connection to the aircraft is temporary and restricted to battery recharging from an existing on-board power supply. Equipment from this class contain Type B applications for electronic checklists and aeronautical charts.

- **Class 2:** This class of EFB requires a limited NAA airworthiness approval. Although similar to Class 1 devices, Class 2 EFBs can be connected to the aircraft's data link ports and retrieve information directly from its flight computers. This connection enables the EFB to obtain the actual conditions for any given moment of a flight and perform real-time performance calculations.
- **Class 3:** This type of system involves a more extensive certification process. Namely, it requires a Supplemental (Aircraft) Type Certificate as well as a NAA Airworthiness Approval. These devices support a broader connection to the aircraft's flight systems, and some models can even communicate with the Global Positioning System (GPS) and the Flight Management System (FMS). Then, the EFB can process a considerable array of information regarding the flight dynamics of the airplane and display it in the form of a detailed, moving map.

Due to technological evolution of EFBs and the associated increase in its complexity, this classification was deemed ambiguous. Therefore, and in order to harmonise these definitions with the International Civil Aviation Authority (ICAO) terminology, EASA introduced the notions of portable and installed EFBs [5]. According to this standard, an installed EFB is a device that is considered to be part of the aircraft, and therefore is included in the aircraft's airworthiness certificate. Conversely, a portable EFB can be used inside or outside the flight deck and is not covered by the aforementioned certificate.

Regarding software certification compatibility, installed EFB hardware can host Type A, B and Miscellaneous applications. In contrast, portable systems can only host software from Types A and B.

2.4 EFB implementation: operational effects

Every operational decision translates into advantages and hindrances associated to it. The implementation of an EFB infrastructure is no exception. The present section provides a comprehensive analysis of the arguments for and against the introduction of this technology in a commercial airline's routine operations.

Benefits

The transition into an EFB-based operation provides gains in two main fields: the flight deck and the back-end, supporting activities.

In the flight deck, the EFB potentiates an increase in operational and crew performance efficiency. By providing accurate performance data regarding real-time flight conditions, this tool eliminates the need for interpolations and corrections. Therefore, it alleviates pilot workload, which ultimately increases safety, and also mitigates potential calculation errors originated during these operations. This, in turn, improves the aircraft's fuel consumption and overall performance.

This solution is also superior from a cockpit ergonomics perspective. With an EFB device, the crew members can access the information they need in a more expeditious manner, thanks to its user-friendly layout. This is a major improvement from the traditional flight bag experience, where a pilot would have to search for specific data through hundreds of paper pages from several manuals and charts.

Reports from operators that adopted this technology also point out a considerable weight reduction. For instance, by replacing the conventional flight bag with a $0.6\,\mathrm{kg}$ Apple iPad-based EFB, American Airlines achieved a reduction in weight of over $16\,\mathrm{kg}$ per kit, eliminating in the process one of the major sources of pilot injuries. Furthermore, this weight reduction ultimately translated into more than 1.2 Million USD in yearly fuel cost savings [14].

The implementation of an EFB solution also provides benefits to the daily activities performed by Flight Operations Engineering departments. Aeronautical charts and flight manuals are typically updated several times a month, to account for the ever-changing pieces of information such as NOTAMs[7] and flight restrictions.

Updating a conventional flight bag is an enterprise that involves collecting all the specimens located in the entire operator's fleet, printing the new, updated pages and replacing them in the correct places. This is a cumbersome process that consumes considerable amounts of man-hours and printing supplies. Conversely, performing this operation on an EFB system consists of populating its databases with the revised information and releasing an update to all the devices. This update can then be carried out by the flight crew in any location, provided the device is connected to the internet. The update process of an EFB is therefore less susceptible to human error. Ultimately, this solution provides substantial benefits from both economical and environmental standpoints, as well as an associated increase of operational safety.

In recent times, aircraft manufacturers have been encouraging operators to make the transition into EFBs. In December 2019, Airbus issued a Flight Operations Transmission (FOT) informing its customers that all the performance data currently available in manuals such as the FCOM and the QRH will no longer be published in paper format after November 2021 [15, 16].

Lastly, EFB systems provide virtually limitless customization options that can be tailored to the operator's specific needs. This is particularly true for in-house developed software, as is the case of TAP's EFB solution. In these scenarios, the layout and the way the info is displayed to the flight crew is defined by the airline's Engineering team, which provides additional flexibility to its operations.

Drawbacks

Notwithstanding the strong pro-EFB arguments discussed so far, these systems also introduce a series of risks and weaknesses that must be taken into account during the implementation studies for this type of technology.

The most prominent hindrance to this transition is the inherent initial cost. An EFB infrastructure usually relies on c-PED hardware, which has a substantial acquisition cost. The fact that an infrastructure of this type comprises a significant amount of units (generally, one for each crew member and extra units for development and testing purposes) helps explaining the hefty up-front investment.

[7] NOTAM: Notice To Airmen

One must also take human factors into consideration when implementing this solution. Findings from a study conducted by the FAA revealed that the EFB was a contributing cause to several incidents and accidents over the years, namely runway excursions and crashes at takeoff [17]. Therefore, specific training must be provided to the flight crews and their interaction with the system must be constantly monitored [7].

As with every digital solution, security breaches are a major concern. For instance, an unauthorized access to the infrastructure could lead to a data tampering scenario, which might ultimately compromise the safety level of the entire operation. Furthermore, the increasing degree of interaction between the EFB and several aircraft systems aggravates said risks. Thus, a rigorous protection strategy that covers the entire infrastructure, including servers and databases, must be developed.

As previously discussed, in-house developed EFB systems are a custom solution tailored to the airline's specific needs, which ultimately enhances its operational flexibility. Nonetheless, this benefit comes at the expense of a significant investment in R&D[8], including training, additional man-hours, and extra costs related to software licensing and certification, among other issues.

Remarks

Weighing in the benefits and downsides evaluated so far, one can conclude that the transition into EFBs is a bet that pays off in the long run. An airline with the required financial capability to support the initial investment can then benefit from improved operational safety and enhanced document accessibility and configuration control, as well as sizable savings in terms of flight operations and maintenance costs [18].

2.5 TAP Air Portugal's EFB solution

TAP is one of the airlines that invested a serious effort in transitioning into an EFB-based infrastructure. This transition began in 2010, when TAP rolled out their first in-house developed EFB into the cockpits. This solution comprised a set of Fujitsu T-901 tablet PCs running Microsoft Windows 7 Operating System (OS). This OS was chosen to follow suit with previous work developed by the company. Then, the infrastructure evolved its latest version, now comprising Lenovo ThinkPad X1 Class 1 c-PEDs running Windows 10.

The solution developed by TAP contains both Type A and B applications. Type A apps include Flight Report and Self Briefing tools. On the other hand, Type B applications are created by the e-Ops group, the company's department that supported the present work. This group of apps includes an Operational Flight Plan (OFP) portal, Takeoff and Landing Performance (TLP) calculators and an Operational Library Browser (OLB) containing relevant flight manuals and documents.

This EFB system also includes a module containing the required aeronautical charts to be accessed throughout the flight. However, this application is an outsourced solution called Lido eRoute Manual and

[8]R&D: Research & Development

is provided by Lufthansa Systems [19].

The EFB's hard drives contain two separate partitions. One is a personal partition, where the pilots can find several Miscellaneous apps, such as an Email client and a web browser, and where they can create their own documents and annotations. The other is the EFB partition *per se* that contains the above-mentioned Type A and B applications. This partition is controlled by the airline and the system changes a pilot can perform there are very limited. Therefore, airline policy states that the EFB partition is the only one that can be used in-flight by the crew.

An overview of the several apps that are part of TAP's EFB and that have been discussed so far is provided in Figure 2.6:

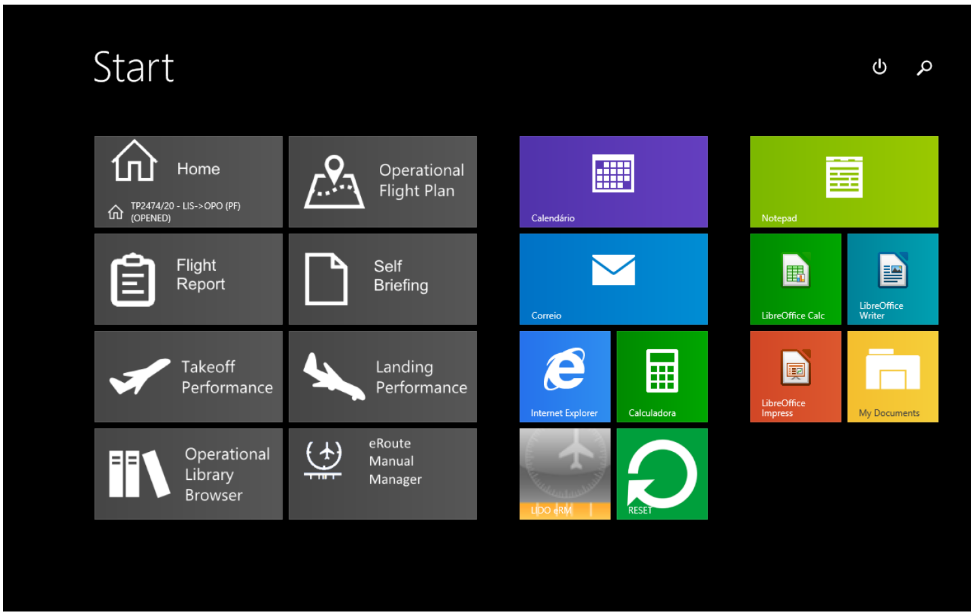


Figure 2.6: Screenshot of TAP's EFB start screen[9].

This system is in constant expansion and incorporates an ever-increasing number of modules. The solution that is described in the current work is expected to be integrated into the company's EFB.

[9]The screenshot that is presented in Figure 2.6 was kindly provided by Eng. José Ricardo Fernandes.

Chapter 3

Aircraft Performance

In the present chapter, all of the aircraft performance concepts that are relevant to the scope of this project are introduced and thoroughly explained. This analysis will empower the reader with a basic notion of these concepts, that will prove to be crucial to understanding the inner workings of the software solution presented in this thesis.

Section 3.1 introduces the concept of International Standard Atmosphere (ISA). Additionally, this section also evaluates the distribution of pressure, temperature and density in the two lowest layers of the atmosphere: troposphere and lower stratosphere. Section 3.2 explains the most relevant air speed definitions that are used over the course of the present work.

3.1 The International Standard Atmosphere

The atmosphere is a gaseous mixture of approximately 78% nitrogen, 21% oxygen and 1% other gases that surrounds the earth. Its properties aren't homogeneous throughout it, varying with factors such as geographic position, altitude and time of measurement. In order to compare aircraft performance in any point and time, ICAO defined the International Standard Atmosphere (ISA), which is a set of standard atmospheric properties that represent the "average" conditions [20]. According to this standard, the atmosphere is composed of a dry, perfect gas and its pressure, density and temperature vary exclusively with altitude [21]. The typical flight envelope of a subsonic aircraft comprehends a range of altitudes covering the troposphere and lower stratosphere. Therefore, this section focuses on these two layers of the atmosphere.

3.1.1 Relevant units

The units that will be used to quantify measurements throughout this work are the following:

Distance: nautical miles [NM]

Mass $[m]$**:** kilogram [kg]

Density $[\rho]$**:** kilogram per cubic meter [$\mathrm{kg\,m^{-3}}$]

Temperature $[T]$**:** Kelvin [K] or Degrees Celsius [°C]

Pressure $[p]$**:** hectopascal [hPa]

Speed $[V]$**:** meter per second [$\mathrm{m\,s^{-1}}$] or knot [kt]

Altitude $[h]$**:** feet [ft] or FL*

*FL isn't a unit in itself, but rather an altitude expressed in hundreds of feet (e.g., FL395 corresponds to 39 500 ft).

It is worth noting that the list of units presented above also applies to the constants that appear in the several equations that are part of this chapter.

3.1.2 Mean Sea Level conditions

The ISA physical properties at Mean Sea Level (MSL), where $h_0 = 0\,\mathrm{ft}$, are displayed in Equation 3.1 [22, 23]:

$$\begin{aligned} p_0 &= 1013.25\,\mathrm{hPa} \\ g_0 &= 9.806\,\mathrm{m\,s^{-1}} \\ \rho_0 &= 1.225\,\mathrm{kg\,m^{-3}} \\ T_0 &= 15\,^{\circ}\mathrm{C} = 288.15\,\mathrm{K} \end{aligned} \tag{3.1}$$

3.1.3 Temperature modelling

In ISA conditions, it is assumed that below the tropopause ($h_{TP} = 36\,089\,\mathrm{ft}$) the temperature varies with altitude at a fixed rate of $a_T = -0.001\,98\,^{\circ}\mathrm{C/ft}$, also known as the atmospheric lapse rate [23]. For a pair of altitudes h and h_1, with corresponding temperatures T and T_1, the lapse rate is expressed in the following manner:

$$a = \frac{T - T_1}{h - h_1},\ h > h_1 \tag{3.2}$$

The temperature of a given point as a function of its altitude can be calculated with Equation (3.3):

$$T(h) = T(h_1) + a(h - h_1) \tag{3.3}$$

We can rewrite the previous expression for the case where $h_1 = h_0$:

$$T(h) = T_0 + a_T(h - h_0) \tag{3.4}$$

In the lower stratosphere ($36\,089 < h < 65\,617\,\mathrm{ft}$) , the temperature remains constant, at a value of $-56.5\,^{\circ}\mathrm{C}$ [24]. Combining this piece of information and rewriting Eq.(3.3) for MSL conditions (i.e., $h_1 = h_0$ and $T_1 = T_0$), the temperature of any point of the troposphere or the lower stratosphere can be determined through the following expression:

$$T(h) = \begin{cases} 15 - 0.00198 \times h & 0 < h \leq 36\,089\,\text{ft} \\ -56.5 & 36\,089 < h \leq 65\,617\,\text{ft} \end{cases} \quad [°\text{C}] \tag{3.5}$$

where h is the altitude of said point, in feet (ft).

Furthermore, this variation is illustrated in Fig. 3.1:

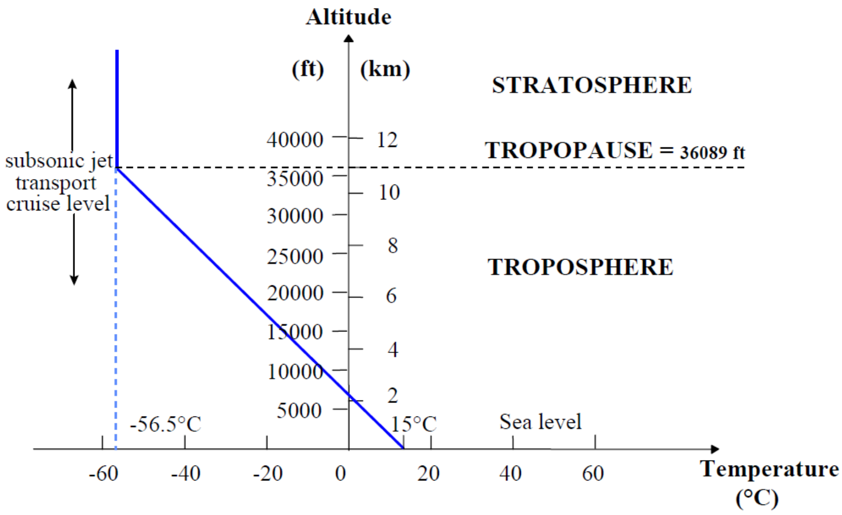


Figure 3.1: ISA temperature variation with altitude [22].

3.1.3.1 ISA Deviation

As previously stated, the ISA is a model that is used as a reference to compare real atmospheric conditions, such as the Outside Air Temperature (OAT), and the corresponding aircraft performance. Therefore, actual flight conditions are typically expressed in the form of $ISA \pm \Delta ISA$ for a given flight level, where $\Delta ISA = OAT - T_{ISA}(h_p)$ [22].

Applying this logic to the case of an aircraft flying at an altitude of 35 000 ft (i.e., FL 350) and an OAT of -39 °C, and using Eq.(3.5), one will obtain a $T_{ISA} = -54$ °C, and thus $\Delta ISA = -39 - (-54) = +15$ °C. Since most performance data sources adhere to this convention, the data that applies to these flight conditions will be categorized as 'ISA+15'.

3.1.4 Pressure and density modelling

The evaluation of air pressure and density variation with altitude in ISA conditions begins with an equilibrium of vertical forces applied to a quiescent, infinitesimal sample of atmospheric air, illustrated in Fig. 3.2:

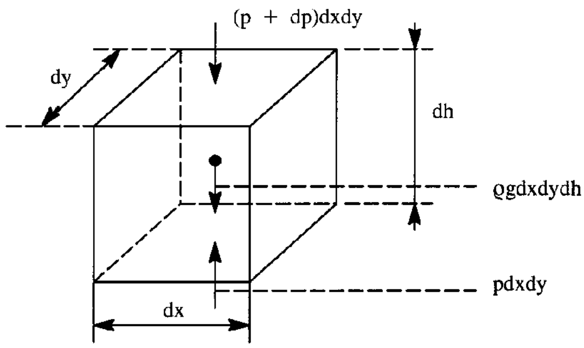


Figure 3.2: Vertical forces equilibrium of a sample of atmospheric air [23].

The equilibrium is described by Eq.(3.6):

$$p \, \mathrm{d}x \, \mathrm{d}y - (p + \mathrm{d}p) \, \mathrm{d}x \, \mathrm{d}y - \rho g \, \mathrm{d}x \, \mathrm{d}y \, \mathrm{d}h = 0 \tag{3.6}$$

This result can be further simplified:

$$\mathrm{d}p = -\rho g \, \mathrm{d}h \tag{3.7}$$

As previously discussed, the ISA standard assumes that atmospheric air behaves as a ideal gas, thus obeying to the following law [23]:

$$p = \rho g R T \tag{3.8}$$

where $R = 29.26\,\mathrm{m\,K^{-1}} = 95.997\,\mathrm{ft\,K^{-1}}$ represents the gas constant for dry air and T is the absolute temperature of said gas, in degrees Kelvin [K].

The division of Eq.(3.6) by Eq.(3.8) results in:

$$\frac{\mathrm{d}p}{p} = -\frac{\mathrm{d}h}{RT} \tag{3.9}$$

Since the temperature distribution in the troposphere differs from the one in the stratosphere, as stated in Subsection 3.1.3, the same will occur for the pressure distribution, and thus both cases shall be considered.

3.1.4.1 Pressure and density distributions in the troposphere: $0 < h \leq 36\,089\,\mathrm{ft}$

As was analysed in the previous subsection, the temperature distribution in the troposphere is given by Eq.(3.4). Its differentiation yields:

$$\mathrm{d}T = a \, \mathrm{d}h \tag{3.10}$$

Substituting this conclusion into Eq.(3.9) results in:

$$\frac{\mathrm{d}p}{p} = -\frac{\mathrm{d}T}{aRT} \tag{3.11}$$

The relationship between the pressure at any altitude p and the pressure at a reference altitude p_1 can be obtained through integration of Eq.(3.11):

$$\frac{p}{p_1} = \left(\frac{T}{T_1}\right)^{-\frac{1}{aR}} = \left[1 + \frac{a}{T_1}(h - h_1)\right]^{-\frac{1}{aR}} \tag{3.12}$$

Furthermore, the corresponding relationship for densities can be obtained by applying the ideal gas law [Eq.(3.8)] to the previous equation:

$$\frac{\rho}{\rho_1} = \left(\frac{p}{p_1}\right)\left(\frac{T}{T_1}\right) = \left(\frac{T}{T_1}\right)^{\left(-\frac{1}{aR}-1\right)} \tag{3.13}$$

Both these expressions gain particular relevance when they are defined in relation to the values of pressure, temperature and density at MSL. From this comes that the pressure and density distributions with altitude in the troposphere are given by the following equations:

$$p(h) = 1013.25 \cdot \left(1 - \frac{0.00198 \cdot h}{288.15}\right)^{5.2579} \quad \text{[hPa]} \tag{3.14}$$

$$\rho(h) = 1.225 \cdot \left(1 - \frac{0.00198 \cdot h}{288.15}\right)^{4.2579} \quad [\text{kg m}^{-3}] \tag{3.15}$$

3.1.4.2 Pressure and density distributions in the stratosphere: $36\,089 < \boldsymbol{h} \leq 65\,617$ ft

As previously discussed, the stratosphere is characterized by a constant temperature of $T_{ST} = -56.5\,°\text{C} = 216.65\,\text{K}$. Due to this fact, the integration of Eq.(3.9) yields:

$$\ln\left(\frac{p}{p_{ref}}\right) = -\left(\frac{h - h_{ref}}{RT_{ref}}\right) \tag{3.16}$$

Solving this expression for p and assuming the tropopause conditions as reference ($h_{ref} = h_{TP} = 36\,089$ ft, $p_{ref} = p_{TP} = 226.32$ hPa, $T_{ref} = T_{TP} = T_{ST} = 216.65$ K), the pressure distribution in the stratosphere for a given altitude h is given by:

$$p(h) = 226.32 \cdot \exp\left[-\left(\frac{h - 36089}{20797.8}\right)\right] \quad \text{[hPa]} \tag{3.17}$$

By adapting Eq.(3.8), one can obtain:

$$\frac{p_1}{p_2} = \frac{\rho_1}{\rho_2} \Longrightarrow \rho_1 = p_1 \cdot \frac{\rho_2}{p_2} \tag{3.18}$$

The density value for the tropopause can be obtained through Eq.(3.15): $\rho_{TP} = 0.364\,\text{kg m}^{-3}$. By setting point 2 as the tropopause, as well as replacing Eq.(3.17) in the previous equation, it is possible to obtain the density distribution in the stratosphere:

$$\rho(h) = 0.364 \cdot \exp\left[-\left(\frac{h - 36089}{20797.8}\right)\right] \quad [\text{kg m}^{-3}] \tag{3.19}$$

3.1.4.3 Summary

In conclusion, the distributions of pressure and density in altitude are given by Eq.(3.20):

$$p(h) = \begin{cases} 1013.25 \cdot \left(1 - \frac{0.0019812 \cdot h}{288.15}\right)^{5.2579} & 0 < h \leq 36\,089\,\text{ft} \\ 226.32 \cdot \exp\left[-\left(\frac{h-36089}{20797.8}\right)\right] & 36\,089 < h \leq 65\,617\,\text{ft} \end{cases} \quad [\text{hPa}] \tag{3.20a}$$

$$\rho(h) = \begin{cases} 1.225 \cdot \left(1 - \frac{0.0019812 \cdot h}{288.15}\right)^{4.2579} & 0 < h \leq 36\,089\,\text{ft} \\ 0.364 \cdot \exp\left[-\left(\frac{h-36089}{20797.8}\right)\right] & 36\,089 < h \leq 65\,617\,\text{ft} \end{cases} \quad [\text{kg}\,\text{m}^{-3}] \tag{3.20b}$$

3.2 Operational Speeds

The operation of an aircraft is a complex task that involves a variety of activities such as flying and navigating *per se*, flight planning and performance optimization. The speed definition that is used in each activity isn't the same for all of them, in order to increase efficiency. These types of speed will be thoroughly explained in this section (based on [23, 25]).

3.2.1 Indicated Air Speed

As the name suggests, the Indicated Air Speed (IAS) is the speed that is displayed on the flight instruments located in the cockpit. The calculation of said speed requires the application of Bernoulli's principle, according to which the summation of the dynamic and static pressures (p_d and p_s, respectively) of a low-speed flow, where the constant density assumption is valid, remains constant inside a tube:

$$p_d + p_s = p_{tot} = constant \tag{3.21}$$

The definition of dynamic pressure is given by:

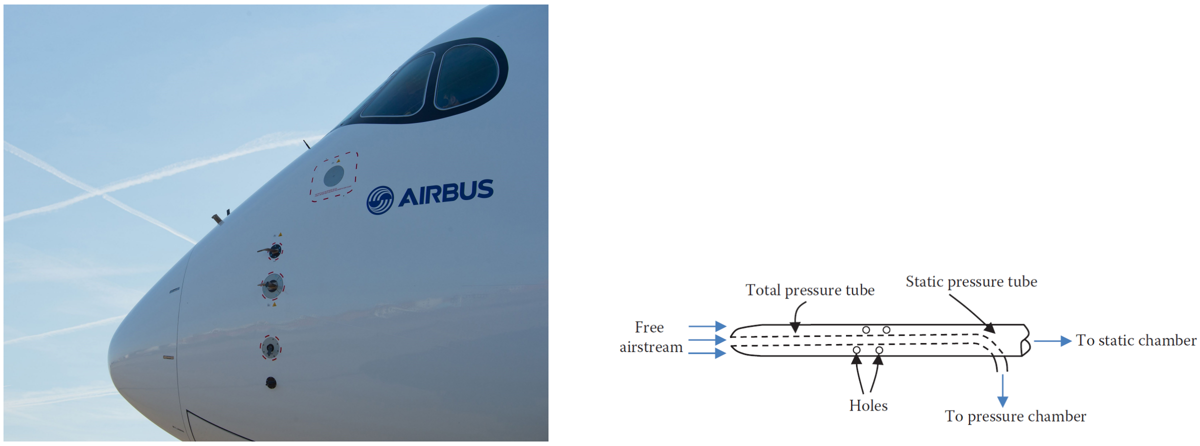
$$p_d = q = \frac{1}{2}\rho V^2 \tag{3.22}$$

where V is the speed of the airflow.

The IAS is then a function of the total and static pressures, corrected for instrument error. It is a variable of particular interest because the flight characteristics of an aircraft change with the reduction in atmospheric density [26].

3.2.1.1 Pressure measurements

The pressures that were referred in the previous subsection are measured by a Pitot tube, illustrated in Figure 3.3(a). This device comprises two fundamental parts: the Pitot itself (surrounded by the red circles) and the static probe (surrounded by the red square). These parts measure the total and the static pressures, respectively. In some cases, both these parts are combined into a single assembly called the Pitot-static tube, such as the one depicted in Fig. 3.3(b).



(a) Detail of the Airbus A350 nose section (adapted from [27]).

(b) Schematic of a Pitot-static tube [25].

Figure 3.3: Pitot tube mechanism.

Having measured the values of the total and static pressures, the IAS value is then obtained based on these measurements and displayed to the pilots in the cockpit.

3.2.2 Calibrated Air Speed

The Calibrated Air Speed (CAS) corresponds to the IAS value corrected for position errors. Due to the location of the Pitot and static probes, discussed in the previous subsection, the air flow passing through those devices is disturbed by the fuselage, and therefore the static pressure in that point is not the same as the pressure in the free, undisturbed air stream. This induces said position errors into the IAS measurement.

To counteract this effect, aircraft manufacturers perform flights in formation with another airplane that carries specifically calibrated instruments and compare the air speed values of both in real time. This data collection will later translate into an air speed correction table. By applying said corrections to a given IAS value, one can obtain the corresponding CAS.

3.2.3 Equivalent Air Speed

The EAS results from the correction of the Equivalent Air Speed (EAS) taking into account the adiabatic compressibility effects present at the altitude of flight. At sea-level under ISA conditions, the EAS and the CAS are the same, and below 10 000 ft and 250 kt CAS the difference between both speeds is negligible [28].

Since the Bernoulli's equation only remains valid for low, subsonic speed incompressible flow, for flight conditions located outside of the referred flight envelope it is necessary to correct the CAS value by applying a compressibility corrective factor, K: $V_{EAS} = K \cdot V_{CAS}$.

Another way to write the expression for the EAS is to relate it with the definition of dynamic pressure, introduced in Eq.(3.22):

$$p_d = \frac{1}{2}\rho_0 V_{EAS}^2 \Longrightarrow V_{EAS} = \sqrt{\frac{2(p_t - p_s)}{\rho_0}} \tag{3.23}$$

The EAS is a relevant variable because, for subsonic flight, the aerodynamic forces and moments exerted on an aircraft are proportional to the square of the EAS.

3.2.4 True Air Speed

As discussed in the previous topic, the EAS considers a scenario of an aircraft flying in ISA conditions. However, if the OAT at the flight's altitude does not comply with the ISA standard, the air density will also be different. The True Air Speed (TAS) results from the correction of the EAS taking this detail into consideration.

Rewriting the dynamic pressure definition from Eq.(3.22) yields:

$$p_d = \frac{1}{2}\rho_0 V_{EAS}^2 = \frac{1}{2}\rho V_{TAS}^2 \Longrightarrow V_{TAS} = \frac{V_{EAS}}{\sqrt{\sigma}} \tag{3.24}$$

where ρ is the actual air density at the flight's altitude σ is the relative air density (ρ/ρ_0).

Of all the air speed definitions introduced in this section, the TAS is the one that most accurately assesses the speed of an aircraft relative to the mass in which it is flying [29].

3.2.4.1 Summary of air speed definitions

The schematic illustrated in Figure 3.4 presents a concise summary of the air speed definitions introduced up until this point:

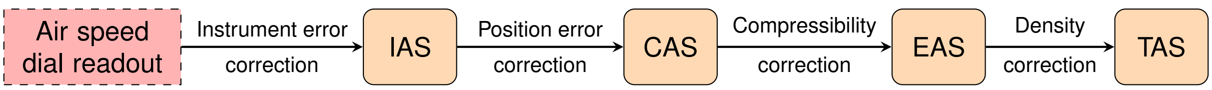


Figure 3.4: Air speed definitions.

3.2.5 Ground Speed

The Ground Speed (GS) represents the aircraft speed in a fixed ground reference system [22]. It corresponds to the correction of TAS accounting for wind effects. Mathematically, it translates into the vectorial summation of the TAS with the Wind Speed (WS):

$$\overrightarrow{GS} = \overrightarrow{TAS} + \overrightarrow{WS} \tag{3.25}$$

The angle between the TAS and the WS is defined as the Drift Angle (DA). These concepts are graphically represented on Fig. 3.5:

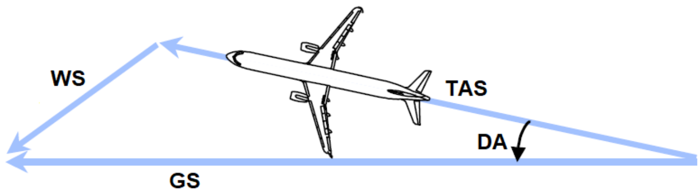


Figure 3.5: GS vectorial summation (adapted from [22]).

3.2.6 Mach number

The Mach number M is a non-dimensional parameter that represents the ratio of TAS to the speed of sound at the current flight altitude (V_a):

$$M = \frac{TAS}{V_a} \tag{3.26}$$

The speed of sound for a given flight altitude is determined via the following expression [25]:

$$V_a = \sqrt{\gamma R T} \tag{3.27}$$

where γ is the ratio of specific heats ($= 1.4$ for air at sea level and ISA conditions), R is the gas constant ($=$ 287 J kg^{-1} K) and T is the absolute OAT (i.e., in Kelvin). Replacing these values in the previous equation yields:

$$V_a[\mathrm{m\,s^{-1}}] \approx 20 \cdot \sqrt{OAT[\mathrm{K}]} \Longrightarrow V_a[\mathrm{kt}] \approx 39 \cdot \sqrt{OAT[\mathrm{K}]} \tag{3.28}$$

Therefore, Eq.(3.26) can be written as a function of TAS and OAT:

$$M = \frac{TAS[\mathrm{kt}]}{39 \cdot \sqrt{273.15 + OAT[^\circ\mathrm{C}]}} \tag{3.29}$$

3.2.7 Additional operating speed definitions

3.2.7.1 V_{MO}/M_{MO}

This set of speeds represents the Maximum Operating Limit Speeds, and are specific for each aircraft. According to JAR[1] 25.1505 Subpart G, *"(The V_{MO}) may not be deliberately exceeded in any regime of flight (climb, cruise, or descent), unless a higher speed is authorized for flight test or pilot training operations"* [30].

[1]JAR: Joint Aviation Requirement

3.2.7.2 Green Dot speed

Green Dot (GD) is a flight speed estimation at which the best lift-to-drag ratio is achieved (i.e., the speed that maximizes this ratio) [22], and therefore represents the point where aerodynamic efficiency is maximum. Furthermore, it's also the speed that allows the maximum climb gradient in a One Engine Inoperative (OEI) scenario.

There are engine failure scenarios where the associated performance degradation makes it impossible for the aircraft to maintain its assigned altitude. In these situations, the GD speed provides the minimum descent gradient possible. This descent procedure is known as Drift Down descent, and therefore the GD speed is also referred to as Drift Down speed in some technical documentation.

3.2.7.3 Long Range Cruise speed

The concept of Long Range Cruise (LRC) speed is intimately related to the Specific Range (SR) of the aircraft. This parameter provides the distance covered per unit of fuel, and is given by the following expression:

$$\text{SR [NM/(ton of fuel)]} = \frac{\text{TAS}}{\text{Fuel consumption per hour}} \tag{3.30}$$

The LRC speed is the speed at which, for a given aircraft weight and flight altitude, the SR corresponds to 99% of the maximum SR. Conversely, the air speed that corresponds to the maximum value of SR is the Maximum Range (MR) speed [22]. For a given weight and altitude, the variation of SR with the air speed (Mach) is plotted in Figure 3.6:

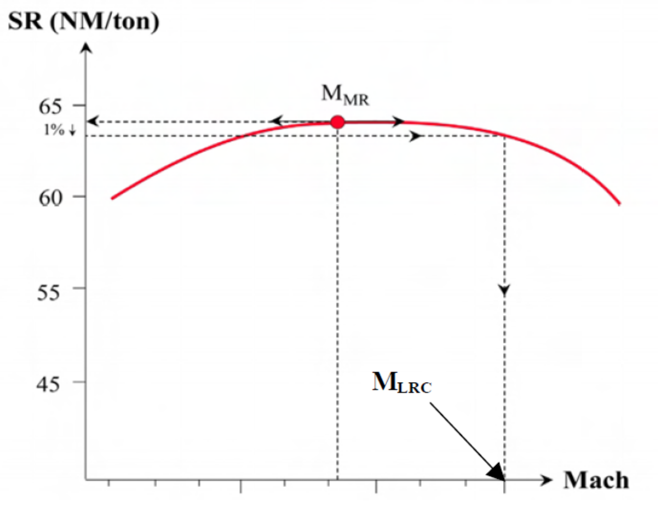


Figure 3.6: Variation of SR with the air speed (adapted from [22]).

From an economic point of view, this is a relevant definition because it is considered that the reduction of SR in 1% is compensated by the increase in cruise speed. This argument is supported by the flatness of the curve in the region that is indicated in Figure 3.6.

3.2.7.4 Stall speed

The stall speed is the minimum, steady flight speed at which the aircraft is controllable [31].

Air velocity over a given wing increases with the angle of attack α. This results in a decrease in air pressure and an increase of the lift coefficient (C_L). The lift force has to balance the aircraft weight, that is assumed constant at a given time instant. This balance is described by Equation 3.31:

$$\text{Weight} = \text{Lift} = \frac{1}{2}\rho S(TAS)^2 C_L = \text{constant}, \tag{3.31}$$

where S represent the wing's area. Considering that all the other parameters of the equation remain constant, an increase of C_L implies a decrease of air speed.

The lift coefficient will then increase with α up to a maximum value of $C_{L_{MAX}}$, and then decreases abruptly when α is increased above a certain value. This behaviour is described by the graph of Figure 3.7. At this point, the airflow is significantly separated from the airfoil, to the extent that the lift it generates can no longer balance the weight of the aircraft. This phenomenon is known as stall [22].

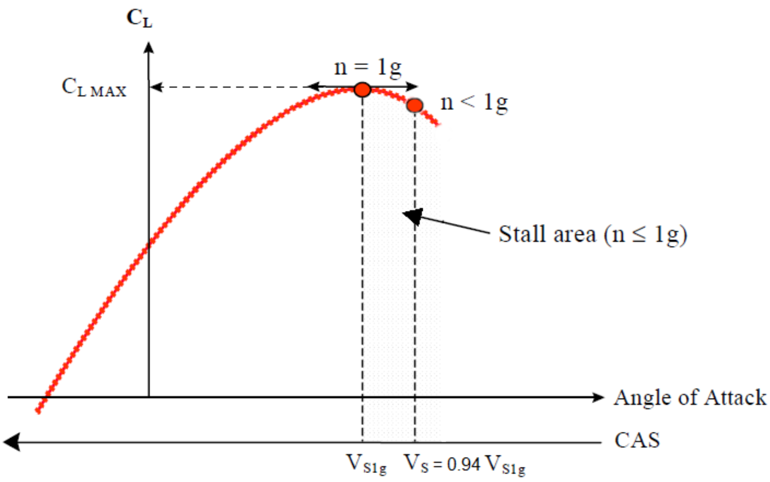


Figure 3.7: C_L variation with the angle of attack (adapted from [22]).

Two stall speeds can then be identified:

- $V_{S_{1g}}$: speed that corresponds to the maximum lift coefficient, right before it starts to decrease. At this point, the load factor n (which is the lift-to-weight ratio) is still equal to one. This is the stall speed definition adopted by regulation JAR 25.103 [30].
- V_S : this speed corresponds to the conventional stall, where the lift coefficient abruptly decreases. At that moment, the load factor n is always less than one.

Chapter 4

Technical Documentation: the Quick Reference Handbook

This chapter focuses on the aircraft's technical documentation, and particularly on the QRH, the foundation of the present work. Section 4.1 provides an overview of the Operations Manual, in which the QRH is integrated. Section 4.2 covers the general structure of the QRH and then analyses the In Flight Performance chapter, where one can find the several flight scenarios that are replicated during this project.

4.1 Operations Manual

The Operations Manual (OM) is defined by ICAO as "*a manual containing procedures, instructions and guidance for use by operational personnel in the execution of their duties*" [32]. Aspects of the operation such as crew training, aircraft performance and navigation are thoroughly covered by the OM.

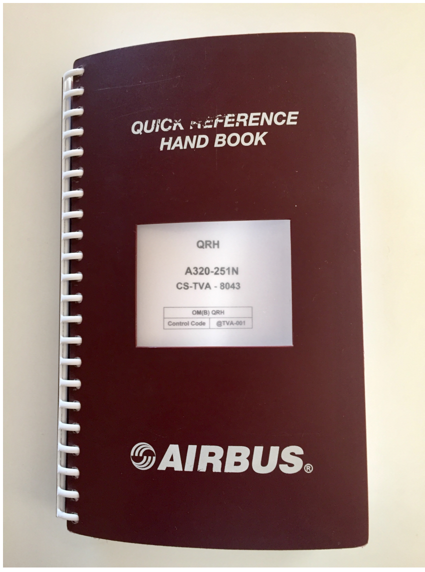
The level of detail embedded into this manual depends on the air operator and the complexity of its operation, namely the type and number of aircraft it operates. Notwithstanding, the main structure and contents of the OM is stipulated by Regulation (EU[1]) 965/2012, specifically by sub-part ORO.MLR.101. According to this regulation, the Operations Manual shall comprise four main parts [33]:

- **Part A:** comprises all non-type related operational policies, instructions and procedures;
- **Part B:** dedicated to aircraft operating matters, Part B encompasses all type-related instructions and procedures, taking into account differences between types/classes, variants or individual aircraft used by the operator. The aforementioned QRH integrates Part B of the OM, and is comprehensively analysed in the next section;
- **Part C:** covers the commercial air transport operations, and contains all the instructions and information needed regarding the operator's target geographic areas of activity;
- **Part D:** focuses on the training aspects, incorporating all the training instructions for personnel that are required for a safe operation.

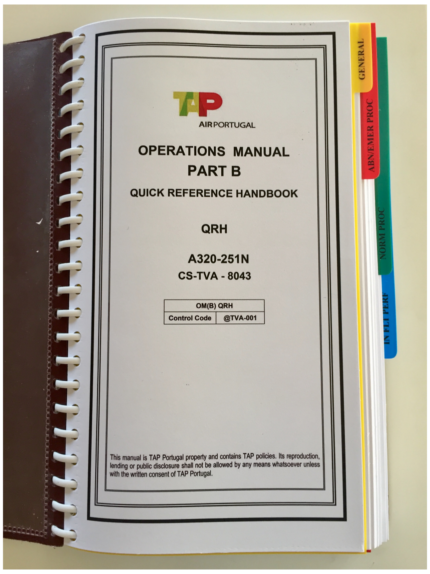
[1] EU: European Union

4.2 Quick Reference Handbook

The QRH is a flight manual published by air operators that contains all the applicable procedures for normal and abnormal conditions that the flight crew might encounter during the aircraft's operation. It is provided as a small format, spiral-bound publication such as the example depicted in Figure 4.1, and is intended to be a convenient, easy-to-use resource in the cockpit. This ergonomic format ensures that the pilots perform the necessary actions in the correct sequence and reduces the risk of overlooking critical tasks, especially during emergency situations [34].



(a) Front cover (approx. 285 mm × 195 mm).



(b) Title page (280 mm × 155 mm).

Figure 4.1: TAP Air Portugal's QRH for the Airbus A320-251 [35].

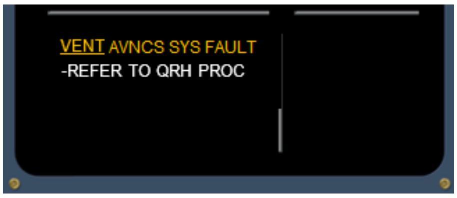
Performance data and its respective corrections are also provided for specific conditions [36]. Said data varies with the aircraft's specifications and, for instance, with modifications and repairs that were performed throughout its life cycle. Therefore, the QRH is an aircraft and operator-specific manual.

As previously stated, the QRH is incorporated into Part B of the OM. However, this is a stand-alone document that can be used independently from other flight manuals. Its structure is generally fixed and contains the following chapters [35]:

1. **General:** highlights the most significant changes that are included into the QRH's most recent revisions.
2. **Abnormal and emergency procedures:** contains the procedures that the flight crew shall adhere to in order to maintain a safe flight.
3. **Normal procedures:** lists the steps that must be taken by the crew during the daily, routine operation of the aircraft;
4. **In Flight Performance:** comprises aircraft performance data tables. It is subdivided into two main sections – Low and High-Speed Performance (LSP and HSP, respectively). The latter includes the tables and charts that motivated the present work, and that will be examined in the next section.

5. **Operational Data:** sums up the several configuration specifications regarding the equipment installed on the aircraft.
6. **Operations Engineering Bulletins (OEBs):** contains temporary procedures published for flight crews that must be applied until a corrective, permanent solution is installed on the aircraft [37].

TAP's Airbus fleet is equipped with Electronic Centralized Aircraft Monitor (ECAM). This system monitors and provides information on several aircraft systems condition to the pilots. Furthermore, in case of a malfunction, the ECAM displays the specific fault and the corresponding corrective steps that must be taken by the flight crew. In aircraft equipped with this system, the QRH is used in coordination with the ECAM or as a back-up of it [36]. An example of this coordination when a fault is detected in the aircraft's ventilation (VENT) system is illustrated in Figure 4.2. By integrating these two resources, this feature enhances the crew's response to abnormal scenarios.



(a) ECAM display referencing a QRH procedure (adapted from [34]).

ECAM System	System malfunction or ECAM Alert (Affected System)	Reset Procedure
VENT	VENT AVNCS SYS FAULT (AEVC)	On ground only: - Pull C/B Y17 on 122VU - Wait 5 s before pushing the C/B.

(b) Corresponding procedure in the aircraft's QRH (adapted from [35]).

Figure 4.2: Coordination between the ECAM system and the QRH.

4.2.1 In Flight Performance

This chapter of the QRH contains performance data charts and tables for normal and abnormal flight conditions. As previously mentioned, the In Flight Performance chapter is divided into two main sections: LSP and HSP. The LSP section mainly focuses on Landing Performance Assessment, providing estimates on landing distances considering scenarios with or without failures in vital systems, such as Hydraulic, Brake or Engine-related systems.

Likewise, the HSP section provides performance data for the same types of flight conditions, but regarding the Climb, Cruise and Descent stages of the flight, during which the aircraft flies at a higher air speed. The structure of this section is presented below, where the underlined topics refer to the cases that are analysed and replicated during this thesis:

1. **One Engine Inoperative (OEI):**
   1.1 Ceilings;
   1.2 Gross Flight Path Descent at Green Dot (GD) Speed;
   1.3 Cruise at Long Range Cruise (LRC) Speed;
   1.4 In Cruise Quick Check Long Range.
2. **All Engines Operative:**
   2.1 Optimum & Maximum Altitudes;

2.2 In Cruise Quick Check at a Given Mach Number;

2.3 Cost Index for LRC Speed;

2.4 Standard Descent;

2.5 Quick Determination Table of Alternate Flight Planning.

3. **Flight Without Cabin Pressurization:**

   3.1 In Cruise Quick Check FL100 Long Range.

4. **Miscellaneous:**

   4.1 Ground Distance / Air Distance Conversion;

   4.2 IAS / MACH Conversion;

   4.3 ISA Temperature and Pressure Altitude Correction;

   4.4 Wind Component;

   4.5 Altitude Temperature Correction.

5. **Climb Gradient:**

   5.1 **Maximum Climb Gradient:**

      i. Max Climb Gradient – ISA+10 & Below;

      ii. Max Climb Gradient – ISA+20.

   5.2 **Approach Climb Gradient:**

      i. Approach Climb Gradient – ISA+10 & Below;

      ii. Approach Climb Gradient – ISA+20.

6. **Optimum Altitude:**

   6.1 Cruise Climb Optimum Altitude.

The underlined contents of this QRH's section are included in Appendix A.

Chapter 5

QRH's Flight Scenarios

The present chapter intends to explore in depth the QRH's performance tables and charts that were replicated during the course of this project, and that were previously listed in Chapter 4. Throughout the chapter, the author discusses the set of initial conditions that defines each case, as well as the corresponding data parameters resulting from it. Moreover, additional performance concepts are introduced whenever deemed necessary, in order to further elucidate the reader on these specific scenarios. The performance charts and tables that are analysed in this chapter can also be consulted in Appendix A.

5.1 One Engine Inoperative

All the cases included into this section of the QRH apply to the abnormal scenario of one of the aircraft's engine not being usable during flight. This situation imposes different limits on the thrust that can be applied by the flight crew. These QRH cases are presented in Section A.1 of Appendix A.

Considering the scope of the current work, the following thrust limit definitions must be introduced [22]:

- **Take-Off/Go-Around (TO/GA) thrust:** represents the maximum thrust level an engine can provide during the phases of take-off and go-around. This thrust level is certified to be used for a maximum of 10 minutes in case of engine failure, or 5 minutes with all engines operative. This time limitation is intended to protect the engine from potential damages that could result from prolonged application of this thrust setting.
- **Climb (CL) thrust:** corresponds to the maximum available thrust during the climb stage. The maximum climb thrust is greater than the maximum cruise thrust, but also less than the TO/GA thrust.
- **Maximum Continuous Thrust (MCT):** it's the maximum thrust that can be used indefinitely in a scenario of OEI, without raising concerns about the integrity of the remaining operative engine(s).

Due to the nature of these situations, OEI tables are computed considering a MCT setting. Additional configurations are common to all the cases: High Air Conditioning (A/C), Anti Ice (AI) Off and a Center of Gravity (CG) located at 33% of the wing's Mean Aerodynamic Chord (MAC). However, each case includes a table of corrections, in order to adapt the provided data to different AI and A/C settings from the ones assumed in this section of the QRH.

5.1.1 Ceilings

This part presents the gross altitude ceiling of the aircraft at any given moment of the flight as a function of its weight, its speed setting (GD or LRC speeds, previously defined in Chapter 3) and the ISA deviation that is measured at that time (ISA and ISA+10, ISA+15 or ISA+20). The information is displayed in graphic format, and is exemplified in Figure A.1 of Appendix A.

The gross ceiling represents the absolute maximum altitude that can be maintained by the aircraft in a OEI scenario, and where its climb gradient is null. Conversely, the net ceiling defines the maximum altitude that can be reached, while still being able to achieve a minimum fixed, positive climb gradient. Regulation JAR 25.123 stipulates that for twin-engined aircraft in OEI conditions, the climb gradient value shall correspond to 1.1% [30].

5.1.2 Gross Flight Path Descent at Green Dot Speed

This table provides estimates on the time, distance and fuel consumption during a descent motivated by engine failure. Moreover, it also indicates the recommended initial air speed and the final, level-off altitude. Said data is adjusted according to the aircraft's initial Flight Level (FL) and Gross Weight (GW), as can be observed in Figure A.2 of Appendix A.

This procedure is also known as Drift Down descent. It states that after an engine failure, when level flight can no longer be maintained, the flight crew shall select the MCT setting on the remaining engine, decelerate to GD speed and descend until reaching the drift down ceiling [22].

A Drift Down descent takes place at the smallest descent gradient possible. Therefore, during this procedure, the highest altitude possible is maintained over the longest distance.

Aircraft operators are required by law to be provided with accurate performance data that characterizes the Drift Down procedure. Said data shall be calculated assuming the flight conditions stipulated by JAR 25.123 [30]:

> **"JAR 25.123 – En-route flight paths:**
>
> (a) For the en-route configuration, the flight paths [...] must be determined at each weight, altitude, and ambient temperature, within the operating limits established for the aeroplane. The variation of weight along the flight path, accounting for the progressive consumption of fuel and oil by the operating engines, may be included in the computation. The flight paths must be determined at any selected speed, with —
>
> (1) The most unfavourable centre of gravity;
>
> (2) The critical engines inoperative;
>
> (3) The remaining engines at the available maximum continuous power or thrust [...]"

One must be aware of the difference between gross and net flight paths. While the first is the path actually flown by the aircraft, the latter represents the flight path resulting from imposing a penalty in its climb performance, which will in turn affect the descent gradient.

Both these gradient definitions are then related by the following expression:

$$\textbf{Net flight path gradient} = \textbf{Gross flight path gradient} - \textbf{Gradient Penalty} \tag{5.1}$$

The gradient penalty indicated in this expression is again stipulated by JAR 25.123 and assumes the value of 1.1% for a twin-engined aircraft in this flight scenario [30]. The Drift Down descent procedure, as well as the gross and net flight paths, are illustrated in Figure 5.1:

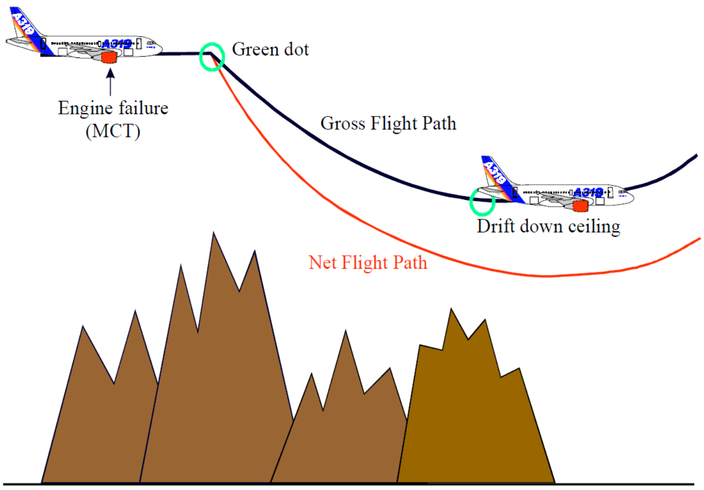


Figure 5.1: Drift Down descent procedure (adapted from [22]).

5.1.3 Cruise at Long Range Cruise speed

The following table, presented in Figure A.3, contains performance data regarding cruise flight conditions at LRC speed. More specifically, speed information is provided in the form of Mach, IAS and TAS. Additional information such as the rotational speed of the engines' low-pressure spool, commonly defined as N1 [%], the total fuel flow [$\mathrm{kg\,h^{-1}}$] and the specific range in terms of fuel consumption [$\mathrm{NM/1000kg}$] is also provided.

5.1.4 In Cruise Quick Check Long Range

The data provided by this table concerns a flight scenario comprising two main stages: a cruise part at constant altitude followed by a descent to landing. The table provides information on the time and fuel consumption during that flight, depending on the initial FL and the total air distance covered by the aircraft. Furthermore, a reference initial weight of $55\,000\,\mathrm{kg}$ is assumed. The initial flight conditions can be verified in Figure A.4.

In terms of speeds, the cruise segment takes place at LRC speed, while the descent follows a constant IAS/Mach law: M0.78/300kt/250kt. A descent operated at a given, constant IAS/Mach law is governed by two reference altitudes: the fixed value of 10 000 ft and the crossover altitude, that varies with air speed. For the speed law that commands the descent presented in this table, the crossover altitude is the altitude where 300 kt IAS corresponds to M0.78, and it's approximately 29 314 ft. Therefore, a descent at constant IAS/Mach law comprises 3 main stages [22]:

1. **Above the crossover altitude:** descent at constant Mach – M0.78.
2. **Below the crossover altitude and above 10 000 ft:** descent at constant air speed – 300 kt IAS. This value corresponds to a more optimum descent speed.
3. **Below 10 000 ft:** descent at constant air speed – 250 kt IAS. This value is imposed by air traffic control regulations.

This procedure is summarized in graphical form in Figure 5.2:

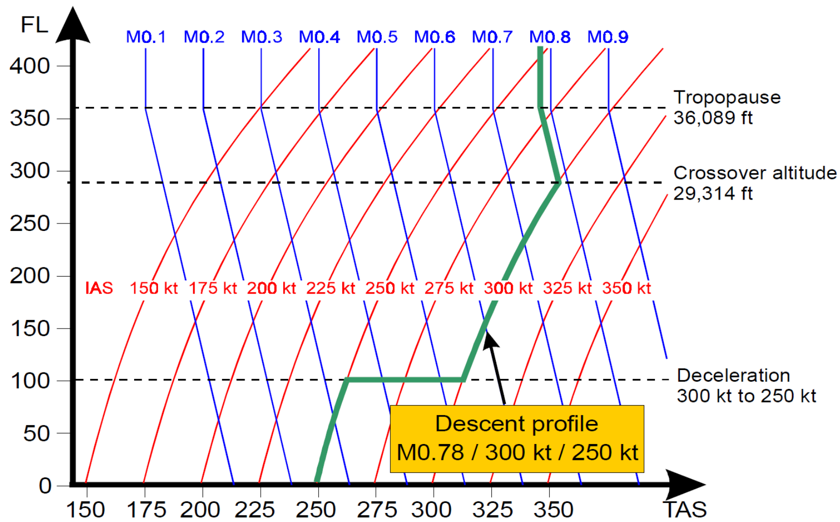


Figure 5.2: Descent procedure at constant IAS/Mach law: M0.78/300kt/250kt [22].

Moreover, the table also takes into account the possibility of low visibility conditions during the approach phase, which would require the adoption of an Instrument Meteorological Conditions (IMC) procedure. Therefore, the data provided in the table includes a corrective factor for the expected duration of the flight and the corresponding fuel consumption (+6 min and +120 kg, respectively). These corrections intend to account for the longer flight time, and therefore extra fuel consumption, that this type of approach involves, compared to the ones that are carried out under Visual Meteorological Conditions (VMC).

5.2 Flight Without Cabin Pressurization

At typical cruise altitudes, the surrounding atmosphere does not contain enough oxygen to support the normal breathing process of human beings. Therefore, that oxygen is provided by a pressurized cabin environment.

In the event of an in-flight loss of cabin pressure, an emergency back-up oxygen supply system provides oxygen to the passengers and the crew. Notwithstanding, this system can only provide enough oxygen to the cabin for a limited amount of time. Therefore, an immediate descent must be performed. This is similar to what happens in the aforementioned scenario of engine failure. However, in this case, the descent is not dictated by a performance constraint, but rather by the oxygen supply system constraint [22].

After descent, the level off occurs at a flight altitude where artificial oxygen supply is no longer necessary, typically at 10 000 ft. The data tables presented in the QRH concerning cabin depressurization are valid from this point in flight onwards, and are available in Section A.2 of Appendix A.

5.2.1 In Cruise Quick Check FL100 Long Range

The rationale behind this QRH's table is similar to the one behind the 'In Cruise Quick Check' table, that was previously introduced in Subsection 5.1.4. Once again, the flight path comprises two distinct phases: a cruise section at FL100 and LRC speed, followed by a descent at constant speed (250 kt IAS). This QRH's table is represented in Figure A.5.

The table contains estimates on total flight time and fuel consumption as a function of the initial weight and the total air distance covered during said flight. This data is valid in ISA standard conditions and a CG located at 25% of MAC aft of the wing's leading edge. Furthermore, the assumed settings for the auxiliary systems are Normal A/C and AI Off. Additional corrective factors for A/C Off and Engine or Total AI are also provided.

The probability of encountering low visibility conditions on approach, which would in turn enforce the IMC procedure detailed in Subsection 5.1.4, is also accounted for in this data set.

5.3 Climb Gradient

The present section of the QRH contains data regarding the aircraft's climb performance in different scenarios, and can be consulted in Section A.3 of Appendix A. The most valuable piece of data provided by these tables is the climb gradient: the ratio between the increase of altitude and the covered, horizontal air distance, expressed as a percentage [%]. The climb gradient is intrinsically related to the climb angle γ, also referred to as flight path angle, which is the angle between the aircraft's aerodynamic axis and the horizon (horizontal axis) [22]. This geometrical relationship can be obtained from a balance of the forces acting on the aircraft during climb. Such balance is illustrated on Figure 5.3:

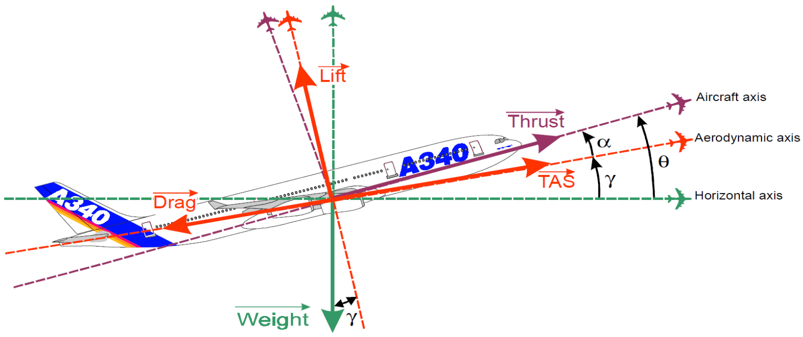


Figure 5.3: Balance of forces during climb[1] (adapted from [22]).

Therefore, the balances of forces along the aerodynamic and the vertical axes, represented above in Figure 5.3 (in red), are given by the following equations [22]:

$$\text{Thrust} \times \cos\alpha = \text{Drag} + \text{Weight} \times \sin\gamma \tag{5.2}$$

$$\text{Lift} = \text{Weight} \times \cos\gamma \tag{5.3}$$

where α represents the angle of attack.

Let γ and α be small enough so that the following expressions are valid:

$$\begin{gathered} \sin\gamma \approx \tan\gamma \approx \gamma\,[rad] \\ \cos\gamma \approx 1 \approx \cos\alpha \end{gathered} \tag{5.4}$$

Replacing these approximations in Equations 5.2 and 5.3 results in:

$$\text{Thrust} = \text{Drag} + \text{Weight} \times \gamma \Rightarrow \gamma[rad] = \frac{\text{Thrust} - \text{Drag}}{\text{Weight}} \tag{5.5}$$

$$\text{Lift} = \text{Weight} \tag{5.6}$$

By establishing the equality of Equation 5.6 into Equation 5.5, one will obtain:

$$\gamma[rad] = \frac{\text{Thrust}}{\text{Weight}} - \frac{\text{Drag}}{\text{Lift}} \tag{5.7}$$

By introducing the Lift-to-Drag ratio (L/D), the expression for the climb angle becomes:

$$\gamma[rad] = \frac{\text{Thrust}}{\text{Weight}} - \frac{1}{L/D} \tag{5.8}$$

Therefore, and following the approximations defined in Equation 5.4, the climb gradient can be defined according to the following expression:

$$\text{Climb Gradient}[\%] = 100 \times \tan\gamma \approx 100 \times \left(\frac{\text{Thrust}}{\text{Weight}} - \frac{1}{L/D}\right) \tag{5.9}$$

[1] For simplification purposes, the thrust vector is represented parallel to the aircraft longitudinal axis.

5.3.1 Maximum Climb Gradient

The following table provides the maximum climb gradient that can be achieved by the aircraft as a function of its GW and the pressure altitude it's flying at. Said data is valid for an All Engines Operative scenario with CL thrust setting, CG located at 33% of the MAC, Normal A/C and AI Off. Two sets of ISA deviations are considered: ISA+10 and below, and ISA+20. Additionally, corrective factors for Engine and Total AI settings are also provided, as can be observed in Figures A.6 and A.7.

Considering the definition of climb gradient presented in Equations 5.5 and 5.8, one can conclude that for a given thrust rating and gross weight, the climb gradient is maximum when $(\text{Thrust} - \text{Drag})$ is maximum. Bearing in mind that, in this case, Thrust is constant, the maximum climb gradient is obtained when Drag is minimum (i.e., when the lift-to-drag ratio is maximum). As seen in Chapter 3, the speed that maximizes L/D is the Green Dot (GD) speed.

Therefore, the maximum climb gradients computed in this table were obtained for GD speed. The corresponding CAS values are also part of the table.

5.3.2 Approach Climb Gradient

The Approach Climb Gradient tables, which are represented in Figures A.8 and A.9, indicate the aircraft's climb gradient performance during the approach phase of the flight in a scenario of OEI. Said data is provided for a given set of pressure altitudes, high-lift devices configuration (CONF 2 and 3) and aircraft GW.

The approach speed is defined by the following speed rule: $V/V_{S_{1g}} = 1.23$. This rule determines that the approach speed shall be, at least, 23% higher than the stall speed $V_{S_{1g}}$ imposed by JAR regulations, that was previously detailed in Chapter 3 [30].

The assumed system settings in this table are TO/GA thrust, Normal A/C and AI Off. Corrections for Engine and Total AI settings are also provided. Two sets of ISA deviation are considered: ISA+10 and below, and ISA+20. The data is valid for any CG position that is covered by the certified flight envelope.

Dark gray-shaded cells of the table indicate an approach climb gradient that is lower than the minimum 2.1% required by JAR 25.121 Subpart B [30]. On the other hand, light gray-shaded cells alert for a climb gradient value below the 2.5% requirement for instrument approaches with decision heights below 200 ft, such as ILS[2] CAT II and III. This requirement is imposed by EU-OPS 1.510 Subpart B [38].

[2] ILS: Instrument Landing System

Chapter 6

Computational Methodology

The current chapter aims to guide the reader through the development process of the proposed solution. Section 6.1 starts off by providing an overview of all the software tools that are used during this process. This Section also introduces the basic notions and concepts that one should be aware of in order to comprehend the several work stages that are analysed in this chapter.

Section 6.2 approaches in detail each phase of the development process. Moreover, the inner workings of each of the several modules that form the proposed solution are also scrutinized in this Section.

6.1 Software tools

6.1.1 Airbus PEP

Performance Engineer's Programs is a Windows-based software developed by Airbus and distributed to its aircraft's operators. It contains several computational modules that execute comprehensive aircraft performance calculations for any flight phase. These modules are divided into two categories: Low Speed and High Speed Performance (LSP and HSP, respectively). LSP modules focus primarily on take-off and landing flight phases. Conversely, HSP modules cover the stages of climb, cruise, descent and holding, as well as additional flight planning scenarios. The modules that are featured in these categories are listed below:

- **Low Speed Performance (LSP)**: FM, Operational Flight Path, Takeoff and Landing Optimization (TLO);
- **High Speed Performance (HSP)**: Aircraft Performance Monitoring (APM) tool, Flight Planning (FLIP) computation, Fuel Temperature Prediction (FTP), IFP;

Using PEP, it is possible to replicate performance data tables and charts such as the ones currently present in the FCOM and the QRH, one of the main goals of the present enterprise.

PEP is the performance data provider to the application developed during the course of current work. Performance data is automatically calculated during PEP sessions, according to the parameters included in the required input files. Each PEP session is based on two input files. The first is a .PEP file that defines each session and indicates the resulting output file names. The second input file type depends on the module used during said session.

PEP provides a user-friendly Graphical User Interface (GUI), which is displayed in Figure 6.1. Using this GUI, the user can easily configure the desired sessions without having to deal directly with PEP's internal parameters. These parameters will be analysed in this section.

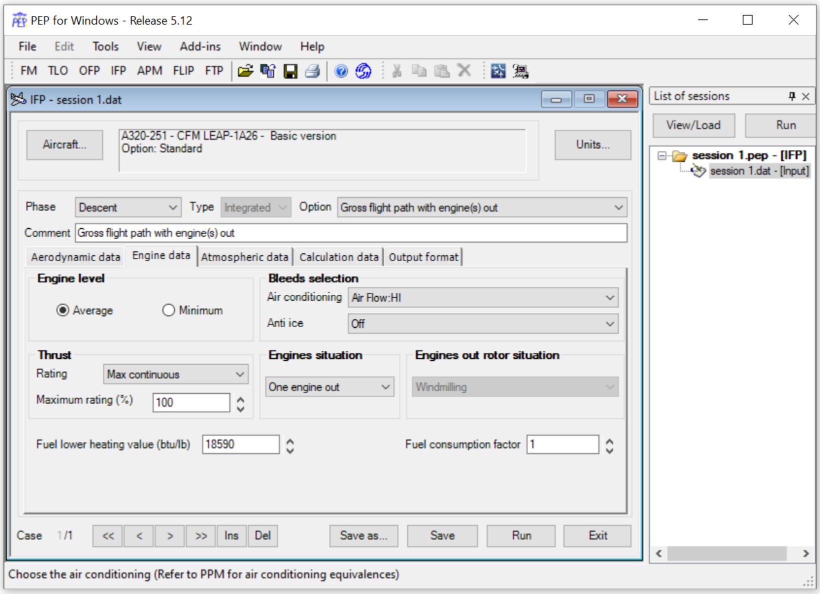


Figure 6.1: PEP's GUI for the IFP module.

Given the considerable amount of PEP sessions and corresponding input files required by this project, resorting to PEP's GUI was not deemed feasible by the author. Therefore, said files were automatically generated and customized to each flight scenario by a C# routine, developed as part of this project. This C# routine is further detailed in Section 6.2.1.

PEP sessions are normally launched individually from the program's GUI. To process a larger amount of sessions at once, this software also incorporates a Batch Manager add-on. As indicated by its name, this utility allows the user to set a group of several PEP sessions and specify a start and end time. The Batch Manager will then automatically run the sessions in a sequenced manner in the time frame defined by the user. The current work took advantage of this functionality to expedite the data computation process.

The present work makes use of PEP version 5.12. Furthermore, and as was previously mentioned, it specifically resorts to the In Flight Performance (IFP) and Flight Manual (FM) modules, that will be further analysed hereafter.

6.1.1.1 IFP module

This HSP module is targeted at the climb, cruise, descent and holding segments of the flight. This module is used for all the scenarios described in this paper, except for 'Approach Climb Gradient'.

Input files The IFP-specific input is a .DAT file. This file fully defines the simulation case and its attributes, such as the applicable performance databases, the flight phase and the settings for the aircraft's Center of Gravity (CG) location and the Anti Ice (AI) and Air Conditioning (A/C) systems. These files are formatted according to specific guidelines defined in PEP's documentation, and its format depends on the flight scenario considered during computations [39].

Airbus' documentation provides an exhaustive input parameters' description. However, the author prefers to introduce a more concise overview of the most important aspects. With that in mind, a .DAT file is presented in Listing B.1 of Appendix B. This file defines a Long Range Cruise (LRC) speed calculation for a One Engine Inoperative (OEI) flight scenario.

In this file, lines 1 to 4 state the aircraft type used in the calculations and the corresponding performance databases. Line 5 is a comment line that can be edited by the user. The next line introduces a series of inputs that fully characterize the computation. In this case, '122' is the KDPH parameter and defines a single-point computation ('1') during cruise ('2') for 'Cruise at GD or LRC speed' ('2'). In the same line, 'GC6' represents the KODIM parameter, specifying the bleed status: Total AI ON ('G'), High A/C ('C') and average engine level ('6') in a OEI scenario. After that, lines 9 to 11 are more intuitive and indicate the ISA deviations, altitudes and weights, respectively. '0.99' in line 12 represents the speed optimization code and points to the LRC speed definition, introduced in Subsection 3.2.7. The second-to-last line contains a set of PEP-specific internal codes, while the last line indicates the end of the input file.

Output files The outputs generated by PEP calculations can be provided in several formats and file types, according to the user's preferences: detailed, formatted, table and tabulated network. In order to collect the largest amount of information in the most efficient manner possible, the tabulated network file (.CSV[1] file) was selected during this work. As the name suggests, the data columns contained in these files are separated by a comma, which expedites the process of incorporating said data into suitable databases. The corresponding .CSV file to the calculation described in the previous paragraph is provided in Listing B.3 of Appendix B.

6.1.1.2 FM module

Flight Manual (FM) is PEP's LSP module that enables performance calculations of regulatory data regarding the take-off, approach and landing flight phases. The current work resorted to this module exclusively for calculations regarding the 'Approach Climb Gradient' table.

Input files The FM module uses a .ACG file as input. This module exhaustively details the flight conditions in analysis, and therefore its input files tend to be significantly long (∼400 lines of code). A snapshot of an .ACG file for an 'Approach Climb Gradient' computation is displayed in Listing B.2 of Appendix B. As may be noticed, the input description in this files is self-explanatory.

[1] CSV: Comma-Separated Values

Output files The FM provides the same choice of output types as the previously analysed IFP module. Therefore, the .CSV output files were chosen, for the same reasons described in Subsection 6.1.1.1. Furthermore, the output .CSV file generated during the session described in the previous paragraph is shown in Listing B.4 of Appendix B.

6.1.2 Microsoft Visual Studio

The Integrated Development Environment (IDE) chosen for building this tool is *Microsoft Visual Studio 2019 Enterprise*. This is the same IDE used by TAP Air Portugal's eOps team during the development process of the company's EFB solution.

TAP's EFB solution is developed in both VB.NET[2] and C# programming languages. To ensure the interoperability between both these languages, the global solution relies on the .NET Framework. The application developed in the current work uses .NET version 4.7.2.

This particular project relies on relational databases to store a sizeable amount of data. In order to achieve a higher level of abstraction and manipulate these databases directly through an object-oriented programming language, as is the case of C#, an Object-Relational Mapping (O/RM) framework was used. More specifically, this project makes use of Entity Framework (EF), version 6.4.4 [40].

6.1.3 Microsoft SQL Server Management Studio

Microsoft SQL Server Management Studio is a software that provides a set of tools to plan, create and configure Structured Query Language (SQL) databases.

As is discussed in the following section, this project involved the construction of a custom database to store aircraft performance data. During the planning phase of this work, the author decided to develop a SQL infrastructure to process and organize that information in a logical manner.

SQL Server Management Studio is used throughout the entire development process to manage the aforementioned infrastructure, as well as to retrieve data from the database that resulted from that process. The present project resorts to version 18.7.1 of this software.

6.2 Computational process phases

The computational development process of this project included the following stages:

1. Input file generation;
2. Computation of PEP sessions;
3. Database planning and construction;
4. Import of performance data;
5. Data fetching.

Each of these phases are thoroughly detailed hereafter.

[2]VB: Visual Basic

6.2.1 Input file generation

As mentioned in the previous section, the input files are automatically generated by a specially developed C# routine. This solution, that was named `PEP_FileCreator`, comprises the following files:

- **Program.cs:** main file that calls the several input file creation methods.
- **AirplaneManager.cs:** defines the 'Airplane' class and its intrinsic properties (e.g. aircraft type and corresponding performance databases). Additionally, this file also specifies such properties for each aircraft type that is part of TAP's fleet.
- **VariableLoopCreator.cs:** by default, each PEP session only computes data for 50 values of altitude, weight and air distance. To overcome such limitation, this module splits the range of values required by each QRH's table into sets of 50 values. Each set originates one PEP session.
- **ClimbGrad.cs, FltWOCabPress.cs and OneEngInop.cs:** contain the methods that define the required flight conditions to replicate the 'Climb Gradient', 'Flight Without Cabin Pressurization' and 'One Engine Inoperative' QRH's sections, respectively.
- **FileCreatorFM.cs and FileCreatorIFP.cs:** these methods receive the flight parameters defined in the previous steps and generate the corresponding input files. One of these two methods is called depending on the PEP module (FM or IFP, respectively) required for the current calculation.

The program's workflow and the connection between these methods and files are depicted in the diagram of Figure 6.2:

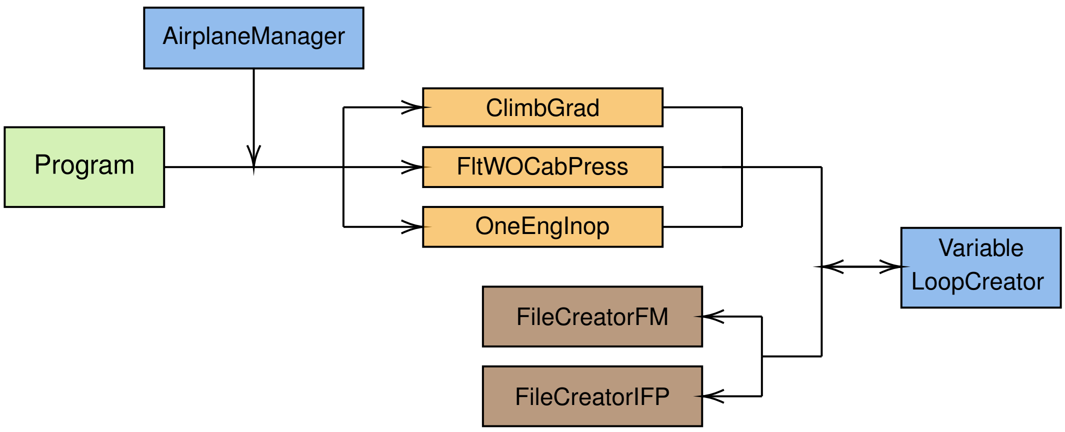


Figure 6.2: Workflow of the input file generation program.

In this diagram, each block background colour represents a specific type of object:

- **Green:** initialization method;
- **Blue:** auxiliary method;
- **Yellow:** method that defines a set of conditions for each flight scenario;
- **Brown:** file-writing method.

The IFM-specific input files generated by this program adhere to the following naming convention:

[1]_[2]_[3]_[4]_AI-[5]_AC-[6]_CG-[7]_[8].[9],

where:

- **[1]:** Aircraft model identification;
- **[2]:** Aircraft version;
- **[3]:** Computation case;
- **[4]:** Computation sub-case;
- **[5]:** AI setting;
- **[6]:** A/C setting;
- **[7]:** Position of the CG;
- **[8]:** Number of the computation (of its kind);
- **[9]:** File extension.

As an example, the .DAT input file name that was previously described in topic 6.1.1.1, and illustrated in Listing B.1 of Appendix B, is provided below:

A320-251_Basic version_OneEngInop_CruiseLRCspeed_AI-G_AC-C_CG-0.33_6.dat

On the other hand, the input files for the FM module follow a similar convention, but with some minor differences:

[1]_[2]_[3]_[4]_AI-[5]_AC-[6]_CONF-[7]_ISA-[8]_[9].[10],

where:

- **[1]:** Aircraft model identification;
- **[2]:** Aircraft version;
- **[3]:** Computation case;
- **[4]:** Computation sub-case;
- **[5]:** AI setting (specific to the FM module);
- **[6]:** A/C setting;
- **[7]:** Position of high lift devices (i.e., slats and flaps);
- **[8]:** ISA deviation;
- **[9]:** Number of the computation (of its kind);
- **[10]:** File extension.

Based on this naming convention, the .ACG input file presented in Listing B.2, that defines a PEP FM computation for the 'Approach Climb Gradient' tables of the QRH (Figures A.8 and A.9), has the following name:

A320-251_Basic version_ClimbGrad_AppClimbGrad_AI-1_AC-1_CONF 1+F_ISA-0_1.acg

The proposed solution calculates performance for the aircraft configurations that are covered in the QRH. Additionally, it also computes data for alternative configurations that involve different AI and A/C settings. The aforementioned naming conventions allow the immediate identification of a given file's assumed aircraft configuration based on its name.

Before executing the program, the user must specify the destination folder where the input files will be created and the target aircraft type(s) and scenarios of the QRH. During its execution, the program provides several messages to the user regarding its current status. These messages include information about the files that are being generated at that time, such as the target aircraft and the corresponding

QRH scenario. The number and type of files that were generated for each of the previous QRH scenarios are also displayed in these messages. An example of the messages that are presented to the user during the program's execution is provided in Figure 6.3:

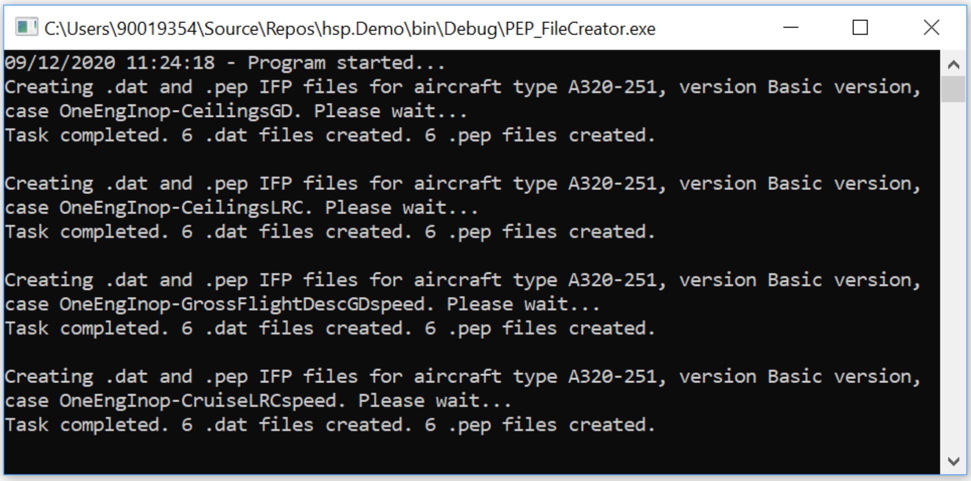


Figure 6.3: `PEP_FileCreator` program execution.

6.2.2 Computation of PEP sessions

The PEP sessions defined in the previous step are now ready to be computed. To expedite the process, these sessions are computed in batch, according to the procedure described in Section 6.1.1.

After being processed by PEP, the software returns the corresponding sessions' output files. These files have the same name as the input files that originated them, apart from a different file extension (.CSV). The two naming conventions that are presented in Subsection 6.2.1 were designed with the main goal of streamlining the process of importing the performance data contained in these output files to a database. This process is further detailed in the next topic of the current Chapter.

Replicating the QRH's tables detailed in Chapter 5 for all the aircraft types present in TAP's fleet required a total of 135 603 PEP sessions, 10 668 of which were for the Airbus A320-251 type alone. For this specific type, each table of the QRH involved the following number of sessions:

- **OEI:**
  - Ceilings: 12
  - Gross Flight Path Descent at GD Speed: 18
  - Cruise at LRC Speed: 6
  - In Cruise Quick Check Long Range: 2 280
- **Flight Without Cabin Pressurization:**
  - In Cruise Quick Check FL100 Long Range: 8 271
- **Climb Gradient:**
  - Maximum Climb Gradient: 9
  - Approach Climb Gradient: 72

6.2.3 Database planning and construction

The computational stage described in the previous topic generated an extensive set of performance data. To store said data, the author developed a dedicated database infrastructure. This was achieved via an EF Code-First approach. This methodology allows a developer to directly code the infrastructure's model and domain classes definitions. Each database table corresponds to a class of the coded model, and each table column is specified as a property of that class. Based on that code, EF's Application Programming Interface (API) will then generate the desired database.

The database that resulted from this project was named `EFB-HSP_Data` and is summarized in the schematic of Figure B.1. This is a relational database, meaning that its structure allows the user to identify and access data in relation to another piece of data that is also stored in the database [41]. This database comprises a total of four tables:

- **'Dataset':** this is the main table, which contains the performance data parameters that are obtained from PEP's CSV output files, previously described in Section 6.1.1. Moreover, this table also stores the corresponding PEP input parameters that are used to compute said data.
- **'Airplane':** incorporates information regarding the aircraft that are part of TAP's fleet. Aircraft type-specific data is also stored in this table.
- **'PEPdatabase':** indicates the PEP-specific aircraft performance databases that are used during the calculation of a given data set.
- **'Case':** establishes an unequivocal connection between any piece of data and the specific scenario to which it belongs. Additionally, this table also locates said scenario in the aircraft's OM, and identifies which PEP module is required to replicate that scenario.

To ensure the correct tracking and management of the information included in this database, every table includes an 'Author' and 'UpdateDate' field. These fields are intended to clearly identify the person or process that inserted/updated a given piece of data into the DB structure and the moment when it took place, respectively.

As can be observed in the schematic of Figure B.1, all the tables that are part of this database are related to each other by a One-To-Many relationship (represented in the schematic as $1-*$). In a One-To-Many relationship, a data record of one table is associated with one or more records of another table. Let's clarify this concept with an example from the database that is the subject of the present Section. For the sake of argument, let's consider the relationship between the 'Airplane' and 'Dataset' tables. Each record in the 'Dataset' table was calculated for a specific, single aircraft type, which is stored in the 'Aircraft' table. Nonetheless, for each aircraft type, there are multiple (i.e., many) pieces of performance data that pertains to it.

6.2.4 Import of performance data

Having developed an appropriate database in the previous topic, the next step consists in reading the performance data contained in PEP's CSV files and import it into that database. Given the considerable amount of files to import, the author decided to automatize this process.

To do so, the process relied heavily on ‘CsvHelper’, an open-source .NET library specifically designed to read and write CSV files [42]. When combined with Entity Framework, this library allows the user to read several CSV files into a data set and then use it to populate a specified database.

PEP’s CSV output files follow the general layout convention that is presented in Listing B.3 of Appendix B. However, the order of the columns and the data parameters that are displayed vary with the type of calculation that generated the file. Therefore, CsvHelper’s seed method requires one class mapping per computation case. This procedure consists of associating the properties of each database table to its respective column position on the CSV output file. To further clarify this procedure, the ‘Dataset’ table’s class mapping for the ‘Cruise at LRC Speed’ flight conditions, that were previously described in Section 6.1.1.1, is included in Listing B.5.

The majority of the data parameters are obtained from the contents of each .CSV output file *per se*. However, additional information such as the aircraft type and model, the position of the CG and the configuration of the high lift devices is directly retrieved from the respective file name and then incorporated into the database. This is only made possible by the fixed naming conventions that were discussed in the previous topic of the current Section.

PEP computations provide the required data parameters to replicate the HSP tables that are part of the QRH. Said files also contain additional parameters, such as the lift and drag coefficients (C_L and C_D, respectively), and the total thrust produced by the engines. Despite the fact that these are not essential to the QRH’s tables, the author decided to also import them into the database. This is done with the intent of future-proofing the solution and to facilitate the implementation of further developments and new features by TAP’s e-Operations group.

6.2.5 Data fetching

After populating the database with the data sets obtained from the CSV files, its contents can be inspected and manipulated using SQL Server Management Studio software and the adequate SQL syntax. Furthermore, this database structure also enables the user to fetch the required data to replicate the QRH’s tables and charts that were previously analysed in Chapter 5.

The procedure to obtain the relevant data parameters for the ”Gross Flight Descent at Green Dot Speed” table of the Airbus A320-251 QRH is exemplified hereafter. As can be verified in Figure A.2, the data contained in this table is valid for the following conditions:

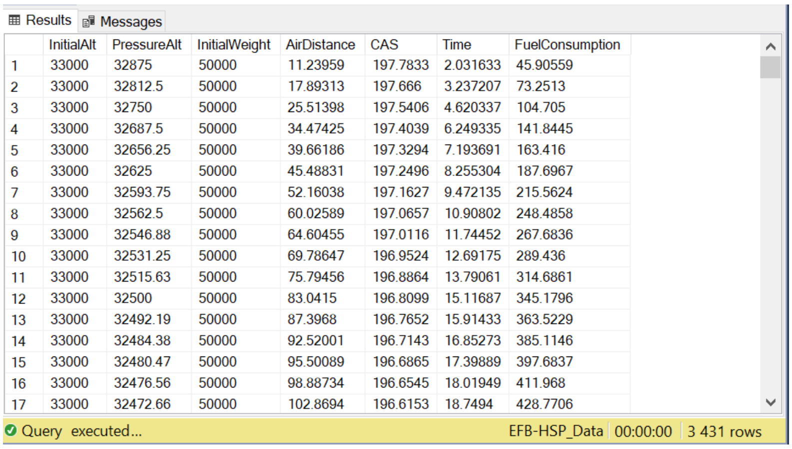
- **Engine status:** One Engine Inoperative;
- **Thrust setting:** Maximum continuous;
- **Speed rule:** GD;
- **CG:** 33%;
- **ISA deviation:** 0;
- **A/C setting:** High;
- **AI setting:** Off;

According to the database definitions set by the author, the Airbus A320-251 aircraft type sports the identification number 5, while the "Gross Flight Descent at Green Dot Speed" scenario corresponds to case no. 6 of the 'Case' DB table. Therefore, the SQL query that fetches the data set from the database that meets the above-mentioned conditions is detailed in Listing 6.1:

Listing 6.1: SQL query applied to `EFB-HSP_Data` database.

```
SELECT InitialAlt, PressureAlt, InitialWeight, AirDistance, CAS,
    Time, FuelConsumption
FROM [EFB-HSP_Data].[dbo].[Dataset]
WHERE (Airplane_Id = 5 AND Case_Id = 6 AND SpeedRule = ‘GD’
    AND CG = ‘0.33’ AND ISA = 0 AND AntiIce = ‘0’
    AND AirConditioning =‘C’)
```

Executing this query in Microsoft SQL Server Management Studio produces the result that is depicted in Figure 6.4.



	InitialAlt	PressureAlt	InitialWeight	AirDistance	CAS	Time	FuelConsumption
1	33000	32875	50000	11.23959	197.7833	2.031633	45.90559
2	33000	32812.5	50000	17.89313	197.666	3.237207	73.2513
3	33000	32750	50000	25.51398	197.5406	4.620337	104.705
4	33000	32687.5	50000	34.47425	197.4039	6.249335	141.8445
5	33000	32656.25	50000	39.66186	197.3294	7.193691	163.416
6	33000	32625	50000	45.48831	197.2496	8.255304	187.6967
7	33000	32593.75	50000	52.16038	197.1627	9.472135	215.5624
8	33000	32562.5	50000	60.02589	197.0657	10.90802	248.4858
9	33000	32546.88	50000	64.60455	197.0116	11.74452	267.6836
10	33000	32531.25	50000	69.78647	196.9524	12.69175	289.436
11	33000	32515.63	50000	75.79456	196.8864	13.79061	314.6861
12	33000	32500	50000	83.0415	196.8099	15.11687	345.1796
13	33000	32492.19	50000	87.3968	196.7652	15.91433	363.5229
14	33000	32484.38	50000	92.52001	196.7143	16.85273	385.1146
15	33000	32480.47	50000	95.50089	196.6865	17.39889	397.6837
16	33000	32476.56	50000	98.88734	196.6545	18.01949	411.968
17	33000	32472.66	50000	102.8694	196.6153	18.7494	428.7706

Query executed... EFB-HSP_Data 00:00:00 3 431 rows

Figure 6.4: Query execution result.

After executing the query, the data set that is returned by it can be directly exported from the database into a CSV file. This strategy expedites the post-processing stage that is discussed in the next Chapter.

An analogous procedure can be implemented to replicate the remaining cases of the QRH. The necessary data sets can be obtained by modifying the appropriate parameters in the SQL query displayed in Listing 6.1. Moreover, this methodology remains valid for all the aircraft types that are part of TAP's fleet, and that are listed in Table 1.1 of Chapter 1.

Chapter 7

Results

The main goal of this chapter is to present and discuss the results that are obtained during the course of the present work.

Section 7.1 performs a replication of the several tables and charts of the QRH that are the starting point of this project. The results of such replication are compared with the ones that are published in the QRH. The eventual differences that may be verified during this stage are thoroughly analysed and discussed.

The final Section 7.2 focuses on simulating a real operational scenario. Performance data for this scenario is computed by using the proposed solution, as well as the QRH. Both results sets are then compared with PEP's actual values for the same flight conditions. The section ends with an overview of the operational benefits provided by the tool that is developed in this project, when compared to the QRH-based methods of performance data retrieval.

7.1 QRH replication

7.1.1 Introductory remarks

As has been mentioned in the previous chapters, the main goal of this project is to replicate part of the flight scenarios that are currently included in the HSP section of the QRH. The present section analyses the methods used to recreate the several tables and plots of the aforementioned QRH's section, based on the required performance data that was previously imported into the DB.

The replication process adheres to the same visual format that is currently used in the QRH. Whenever deemed necessary by the author, alternative formats to present the same information in a more precise manner are also explored.

Furthermore, a data verification process also takes place in this section. To do so, the replicated tables and charts are compared with the ones that are currently included in the paper version of the QRH. The eventual differences that might be identified during this stage are discussed accordingly. Two major indicators that are going to be used to assess these differences are the Absolute and Relative

Errors (AE and RE, respectively). In the scope of this Section, these two indicators are defined for each parameter P that is displayed in the QRH, according to Equations 7.1 and 7.2:

$$AE = P_{DB} - P_{QRH} \tag{7.1}$$

$$RE[\%] = \frac{P_{DB} - P_{QRH}}{P_{QRH}} \times 100, \tag{7.2}$$

where P_{QRH} represents a given parameter obtained from the QRH and P_{DB} represents the corresponding parameter that is retrieved from the DB that was developed during the present work.

It is worth pointing out that the DB's performance values that are analysed in this Section correspond to the exact values that were generated during PEP sessions, without any rounding or approximation.

7.1.2 One Engine Inoperative

7.1.2.1 Ceilings

As was previously discussed in Subsection 5.1.1, this scenario covers the gross ceilings at LRC and GD speeds for an aircraft configuration of High A/C and AI Off. The data set contained in this case, that is displayed in Figure A.1 of Appendix A, is now replicated based on the information that was retrieved from the DB. These results are presented in Figure C.1 of Appendix C.

As one can observe in the aforementioned figures, the information regarding this scenario is presented in the paper-based QRH in the form of a chart. This fact makes the process of retrieving data rather inaccurate. To overcome such limitation, the author rearranged the replicated data set into a table. These results are shown in Table C.1.

Moreover, the graphic format that was chosen to display the information for this scenario in the QRH does not allow an accurate comparison between this data set and the corresponding one that was obtained from the DB.

7.1.2.2 Gross Flight Path Descent at GD Speed

The 'Gross Flight Path Descent at GD Speed' scenario (Figure A.2) is valid for the conditions that were previously defined in Subsection 5.1.2. Taking into account this set of conditions, it is now possible to replicate the respective table in the manner that is presented in Table C.2.

The obtained values can be compared with the ones that are part of the QRH. This comparison is performed in Table 7.1:

Table 7.1: Error analysis for 'Gross Flight Path Descent at GD Speed' scenario.

Parameter	Maximum RE	Maximum AE	Location in table (row/column)
Distance [NM]	1.0%	2.2 NM	70ton/FL290
Initial speed [kt]	0%	0 kt	All
Time [min]	-1.9%	-0.5 min	58ton/FL290
Fuel [kg]	-8.5%	-51 kg	54ton/FL310
Level off [ft]	0.4%	96 ft	72ton/FL310

As one can observe in the table, the error associated with the distance, initial speed, time and level off altitude parameters is always less than 2%. Apart from the distance, all of these parameters have an associated AE that is inferior to the QRH's resolution: 1 NM for distance, 1 kt for initial speed, 1 min for time, 100 kg for fuel and 100 ft for level off altitude.

The level off altitude in the QRH is conservatively rounded off to the lower hundred. According to this method, an altitude of 24 390 ft is displayed as 24 300 ft in the QRH, and so on. This fact may help explain the difference of 0.4% that is verified for this parameter.

The relative error of the fuel consumption parameter stands out from the rest, at -8.5%. It is worth noting that while the QRH's values for this parameter are rounded off to the hundreds of kilograms, the ones that were retrieved from the DB ensure a precision of 5 decimal places of kilogram. Nonetheless, the corresponding absolute error is 51 kg, which is lower than the QRH's resolution (100 kg). Therefore, the notably high value of RE may be motivated by the rounding method applied to this parameter in the QRH and the coarse units that are presented in the manual (i.e., tonnes instead of kilograms).

7.1.2.3 Cruise at LRC Speed

As was previously mentioned in Subsection 5.1.3, this scenario is established for an aircraft configuration of OEI, MCT limits, High A/C, AI Off, no ISA deviation and CG located at 33% of MAC. The QRH's table for this scenario is presented in Figure A.3 and has a resolution of 0.1 pp[1] for N1, 1 kg h^{-1} for fuel flow, 0.1 NM/1000kg for SR, 0 001 for Mach and 1 kt for CAS and TAS parameters.

The aforementioned QRH's table can now be replicated based on the information that is available in the DB. This exercise is performed in Table C.3 of Appendix C.

A value comparison between the QRH's table of Figure A.3 and corresponding replicated table is depicted in Table 7.2:

Table 7.2: Error analysis for 'Cruise at LRC Speed' scenario.

Parameter	**Maximum RE**	**Maximum AE**	**Location in table (row/column)**
N1 [%]	-0.6%	-0.4 pp	64ton/FL100
Fuel flow [kg h^{-1}]	-1.8%	-35.2 kg h^{-1}	64ton/FL100
SR [NM/1000kg]	0.9%	1.5 NM/1000kg	56ton/FL100
Mach [adim.]	-1.1%	-0.005	52ton/FL150
CAS [kt]	-1.1%	-2.3 kt	50ton/FL150
TAS [kt]	-1.2%	-3.5 kt	64ton/FL100

7.1.2.4 In Cruise Quick Check Long Range

According to what has been explained in Subsection 5.1.4, this scenario involves two different flight stages: cruise and descent. In the QRH, the aircraft's total fuel consumption, covered air distance and corresponding flight time is the sum of these measurements over the two individual stages.

The computation of the required performance parameters requires a minimum of one PEP session per stage for a given set of aircraft configuration: initial weight, altitude and A/C and AI settings. For the

[1] pp: percentage point

Airbus A320-251 type alone, this process involved a total of 2280 sessions: 1794 for Cruise and 486 for Descent.

For each individual combination of cruise+descent (that corresponds to a square in the QRH's table of Figure A.4), continuity between both these stages must be ensured. Therefore, the aircraft's final conditions for cruise must match its descent's initial conditions.

The aircraft's performance during descent is influenced by the conditions that are verified in the beginning of this stage. In turn, the descent's initial conditions depend on the aircraft's performance during the cruise stage of the flight. Likewise, its performance during cruise varies depending on this phase's initial conditions.

As a result, the process of recreating the QRH's table for this flight scenario involves a multi-stage iterative process. Given the extensive amount of data pertaining to the scenario, the author was not able to develop an efficient process to automatically match the corresponding cruise and descent phases. Notwithstanding, the necessary performance data was obtained through PEP and then incorporated into the solution's DB.

7.1.3 Flight Without Cabin Pressurization

7.1.3.1 In Cruise Quick Check FL100 Long Range

The present flight scenario is similar to the 'In Cruise Quick Check Long Range' that was analysed in the previous Subsection. The required performance data to replicate this QRH's scenario was calculated through a total of 8271 PEP sessions, for the A320-251 type alone: 8190 for cruise and 81 for descent.

The case's computational constraints are analogous to the ones that were discussed for the aforementioned 'In Cruise Quick Check Long Range' scenario. For identical reasons, it was not possible to automatically process the performance data that was obtained from PEP's sessions, in order to present it in the same format as the QRH (see Figure A.5).

At this point, it should be noted that although the complete replication of the QRH's table was not fully achieved, the acquired results were correctly imported into the DB. Furthermore, said results can now be retrieved from the solution's DB to be manually manipulated by using the adequate SQL syntax.

7.1.4 Climb Gradient

7.1.4.1 Maximum Climb Gradient

The Maximum Climb Gradient tables are valid for the conditions that were defined in Subsection 5.3.1: Climb thrust at GD speed, CG located at 33% of MAC, Normal A/C and AI Off. Two main ISA deviations are considered: ISA+10 and below, and ISA+20. Each of these deviations corresponds to a QRH's table. Both these tables are illustrated in Figures A.6 and A.7, respectively.

By analysing the two aforementioned tables, one can conclude that for a given aircraft configuration, flight level and weight, its climb performance is reduced by the increase of ISA deviation. Therefore, the first scenario (ISA+10 and below) was calculated for the most penalizing ISA deviation covered by this set (i.e., ISA+10). The results that were obtained allowed the replication of the corresponding QRH's table, that is presented in Table C.4.

At this point, the obtained results can be compared with the ones that are presented in the QRH. This comparison is summarized in Table 7.3:

Table 7.3: Error analysis for 'Maximum Climb Gradient - ISA+10 & Below' scenario.

Parameter	Maximum RE	Maximum AE	Location (row/column)	Average RE
Climb gradient [%]	0.09%	0.009pp	77ton/10000ft	0.03%

The differences verified between the values from the QRH and from the DB are negligible, especially when compared with the QRH's precision of $0.1\,\mathrm{pp}$ for the climb gradient parameter. Nonetheless, this difference might be explained by the precision associated to each type of results. The DB's values have a precision of up to seven decimal places. On the other hand, the values from the QRH are rounded off to a single decimal place.

An analogous procedure was applied to replicate the QRH's table for a deviation of ISA+20, that is illustrated in Figure A.7. The corresponding results are available in Table C.5. Similarly to what has been performed for the previous scenario, the differences between the QRH's values and the ones obtained from the DB are summarized in Table 7.4:

Table 7.4: Error analysis for 'Maximum Climb Gradient - ISA+20' scenario.

Parameter	Maximum RE	Maximum AE	Location (row/column)	Average RE
Climb gradient [%]	8.48%	0.70pp	76ton/8000ft	6.68%

The high values of error indicated in the table are a source of concern, especially when compared with the ones in Table 7.3, that relates to a similar flight scenario. The highest AE value is significantly larger than the QRH's resolution of $0.1\,\mathrm{pp}$. Furthermore, the average RE is also considerable, which points into a systematic error that is common to all the values of the table.

A data analysis was conducted in order to determine the root cause of such disparities. One of the hypotheses that was considered was an error induced by PEP's computation engine, that might have originated inaccurate data. However, this thesis was discarded, based on the good results that were obtained for the previous case of ISA+10 deviation. The reader must be reminded that the only difference between the previous and the current case's configuration is the ISA deviation. That difference alone should not motivate such a discrepancy in values motivated by a PEP's error. Therefore, this theory was ruled out.

The next step of this troubleshooting process consisted in testing different aircraft configurations and comparing the obtained results with the QRH's table of Figure A.7. The configuration that provided the closest results was the same as indicated in the QRH, but with the AI system set to Total (i.e., Engine + Wings), instead of Off. Using this configuration, the differences between the QRH's values and the ones obtained with PEP are outlined in Table 7.5.

The low values of error that are verified in this scenario are in line with what is achieved in the previous case of ISA+10 deviation (see Table 7.3). These new indicators cast doubts as to whether the

Table 7.5: Error analysis for 'Maximum Climb Gradient - ISA+20, Total AI' scenario.

Parameter	Maximum RE	Maximum AE	Location (row/column)	Average RE
Climb gradient [%]	0.11%	0.009pp	76ton/10000ft	0.04%

aircraft configuration that is indicated in the QRH's table corresponds to the actual data that is displayed in the same table. This theory was discussed with TAP's engineers from the e-Operations group. These engineers conducted an independent verification process that confirmed the author's hypothesis: the QRH's data for this table was calculated for an AI configuration of Total instead of Off, contrarily to what is indicated in the table's heading. Having identified the cause of these discrepancies, the issue was then reported to TAP's Flight Operations department so that the necessary fixes to the table's heading could be accomplished.

The table for this 'Maximum Climb Gradient - ISA+20' is replicated in Figure C.6, now containing the revised heading section and the corresponding performance data.

7.1.4.2 Approach Climb Gradient

The Approach Climb Gradient tables of the QRH assume the aircraft configuration that was previously introduced in Subsection 5.3.2: OEI with TO/GA thrust setting, A/C On, AI Off and a speed rule of $V/V_{S_{1g}} = 1.23$. The QRH's tables cover two main sets of ISA deviations: ISA+10 and Below, and ISA+20. The two QRH's tables are available in Figures A.8 and A.9, respectively.

Following a similar approach to the one presented in the previous topic, the necessary results to replicate the 'ISA+10 & Below' table were calculated for an ISA+10 deviation. This replication is accomplished in Table C.7. Furthermore, the comparison between the QRH's values for this scenario and the corresponding ones from the DB is summarized in Table 7.6:

Table 7.6: Error analysis for 'Approach Climb Gradient - ISA+10 & Below' scenario.

Parameter	Maximum RE	Maximum AE	Location (row/column)	Average RE
Climb gradient [%]	2.97%	0.095pp	75ton/CONF 3 - 6000ft	0.81%

The maximum AE of $0.095\,\text{pp}$ is inferior to the precision of $0.1\,\text{pp}$ in the QRH's table. Nonetheless, this difference can be justified by the fact that the QRH's values are conservatively rounded down to the nearest decimal place. When this rounding method was applied to the DB's values, they matched exactly the corresponding ones from the QRH, as can be concluded by comparing Table 7.6 with the QRH's table of Figure A.8.

The same rationale was employed to the 'ISA+20' QRH's table, that is replicated in Table C.8. An overview of the differences between the results obtained from the DB for this scenario and the corresponding ones from the QRH's table is provided in Table 7.7.

Once again, the maximum AE for this case is inferior to the QRH's table of $0.1\,\text{pp}$. The theory that defends that the main cause of error is the rounding method applied to the QRH's values (round down to the nearest decimal place) also remains valid for the condition of ISA+20 deviation, given the exact

Table 7.7: Error analysis for 'Approach Climb Gradient - ISA+20' scenario.

Parameter	Maximum RE	Maximum AE	Location (row/column)	Average RE
Climb gradient [%]	2.83%	0.099pp	74ton/CONF 3 - 5000ft	0.79%

match between the QRH's values of Figure A.9 and the corresponding DB's values presented in Table C.8.

7.2 Application to simulated flight conditions

In the present section, the proposed solution is subjected to a test in order to assess its computational capabilities. The test simulates two performance calculations for the 'Gross Flight Path Descent at GD Speed' scenario that was previously covered in Subsections 5.1.2 and 6.1.1. The characteristics of each of these two calculation cases were chosen arbitrarily and are detailed below:

- **First case:**
  - ISA deviation: None;
  - Position of CG: 33% of MAC;
  - Initial Gross Weight (GW): 56 400 kg;
  - Initial Altitude: FL310;
  - A/C setting: High;
  - AI setting: Off;
- **Second case:**
  - ISA deviation: None;
  - Position of CG: 33% of MAC;
  - Initial GW: 67 200 kg;
  - Initial Altitude: FL370;
  - A/C setting: High;
  - AI setting: Total AI On;

The performance parameters for both these cases are first obtained from the QRH's table, and then using the solution that was developed during this project. The results from both sources are then compared with the actual values that are provided by PEP software. This time, the relative error (RE) of a given parameter $P_{QRH,DB}$ (that can be either obtained from the QRH or from the solution's DB, respectively) is defined in relation to the corresponding parameter's value that is obtained from PEP, P_{PEP}, as is explained in Equation 7.3:

$$RE_{QRH,DB}[\%] = \frac{P_{QRH,DB} - P_{PEP}}{P_{PEP}} \times 100 \tag{7.3}$$

7.2.1 First case

7.2.1.1 Calculation based on the QRH

As one can observe in the corresponding table of the QRH for this scenario (see Figure A.2), the aircraft's initial GW that characterises this case (56 400 kg) is not included in the table. Instead, this is an intermediate weight that is located between GW's rows 56 and 58 ton of the QRH's table. It is worth pointing out that the QRH allows interpolations for intermediate values of GW, but not for intermediate values of initial altitude [35]. Therefore, the performance values must be retrieved from the QRH through a process of linear interpolation. The method to interpolate a given QRH's performance parameter P, for a specific initial altitude h and gross weight GW_i, is described in Equation 7.4:

$$\begin{gathered}\frac{P(h,GW_i)-P(h,GW_1)}{GW_i-GW_1}=\frac{P(h,GW_2)-P(h,GW_1)}{GW_2-GW_1}\implies \\ \implies P(h,GW_i)=P(h,GW_1)+(GW_i-GW_1)\times\frac{P(h,GW_2)-P(h,GW_1)}{GW_2-GW_1},\end{gathered} \tag{7.4}$$

where GW_1 and GW_2 are two consecutive values of GW that are covered by the table and that verify the following condition: $GW_1 < GW_i < GW_2$.

As was previously mentioned, the present case's target initial GW of 56 400 kg is located between 56 and 58 ton in the QRH's table. A snapshot of the QRH for the aforementioned initial GWs and the case's initial FL is provided in Figure 7.1. The case's relevant performance values are highlighted by the red rectangle in the Figure:

GROSS FLIGHT PATH DESCENT AT GREEN DOT SPEED - 1 ENGINE OUT							
MAX. CONTINUOUS THRUST LIMITS HIGH AIR CONDITIONING ANTI ICE OFF			ISA CG=33.0%		**DISTANCE (NM)** **TIME (MIN)** **INITIAL SPEED (KT)** **FUEL (1000KG)** **LEVEL OFF (FT)**		
INIT. GW (1000KG)	**INITIAL FLIGHT LEVEL**						
	250	**290**	**310**	**330**	**350**	**370**	**390**
56			203 37 208 0.9 29600	258 47 210 1.2 29700	290 52 212 1.3 29800	311 55 214 1.3 29800	331 58 216 1.4 29900
58		128 24 210 0.6 28400	220 40 212 1.0 28600	267 48 214 1.2 28700	297 53 216 1.3 28700	320 57 218 1.4 28700	339 60 220 1.5 28800

Figure 7.1: Snapshot of the 'Gross Flight Path Descent at GD Speed' QRH's table for the first case (adapted from [35]).

Based on the highlighted values of Figure 7.1, the corresponding performance values for the case's target initial GW can finally be obtained through the interpolation process that is detailed above in Equation 7.4:

$$\text{Distance (FL310, 56400kg)} = 203 + (56400 - 56000) \times \frac{220 - 203}{58000 - 56000} = 206.4NM \tag{7.5}$$

$$\text{Initial speed (FL310, 56400kg)} = 208 + (56400 - 56000) \times \frac{212 - 208}{58000 - 56000} = 208.8kt \tag{7.6}$$

$$\text{Time (FL310, 56400kg)} = 37 + (56400 - 56000) \times \frac{40 - 37}{58000 - 56000} = 37.6min \tag{7.7}$$

$$\text{Fuel (FL310, 56400kg)} = 900 + (56400 - 56000) \times \frac{1000 - 900}{58000 - 56000} = 920kg \tag{7.8}$$

$$\text{Level off (FL310, 56400kg)} = 29600 + (56400 - 56000) \times \frac{29600 - 28600}{58000 - 56000} = 29400ft \tag{7.9}$$

The obtained performance values in the previous calculations are compiled into Table 7.8:

Table 7.8: QRH's performance data for $h = FL310$, including the case's target Initial GW $= 56400kg$.

Parameter	**Initial GW [ton]**		
	56	**56.4**	**58**
Distance [NM]	203	206.4	220
Initial speed [kt]	208	208.8	212
Time [min]	37	37.6	40
Fuel [kg]	900	920	1000
Level off [ft]	29600	29400	28600

7.2.1.2 Calculation from the solution's DB

The data that is available in the DB has enough resolution to include this case's target initial GW and FL. Therefore, the required performance values for this scenario can be directly retrieved from the DB, without any intermediate interpolation process. The case's descent profile can be fetched from the DB by running the following SQL query:

Listing 7.1: SQL query for the first case of 'Gross Flight Path Descent at GD Speed' scenario.

```
SELECT AirDistance, CAS, Time, FuelConsumption, PressureAlt
FROM [EFB-HSP_Data].[dbo].[Dataset]
WHERE (Airplane_Id = 5 AND Case_Id = 6 AND SpeedRule = 'GD'
    AND CG = '0.33' AND ISA = 0 AND InitialWeight = 56400
    AND InitialAlt = 31000 AND AntiIce = '0'
    AND AirConditioning ='C')
```

The results that are returned by the previous query are presented in Figure 7.2. Based on the results that are displayed in this Figure, the relevant performance parameters for this case are summarized in Table 7.9.

Results | Messages

	AirDistance	CAS	Time	FuelConsumption	PressureAlt
1	0	208.8	0	0	31000
2	12.087	208.443	2.152465	53.51835	30750
3	26.0853	208.0677	4.659988	116.1989	30500
4	42.78546	207.6666	7.669434	191.8201	30250
5	52.59961	207.4518	9.446082	236.6365	30125
6	63.76615	207.2243	11.47386	287.9178	30000
7	76.80198	206.9789	13.84863	348.1295	29875
8	92.57289	206.7076	16.73113	421.3969	29750
9	101.9785	206.5571	18.4546	465.2809	29687.5
10	112.8621	206.3928	20.45245	516.2086	29625
11	125.9344	206.2078	22.85651	577.561	29562.5
12	133.7517	206.1027	24.29625	614.3362	29531.25
13	142.8939	205.9854	25.98175	657.4152	29500
14	148.1785	205.9198	26.95683	682.3481	29484.38
15	154.1366	205.8479	28.05683	710.4836	29468.75
16	161.0268	205.7672	29.32969	743.0506	29453.13
17	169.3483	205.6731	30.86799	782.4222	29437.5
18	174.386	205.6173	31.79978	806.2764	29429.69
19	180.402	205.5526	32.91296	834.7791	29421.88
20	183.9888	205.5145	33.57686	851.7802	29417.97
21	188.2033	205.4707	34.35716	871.7635	29414.06
22	193.4418	205.4174	35.32732	896.6111	29410.16
23	196.7864	205.3835	35.9469	912.4803	29408.2
24	201.1586	205.3404	36.75699	933.23	29406.25
25	208.502	205.2695	38.11803	968.0924	29404.3
26	215.3156	205.2029	39.38129	1000.45	29403.75

EFB-HSP_Data | 00:00:00 | 26 rows

Figure 7.2: Results from the SQL query for the first case.

Table 7.9: DB's performance data for $h = FL310$ and Initial GW $= 56400kg$.

Parameter	DB's value
Distance [NM]	215.3156
Initial speed [kt]	208.8
Time [min]	39.38129
Fuel [kg]	1000.45
Level off [ft]	29403.75

7.2.1.3 Calculation from a PEP session

The exact performance values for the present case can be directly computed in PEP. To do so, an adequate PEP session must be configured. The .DAT input file for the aforementioned session is shown in Listing 7.2:

Listing 7.2: .DAT input file for a PEP session regarding the first case.

```
A320-251                         1     0     1     3
AERO       03/03/16   AE251A02.BDC
ENGINE     12/05/16   ME251A03.BDC
GENERAL    03/03/16   GE251A02.BDC
Gross flight path with engine(s) out
 235 131 000    0 0 1 0C6   KG    00000 DC PC                      0 0
3        100      .33      0       0       0       0       0
      18590   0
      1   1   1   2   1   0
0
```

```
56400
0
1          1
31000
0          0          0          1          1          0          0          0          0
END
```

This input file clearly indicates the case's target initial GW and altitude (56 400 kg and 31 000 ft, respectively). The aircraft configuration of AI Off ('0') and High A/C ('C') is defined by the KODIM parameter '0C6', according to the methodology that was previously introduced in Subsection 6.1.1.

A snapshot of the output CSV file that is returned by the aforementioned PEP session is now presented in Figure 7.3:

DT	WGTI	ALTI	ALT.	ALTG	TIME	FUEL	DIST	CAS
DG.C	KG	FT	FT	FT	MN	KG	NM	KT
0	56400	31000	31000	31000	0	0	0	208.8
0	56400	31000	30750	30750	2.152465	53.51835	12.087	208.443
0	56400	31000	30500	30500	4.659988	116.1989	26.0853	208.0677
0	56400	31000	30250	30250	7.669434	191.8201	42.78546	207.6666
0	56400	31000	30125	30125	9.446082	236.6365	52.59961	207.4518
0	56400	31000	30000	30000	11.47386	287.9179	63.76615	207.2243
0	56400	31000	29875	29875	13.84864	348.1295	76.80198	206.9789
0	56400	31000	29750	29750	16.73113	421.3969	92.57289	206.7076
0	56400	31000	29687.5	29687.5	18.4546	465.281	101.9785	206.5571
0	56400	31000	29625	29625	20.45245	516.2086	112.8621	206.3928
0	56400	31000	29562.5	29562.5	22.85651	577.561	125.9344	206.2078
0	56400	31000	29531.25	29531.25	24.29625	614.3362	133.7517	206.1027
0	56400	31000	29500	29500	25.98175	657.4152	142.8939	205.9854
0	56400	31000	29484.38	29484.38	26.95683	682.3482	148.1785	205.9198
0	56400	31000	29468.75	29468.75	28.05683	710.4836	154.1366	205.8479
0	56400	31000	29453.13	29453.13	29.32969	743.0506	161.0268	205.7672
0	56400	31000	29437.5	29437.5	30.868	782.4222	169.3483	205.6731
0	56400	31000	29429.69	29429.69	31.79978	806.2764	174.386	205.6173
0	56400	31000	29421.88	29421.88	32.91296	834.7791	180.402	205.5526
0	56400	31000	29417.97	29417.97	33.57686	851.7802	183.9888	205.5145
0	56400	31000	29414.06	29414.06	34.35716	871.7635	188.2033	205.4707
0	56400	31000	29410.16	29410.16	35.32732	896.6111	193.4418	205.4174
0	56400	31000	29408.2	29408.2	35.9469	912.4804	196.7864	205.3835
0	56400	31000	29406.25	29406.25	36.75699	933.2301	201.1586	205.3404
0	56400	31000	29404.3	29404.3	38.11803	968.0924	208.5021	205.2695
0	56400	31000	29403.75	29403.75	39.38129	1000.45	215.3156	205.2029
INPUT DATA	IFP							
END								

Figure 7.3: CSV output file of the first case's PEP session.

The relevant results that are retrieved from this PEP session are summarized in Table 7.10:

Table 7.10: PEP's performance data for $h = FL310$ and Initial GW $= 56400kg$.

Parameter	**PEP's value**
Distance [NM]	215.3156
Initial speed [kt]	208.8
Time [min]	39.38129
Fuel [kg]	1000.45
Level off [ft]	29403.75

7.2.2 Second case

7.2.2.1 Calculation based on the QRH

Similarly to what was verified in the first case, the target initial GW for the current case is not directly contemplated in the QRH's table. Instead, the GW of 67 200 kg is located between the 66 and 68 ton's rows of the table. The performance values contained in these rows are presented in Figure 7.4:

GROSS FLIGHT PATH DESCENT AT GREEN DOT SPEED - 1 ENGINE OUT							
MAX. CONTINUOUS THRUST LIMITS HIGH AIR CONDITIONING ANTI ICE OFF			ISA CG=33.0%	DISTANCE (NM) TIME (MIN) INITIAL SPEED (KT) FUEL (1000KG) LEVEL OFF (FT)			
INIT. GW	**INITIAL FLIGHT LEVEL**						
(1000KG)	**250**	**290**	**310**	**330**	**350**	**370**	**390**
66		226 41 226 1.2 25600	258 46 228 1.3 25700	283 50 230 1.4 25700	301 53 232 1.5 25700	319 56 234 1.5 25700	334 58 236 1.6 25800
68		196 35 230 1.0 25100	226 40 232 1.2 25200	250 44 234 1.3 25200	268 47 236 1.3 25200	286 49 238 1.4 25200	301 51 240 1.4 25200

Figure 7.4: Snapshot of the 'Gross Flight Path Descent at GD Speed' QRH's table for the second case (adapted from [35]).

The performance parameters for this case must be interpolated from the highlighted values that are displayed in Figure 7.4. By applying the method described in Equation 7.4, the corresponding values are calculated as follows:

$$\text{Distance (FL370, 67200kg)} = 319 + (67200 - 66000) \times \frac{286 - 319}{68000 - 66000} = 299.2NM \tag{7.10}$$

$$\text{Initial speed (FL370, 67200kg)} = 234 + (67200 - 66000) \times \frac{238 - 234}{68000 - 66000} = 236.4kt \tag{7.11}$$

$$\text{Time (FL370, 67200kg)} = 56 + (67200 - 66000) \times \frac{49 - 56}{68000 - 66000} = 51.8min \tag{7.12}$$

$$\text{Fuel (FL370, 67200kg)} = 1500 + (67200 - 66000) \times \frac{1400 - 1500}{68000 - 66000} = 1440kg \tag{7.13}$$

$$\text{Level off (FL370, 67200kg)} = 25700 + (67200 - 66000) \times \frac{25200 - 25700}{68000 - 66000} = 25400ft \tag{7.14}$$

The performance values that were obtained in the previous calculations are compiled into Table 7.11.

The aircraft configuration for this case differs from the one that is covered by the QRH's table. While the values in this table are valid for an AI Off configuration, the current case assumes a Total AI On setting. To account for this different setting, one must correct the values obtained in Equations 7.10 to 7.14 with the corrective factors that are provided in the QRH's table (see Figure A.2). The QRH's corrective factors for a configuration of Total AI On are displayed in Table 7.12.

The corrected QRH's values for case's configuration of Total AI On are now presented in Table 7.13.

Table 7.11: QRH's performance data for $h = FL370$, now including Initial GW $= 67200kg$.

Parameter	**Initial GW [ton]**		
	66	**67.2**	**68**
Distance [NM]	319	299.2	286
Initial speed [kt]	234	236.4	238
Time [min]	56	51.8	49
Fuel [kg]	1500	1440	1400
Level off [ft]	25700	25400	25200

Table 7.12: List of QRH's corrective factors for Total AI On setting [35].

Parameter	**Corrective factor**
Distance [NM]	+15%
Time [min]	+16%
Fuel [kg]	+18%
Level Off [ft]	-700ft

Table 7.13: QRH's performance data for $h = FL370$, Initial GW $= 67200kg$ and Total AI On.

Parameter	**QRH's value**
Distance [NM]	344.1
Initial speed [kt]	236.4
Time [min]	60.1
Fuel [kg]	1699
Level off [ft]	24700

7.2.2.2 Calculation from the solution's DB

Similarly to what was verified in the previous case, the DB can provide the required performance values without the need for intermediate interpolation stages. The descent profile for this case can be retrieved by running the following SQL query:

Listing 7.3: SQL query for the second case of 'Gross Flight Path Descent at GD Speed' scenario, considering AI Off.

```
SELECT AirDistance, CAS, Time, FuelConsumption, PressureAlt
FROM [EFB-HSP_Data].[dbo].[Dataset]
WHERE (Airplane_Id = 5 AND Case_Id = 6 AND SpeedRule = ‘GD’
    AND CG = ‘0.33’ AND ISA = 0 AND InitialWeight = 67200
    AND InitialAlt = 37000 AND AntiIce = ‘0’
    AND AirConditioning =‘C’)
```

The results that are returned by this query are presented in Figure 7.5. Moreover, the relevant parameters that are obtained from the aforementioned query's results are listed in Table 7.14.

Using the corrective factors presented in Table 7.12, it is now possible to convert the DB's values of Table 7.14 to a Total AI On setting. This is achieved in Table 7.15.

Results | Messages

	AirDistance	CAS	Time	FuelConsumption	PressureAlt
1	0	236.4	0	0	37000
2	7.362815	235.4463	1.060572	22.04713	36089.29
3	7.362815	235.4451	1.060572	22.04713	36089.19
4	8.086207	235.3515	1.166089	24.27435	36000
5	16.48287	234.2982	2.404779	50.92605	35000
6	25.53462	233.2374	3.76827	81.29282	34000
7	35.45763	232.1671	5.294572	116.4448	33000
8	46.49775	231.0846	7.028638	157.7247	32000
9	59.06508	229.985	9.044459	207.5271	31000
10	73.40762	228.8652	11.394	267.4018	30000
...					
41	299.3596	221.9123	51.78764	1448.57	25408.2
42	302.1717	221.8793	52.30453	1464.405	25408.11

EFB-HSP_Data | 00:00:00 | 42 rows

Figure 7.5: Results from the SQL query for the second case, considering AI Off.

Table 7.14: DB's performance data for $h = FL370$, Initial GW $= 67200kg$ and AI Off.

Parameter	DB's value
Distance [NM]	302.1717
Initial speed [kt]	236.4
Time [min]	52.30453
Fuel [kg]	1464.405
Level off [ft]	25408.11

Table 7.15: DB's performance data for $h = FL370$, Initial GW $= 67200kg$ (corrected for Total AI On setting).

Parameter	DB's value
Distance [NM]	347.4975
Initial speed [kt]	236.4
Time [min]	60.67325
Fuel [kg]	1728
Level off [ft]	24708.11

As was stated in Subsection 6.2.1, the proposed solution includes data for alternative aircraft configurations that are not directly covered by the QRH. Therefore, the descent profile for this case can also be directly retrieved from the DB, without the need for additional AI-related corrections. To do so, one can adapt the SQL query that is presented in Listing 7.3 by modifying the 'AntiIce' parameter from '0' to 'G' (i.e., from 'AI Off' to 'Total AI On'):

Listing 7.4: SQL query for the second case of 'Gross Flight Path Descent at GD Speed' scenario, considering Total AI On.

```
SELECT SELECT AirDistance, CAS, Time, FuelConsumption, PressureAlt
FROM [EFB-HSP_Data].[dbo].[Dataset]
WHERE (Airplane_Id = 5 AND Case_Id = 6 AND SpeedRule = 'GD'
    AND CG = '0.33' AND ISA = 0 AND InitialWeight = 67200
    AND InitialAlt = 37000 AND AntiIce = 'G'
    AND AirConditioning ='C')
```

The results that are returned by the revised query are presented in Figure 7.6:

Results | Messages

	AirDistance	CAS	Time	FuelConsumption	PressureAlt
1	0	236.4	0	0	37000
2	7.273328	235.4457	1.047689	22.34304	36089.29
3	7.273328	235.4445	1.047689	22.34304	36089.19
4	7.986246	235.3508	1.151678	24.59825	36000
5	16.23883	234.2969	2.369127	51.55936	35000
6	25.102	233.2356	3.704229	82.19208	34000
7	34.77866	232.1651	5.192662	117.4252	33000
8	45.41744	231.0839	6.863712	158.067	32000
9	57.27397	229.9886	8.765526	205.6812	31000
10	70.63721	228.8759	10.9546	262.0687	30000
...					
42	280.4125	221.8936	48.51303	1383.549	25259.77
43	285.2906	221.8357	49.41196	1411.876	25259.44

EFB-HSP_Data | 00:00:00 | 43 rows

Figure 7.6: Results from the SQL query for the second case, considering Total AI On.

The relevant parameters that can be extracted from the revised query's results are summarized in Table 7.16.

Table 7.16: DB's performance data for $h = FL370$, Initial GW $= 67200kg$ and Total AI On.

Parameter	**DB's value**
Distance [NM]	285.2906
Initial speed [kt]	236.4
Time [min]	49.41196
Fuel [kg]	1411.876
Level off [ft]	25259.44

7.2.2.3 Calculation from a PEP session

The accurate performance values that are valid for this case can be obtained from a PEP session. Said session is defined by the .DAT input file that is presented below in Listing 7.5:

Listing 7.5: .DAT input file for a PEP session regarding the second case.

```
A320-251                1    0    1    3
AERO       03/03/16   AE251A02.BDC
ENGINE     12/05/16   ME251A03.BDC
GENERAL    03/03/16   GE251A02.BDC
Gross flight path with engine(s) out
 235 131 000   0 0 1 GC6  KG   00000 DC DG                 0 0
3        100     .33      0       0       0       0       0
    18590   0
   1   1   1   2   1   0
0
67200
0
1       1
37000
0       0       0       1       1       0       0       0       0
END
```

The specific aircraft configuration of Total AI On (‘G’) and High A/C (‘C’) for this case is precisely defined in the KODIM parameter (‘GC6’). The output file that is generated by the PEP session of Listing 7.5 is now presented in Figure 7.7:

DT	WGTI	ALTI	ALT.	ALTG	TIME	FUEL	DIST	CAS
DG.C	KG	FT	FT	FT	MN	KG	NM	KT
0	67200	37000	37000	37000	0	0	0	236.4
0	67200	37000	36089.29	36089.29	1.047689	22.34305	7.273328	235.4457
0	67200	37000	36089.19	36089.19	1.047689	22.34305	7.273328	235.4445
0	67200	37000	36000	36000	1.151678	24.59825	7.986246	235.3508
0	67200	37000	35000	35000	2.369127	51.55936	16.23883	234.2969
0	67200	37000	34000	34000	3.704229	82.19208	25.102	233.2356
0	67200	37000	33000	33000	5.192662	117.4253	34.77866	232.1652
0	67200	37000	32000	32000	6.863712	158.067	45.41744	231.0839
0	67200	37000	31000	31000	8.765526	205.6812	57.27397	229.9887
0	67200	37000	30000	30000	10.9546	262.0687	70.63721	228.8759
0	67200	37000	29000	29000	13.47944	328.5908	85.72826	227.7428
0	67200	37000	28500	28500	14.9275	367.565	94.24663	227.1649
0	67200	37000	28000	28000	16.58524	413.1408	103.8953	226.5737
0	67200	37000	27500	27500	18.52576	467.6304	115.0697	225.9648
0	67200	37000	27000	27000	20.86966	534.8456	128.4221	225.3304
0	67200	37000	26750	26750	22.25912	575.3147	136.2729	224.9994
0	67200	37000	26500	26500	23.8448	621.973	145.1834	224.6561
0	67200	37000	26250	26250	25.69379	676.9365	155.5157	224.2962
0	67200	37000	26000	26000	27.91765	743.7204	167.8728	223.9127
0	67200	37000	25875	25875	29.23295	783.5218	175.15	223.708
0	67200	37000	25750	25750	30.7354	829.2182	183.4383	223.4916
0	67200	37000	25625	25625	32.493	882.9526	193.1052	223.2592
0	67200	37000	25500	25500	34.62425	948.4601	204.7912	223.0033
0	67200	37000	25468.75	25468.75	35.25651	967.9747	208.2511	222.9328
0	67200	37000	25437.5	25437.5	35.97276	990.1461	212.1675	222.8572
0	67200	37000	25406.25	25406.25	36.80106	1015.861	216.6927	222.7746
0	67200	37000	25375	25375	37.78581	1046.523	222.0679	222.682
0	67200	37000	25359.38	25359.38	38.35982	1064.435	225.1989	222.6324
0	67200	37000	25343.75	25343.75	39.00643	1084.642	228.7242	222.5745
0	67200	37000	25328.13	25328.13	39.74927	1107.89	232.7721	222.5124
0	67200	37000	25312.5	25312.5	40.62693	1135.397	237.5522	222.4418
0	67200	37000	25304.69	25304.69	41.13818	1151.437	240.3354	222.4036
0	67200	37000	25296.88	25296.88	41.71672	1169.601	243.484	222.3577
0	67200	37000	25289.06	25289.06	42.38645	1190.645	247.1277	222.3079
0	67200	37000	25281.25	25281.25	43.18869	1215.869	251.4906	222.2497
0	67200	37000	25277.34	25277.34	43.66502	1230.854	254.0804	222.2175
0	67200	37000	25273.44	25273.44	44.21697	1248.224	257.0807	222.1771
0	67200	37000	25269.53	25269.53	44.88065	1269.117	260.6874	222.1315
0	67200	37000	25265.63	25265.63	45.73276	1295.952	265.3168	222.0742
0	67200	37000	25263.67	25263.67	46.29725	1313.734	268.3829	222.0365
0	67200	37000	25261.72	25261.72	47.06553	1337.939	272.5548	221.9866
0	67200	37000	25259.77	25259.77	48.51303	1383.549	280.4125	221.8936
0	67200	37000	25259.44	25259.44	49.41196	1411.876	285.2906	221.8357
INPUT DATA	IFP							
END								

Figure 7.7: CSV output file of the second case’s PEP session.

The parameters of interest that are obtained from the PEP session’s output file are listed in Table 7.17.

Table 7.17: PEP's performance data for $h = FL370$, Initial GW $= 67200kg$ and Total AI On.

Parameter	PEP's value
Distance [NM]	285.2906
Initial speed [kt]	236.4
Time [min]	49.41196
Fuel [kg]	1411.876
Level off [ft]	25259.44

7.2.3 Final remarks

For the two cases in analysis, the methods that are described in the present section allowed the retrieval of performance parameters from three distinct data sources: QRH, DB and PEP sessions. The obtained results are compiled into Table 7.18:

Table 7.18: QRH's, DB's and PEP's performance data for the two cases in analysis.

Parameter	First case			Second case			
	QRH	DB	PEP	QRH	DB_I	DB_{II}	PEP
Distance [NM]	206.4	215.3156	215.3156	344.1	347.4975	285.2906	285.2906
Initial speed [kt]	208.8	208.8	208.8	236.4	236.4	236.4	236.4
Time [min]	37.6	39.38129	39.38129	60.1	60.67325	49.41196	49.41196
Fuel [kg]	920	1000.45	1000.45	1699	1728	1411.876	1411.876
Level off [ft]	29400	29403.75	29403.75	24700	24708.11	25259.44	25259.44

In Table 7.18, the "DB_I" column contains the values that were retrieved from the solution's DB for AI Off setting, and then corrected for Total AI On using the QRH's factors. On the other hand, the values in "DB_{II}" were directly retrieved from the DB considering the Total AI On setting.

The values that were calculated based on the QRH and on the solution's DB can be compared with the ones that were obtained from PEP sessions. To do so, one can use the expression for the Relative Error (RE) that was introduced in Equation 7.3. This is accomplished in Table 7.19:

Table 7.19: Error analysis for the calculated performance parameters.

Parameter	First case		Second case		
	RE_{QRH}	RE_{DB}	RE_{QRH}	RE_{DB_I}	$RE_{DB_{II}}$
Distance [NM]	-4.14%	0.00%	20.61%	21.80%	0.00%
Initial speed [kt]	0.00%	0.00%	0.00%	0.00%	0.00%
Time [min]	-4.52%	0.00%	21.63%	22.79%	0.00%
Fuel [kg]	-8.04%	0.00%	20.34%	22.39%	0.00%
Level off [ft]	-0.01%	0.00%	-2.21%	-2.18%	0.00%

By analysing the error values expressed in Table 7.19, it can be concluded that, for both cases, the performance values that were retrieved from the solution's DB match exactly with the ones that were obtained from PEP for the same aircraft configuration. This match is not unexpected, since the data sets that were used to populate the DB were also generated by PEP.

Regarding the initial speed parameter for both cases, the difference between the obtained values from both the QRH and the DB, and the actual PEP's values is null. This fact indicates that the precision of this result is not affected by the interpolation process that was applied to the QRH's values.

One noticeable aspect in the Table 7.19 is the significant error that is verified for most of the second case's performance parameters: distance, time and fuel. Moreover, the error associated with the level off altitude has also increased considerably, when compared with the error value for the same parameter in the first case. As one might recall from Subsection 7.2.2, the calculation process of these four parameters included a QRH-imposed correction factor to account for the Total AI On setting. The obtained results indicate that the QRH's correction factors can be a potential source of error during the calculations.

Moreover, one can observe that, apart from the level off altitude and initial speed parameters, the RE associated with the first data retrieval method from the DB (i.e., RE_{DB_I}) is marginally higher than what is verified for the QRH-based retrieval method. The reader should be reminded that the former method resorted to the corrective factors that are presented in the QRH to convert the DB's values from AI Off to Total AI On setting. These differences might indicate that the application of the QRH's corrective factors to the DB's values reduces its accuracy. To minimize the discrepancies that were verified at this stage, the author recommends the calculation of DB-specific corrective factors. Nonetheless, no differences are verified when using the DB's performance data set that was directly calculated for the Total AI On conditions, as is demonstrated by the $RE_{DB_{II}}$ column of Table 7.19.

Considering the results that were obtained using the QRH, the discrepancies that are verified for the first case, in comparison with the second one, are smaller. Nonetheless, these errors are not negligible, and might be the result of two contributions: the error associated with the QRH's retrieval method, that was analysed in Subsection 7.1, and a potential error that might be introduced by the interpolation process.

The test that was carried out in this Section highlights the operational benefits of the solution, when compared with the traditional, QRH-based data retrieval process. When using the QRH, the method involved five intermediate interpolations for the first case. For the second case, this process was even more laborious, having required a total of five interpolations and four corrections. By comparison, the necessary data for each of the two cases was fetched from the solution's DB through a single SQL query.

All in all, this test has demonstrated that the proposed solution is a valid alternative to the QRH's tables and charts. For the two cases in analysis, the solution was able to provide more accurate performance parameters in a more direct and expeditious manner, when compared to the QRH.

Chapter 8

Conclusions

This closing chapter presents the author's final conclusions and remarks regarding the present work. A balance of the project's activities and its corresponding results is also performed in this chapter. Additionally, the author provides some insights into the developments that can be explored in the future based on the solution that resulted from this project.

8.1 Remarks

The initial challenge proposed by the e-Operations group of TAP Air Portugal was accepted with great enthusiasm by the author. The opportunity to provide a relevant contribution to the airline industry, and particularly to TAP's flight operations, has been the author's most preeminent motivation throughout the project.

Despite the fact that the thesis' primary objective was the development of a computational tool, a substantial initial effort was made to understand the inner workings of PEP. This stage examined the software's internal methods, capabilities and limitations, particularly those related with the FM and IFP modules. The architecture of PEP's different input and output files was also analysed in detail. This ended up being one of the most time-consuming phases of this project. However, considering that PEP is the primary data source of the proposed solution, this stage has paved the way for the project developments that took place from that point onwards.

It is worth noting that Airbus did not disclose the required PEP's input parameters to generate each of the QRH's flight scenarios that are covered in this thesis, despite TAP's several requests. Therefore, and based on the summarized information that is provided in the QRH, as well as the guidance provided by TAP's engineers, the author had to determine said parameters through a trial-and-error approach. In the end, the project employed the parameters that produced the closest results to the ones that are presented in the QRH.

The development process involved working for the first time with software tools such as Microsoft Visual Studio, Entity Framework and SQL. By using this set of tools, the author was able to create two main programs to automatically generate PEP's input files and to import the corresponding outputs into a custom-made database infrastructure, respectively.

8.2 Achievements

The core goals that the author has set out to achieve with the present work were previously defined in Section 1.2. At this point, one could now assert that these have been successfully attained. As intended, the computational solution that was developed during this project is capable of presenting the adequate performance parameters to recreate the selected HSP's flight scenarios of the QRH. Additionally, the solution is also capable of performing direct performance calculations, without the need for any intermediate interpolations or corrections.

Initially, one of the project's goals was the development of a software application for TAP's EFB solution. However, this goal was readjusted during the course of the project. Following a recommendation from the e-Operations' engineers, the author decided to prioritize the company's short-term operational needs, considering the deadline stipulated by Airbus for the removal of several performance chapters from its paper-based flight manuals [15, 16]. From that point onwards, the project concentrated efforts on replicating the QRH's tables and charts that are presented in this thesis.

When put up to test against the QRH, the proposed solution provided more accurate results than the latter with minimal user's involvement. To obtain the required performance parameters for each of the two cases that were considered in this thesis, the QRH-based method involved up to five interpolations and four corrections, to account for alternative aircraft's systems configurations. In contrast, the corresponding data retrieval from the solution's DB was executed through a single SQL query.

8.3 Future Work

TAP's e-Operations team is now empowered with a tool that covers a vast amount of information regarding the QRH's flight scenarios that are approached in this thesis. Moreover, the developed tool is valid for all the aircraft types that are part of TAP's fleet as of November 2020. Given its increased level of detail over the QRH's tables and charts, this information could be used in future operational planning activities. Using these resources, the team can now perform more comprehensive analyses of different flight scenarios, such as flight descent profiles and climb and cruise performance.

This thesis has looked into alternative formats for presenting the QRH's contents in a more effective manner. Having the required information available in a digital format broadens the scope of possibilities regarding what can be achieved in this field. Should this work be continued, it will improve the flight crew's interaction with the manual, which will ultimately translate into additional gains in operational efficiency and safety.

Since the initial development stages, this solution was designed to support future developments that the e-Operations team might conduct. Therefore, the solution is prepared to include additional aircraft types and flight scenarios, that can belong either to the QRH or to other performance manuals. This feature is intended to future-proof the solution and to increase its operational flexibility.

Ultimately, the proposed solution could be used as a solid computational basis, upon which the e-Operations group could build an application for the company's EFB. Combining the accurate performance calculation capabilities of the solution with an optimized GUI would ultimately translate into significant gains in operational efficiency and safety.

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Appendix A

QRH–HSP tables and charts

This Appendix contains the tables and charts from the QRH that were replicated during this project. Moreover, the objects presented hereafter are part of the QRH manual for the Airbus A320-251' aircraft type [35].

A.1 One Engine Inoperative

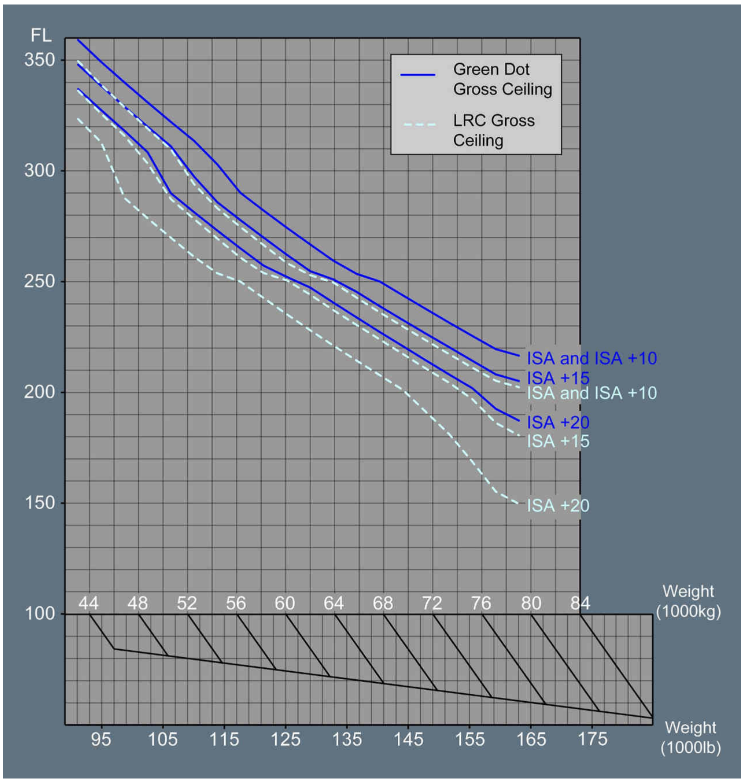
A.1.1 Ceilings

TAP PORTUGAL A320-251N QUICK REFERENCE HANDBOOK	IN FLIGHT PERFORMANCE	PER-L 1/6 14 SEP 18

CEILINGS

ONE ENGINE OUT

GROSS CEILING at LONG RANGE and GREEN DOT SPEEDS Pack Flow Hi - Anti ice OFF



CORRECTIONS		ISA	ISA + 10	ISA + 15	ISA + 20
LONG RANGE	ENGINE ANTI ICE ON	-100 ft	-1 100 ft	-1 700 ft	-2 700 ft
	TOTAL ANTI ICE ON	-800 ft	-2 800 ft	-3 700 ft	-4 600 ft
GREEN DOT	ENGINE ANTI ICE ON	-100 ft	-800 ft	-1 000 ft	-1 500 ft
	TOTAL ANTI ICE ON	-800 ft	-2 400 ft	-2 800 ft	-3 200 ft

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Figure A.1: QRH's chart for 'Ceilings' scenario [35].

A.1.2 Gross Flight Path Descent at Green Dot Speed

TAP PORTUGAL A320-251N QUICK REFERENCE HANDBOOK	IN FLIGHT PERFORMANCE	PER-L 2/6 14 SEP 18

GROSS FLIGHT PATH DESCENT AT GREEN DOT SPEED

GROSS FLIGHT PATH DESCENT AT GREEN DOT SPEED - 1 ENGINE OUT

MAX. CONTINUOUS THRUST LIMITS	ISA	DISTANCE (NM)	TIME (MIN)
HIGH AIR CONDITIONING	CG=33.0%	INITIAL SPEED (KT)	FUEL (1000KG)
ANTI ICE OFF		LEVEL OFF (FT)	

INIT. GW (1000KG)	INITIAL FLIGHT LEVEL 250	290	310	330	350	370	390
50				130 24 198 0.5 32400	206 37 200 0.8 32500	242 43 202 1.0 32600	266 47 204 1.0 32600
52				173 31 202 0.7 31600	223 40 204 0.9 31700	253 45 206 1.0 31800	276 49 208 1.1 31800
54			121 22 204 0.6 30600	208 38 206 0.9 30800	243 43 208 1.0 30900	265 47 210 1.1 30900	285 50 212 1.2 31000
56			203 37 208 0.9 29600	258 47 210 1.2 29700	290 52 212 1.3 29800	311 55 214 1.3 29800	331 58 216 1.4 29900
58		128 24 210 0.6 28400	220 40 212 1.0 28600	267 48 214 1.2 28700	297 53 216 1.3 28700	320 57 218 1.4 28700	339 60 220 1.5 28800
60		168 31 214 0.8 27700	228 41 216 1.1 27800	264 48 218 1.2 27900	290 52 220 1.3 27900	309 55 222 1.4 27900	327 57 224 1.5 28000
62		194 35 218 1.0 27000	239 43 220 1.2 27100	270 48 222 1.3 27100	292 52 224 1.4 27200	311 55 226 1.4 27200	328 57 228 1.5 27200
64		212 38 222 1.1 26300	249 45 224 1.3 26400	274 49 226 1.4 26400	297 52 228 1.4 26400	313 55 230 1.5 26500	330 57 232 1.5 26500
66		226 41 226 1.2 25600	258 46 228 1.3 25700	283 50 230 1.4 25700	301 53 232 1.5 25700	319 56 234 1.5 25700	334 58 236 1.6 25800
68		196 35 230 1.0 25100	226 40 232 1.2 25200	250 44 234 1.3 25200	268 47 236 1.3 25200	286 49 238 1.4 25200	301 51 240 1.4 25200
70	90 16	212 38	238 42	258 45	274 47	289 49	303 51

CORRECTIONS	ENGINE ANTI ICE ON	TOTAL ANTI ICE ON
FUEL	+ 4 %	+ 18 %
TIME	+ 1.5 %	+ 16 %
DISTANCE	+ 3 %	+ 15 %
LEVEL OFF	- 35 ft	- 700 ft

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Figure A.2: QRH's table for 'Gross Flight Path Descent at Green Dot Speed' scenario [35].

A.1.3 Cruise at Long Range Cruise Speed

TAP PORTUGAL A320-251N QUICK REFERENCE HANDBOOK	IN FLIGHT PERFORMANCE	PER-L 4/6 14 SEP 18

CRUISE AT LONG RANGE CRUISE SPEED

CRUISE - LONG RANGE - 1 ENGINE OUT

MAX. CONTINUOUS THRUST LIMITS	ISA	**N1 (%)**	**MACH**
HIGH AIR CONDITIONING	CG=33.0%	**FUEL FLOW (KG/H)**	**IAS (KT)**
ANTI ICE OFF		**SR (NM/1000KG)**	**TAS (KT)**

WEIGHT (1000KG)	FL100		FL150		FL190		FL210		FL230		FL250	
50	70.4	.414	74.4	.447	78.4	.484	79.2	.485	82.5	.526	84.7	.549
	1539	229	1503	225	1502	225	1446	216	1524	226	1531	226
	171.8	264	186.4	280	198.6	298	205.3	297	209.4	319	216.0	331
52	71.0	.416	75.8	.459	79.2	.488	80.4	.495	83.7	.534	85.5	.554
	1573	229	1576	230	1550	227	1518	221	1585	230	1580	229
	168.6	265	182.3	287	194.2	301	199.5	303	204.6	324	211.2	334
54	71.9	.422	76.8	.465	79.6	.486	82.8	.523	84.8	.544	86.2	.555
	1627	233	1630	234	1575	226	1649	234	1652	234	1617	229
	165.5	269	178.6	291	190.4	300	194.1	320	200.0	330	206.7	334
56	73.3	.433	77.6	.469	80.4	.490	83.7	.529	85.8	.552	87.2	.563
	1705	239	1676	236	1625	228	1702	237	1713	238	1682	232
	162.0	276	175.2	294	185.9	302	190.1	324	195.8	335	201.6	339
58	74.2	.439	78.7	.478	82.7	.516	84.8	.539	86.5	.555	88.2	.569
	1761	242	1742	240	1761	240	1773	241	1755	239	1740	235
	159.0	280	171.8	299	180.9	319	185.9	330	191.7	337	196.7	342
60	75.0	.444	80.0	.489	83.7	.525	85.8	.547	87.1	.557	89.0	.572
	1813	245	1821	246	1829	245	1838	245	1799	240	1795	236
	156.2	283	168.3	307	177.1	324	182.2	335	187.9	338	191.9	345
62	76.1	.452	80.5	.490	84.7	.532	86.7	.553	88.2	.566	90.3	.582
	1881	250	1855	246	1890	248	1896	248	1872	244	1876	241
	153.4	289	165.3	307	173.6	328	178.6	339	183.4	343	186.8	350
64	77.3	.461	80.8	.488	85.6	.540	87.2	.555	89.1	.570	91.5	.589
	1955	255	1879	245	1959	252	1938	249	1928	245	1949	244
	150.7	295	162.6	306	170.1	333	175.2	340	179.4	346	182.0	355
66	78.0	.466	81.4	.490	86.6	.548	88.0	.559	89.9	.575	91.6	.577
	2007	258	1925	246	2025	256	1992	251	1992	248	1942	239
	148.1	297	159.4	307	166.9	338	171.7	342	175.2	349	178.9	347
68	78.7	.469	83.2	.509	87.3	.553	89.0	.567	91.2	.584	91.8	.551
	2054	259	2048	256	2083	258	2065	254	2075	252	1929	227
	145.8	299	155.7	319	163.8	341	168.0	347	170.8	354	171.9	332
70	79.4	.473	84.4	.522	87.9	.555	89.8	.571	92.2	.590		
	2105	262	2144	263	2125	259	2122	256	2146	254		
	143.5	302	152.5	327	161.0	342	164.6	349	166.8	358		
72	80.6	.484	85.0	.525	88.6	.559	90.6	.576	92.3	.580		

CORRECTIONS	ENGINE ANTI ICE ON	TOTAL ANTI ICE ON
FUEL	+ 1.5 %	+ 4 %

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Figure A.3: QRH's table for 'Cruise at Long Range Cruise Speed' scenario [35].

A.1.4 In Cruise Quick Check Long Range

TAP PORTUGAL A320-251N QUICK REFERENCE HANDBOOK	IN FLIGHT PERFORMANCE	PER-L 6/6 14 SEP 18

IN CRUISE QUICK CHECK LONG RANGE

IN CRUISE QUICK CHECK FROM ANY MOMENT IN CRUISE TO LANDING - 1 ENGINE OUT
CRUISE : LONG RANGE - DESCENT : M.78/300KT/250KT
IMC PROCEDURE : 120 KG (6 MIN)

REF. INITIAL WEIGHT = 55000 KG HIGH AIR CONDITIONING ANTI ICE OFF	ISA CG=33.0%	FUEL CONSUMED (KG) TIME (H.MIN)

AIR DIST. (NM)	FLIGHT LEVEL						CORRECTION ON FUEL CONSUMPTION (KG/1000KG)		
	100	150	200	220	240	250	FL100 FL150	FL200 FL220	FL240 FL250
200	1206	1080	969	930	893	874	8	7	5
	0.50	0.47	0.45	0.43	0.42	0.42			
300	1810	1640	1490	1439	1387	1360	14	13	11
	1.12	1.07	1.05	1.01	1.00	1.00			
400	2410	2197	2006	1945	1878	1843	19	19	16
	1.35	1.28	1.25	1.20	1.18	1.18			
500	3006	2750	2519	2448	2366	2324	25	25	22
	1.58	1.49	1.45	1.39	1.36	1.36			
600	3599	3300	3029	2948	2852	2802	30	30	27
	2.20	2.10	2.05	1.57	1.54	1.54			
700	4189	3847	3537	3446	3335	3278	36	36	33
	2.43	2.31	2.26	2.16	2.12	2.12			
800	4776	4391	4041	3935	3816	3751	42	42	38
	3.06	2.52	2.46	2.35	2.30	2.30			
900	5359	4932	4543	4421	4293	4222	47	48	43
	3.29	3.13	3.06	2.54	2.48	2.48			
1000	5939	5469	5042	4904	4768	4690	53	55	49
	3.52	3.34	3.27	3.13	3.07	3.06			
1100	6516	6003	5539	5383	5240	5156	58	61	55
	4.14	3.55	3.47	3.32	3.25	3.24			
1200	7089	6534	6032	5859	5710	5619	64	67	60
	4.37	4.17	4.07	3.51	3.43	3.42			
1300	7659	7063	6523	6336	6177	6079	69	73	65
	5.00	4.39	4.27	4.10	4.02	4.00			
1400	8226	7588	7011	6815	6641	6537	74	78	70
	5.23	5.01	4.47	4.29	4.21	4.18			

CORRECTIONS	ENGINE ANTI ICE ON	TOTAL ANTI ICE ON
FUEL	+ 1 %	+ 8.5 %

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Figure A.4: QRH's table for 'In Cruise Quick Check Long Range' scenario [35].

A.2 Flight Without Cabin Pressurization

A.2.1 In Cruise Quick Check FL100 Long Range

TAP PORTUGAL
A320-251N
QUICK REFERENCE HANDBOOK

IN FLIGHT PERFORMANCE

PER-N
1/2
20 MAR 18

IN CRUISE QUICK CHECK FL 100 LONG RANGE

IN CRUISE QUICK CHECK FROM ANY MOMENT IN CRUISE TO LANDING - ALL ENGINES
CRUISE : LONG RANGE AT FL100 - DESCENT : 250KT
IMC PROCEDURE : 120 KG (6 MIN)

NORMAL AIR CONDITIONING ANTI ICE OFF	ISA CG=25.0%	FUEL CONSUMED (KG) TIME (H.MIN)

AIR DIST. (NM)	INITIAL WEIGHT (1000KG) 50	55	60	65	70	75	79
40	279 0.15	276 0.15	273 0.15	272 0.15	272 0.14	273 0.14	
60	403 0.19	404 0.19	404 0.19	406 0.18	410 0.18	416 0.18	421 0.18
80	527 0.23	531 0.23	534 0.23	540 0.22	549 0.22	559 0.22	568 0.21
100	651 0.28	659 0.27	664 0.27	673 0.26	687 0.26	702 0.25	715 0.25
120	775 0.32	786 0.31	793 0.31	807 0.30	825 0.30	844 0.29	861 0.28
140	898 0.36	913 0.34	923 0.35	940 0.34	963 0.33	987 0.33	1008 0.32
160	1022 0.41	1041 0.38	1053 0.39	1074 0.38	1101 0.37	1130 0.36	1154 0.35
180	1145 0.45	1168 0.42	1183 0.43	1207 0.42	1239 0.41	1272 0.40	1300 0.39
200	1268 0.50	1295 0.46	1312 0.47	1340 0.46	1377 0.45	1414 0.44	1446 0.42
220	1392 0.54	1422 0.50	1442 0.51	1473 0.50	1514 0.49	1556 0.47	1592 0.46
240	1515 0.58	1549 0.54	1571 0.55	1606 0.54	1652 0.52	1698 0.51	1738 0.50
260	1638 1.03	1676 0.58	1701 0.59	1738 0.58	1789 0.56	1840 0.55	1883 0.53
280	1760 1.07	1803 1.02	1830 1.03	1871 1.02	1926 1.00	1982 0.58	2029 0.57
300	1883 1.11	1930 1.06	1960 1.07	2003 1.06	2063 1.04	2123 1.02	2174 1.00
320	2006 1.16	2057 1.10	2089 1.11	2136 1.10	2200 1.08	2265 1.06	2319 1.04
340	2128 1.20	2184 1.14	2218 1.15	2268 1.14	2337 1.12	2406 1.09	2464 1.07

CORRECTIONS	AIR CONDITIONING OFF	ENGINE ANTI ICE ON	TOTAL ANTI ICE ON
FUEL	- 2 %	+ 2 %	+ 9 %

TAP MSN 08043 **CS-TVA**

Figure A.5: QRH's table for 'In Cruise Quick Check FL100 Long Range' scenario [35].

A.3 Climb Gradient

A.3.1 Maximum Climb Gradient - ISA+10 & Below

TAP PORTUGAL
A320-251N
QUICK REFERENCE HANDBOOK

IN FLIGHT PERFORMANCE

PER-MCG
1/2
20 MAR 18

MAX CLIMB GRADIENT - ISA + 10 & BELOW

ALL ENGINES

EN-ROUTE CONFIGURATION: CLIMB THRUST - ALL ENGINES - GREEN DOT SPEED

CG = 33.0%
NORMAL AIR CONDITIONING

ANTI-ICING OFF
ISA + 10°C & BELOW

CLIMB GRADIENT (%)

GW (ton)	CAS (kt)	Pressure Altitude (ft)										AI ON Correction
		1500	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**10000**	
48	**181**	28.3	28.0	27.3	26.6	25.9	25.3	24.7	24.1	23.5	22.9	-1.6
49	**183**	27.4	27.1	26.4	25.7	25.1	24.5	23.9	23.4	22.8	22.2	-1.5
50	**185**	26.6	26.2	25.6	24.9	24.3	23.7	23.2	22.6	22.1	21.5	-1.5
51	**187**	25.7	25.4	24.8	24.2	23.6	23.0	22.5	21.9	21.4	20.8	-1.4
52	**189**	25.0	24.6	24.0	23.4	22.8	22.3	21.8	21.3	20.7	20.2	-1.4
53	**191**	24.2	23.9	23.3	22.7	22.2	21.6	21.1	20.6	20.1	19.6	-1.3
54	**193**	23.5	23.2	22.6	22.1	21.5	21.0	20.5	20.0	19.5	19.0	-1.3
55	**195**	22.8	22.5	22.0	21.4	20.9	20.3	19.9	19.4	18.9	18.4	-1.3
56	**197**	22.2	21.9	21.4	20.8	20.3	19.8	19.3	18.8	18.3	17.9	-1.3
57	**199**	21.5	21.3	20.8	20.2	19.7	19.2	18.8	18.3	17.8	17.4	-1.2
58	**201**	21.0	20.7	20.2	19.7	19.1	18.6	18.2	17.7	17.3	16.9	-1.2
59	**203**	20.4	20.1	19.6	19.1	18.6	18.1	17.7	17.3	16.8	16.4	-1.2
60	**205**	19.8	19.6	19.1	18.6	18.1	17.6	17.2	16.8	16.3	15.9	-1.1
61	**207**	19.3	19.1	18.6	18.1	17.6	17.1	16.7	16.3	15.9	15.5	-1.1
62	**209**	18.8	18.6	18.1	17.6	17.1	16.7	16.3	15.9	15.4	15.0	-1.1
63	**211**	18.3	18.1	17.6	17.1	16.7	16.2	15.8	15.4	15.0	14.6	-1.1
64	**213**	17.8	17.6	17.1	16.7	16.2	15.8	15.4	15.0	14.6	14.2	-1.1
65	**215**	17.4	17.1	16.7	16.2	15.8	15.4	15.0	14.6	14.2	13.8	-1.0
66	**217**	16.9	16.7	16.3	15.8	15.4	15.0	14.6	14.2	13.8	13.5	-1.0
67	**219**	16.5	16.3	15.8	15.4	15.0	14.6	14.2	13.8	13.5	13.1	-1.0
68	**221**	16.1	15.9	15.4	15.0	14.6	14.2	13.9	13.5	13.1	12.8	-1.0
69	**223**	15.7	15.5	15.1	14.6	14.2	13.8	13.5	13.1	12.8	12.4	-1.0
70	**225**	15.3	15.1	14.7	14.3	13.9	13.5	13.1	12.8	12.4	12.1	-0.9
71	**227**	14.9	14.7	14.3	13.9	13.5	13.1	12.8	12.4	12.1	11.8	-0.9
72	**229**	14.6	14.4	14.0	13.6	13.2	12.8	12.5	12.1	11.8	11.5	-0.9
73	**231**	14.2	14.0	13.6	13.2	12.9	12.5	12.2	11.8	11.5	11.2	-0.9
74	**233**	13.9	13.7	13.3	12.9	12.6	12.2	11.9	11.5	11.2	10.9	-0.9
75	**235**	13.5	13.3	13.0	12.6	12.2	11.9	11.6	11.2	10.9	10.6	-0.9
76	**237**	13.2	13.0	12.7	12.3	11.9	11.6	11.3	11.0	10.7	10.3	-0.8
77	**239**	12.9	12.7	12.4	12.0	11.7	11.3	11.0	10.7	10.4	10.1	-0.8

Total / ENG Anti-ice ON: reduce gradient using AI ON correction (Δ%)

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Figure A.6: QRH's table for 'Maximum Climb Gradient - ISA+10 & Below' scenario [35].

A.3.2 Maximum Climb Gradient - ISA+20

TAP PORTUGAL
A320-251N
QUICK REFERENCE HANDBOOK

IN FLIGHT PERFORMANCE

PER-MCG
2/2
20 MAR 18

MAX CLIMB GRADIENT - ISA + 20

ALL ENGINES

EN-ROUTE CONFIGURATION: CLIMB THRUST - ALL ENGINES - GREEN DOT SPEED											
CG = 33.0% NORMAL AIR CONDITIONING					ANTI-ICING OFF ISA + 20°C				CLIMB GRADIENT (%)		
GW	CAS	Pressure Altitude (ft)									
(ton)	(kt)	**1500**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**10000**
48	**181**	23.2	22.8	22.2	21.6	21.0	20.4	19.9	19.3	18.8	18.3
49	**183**	22.4	22.1	21.5	20.9	20.3	19.8	19.2	18.6	18.2	17.7
50	**185**	21.7	21.4	20.8	20.2	19.7	19.1	18.6	18.0	17.6	17.1
51	**187**	21.0	20.7	20.2	19.6	19.0	18.5	18.0	17.5	17.0	16.5
52	**189**	20.4	20.1	19.5	19.0	18.4	17.9	17.4	16.9	16.4	16.0
53	**191**	19.8	19.5	18.9	18.4	17.9	17.4	16.9	16.4	15.9	15.4
54	**193**	19.2	18.9	18.4	17.8	17.3	16.9	16.4	15.8	15.4	14.9
55	**195**	18.6	18.3	17.8	17.3	16.8	16.3	15.9	15.3	14.9	14.5
56	**197**	18.1	17.8	17.3	16.8	16.3	15.9	15.4	14.9	14.4	14.0
57	**199**	17.5	17.3	16.8	16.3	15.8	15.4	14.9	14.4	14.0	13.6
58	**201**	17.0	16.8	16.3	15.8	15.4	14.9	14.5	14.0	13.6	13.2
59	**203**	16.6	16.3	15.8	15.4	14.9	14.5	14.0	13.6	13.2	12.8
60	**205**	16.1	15.9	15.4	14.9	14.5	14.1	13.6	13.2	12.8	12.4
61	**207**	15.6	15.4	15.0	14.5	14.1	13.7	13.2	12.8	12.4	12.0
62	**209**	15.2	15.0	14.5	14.1	13.7	13.3	12.8	12.4	12.0	11.7
63	**211**	14.8	14.6	14.1	13.7	13.3	12.9	12.5	12.0	11.7	11.3
64	**213**	14.4	14.2	13.8	13.3	12.9	12.5	12.1	11.7	11.4	11.0
65	**215**	14.0	13.8	13.4	12.9	12.6	12.2	11.8	11.4	11.0	10.7
66	**217**	13.6	13.4	13.0	12.6	12.2	11.9	11.5	11.0	10.7	10.4
67	**219**	13.3	13.1	12.7	12.2	11.9	11.5	11.1	10.7	10.4	10.1
68	**221**	12.9	12.7	12.3	11.9	11.6	11.2	10.8	10.4	10.1	9.8
69	**223**	12.6	12.4	12.0	11.6	11.3	10.9	10.5	10.1	9.8	9.5
70	**225**	12.2	12.0	11.7	11.3	11.0	10.6	10.2	9.9	9.5	9.2
71	**227**	11.9	11.7	11.4	11.0	10.7	10.4	10.0	9.6	9.3	9.0
72	**229**	11.6	11.4	11.1	10.7	10.4	10.1	9.7	9.3	9.0	8.7
73	**231**	11.3	11.1	10.8	10.4	10.1	9.8	9.4	9.1	8.8	8.5
74	**233**	11.0	10.9	10.5	10.2	9.8	9.5	9.2	8.8	8.5	8.2
75	**235**	10.8	10.6	10.2	9.9	9.6	9.3	8.9	8.6	8.3	8.0
76	**237**	10.5	10.3	10.0	9.6	9.3	9.0	8.7	8.3	8.1	7.8
77	**239**	10.2	10.1	9.7	9.4	9.1	8.8	8.5	8.1	7.9	7.6

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Figure A.7: QRH's table for 'Maximum Climb Gradient - ISA+20' scenario [35].

A.3.3 Approach Climb Gradient - ISA+10 & Below

TAP PORTUGAL **A320-251N** QUICK REFERENCE HANDBOOK	IN FLIGHT PERFORMANCE	PER-ACG **2/4** 18 APR 18

APPROACH CLIMB GRADIENT - ISA + 10 & BELOW

APPROACH CONFIGURATION: TOGA THRUST - ONE ENGINE INOPERATVE														
V/Vs = 1.23 A/C ON			ANTI-ICING OFF ISA + 10°C & BELOW					APPROACH CLIMB GRADIENT (%)						
GW (ton)	Pressure Altitude (ft)													
	CONF 2						AI ON	CONF 3						AI ON
	1000	2000	3000	4000	5000	6000	Correction	1000	2000	3000	4000	5000	6000	Correction
48	12.3	12.2	12.1	11.8	11.6	11.3	**0.1**	11.9	11.8	11.6	11.4	11.2	10.9	**0.1**
49	11.8	11.7	11.6	11.4	11.2	10.9	**0.1**	11.3	11.2	11.1	10.8	10.6	10.3	**0.1**
50	11.4	11.3	11.2	10.9	10.8	10.5	**0.1**	10.8	10.7	10.6	10.3	10.2	9.8	**0.1**
51	11.0	10.9	10.8	10.5	10.4	10.1	**0.1**	10.4	10.3	10.2	9.9	9.7	9.4	**0.1**
52	10.6	10.5	10.4	10.2	10.0	9.7	**0.1**	10.0	9.9	9.7	9.5	9.3	9.0	**0.1**
53	10.2	10.1	10.0	9.8	9.6	9.4	**0.1**	9.5	9.4	9.3	9.1	8.9	8.7	**0.1**
54	9.8	9.7	9.6	9.4	9.3	9.0	**0.1**	9.2	9.1	9.0	8.7	8.6	8.3	**0.1**
55	9.5	9.4	9.3	9.1	8.9	8.7	**0.1**	8.8	8.7	8.6	8.4	8.3	8.0	**0.1**
56	9.1	9.1	8.9	8.8	8.6	8.4	**0.1**	8.5	8.4	8.3	8.1	7.9	7.7	**0.1**
57	8.8	8.7	8.6	8.4	8.3	8.1	**0.1**	8.1	8.0	7.9	7.8	7.6	7.4	**0.1**
58	8.5	8.4	8.3	8.1	8.0	7.8	**0.1**	7.8	7.7	7.6	7.5	7.3	7.1	**0.1**
59	8.2	8.1	8.0	7.8	7.7	7.5	**0.1**	7.5	7.4	7.3	7.2	7.0	6.8	**0.1**
60	7.9	7.8	7.7	7.5	7.4	7.2	**0.1**	7.2	7.1	7.0	6.9	6.7	6.5	**0.1**
61	7.6	7.5	7.4	7.3	7.1	6.9	**0.1**	6.9	6.9	6.8	6.6	6.5	6.3	**0.1**
62	7.3	7.2	7.1	7.0	6.9	6.7	**0.1**	6.7	6.6	6.5	6.3	6.2	6.0	**0.1**
63	7.1	7.0	6.9	6.7	6.6	6.4	**0.1**	6.4	6.3	6.2	6.1	5.9	5.8	**0.1**
64	6.8	6.7	6.6	6.5	6.3	6.2	**0.1**	6.1	6.1	6.0	5.8	5.7	5.5	**0.1**
65	6.6	6.5	6.4	6.2	6.1	5.9	**0.1**	5.9	5.8	5.7	5.6	5.5	5.3	**0.1**
66	6.3	6.2	6.1	6.0	5.9	5.7	**0.1**	5.6	5.6	5.5	5.3	5.2	5.0	**0.1**
67	6.1	6.0	5.9	5.8	5.6	5.5	**0.1**	5.4	5.3	5.3	5.1	5.0	4.8	**0.1**
68	5.8	5.8	5.7	5.5	5.4	5.2	**0.1**	5.2	5.1	5.0	4.9	4.8	4.6	**0.1**
69	5.6	5.5	5.4	5.3	5.2	5.0	**0.1**	5.0	4.9	4.8	4.7	4.6	4.4	**0.1**
70	5.4	5.3	5.2	5.1	5.0	4.8	**0.1**	4.7	4.7	4.6	4.5	4.4	4.2	**0.1**
71	5.2	5.1	5.0	4.9	4.8	4.6	**0.1**	4.5	4.5	4.4	4.3	4.2	4.0	**0.1**
72	5.0	4.9	4.8	4.7	4.6	4.4	**0.1**	4.3	4.3	4.2	4.1	4.0	3.8	**0.1**
73	4.8	4.7	4.6	4.5	4.4	4.2	**0.1**	4.1	4.1	4.0	3.9	3.8	3.6	**0.1**
74	4.6	4.5	4.4	4.3	4.2	4.0	**0.1**	3.9	3.9	3.8	3.7	3.6	3.4	**0.1**
75	4.4	4.3	4.2	4.1	4.0	3.8	**0.1**	3.7	3.7	3.6	3.5	3.4	3.2	**0.1**
76	4.2	4.1	4.0	3.9	3.8	3.7	**0.1**	3.6	3.5	3.4	3.3	3.2	3.1	**0.1**
77	4.0	3.9	3.8	3.8	3.6	3.5	**0.1**	3.4	3.3	3.2	3.1	3.0	2.9	**0.1**

Total / ENG Anti-ice ON: reduce gradient using AI ON correction (Δ%)

TAP MSN 08043 **CS-TVA**

Figure A.8: QRH's table for 'Approach Climb Gradient - ISA+10 & Below' scenario [35].

A.3.4 Approach Climb Gradient - ISA+20

TAP PORTUGAL
A320-251N
QUICK REFERENCE HANDBOOK

IN FLIGHT PERFORMANCE

PER-ACG
3/4
18 APR 18

APPROACH CLIMB GRADIENT - ISA + 20

APPROACH CONFIGURATION: TOGA THRUST - ONE ENGINE INOPERATVE														
V/Vs = 1.23 A/C ON			ANTI-ICING OFF ISA + 20°C & BELOW						APPROACH CLIMB GRADIENT (%)					
GW (ton)	Pressure Altitude (ft)													
	CONF 2						AI ON	CONF 3						AI ON
	1000	2000	3000	4000	5000	6000	Correction	1000	2000	3000	4000	5000	6000	Correction
48	12.2	12.1	12.0	11.8	11.6	11.3	**0.9**	11.8	11.7	11.6	11.3	11.1	10.8	**0.9**
49	11.8	11.7	11.6	11.3	11.2	10.9	**0.8**	11.3	11.2	11.0	10.8	10.6	10.3	**0.9**
50	11.3	11.2	11.1	10.9	10.7	10.5	**0.8**	10.8	10.7	10.6	10.3	10.1	9.8	**0.9**
51	10.9	10.8	10.7	10.5	10.3	10.1	**0.8**	10.3	10.2	10.1	9.9	9.7	9.4	**0.8**
52	10.5	10.4	10.3	10.1	10.0	9.7	**0.8**	9.9	9.8	9.7	9.4	9.3	9.0	**0.8**
53	10.2	10.1	10.0	9.8	9.6	9.4	**0.8**	9.5	9.4	9.3	9.1	8.9	8.7	**0.8**
54	9.8	9.7	9.6	9.4	9.2	9.0	**0.8**	9.1	9.0	8.9	8.7	8.6	8.3	**0.8**
55	9.4	9.4	9.2	9.1	8.9	8.7	**0.8**	8.8	8.7	8.6	8.4	8.2	8.0	**0.8**
56	9.1	9.0	8.9	8.7	8.6	8.4	**0.7**	8.4	8.3	8.2	8.0	7.9	7.7	**0.7**
57	8.8	8.7	8.6	8.4	8.3	8.0	**0.7**	8.1	8.0	7.9	7.7	7.6	7.4	**0.7**
58	8.5	8.4	8.3	8.1	8.0	7.7	**0.7**	7.8	7.7	7.6	7.4	7.3	7.1	**0.7**
59	8.1	8.1	8.0	7.8	7.7	7.5	**0.7**	7.5	7.4	7.3	7.1	7.0	6.8	**0.7**
60	7.9	7.8	7.7	7.5	7.4	7.2	**0.7**	7.2	7.1	7.0	6.8	6.7	6.5	**0.7**
61	7.6	7.5	7.4	7.2	7.1	6.9	**0.7**	6.9	6.8	6.7	6.6	6.4	6.2	**0.7**
62	7.3	7.2	7.1	7.0	6.8	6.6	**0.7**	6.6	6.5	6.5	6.3	6.2	6.0	**0.7**
63	7.0	6.9	6.9	6.7	6.6	6.4	**0.7**	6.3	6.3	6.2	6.0	5.9	5.7	**0.7**
64	6.8	6.7	6.6	6.5	6.3	6.1	**0.7**	6.1	6.0	5.9	5.8	5.7	5.5	**0.7**
65	6.5	6.4	6.3	6.2	6.1	5.9	**0.7**	5.8	5.8	5.7	5.6	5.4	5.3	**0.6**
66	6.3	6.2	6.1	6.0	5.8	5.7	**0.6**	5.6	5.5	5.5	5.3	5.2	5.0	**0.6**
67	6.0	5.9	5.9	5.7	5.6	5.4	**0.6**	5.4	5.3	5.2	5.1	5.0	4.8	**0.6**
68	5.8	5.7	5.6	5.5	5.4	5.2	**0.6**	5.1	5.1	5.0	4.9	4.8	4.6	**0.6**
69	5.6	5.5	5.4	5.3	5.2	5.0	**0.6**	4.9	4.9	4.8	4.7	4.5	4.4	**0.6**
70	5.3	5.3	5.2	5.1	4.9	4.8	**0.6**	4.7	4.6	4.6	4.4	4.3	4.2	**0.6**
71	5.1	5.1	5.0	4.9	4.7	4.6	**0.6**	4.5	4.4	4.4	4.2	4.1	4.0	**0.6**
72	4.9	4.9	4.8	4.7	4.5	4.4	**0.6**	4.3	4.2	4.2	4.0	3.9	3.8	**0.6**
73	4.7	4.7	4.6	4.5	4.3	4.2	**0.6**	4.1	4.0	4.0	3.8	3.7	3.6	**0.6**
74	4.5	4.5	4.4	4.3	4.2	4.0	**0.6**	3.9	3.8	3.8	3.7	3.5	3.4	**0.6**
75	4.3	4.3	4.2	4.1	4.0	3.8	**0.6**	3.7	3.6	3.6	3.5	3.4	3.2	**0.6**
76	4.2	4.1	4.0	3.9	3.8	3.6	**0.6**	3.5	3.5	3.4	3.3	3.2	3.1	**0.6**
77	4.0	3.9	3.8	3.7	3.6	3.5	**0.6**	3.4	3.3	3.2	3.1	3.0	2.9	**0.6***

Total / ENG Anti-ice ON: reduce gradient using AI ON correction (Δ%)

TAP MSN 08043 **CS-TVA**

Figure A.9: QRH's table for 'Approach Climb Gradient - ISA+20' scenario [35].

Appendix B

Code file snapshots

B.1 PEP's input code

Listing B.1: .DAT input file for 'Cruise at Long Range Cruise (LRC) speed' IFP calculation.

```
A320-251                1    0    1    3
AERO      03/03/16  AE251A02.BDC
ENGINE    12/05/16  ME251A03.BDC
GENERAL   03/03/16  GE251A02.BDC
Cruise at Long Range Cruise speed
 122 131 000   0 0 1 GC6  KG   00000 DC PC                 0 0
3       100     0,33    0       0       0       0       0
    18590   0
   4 999 999   1   0   0
0       10      15      20
10000   25000   1000
50000   79000   2000
.99
1.3     0       0       1       1       0       0       0       0
END
```

Listing B.2: .ACG input file for 'Approach Climb Gradient' FM calculation.

```
 FILE FORMAT NUMBER :   289
 CALCULATION FILE NAME                    : C:\Users\90019354\
    Downloads\PEP-Sessions_Auto-Test\A320-251_Basic
    version_ClimbGrad_AppClimbGrad_AI-1_AC-1_CONF 1+F_ISA-0_1.acg
 OCTOPUS VERSION                          : 38.1.0
*AIRCRAFT FILE                            : C:\Airbus\PEP\Data\
   AE251A04
*FLIGHT MANUAL VERSION                    :    34
 PRECALCULATION FILE                      : OBSOLETE
 NEURONAL FILE                            : OBSOLETE
 AFM NEURONAL FILE                        : C:\Airbus\PEP\Data\
   XE251A04.PRE
*REGULATION                               :     1
*CALCULATION NAME                         :     8
*CALCULATION MODE (1=POINT 2=CURVE 3=NET :     3
*CDL DATA FILE NAME                       : C:\Airbus\PEP\Data\
   CDLA320F.cdl
```

```
*CDL DATA FILE ISSUE                          : 5
*LDFAIL DATA FILE NAME                        : C:\Airbus\PEP\Data\LSAE07
    .fail
*LDFAIL DATA FILE ISSUE                       : 3
*CPDF DATA FILE NAME                          : C:\Airbus\PEP\Data\
    CP32FM01_01.clsd
*CPDF DATA FILE ISSUE                         : 1
 CPDF SINGLE FILE NAME                        : CP32FA06_02.clsd

               ------------------------------
                              UNITS
               ------------------------------
*LENGTH UNIT (1=M  2=FT  3= NAUTICAL MIL :     1
*ALTITUDES UNIT (1=M  2=FT)              :     2
*FORCES UNIT (1=DAN  2=LB)               :     1
*HORIZONTAL SPEED UNIT (1=M/S 2=KM/H 3=K :     3
*VERTICAL SPEED UNIT (1=M/S 2=FT/MN)     :     1
*PRESSURES UNIT (1=HPA 2=IHG)            :     1
*TEMPERATURE UNIT (1=DEG C  2=DEG F)     :     1
*WEIGHT UNIT (1=KG  2=LB)                :     1
*TIME UNIT (1=SEC  2=MN  3=H)            :     1

               ------------------------------
                       AIRCRAFT DATA
               ------------------------------
 WEIGHT                                  :   90000.000
 LATERAL ASYMMETRY OPTION                :     1
 WEIGHT INITIAL POINT                    :   35000.000
 MAXIMUN STRUCTURAL WEIGHT               :   90000.000
 MAXIMUN STRUCTURAL WEIGHT FOR LANDING   :  999000.000
*CONFIGURATION               (CF SUM GLO :     1
 CONFIGURATION INITIAL POINT (CF SUM GLO :     1
 CG FORWARD POSITION                     :       0.000
*CG FORWARD LIMIT CODE (1=BASIC 2=ALTERN :     1
 FLIGHT CG                               :      25.000
 FLIGHT CG INITIAL POINT                 :      25.000

 (continues...)
```

B.2 PEP's output code

Listing B.3: .CSV output file for 'Cruise at Long Range Cruise (LRC) speed' IFP calculation.

```
INPUT DATA   IFP
Cruise at Long Range Cruise speed
 122 131 00000 0 0 1 GC6  KG 0 000000DC PC 0 0      36089.   00 0   0. 00  0.
  3.00     100.0  0.330      0.0       0.0   0.00      0.0      0.0   18590.  0.00
   4 999 999   1   0   0   0   0
      0.     10.     15.     20.
  10000.  25000.   1000.
  50000.  79000.   2000.
    0.99
     1.3       0.       0.       1.       1.       0.       0.       0.       0.       0.
    KMSR,     DT ,    ALT.,    WIND,    WGHT,    MACH,     SR ,    WFE ,     N1 ,    EGT ,    MSAT,    MTAT,
          CAS ,    TAS ,     CL ,     CD ,    ALPH,    DRAG,     FN ,    PCFN
        ,   DG.C,     FT ,     KT ,     KG ,        ,    NMKG,    KG/H,      % ,    DG.C,    DG.C,    DG.C,
           KT ,     KT ,        ,        ,    DEG.,    DAN ,    DAN ,      %
```

```
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.50000000E+05, 0.40111131E+00,
    0.15953270E+00, 0.16049551E+04, 0.69748002E+02, 0.72287275E+03, 0.00000000E+00, 0.00000000E+00,
    0.22136944E+03, 0.25604281E+03, 0.90000000E+21, 0.90000000E+21, 0.31335841E+01, 0.90000000E+21,
    0.90000000E+21, 0.48267235E+02
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.52000000E+05, 0.40436429E+00,
    0.15624696E+00, 0.16519956E+04, 0.70480373E+02, 0.73127537E+03, 0.00000000E+00, 0.00000000E+00,
    0.22318603E+03, 0.25811929E+03, 0.90000000E+21, 0.90000000E+21, 0.32390815E+01, 0.90000000E+21,
    0.90000000E+21, 0.49771655E+02
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.54000000E+05, 0.46398008E+00,
    0.15329134E+00, 0.19320991E+04, 0.75864097E+02, 0.75301201E+03, 0.00000000E+00, 0.00000000E+00,
    0.25656832E+03, 0.29617405E+03, 0.90000000E+21, 0.90000000E+21, 0.22051051E+01, 0.90000000E+21,
    0.90000000E+21, 0.61404633E+02
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.56000000E+05, 0.46010450E+00,
    0.15263371E+00, 0.19242154E+04, 0.75850272E+02, 0.75062503E+03, 0.00000000E+00, 0.00000000E+00,
    0.25439276E+03, 0.29370014E+03, 0.90000000E+21, 0.90000000E+21, 0.24109056E+01, 0.90000000E+21,
    0.90000000E+21, 0.61502460E+02
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.58000000E+05, 0.45629611E+00,
    0.15187242E+00, 0.19178539E+04, 0.75860695E+02, 0.74841464E+03, 0.00000000E+00, 0.00000000E+00,
    0.25225567E+03, 0.29126912E+03, 0.90000000E+21, 0.90000000E+21, 0.26225026E+01, 0.90000000E+21,
    0.90000000E+21, 0.61656268E+02
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.60000000E+05, 0.45534262E+00,
    0.15040859E+00, 0.19324726E+04, 0.76158678E+02, 0.74940119E+03, 0.00000000E+00, 0.00000000E+00,
    0.25172073E+03, 0.29066047E+03, 0.90000000E+21, 0.90000000E+21, 0.27826119E+01, 0.90000000E+21,
    0.90000000E+21, 0.62421951E+02
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.62000000E+05, 0.45607424E+00,
    0.14865482E+00, 0.19584127E+04, 0.76617777E+02, 0.75199666E+03, 0.00000000E+00, 0.00000000E+00,
    0.25213119E+03, 0.29112749E+03, 0.90000000E+21, 0.90000000E+21, 0.29086460E+01, 0.90000000E+21,
    0.90000000E+21, 0.63532439E+02
0.99000000E+00, 0.00000000E+00, 0.10000000E+05, 0.00000000E+00, 0.64000000E+05, 0.46071012E+00,
    0.14663399E+00, 0.20055837E+04, 0.77395183E+02, 0.75698947E+03, 0.00000000E+00, 0.00000000E+00,
    0.25473267E+03, 0.29408673E+03, 0.90000000E+21, 0.90000000E+21, 0.29509091E+01, 0.90000000E+21,
    0.90000000E+21, 0.65352925E+02
```

Listing B.4: .CSV output file for ‘Approach Climb Gradient’ FM calculation.

```
ZP            ,WEIGHT       ,WEIGHT       ,ACG          ,W REGUL ACG  ,REGUL ACG    ,SPEED (CAS)  ,SPEED (
    IAS)   ,REG SP (CAS)  ,REG SP (IAS)
FT            ,KG           ,KG           ,%            ,KG           ,%            ,KT           ,KT
            ,KT            ,KT
     1000.000,    48000.000,    48000.000,       12.364,  9999999.000,        2.100,      116.000,
     116.400,  9999999.000,  9999999.000
     1000.000,    49000.000,    49000.000,       11.791,  9999999.000,        2.100,      116.000,
     116.400,  9999999.000,  9999999.000
     1000.000,    50000.000,    50000.000,       11.278,  9999999.000,        2.100,      116.799,
     117.199,  9999999.000,  9999999.000
     1000.000,    51000.000,    51000.000,       10.821,  9999999.000,        2.100,      117.961,
     118.361,  9999999.000,  9999999.000
     1000.000,    52000.000,    52000.000,       10.385,  9999999.000,        2.100,      119.112,
     119.512,  9999999.000,  9999999.000
     1000.000,    53000.000,    53000.000,        9.965,  9999999.000,        2.100,      120.253,
     120.653,  9999999.000,  9999999.000
     1000.000,    54000.000,    54000.000,        9.562,  9999999.000,        2.100,      121.382,
     121.782,  9999999.000,  9999999.000
     1000.000,    55000.000,    55000.000,        9.182,  9999999.000,        2.100,      122.501,
     122.901,  9999999.000,  9999999.000
     1000.000,    56000.000,    56000.000,        8.836,  9999999.000,        2.100,      123.610,
     124.010,  9999999.000,  9999999.000
     1000.000,    57000.000,    57000.000,        8.502,  9999999.000,        2.100,      124.709,
     125.109,  9999999.000,  9999999.000
     1000.000,    58000.000,    58000.000,        8.180,  9999999.000,        2.100,      125.798,
     126.198,  9999999.000,  9999999.000
     1000.000,    59000.000,    59000.000,        7.869,  9999999.000,        2.100,      126.878,
     127.278,  9999999.000,  9999999.000
     1000.000,    60000.000,    60000.000,        7.569,  9999999.000,        2.100,      127.953,
     128.353,  9999999.000,  9999999.000
     1000.000,    61000.000,    61000.000,        7.281,  9999999.000,        2.100,      129.047,
     129.447,  9999999.000,  9999999.000
     1000.000,    62000.000,    62000.000,        6.999,  9999999.000,        2.100,      130.133,
     130.533,  9999999.000,  9999999.000
     1000.000,    63000.000,    63000.000,        6.727,  9999999.000,        2.100,      131.211,
```

```
        131.611,   9999999.000,   9999999.000
   1000.000,     64000.000,     64000.000,          6.465,    9999999.000,          2.100,        132.281,
        132.681,   9999999.000,   9999999.000
```

B.3 Database planning

Listing B.5: C# code class mapping for 'Dataset' DB's table.

```
public sealed class DataMap_OEI_CruiseLRCspeed : ClassMap<
    Dataset>
{
    public DataMap_OEI_CruiseLRCspeed()
    {
        Map(m => m.ISA).Index(1);
        Map(m => m.PressureAlt).Index(2);
        Map(m => m.WindSpeed).Index(3);
        Map(m => m.InstantWeight).Index(4);
        Map(m => m.Mach).Index(5);
        Map(m => m.SpecificRange).Index(6);
        Map(m => m.FuelFlow).Index(7);
        Map(m => m.N1).Index(8);
        Map(m => m.EGT).Index(9);
        Map(m => m.MaxStatAirTemp).Index(10);
        Map(m => m.MaxTotAirTemp).Index(11);
        Map(m => m.CAS).Index(12);
        Map(m => m.TAS).Index(13);
        Map(m => m.CL).Index(14);
        Map(m => m.CD).Index(15);
        Map(m => m.AngleOfAttack).Index(16);
        Map(m => m.Drag).Index(17);
        Map(m => m.TotalThrust).Index(18);
        Map(m => m.ThrustRatio).Index(19);
    }
}
```

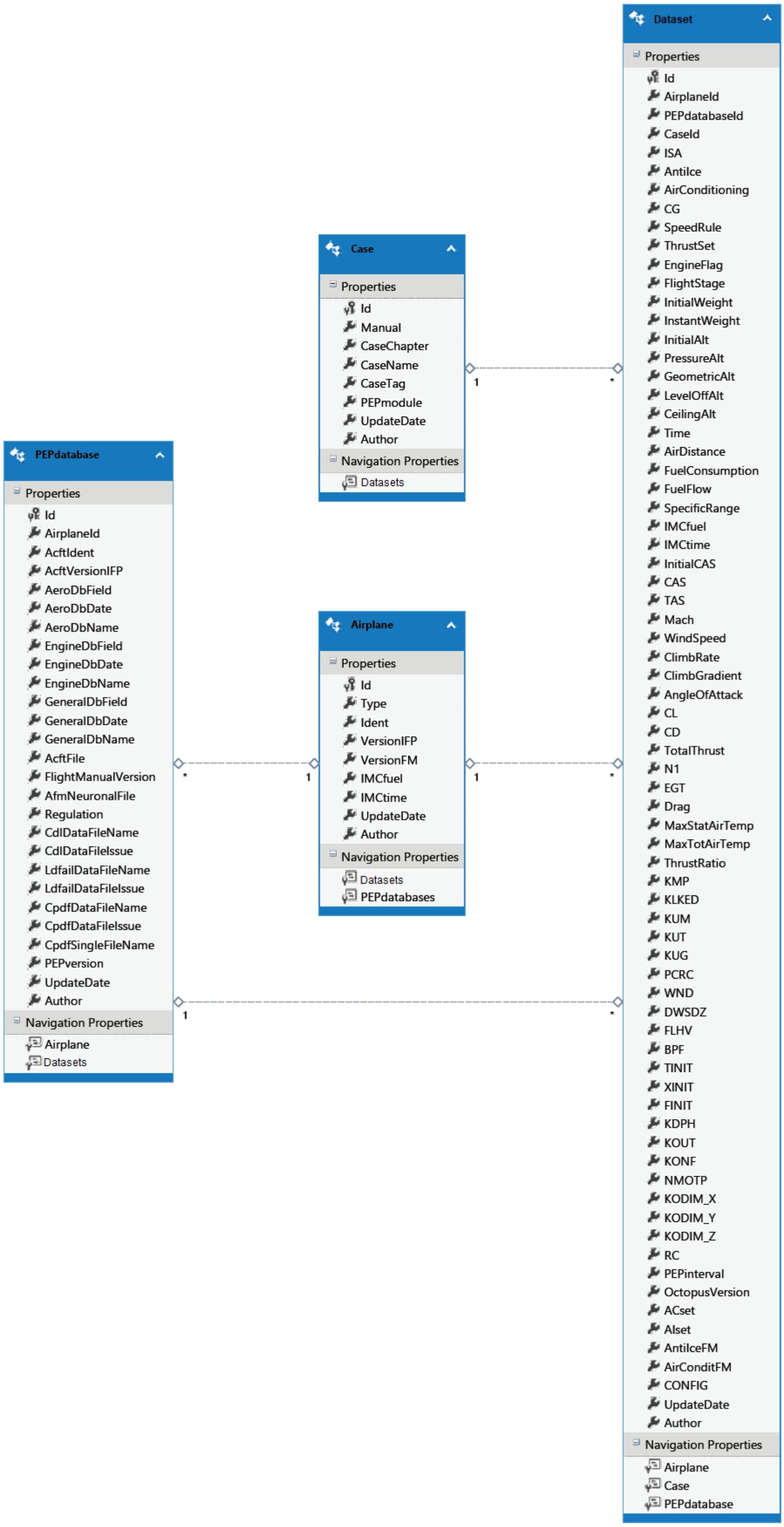

Figure B.1: 'EFB-HSP_Data' database model.

Appendix C

QRH Replication

C.1 One Engine Inoperative

C.1.1 Ceilings

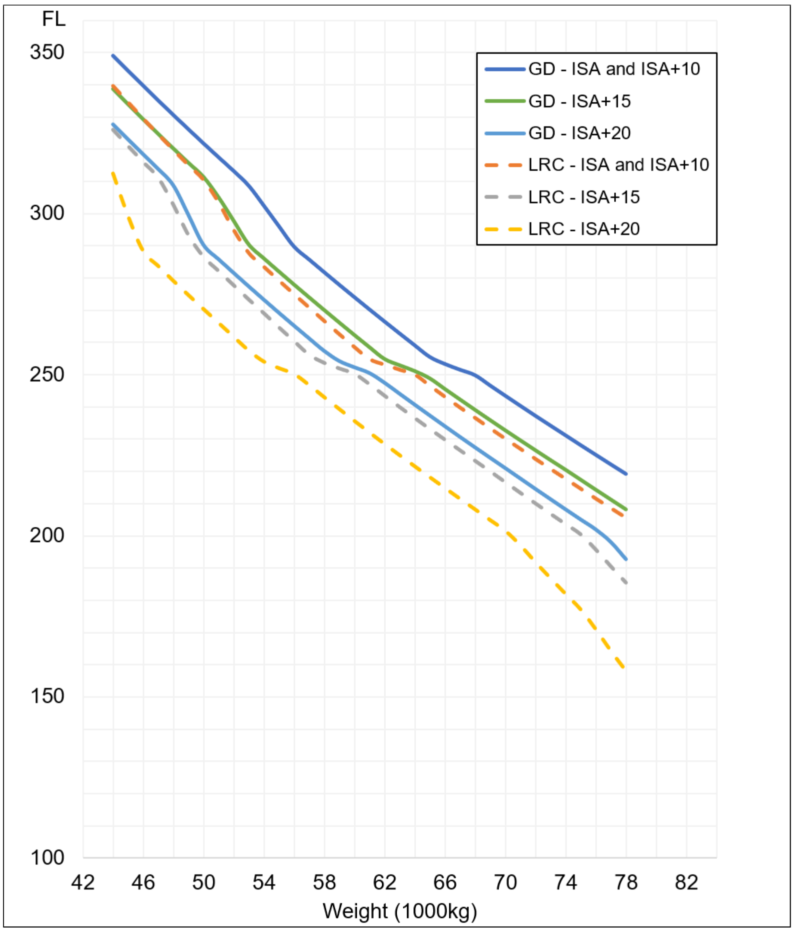

Figure C.1: Replicated chart for 'Ceilings' scenario.

Table C.1: Replicated table for 'Ceilings' scenario.

Weight (ton)	LRC Gross Ceiling (ft)				GD Gross Ceiling (ft)			
	ISA	ISA+10	ISA+15	ISA+20	ISA	ISA+10	ISA+15	ISA+20
44	33970	33953	32612	31253	34946	34913	33860	32765
45	33463	33446	32104	29930	34481	34444	33385	32297
46	32956	32939	31606	28845	34018	33982	32919	31836
47	32479	32447	31119	28377	33563	33523	32463	31379
48	32005	31971	30281	27918	33112	33072	32011	30870
49	31537	31493	29339	27476	32669	32628	31568	29952
50	31074	31037	28669	27041	32233	32189	31130	29021
51	30373	30334	28226	26612	31802	31758	30497	28576
52	29498	29484	27782	26182	31377	31332	29770	28152
53	28793	28769	27340	25752	30938	30874	29034	27733
54	28360	28341	26915	25411	30319	30255	28604	27321
55	27933	27914	26475	25206	29680	29617	28195	26914
56	27512	27492	26049	25026	29036	28984	27792	26514
57	27097	27077	25628	24681	28623	28584	27395	26120
58	26687	26660	25374	24306	28228	28189	27002	25731
59	26286	26250	25202	23937	27838	27799	26613	25417
60	25896	25851	25034	23569	27454	27415	26227	25224
61	25509	25477	24712	23209	27073	27034	25849	25043
62	25323	25305	24355	22852	26698	26658	25484	24743
63	25160	25147	24003	22503	26327	26287	25290	24401
64	25013	24997	23661	22158	25960	25920	25110	24062
65	24683	24651	23323	21821	25597	25558	24882	23726
66	24334	24309	22991	21484	25361	25340	24553	23392
67	23991	23974	22662	21150	25183	25162	24228	23061
68	23665	23653	22335	20821	25014	24991	23906	22736
69	23340	23328	22007	20488	24711	24671	23587	22413
70	23020	23007	21673	20157	24394	24355	23272	22093
71	22709	22694	21341	19706	24080	24041	22961	21770
72	22393	22380	21013	19181	23768	23731	22653	21446
73	22091	22070	20689	18684	23461	23426	22348	21128
74	21787	21764	20369	18193	23157	23124	22048	20811
75	21483	21455	20051	17713	22856	22820	21739	20497
76	21181	21149	19579	17097	22555	22520	21429	20188
77	20882	20852	19058	16427	22258	22222	21124	19797
78	20582	20555	18553	15802	21964	21926	20819	19264

C.1.2 Gross Flight Path Descent at GD Speed

Table C.2: Replicated table for ‘Gross Flight Path Descent at GD Speed’ scenario.

GROSS FLIGHT PATH DESCENT AT GREEN DOT SPEED - 1 ENGINE OUT							
MAX CONTINUOUS THRUST LIMITS HIGH AIR CONDITIONING ANTI ICE OFF			ISA CG=33.0%	DISTANCE (NM) TIME (MIN) INITIAL SPEED (KT) FUEL (1000KG) LEVEL OFF (FT)			
Init. GW (ton)	Initial Flight Level						
	250	290	310	330	350	370	390
50				130 24 198 0.5 32462	206 37 200 0.8 32589	243 43 202 1.0 32642	267 47 204 1.0 32675
52				173 31 202 0.7 31684	224 40 204 0.9 31765	254 45 206 1.0 31808	277 49 208 1.1 31835
54			121 22 204 0.5 30654	208 38 206 0.9 30876	243 43 208 1.0 30949	266 47 210 1.1 30991	285 50 212 1.2 31016
56			204 37 208 0.9 29630	259 47 210 1.2 29780	290 52 212 1.3 29849	313 56 214 1.4 29894	332 58 216 1.4 29927
58		127 24 210 0.6 28467	221 40 212 1.0 28632	268 48 214 1.2 28708	297 53 216 1.3 28751	320 57 218 1.4 28780	339 60 220 1.5 28802
60		169 31 214 0.8 27768	227 41 216 1.1 27870	264 48 218 1.2 27927	290 52 220 1.3 27961	311 55 222 1.4 27986	327 57 224 1.4 28005
62		194 35 218 1.0 27060	239 43 220 1.2 27134	270 48 222 1.3 27180	292 52 224 1.4 27210	311 55 226 1.4 27232	328 57 228 1.5 27249
64		212 39 222 1.1 26356	249 45 224 1.3 26415	276 49 226 1.4 26453	297 53 228 1.4 26480	315 55 230 1.5 26500	331 57 232 1.5 26516
66		225 41 226 1.2 25662	257 46 228 1.3 25710	283 50 230 1.4 25744	302 53 232 1.5 25768	319 56 234 1.5 25787	334 58 236 1.6 25802
68		196 35 230 1.0 25189	225 40 232 1.2 25211	250 44 234 1.3 25227	270 47 236 1.3 25239	286 49 238 1.4 25248	302 51 240 1.4 25256
70	90 16 230 0.5 24553	214 38 234 1.2 24759	238 42 236 1.3 24790	257 45 238 1.3 24812	276 47 240 1.4 24829	290 49 242 1.4 24843	303 51 244 1.5 24854
72	153 27 234 0.9 24046	233 41 238 1.3 24168	256 45 240 1.4 24197	275 48 242 1.5 24219	292 50 244 1.5 24236	305 52 246 1.6 24250	319 54 248 1.6 24261
74	176 31 238 1.1 23475	244 43 242 1.4 23575	266 46 244 1.5 23601	284 49 246 1.5 23622	300 51 248 1.6 23638	314 53 250 1.6 23651	
76	194 34 242 1.2 22904	253 44 246 1.5 22989	273 47 248 1.5 23013	290 50 250 1.6 23032	306 52 252 1.7 23047	319 54 254 1.7 23059	
78	206 36 246 1.3 22338	260 45 250 1.5 22411	279 48 252 1.6 22434	295 50 254 1.7 22452	311 52 256 1.7 22466	323 54 258 1.8 22477	
79	213 37 248 1.3 22057	264 45 252 1.6 22126	281 48 254 1.6 22148	298 50 256 1.7 22165	314 53 258 1.8 22179	326 54 260 1.8 22189	

C.1.3 Cruise at LRC Speed

Table C.3: Replicated table for ‘Cruise at LRC Speed’ scenario.

CRUISE - LONG RANGE - 1 ENGINE OUT												
MAX CONTINUOUS THRUST LIMITS HIGH AIR CONDITIONING ANTI ICE OFF						ISA CG=33.0%		N1 (%) FUEL FLOW (KG/H) SR (NM/1000KG)				MACH CAS (KT) TAS (KT)
WEIGHT (ton)	FL100		FL150		FL190		FL210		FL230		FL250	
50	70.4 1523 173.4	0.414 228 264	74.1 1478 188.0	0.443 223 278	78.1 1481 199.7	0.479 223 296	79.1 1437 206.1	0.484 216 296	82.4 1515 209.9	0.524 225 318	84.5 1521 216.5	0.547 225 329
52	70.9 1556 170.2	0.415 229 265	75.4 1547 183.8	0.454 228 284	79.1 1539 195.1	0.487 226 300	80.2 1503 200.2	0.492 220 301	83.5 1575 205.2	0.532 229 323	85.4 1573 211.6	0.553 228 333
54	71.8 1606 167.0	0.420 232 268	76.5 1606 179.9	0.461 232 289	79.6 1566 191.1	0.485 225 299	82.6 1638 194.6	0.521 233 319	84.7 1642 200.4	0.542 233 329	86.1 1612 207.0	0.554 229 334
56	73.1 1681 163.5	0.431 238 275	77.3 1655 176.4	0.466 234 292	80.3 1614 186.6	0.488 227 301	83.5 1692 190.6	0.527 236 322	85.7 1704 196.2	0.551 237 334	87.2 1676 202.0	0.562 232 338
58	74.0 1736 160.4	0.436 241 279	78.4 1716 172.8	0.473 238 297	82.4 1742 181.5	0.513 239 316	84.7 1762 186.4	0.537 240 328	86.4 1748 192.1	0.553 238 336	88.2 1735 197.1	0.568 235 342
60	74.8 1786 157.6	0.441 244 281	79.8 1800 169.2	0.486 245 305	83.6 1819 177.5	0.524 244 323	85.7 1826 182.5	0.545 244 333	87.1 1792 188.2	0.556 239 337	89.1 1797 192.3	0.574 237 346
62	75.8 1848 154.7	0.448 248 286	80.4 1842 166.0	0.488 246 306	84.5 1878 174.0	0.530 247 327	86.6 1887 178.9	0.552 247 338	88.2 1866 183.7	0.565 243 343	90.3 1870 187.4	0.582 241 350
64	76.9 1920 151.8	0.457 252 292	80.7 1868 163.2	0.487 245 305	85.5 1948 170.5	0.539 251 332	87.2 1931 175.5	0.554 248 339	89.1 1925 179.7	0.570 245 346	91.5 1939 182.7	0.588 243 354
66	77.7 1978 149.2	0.462 256 295	81.3 1912 160.0	0.488 246 306	86.4 2012 167.3	0.546 254 336	87.9 1984 172.1	0.558 250 341	90.0 1993 175.6	0.577 248 350	91.6 1935 179.6	0.577 239 347
68	78.4 2027 146.7	0.466 258 298	82.9 2023 156.2	0.505 254 316	87.2 2072 164.2	0.552 257 340	88.9 2058 168.3	0.566 254 346	91.2 2068 171.4	0.584 252 355	91.8 1920 172.7	0.551 227 332
70	79.1 2077 144.3	0.470 260 300	84.3 2132 152.9	0.520 262 326	87.8 2117 161.3	0.553 258 341	89.8 2119 164.9	0.571 256 349	92.2 2137 167.5	0.590 254 358		
72	80.2 2158 141.8	0.480 265 306	84.9 2180 150.4	0.523 264 328	88.5 2172 158.3	0.557 260 344	90.7 2189 161.4	0.577 259 353	92.3 2133 164.9	0.580 250 352		
74	81.4 2243 139.4	0.490 271 313	85.7 2246 147.7	0.530 267 332	89.5 2251 155.1	0.566 264 349	91.7 2263 157.9	0.584 262 357	92.5 2124 160.0	0.560 241 340		
76	81.8 2278 137.3	0.490 271 313	86.6 2317 145.1	0.537 271 336	90.3 2314 152.1	0.571 267 352	92.7 2335 154.5	0.590 265 361				
78	82.1 2304 135.4	0.489 271 312	87.3 2381 142.7	0.542 274 340	91.2 2386 149.1	0.577 270 356	93.0 2350 152.1	0.584 262 357				
79	82.2 2315 134.5	0.488 270 311	87.7 2417 141.5	0.546 275 342	91.6 2422 147.6	0.580 271 358	93.0 2348 150.8	0.579 260 354				

C.2 Climb Gradient

C.2.1 Maximum Climb Gradient - ISA+10 & Below

Table C.4: Replicated table for 'Maximum Climb Gradient - ISA+10 & Below' scenario.

EN-ROUTE CONFIGURATION: CLIMB THRUST - ALL ENGINES - GREEN DOT SPEED											
CG = 33.0% NORMAL AIR CONDITIONING					ANTI ICE OFF ISA + 10°C & BELOW				**CLIMB GRADIENT (%)**		
GW (ton)	CAS (kt)	Pressure Altitude (ft)									
		1500	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**10000**
48	**181**	28.3	27.9	27.3	26.6	25.9	25.3	24.7	24.1	23.5	22.9
49	**183**	27.4	27.1	26.4	25.7	25.1	24.5	23.9	23.4	22.8	22.2
50	**185**	26.5	26.2	25.6	24.9	24.3	23.7	23.2	22.6	22.1	21.5
51	**187**	25.7	25.4	24.8	24.2	23.6	23.0	22.5	21.9	21.4	20.8
52	**189**	24.9	24.6	24.0	23.4	22.8	22.3	21.8	21.2	20.7	20.2
53	**191**	24.2	23.9	23.3	22.7	22.2	21.6	21.1	20.6	20.1	19.6
54	**193**	23.5	23.2	22.6	22.1	21.5	21.0	20.5	20.0	19.5	19.0
55	**195**	22.8	22.5	22.0	21.4	20.9	20.3	19.9	19.4	18.9	18.4
56	**197**	22.2	21.9	21.4	20.8	20.3	19.8	19.3	18.8	18.3	17.9
57	**199**	21.5	21.3	20.8	20.2	19.7	19.2	18.7	18.3	17.8	17.4
58	**201**	21.0	20.7	20.2	19.6	19.1	18.6	18.2	17.7	17.3	16.9
59	**203**	20.4	20.1	19.6	19.1	18.6	18.1	17.7	17.2	16.8	16.4
60	**205**	19.8	19.6	19.1	18.6	18.1	17.6	17.2	16.8	16.3	15.9
61	**207**	19.3	19.1	18.6	18.1	17.6	17.1	16.7	16.3	15.9	15.5
62	**209**	18.8	18.5	18.1	17.6	17.1	16.7	16.3	15.9	15.4	15.0
63	**211**	18.3	18.1	17.6	17.1	16.7	16.2	15.8	15.4	15.0	14.6
64	**213**	17.8	17.6	17.1	16.7	16.2	15.8	15.4	15.0	14.6	14.2
65	**215**	17.4	17.1	16.7	16.2	15.8	15.4	15.0	14.6	14.2	13.8
66	**217**	16.9	16.7	16.3	15.8	15.4	15.0	14.6	14.2	13.8	13.5
67	**219**	16.5	16.3	15.8	15.4	15.0	14.6	14.2	13.8	13.5	13.1
68	**221**	16.1	15.9	15.4	15.0	14.6	14.2	13.9	13.5	13.1	12.8
69	**223**	15.7	15.5	15.1	14.6	14.2	13.8	13.5	13.1	12.8	12.4
70	**225**	15.3	15.1	14.7	14.3	13.9	13.5	13.1	12.8	12.4	12.1
71	**227**	14.9	14.7	14.3	13.9	13.5	13.2	12.8	12.4	12.1	11.8
72	**229**	14.6	14.3	14.0	13.6	13.2	12.8	12.5	12.1	11.8	11.5
73	**231**	14.2	14.0	13.6	13.2	12.9	12.5	12.2	11.8	11.5	11.2
74	**233**	13.9	13.7	13.3	12.9	12.6	12.2	11.9	11.5	11.2	10.9
75	**235**	13.5	13.3	13.0	12.6	12.2	11.9	11.6	11.2	10.9	10.6
76	**237**	13.2	13.0	12.7	12.3	11.9	11.6	11.3	10.9	10.6	10.3
77	**239**	12.9	12.7	12.4	12.0	11.7	11.3	11.0	10.7	10.4	10.1

C.2.2 Maximum Climb Gradient - ISA+20

Table C.5: Replicated table for 'Maximum Climb Gradient - ISA+20, Anti Ice Off' scenario.

EN-ROUTE CONFIGURATION: CLIMB THRUST - ALL ENGINES - GREEN DOT SPEED											
CG = 33.0% NORMAL AIR CONDITIONING					ANTI ICE OFF ISA + 20°C				**CLIMB GRADIENT (%)**		
GW (ton)	CAS (kt)	Pressure Altitude (ft)									
		1500	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**10000**
48	**181**	24.4	24.1	23.5	22.9	22.3	21.7	21.1	20.5	19.9	19.4
49	**183**	23.6	23.3	22.7	22.1	21.6	21.0	20.4	19.9	19.3	18.7
50	**185**	22.9	22.6	22.0	21.4	20.9	20.3	19.8	19.2	18.7	18.1
51	**187**	22.2	21.9	21.3	20.8	20.2	19.7	19.1	18.6	18.1	17.5
52	**189**	21.5	21.2	20.7	20.1	19.6	19.1	18.5	18.0	17.5	17.0
53	**191**	20.9	20.6	20.0	19.5	19.0	18.5	18.0	17.5	16.9	16.4
54	**193**	20.2	20.0	19.4	18.9	18.4	17.9	17.4	16.9	16.4	15.9
55	**195**	19.6	19.4	18.9	18.4	17.9	17.4	16.9	16.4	15.9	15.5
56	**197**	19.1	18.8	18.3	17.8	17.3	16.9	16.4	15.9	15.4	15.0
57	**199**	18.5	18.3	17.8	17.3	16.8	16.4	15.9	15.4	15.0	14.5
58	**201**	18.0	17.8	17.3	16.8	16.4	15.9	15.4	15.0	14.5	14.1
59	**203**	17.5	17.3	16.8	16.3	15.9	15.4	15.0	14.5	14.1	13.7
60	**205**	17.0	16.8	16.3	15.9	15.4	15.0	14.6	14.1	13.7	13.3
61	**207**	16.5	16.3	15.9	15.4	15.0	14.6	14.1	13.7	13.3	12.9
62	**209**	16.1	15.9	15.4	15.0	14.6	14.1	13.7	13.3	12.9	12.5
63	**211**	15.7	15.4	15.0	14.6	14.2	13.8	13.4	13.0	12.6	12.2
64	**213**	15.2	15.0	14.6	14.2	13.8	13.4	13.0	12.6	12.2	11.8
65	**215**	14.8	14.6	14.2	13.8	13.4	13.0	12.6	12.2	11.9	11.5
66	**217**	14.4	14.2	13.8	13.4	13.0	12.7	12.3	11.9	11.5	11.2
67	**219**	14.1	13.8	13.5	13.1	12.7	12.3	11.9	11.6	11.2	10.8
68	**221**	13.7	13.5	13.1	12.7	12.4	12.0	11.6	11.3	10.9	10.5
69	**223**	13.3	13.1	12.8	12.4	12.0	11.7	11.3	10.9	10.6	10.3
70	**225**	13.0	12.8	12.4	12.1	11.7	11.4	11.0	10.6	10.3	10.0
71	**227**	12.7	12.5	12.1	11.8	11.4	11.0	10.7	10.4	10.0	9.7
72	**229**	12.3	12.2	11.8	11.5	11.1	10.8	10.4	10.1	9.8	9.4
73	**231**	12.0	11.8	11.5	11.2	10.8	10.5	10.1	9.8	9.5	9.2
74	**233**	11.7	11.5	11.2	10.9	10.5	10.2	9.9	9.5	9.2	8.9
75	**235**	11.4	11.3	10.9	10.6	10.3	9.9	9.6	9.3	9.0	8.7
76	**237**	11.1	11.0	10.7	10.3	10.0	9.7	9.4	9.1	8.7	8.4
77	**239**	10.9	10.7	10.4	10.1	9.7	9.4	9.1	8.8	8.5	8.2

Table C.6: Replicated table for 'Maximum Climb Gradient - ISA+20, Total Anti Ice' scenario.

EN-ROUTE CONFIGURATION: CLIMB THRUST - ALL ENGINES - GREEN DOT SPEED											
CG = 33.0% NORMAL AIR CONDITIONING					TOTAL ANTI ICE ISA + 20°C				**CLIMB GRADIENT (%)**		
GW	CAS	Pressure Altitude (ft)									
(ton)	(kt)	**1500**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**10000**
48	**181**	23.2	22.8	22.2	21.6	21.0	20.4	19.9	19.3	18.8	18.3
49	**183**	22.4	22.1	21.5	20.9	20.3	19.8	19.2	18.6	18.2	17.7
50	**185**	21.7	21.4	20.8	20.2	19.7	19.1	18.6	18.0	17.6	17.1
51	**187**	21.0	20.7	20.2	19.6	19.0	18.5	18.0	17.4	17.0	16.5
52	**189**	20.4	20.1	19.5	19.0	18.4	17.9	17.4	16.9	16.4	16.0
53	**191**	19.8	19.5	18.9	18.4	17.9	17.4	16.9	16.3	15.9	15.4
54	**193**	19.2	18.9	18.4	17.8	17.3	16.9	16.4	15.8	15.4	14.9
55	**195**	18.6	18.3	17.8	17.3	16.8	16.3	15.8	15.3	14.9	14.5
56	**197**	18.1	17.8	17.3	16.8	16.3	15.9	15.4	14.9	14.4	14.0
57	**199**	17.5	17.3	16.8	16.3	15.8	15.4	14.9	14.4	14.0	13.6
58	**201**	17.0	16.8	16.3	15.8	15.4	14.9	14.5	14.0	13.6	13.2
59	**203**	16.6	16.3	15.8	15.4	14.9	14.5	14.0	13.6	13.2	12.8
60	**205**	16.1	15.9	15.4	14.9	14.5	14.1	13.6	13.2	12.8	12.4
61	**207**	15.6	15.4	15.0	14.5	14.1	13.7	13.2	12.8	12.4	12.0
62	**209**	15.2	15.0	14.5	14.1	13.7	13.3	12.8	12.4	12.0	11.7
63	**211**	14.8	14.6	14.1	13.7	13.3	12.9	12.5	12.1	11.7	11.3
64	**213**	14.4	14.2	13.7	13.3	12.9	12.5	12.1	11.7	11.4	11.0
65	**215**	14.0	13.8	13.4	12.9	12.6	12.2	11.8	11.4	11.0	10.7
66	**217**	13.6	13.4	13.0	12.6	12.2	11.9	11.5	11.0	10.7	10.4
67	**219**	13.3	13.1	12.6	12.2	11.9	11.5	11.1	10.7	10.4	10.1
68	**221**	12.9	12.7	12.3	11.9	11.6	11.2	10.8	10.4	10.1	9.8
69	**223**	12.6	12.4	12.0	11.6	11.3	10.9	10.5	10.1	9.8	9.5
70	**225**	12.2	12.0	11.7	11.3	11.0	10.6	10.2	9.9	9.5	9.2
71	**227**	11.9	11.7	11.4	11.0	10.7	10.3	10.0	9.6	9.3	9.0
72	**229**	11.6	11.4	11.1	10.7	10.4	10.1	9.7	9.3	9.0	8.7
73	**231**	11.3	11.1	10.8	10.4	10.1	9.8	9.4	9.1	8.8	8.5
74	**233**	11.0	10.9	10.5	10.2	9.8	9.5	9.2	8.8	8.5	8.2
75	**235**	10.8	10.6	10.2	9.9	9.6	9.3	8.9	8.6	8.3	8.0
76	**237**	10.5	10.3	10.0	9.6	9.3	9.0	8.7	8.4	8.1	7.8
77	**239**	10.2	10.1	9.7	9.4	9.1	8.8	8.5	8.1	7.9	7.6

C.2.3 Approach Climb Gradient - ISA+10 & Below

Table C.7: Replicated table for 'Approach Climb Gradient - ISA+10 & Below' scenario.

APPROACH CONFIGURATION: TOGA THRUST - ONE ENGINE INOPERATIVE												
V/Vs = 1.23 A/C ON			ANTI ICE OFF ISA + 10°C & BELOW				APPROACH CLIMB GRADIENT (%)					
GW (ton)	Pressure Altitude (ft)											
	CONF 2						CONF 3					
	1500	2000	3000	4000	5000	6000	1500	2000	3000	4000	5000	6000
48	12.3	12.2	12.1	11.8	11.6	11.3	11.9	11.8	11.6	11.4	11.2	10.9
49	11.8	11.7	11.6	11.4	11.2	10.9	11.3	11.2	11.1	10.8	10.6	10.3
50	11.4	11.3	11.2	10.9	10.8	10.5	10.8	10.7	10.6	10.3	10.2	9.8
51	11.0	10.9	10.8	10.5	10.4	10.1	10.4	10.3	10.2	9.9	9.7	9.4
52	10.6	10.5	10.4	10.2	10.0	9.7	10.0	9.9	9.7	9.5	9.3	9.0
53	10.2	10.1	10.0	9.8	9.6	9.4	9.5	9.4	9.3	9.1	8.9	8.7
54	9.8	9.7	9.6	9.4	9.3	9.0	9.2	9.1	9.0	8.7	8.6	8.3
55	9.5	9.4	9.3	9.1	8.9	8.7	8.8	8.7	8.6	8.4	8.3	8.0
56	9.1	9.1	8.9	8.8	8.6	8.4	8.5	8.4	8.3	8.1	7.9	7.7
57	8.8	8.7	8.6	8.4	8.3	8.1	8.1	8.0	7.9	7.8	7.6	7.4
58	8.5	8.4	8.3	8.1	8.0	7.8	7.8	7.7	7.6	7.5	7.3	7.1
59	8.2	8.1	8.0	7.8	7.7	7.5	7.5	7.4	7.3	7.2	7.0	6.8
60	7.9	7.8	7.7	7.5	7.4	7.2	7.2	7.1	7.0	6.9	6.7	6.5
61	7.6	7.5	7.4	7.3	7.1	6.9	6.9	6.9	6.8	6.6	6.5	6.3
62	7.3	7.2	7.1	7.0	6.9	6.7	6.7	6.6	6.5	6.3	6.2	6.0
63	7.1	7.0	6.9	6.7	6.6	6.4	6.4	6.3	6.2	6.1	5.9	5.8
64	6.8	6.7	6.6	6.5	6.3	6.2	6.1	6.1	6.0	5.8	5.7	5.5
65	6.6	6.5	6.4	6.2	6.1	5.9	5.9	5.8	5.7	5.6	5.5	5.3
66	6.3	6.2	6.1	6.0	5.9	5.7	5.6	5.6	5.5	5.3	5.2	5.0
67	6.1	6.0	5.9	5.8	5.6	5.5	5.4	5.3	5.3	5.1	5.0	4.8
68	5.8	5.8	5.7	5.5	5.4	5.2	5.2	5.1	5.0	4.9	4.8	4.6
69	5.6	5.5	5.4	5.3	5.2	5.0	5.0	4.9	4.8	4.7	4.6	4.4
70	5.4	5.3	5.2	5.1	5.0	4.8	4.7	4.7	4.6	4.5	4.4	4.2
71	5.2	5.1	5.0	4.9	4.8	4.6	4.5	4.5	4.4	4.3	4.2	4.0
72	5.0	4.9	4.8	4.7	4.6	4.4	4.3	4.3	4.2	4.1	4.0	3.8
73	4.8	4.7	4.6	4.5	4.4	4.2	4.1	4.1	4.0	3.9	3.8	3.6
74	4.6	4.5	4.4	4.3	4.2	4.0	3.9	3.9	3.8	3.7	3.6	3.4
75	4.4	4.3	4.2	4.1	4.0	3.8	3.7	3.7	3.6	3.5	3.4	3.2
76	4.2	4.1	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.3	3.2	3.1
77	4.0	3.9	3.8	3.8	3.6	3.5	3.4	3.3	3.2	3.1	3.0	2.9

C.2.4 Approach Climb Gradient - ISA+20

Table C.8: Replicated table for 'Approach Climb Gradient - ISA+20' scenario.

APPROACH CONFIGURATION: TOGA THRUST - ONE ENGINE INOPERATIVE												
V/Vs = 1.23 A/C ON			ANTI ICE OFF ISA + 20°C				APPROACH CLIMB GRADIENT (%)					
GW (ton)	Pressure Altitude (ft)											
	CONF 2						CONF 3					
	1500	2000	3000	4000	5000	6000	1500	2000	3000	4000	5000	6000
48	12.2	12.1	12.0	11.8	11.6	11.3	11.8	11.7	11.6	11.3	11.1	10.8
49	11.8	11.7	11.6	11.3	11.2	10.9	11.3	11.2	11.0	10.8	10.6	10.3
50	11.3	11.2	11.1	10.9	10.7	10.5	10.8	10.7	10.6	10.3	10.1	9.8
51	10.9	10.8	10.7	10.5	10.3	10.1	10.3	10.2	10.1	9.9	9.7	9.4
52	10.5	10.4	10.3	10.1	10.0	9.7	9.9	9.8	9.7	9.4	9.3	9.0
53	10.2	10.1	10.0	9.8	9.6	9.4	9.5	9.4	9.3	9.1	8.9	8.7
54	9.8	9.7	9.6	9.4	9.2	9.0	9.1	9.0	8.9	8.7	8.6	8.3
55	9.4	9.4	9.2	9.1	8.9	8.7	8.8	8.7	8.6	8.4	8.2	8.0
56	9.1	9.0	8.9	8.7	8.6	8.4	8.4	8.3	8.2	8.0	7.9	7.7
57	8.8	8.7	8.6	8.4	8.3	8.0	8.1	8.0	7.9	7.7	7.6	7.4
58	8.5	8.4	8.3	8.1	8.0	7.7	7.8	7.7	7.6	7.4	7.3	7.1
59	8.1	8.1	8.0	7.8	7.7	7.5	7.5	7.4	7.3	7.1	7.0	6.8
60	7.9	7.8	7.7	7.5	7.4	7.2	7.2	7.1	7.0	6.8	6.7	6.5
61	7.6	7.5	7.4	7.2	7.1	6.9	6.9	6.8	6.7	6.6	6.4	6.2
62	7.3	7.2	7.1	7.0	6.8	6.6	6.6	6.5	6.5	6.3	6.2	6.0
63	7.0	6.9	6.9	6.7	6.6	6.4	6.3	6.3	6.2	6.0	5.9	5.7
64	6.8	6.7	6.6	6.5	6.3	6.1	6.1	6.0	5.9	5.8	5.7	5.5
65	6.5	6.4	6.3	6.2	6.1	5.9	5.8	5.8	5.7	5.6	5.4	5.3
66	6.3	6.2	6.1	6.0	5.8	5.7	5.6	5.5	5.5	5.3	5.2	5.0
67	6.0	5.9	5.9	5.7	5.6	5.4	5.4	5.3	5.2	5.1	5.0	4.8
68	5.8	5.7	5.6	5.5	5.4	5.2	5.1	5.1	5.0	4.9	4.8	4.6
69	5.6	5.5	5.4	5.3	5.2	5.0	4.9	4.9	4.8	4.7	4.5	4.4
70	5.3	5.3	5.2	5.1	4.9	4.8	4.7	4.6	4.6	4.4	4.3	4.2
71	5.1	5.1	5.0	4.9	4.7	4.6	4.5	4.4	4.4	4.2	4.1	4.0
72	4.9	4.9	4.8	4.7	4.5	4.4	4.3	4.2	4.2	4.0	3.9	3.8
73	4.7	4.7	4.6	4.5	4.3	4.2	4.1	4.0	4.0	3.8	3.7	3.6
74	4.5	4.5	4.4	4.3	4.2	4.0	3.9	3.8	3.8	3.7	3.5	3.4
75	4.3	4.3	4.2	4.1	4.0	3.8	3.7	3.6	3.6	3.5	3.4	3.2
76	4.2	4.1	4.0	3.9	3.8	3.6	3.5	3.5	3.4	3.3	3.2	3.1
77	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.3	3.2	3.1	3.0	2.9