PILOT WORKLOAD & OPERATIONAL AIRCRAFT SAFETY

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Abstract: This report presents an exploratory study into a theory on the relationship between the operational aircraft safety and pilot workload. The pilot is defined overloaded when workload rises beyond the capacity of the pilot's capabilities. It is assumed that the margin between this so-called boundary of saturation and the actual workload reflects the available or residual attention of the pilot, which is called upon in case of unexpected events or sudden emergency situations. A proposal is made to assess the workload resulting from the Flight Management sub-task, consisting of analytical workload assessment techniques based on Wickens' multiple-resources theory from the field of engineering psychology. Quantification of manual control task workload is done by working out some of the ideas by Padfield from the field of military helicopter flying qualities. Padfield suggests a technique for the calculation of the 'energy applied by the pilot' due to manual control. By means of a workload metric this energy can then be translated to a measure for the pilot workload. An initial validation has been performed by two engineering pilots in a simulator session. Some of the approach procedures were flown, and performance data was recorded for a manual control task workload calculation. Besides this, a very crude timeline task analysis was carried out with the use of an audio-recording of the pilots while flying the procedures.

Keywords: pilot workload, aircraft safety, landing flight procedures, pilot task, simulation of flight procedures

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<th>Issue</th>
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Preface

This report contains a description of my final thesis assignment, which is the last part of the study of Aerospace Engineering at the Delft University of Technology.

During the final thesis I received a lot of support from several people. I would like to thank the following people here in this report:

Jacco Dominicus and Arne Scheffer for their valuable feedback on the sometimes intricate Matlab-program codes.

The KLM-engineering pilots Ernst Meijer and Erik Akker for flying the approach procedures in the simulator.

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And of course my parents for their support during my study.

Thanks for everything!

Delft, August 1998,
Sander van den Berg.
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAS</td>
<td>Amsterdam Airport Schiphol</td>
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<td>ASI</td>
<td>the Airport Safety Index</td>
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<td>ASINOP</td>
<td>Approach Simulation and Noise Program</td>
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<td>ATC</td>
<td>Air Traffic Control</td>
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<td>B747-400</td>
<td>The aircraft type Boeing 747-400</td>
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<td>BASI</td>
<td>Bureau of Air Safety Investigation</td>
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<tr>
<td>CAS</td>
<td>Calibrated Air Speed</td>
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<td>CRM</td>
<td>Crew Resource Management</td>
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<td>CTA</td>
<td>Cognitive Task Analysis</td>
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<td>GD</td>
<td>Gear Down</td>
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<td>GNP</td>
<td>Gross National Product</td>
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<td>GPWS</td>
<td>Ground Proximity Warning System</td>
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<td>GS</td>
<td>Glide Slope</td>
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<td>HF</td>
<td>Human Factors</td>
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<td>HQR</td>
<td>Handling Quality Rating</td>
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<td>ILS</td>
<td>Instrument Landing System</td>
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<td>KLM</td>
<td>Royal Dutch Airlines</td>
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<tr>
<td>LOC</td>
<td>Localizer</td>
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<td>LW</td>
<td>Landing Weight</td>
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<tr>
<td>MLS</td>
<td>Microwave Landing System</td>
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<td>OM</td>
<td>Outer Marker</td>
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<td>PF</td>
<td>Pilot Flying</td>
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<tr>
<td>PID</td>
<td>Proportional-Integrating-Differentiating control</td>
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<td>PNF</td>
<td>Pilot-Not-Flying</td>
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<td>POC</td>
<td>Performance Operating Characteristic</td>
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<tr>
<td>PRF</td>
<td>Performance Resource Function</td>
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<tr>
<td>RLD</td>
<td>'Rijksluchtvaardienst', the Dutch Civil Aviation Authority</td>
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<tr>
<td>rms.</td>
<td>root mean square</td>
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<td>TOMS</td>
<td>Technical Operational Measures Schiphol</td>
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<td>WL</td>
<td>Workload</td>
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</tbody>
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List of Symbols

H  altitude
intH integrated altitude
intV integrated air speed
Ke 'Kosten-eenheid', a measure for noise load
N1 compressor speed of the engines in % RPM, the engine setting
PWL pilot workload
s distance from runway threshold
T_A time available to perform a task
T_R time required to perform a task
uc landing gear
V air speed
V_MAN maneuvring speed
V_REF_25 reference speed for 25 degrees landing flaps
V_REF_30 reference speed for 30 degrees landing flaps
V_REF reference speed
V_{stall} (1g) stall speed

γ aircraft path angle
θ aircraft pitch angle
τ engine setting
Summary

Aircraft noise load is a subject of concern for Amsterdam Airport Schiphol. Together with other companies and institutes they seek a solution to reduce this problem. Adjustments to the operational approach procedures of Schiphol were proposed resulting in a reduction of the noise load contours. But before the implementation of these procedures can take place, the civil aviation authorities demand a "proof of safety".

This is where the first problem surfaces. Aviation safety is barely quantifiable. It is the result of an enormous amount of factors in a highly complex system. Until now the 'aviation safety level' was monitored with the calculation of risk, which can be calculated reasonably good and quite easy, compared to the quantification of the ambiguous safety level itself.

This report presents an exploratory study on the potential quantification of the operational safety of flight procedures. A first design of such a quantification method is presented based on the limitations of the pilot as a human being.

The pilot has to perform a task, which is to fly the airplane as safe and efficient as possible. Carrying out this pilot task requires a certain amount of attention of the pilot, resulting in pilot workload.

A theory is presented on the relationship between the operational aircraft safety and pilot workload. The pilot is defined as overloaded, when workload rises beyond the capacity of the pilot's capabilities. It is assumed that the margin between this so-called boundary of saturation and the actual workload reflects the available or residual attention of the pilot, which is called upon in case of unexpected events and sudden emergency situations.

This theory should not be used for the safety assessment of a single situation or procedure. It should only be applied as a tool to compare a reference and a slightly adjusted situation or procedure relatively.

The reference procedure is defined as an approach with an intercept altitude of 2000 ft, the angle of approach 3°, landing gear is extended at intercept, and landing flaps (30°) are selected after gear is down. The following adjustments to this procedure are considered: higher approach altitude, steeper approaches, reduced flaps, delayed gear, and reduced and delayed flaps, which is the present KLM-procedure.

In this thesis, workload is assumed to be directly related to pilot performance, which in its turn is a result of performing the pilot task. The pilot task is assumed to consists of four sub-tasks, although only the first two sub-tasks are treated in further detail:

1. the Flight Management Task;
2. the Manual Control Task;
3. the Scanning & Monitoring Task, and;
4. all Air Traffic Control-Related Tasks.

A proposal is made to assess the workload resulting from the Flight Management Task, consisting of analytical workload assessment techniques, based on Wickens' multiple-resources theory from the field of engineering-psychology.

Quantification of manual control task workload is done by working out some of the ideas by Padfield from the field of military helicopter flying qualities. Padfield suggests a technique for the calculation of the 'energy applied by the pilot' due to manual control. Via a workload metric this energy can then be translated to a measure for the pilot workload.

This calculation method is translated from military helicopters to large commercial fixed-wing aircraft in symmetric flight, using a flight procedure simulation program called ASINOP. The
aircraft-type that was used in this calculation is the Boeing 747-400. The results of this
manual control task workload calculation technique are somewhat limited by what ASINOP
produces as input parameters.

An initial validation has been performed by two engineering KLM-pilots in a simulator
session. Some of the approach procedures were flown, and performance data was recorded
for a manual control task workload calculation. Besides this, a very crude timeline task
analysis was carried out with the use of an audio-recording of the pilots while flying the
procedures. Performance data that was generated by ASINOP seem intuitively right, but are
not comparable with the results of the simulator session.

The following conclusions are drawn from the manual control task workload calculations:
- Higher approach altitudes could prove to be profitable for the operational safety.
- The analytical manual control task workload calculations of the other approach procedures
  result in a low workload, while much higher values were expected. This is caused by the
  limitations of ASINOP.
- The KLM-procedure of the simulator session results in a much higher manual pitch control
  workload.
# Contents

**PREFACE** .................................................................................................................................. V  
**LIST OF ABBREVIATIONS** ........................................................................................................ vii  
**LIST OF SYMBOLS** .................................................................................................................. viii  
**SUMMARY** ................................................................................................................................ ix  
1. **INTRODUCTION** ................................................................................................................... 1  
2. **AVIATION SAFETY** ............................................................................................................... 5  
   2.1. **INTRODUCTION** .............................................................................................................. 6  
   2.2. **THE NEED FOR AVIATION SAFETY IMPROVEMENTS** .............................................. 6  
   2.3. **QUANTIFICATION OF AVIATION SAFETY** ................................................................. 8  
3. **SAFETY OF FLIGHT PROCEDURES** .................................................................................... 11  
   3.1. **INTRODUCTION** .............................................................................................................. 12  
   3.2. **THE REFERENCE FINAL APPROACH PROCEDURE** .................................................. 13  
   3.3. **THE PROPOSED TOMS APPROACH PROCEDURE ADJUSTMENTS** ..................... 14  
   3.4. **THE ‘SAFETY PROOF’** .................................................................................................. 21  
   3.5. **OPERATIONAL SAFETY ASSESSMENT OF FLIGHT PROCEDURES** ...................... 21  
4. **BASIC PROPOSAL OF THE PILOT WORKLOAD INDEX** .................................................. 25  
   4.1. **INTRODUCTION** .............................................................................................................. 26  
   4.2. **THE AIRPORT SAFETY INDEX** ...................................................................................... 26  
   4.3. **THE PILOT TASK** ........................................................................................................... 29  
   4.4. **THE DEFINITION AND USE OF PILOT WORKLOAD** ................................................ 31  
       4.4.1. **Defining Workload** ................................................................................................. 32  
       4.4.2. **Using Workload** ..................................................................................................... 32  
   4.5. **FROM PILOT TASK TO WORKLOAD** ........................................................................... 33  
   4.6. **FROM WORKLOAD TO SAFETY** .................................................................................... 35  
   4.7. **DISCUSSION** .................................................................................................................. 39  
5. **WICKENS’ MULTIPLE-RESOURCES THEORY (FLIGHT MANAGEMENT WORKLOAD)** ........ 41  
   5.1. **INTRODUCTION** .............................................................................................................. 42  
   5.2. **THE RESOURCE METAPHOR** ....................................................................................... 42  
       5.2.1. **The Single Resource Theory** ..................................................................................... 42  
       5.2.2. **Time-Sharing** .......................................................................................................... 44  
       5.2.3. **The Multiple-Resource Theory** ............................................................................... 46  
       5.2.4. **Discussion** .............................................................................................................. 47  
   5.3. **WORKLOAD ASSESSMENT TECHNIQUES** ................................................................... 48  
       5.3.1. **Empirical Workload Assessment** ................................................................................ 48  
       5.3.2. **Analytical Workload Assessment** .............................................................................. 51  
   5.4. **THE PROPOSED FLIGHT MANAGEMENT WORKLOAD ASSESSMENT TECHNIQUE** .... 54  
   5.5. **DISCUSSION** .................................................................................................................. 56
Introduction
On the 7th of May 1998 Amsterdam Airport Schiphol was placed on the black star list of the International Federation of Air Line Pilot's Associations, more commonly known as IFALPA. This list consists of airports with suspected safety deficiencies. According to IFALPA, one of the official reasons of Schiphol appearing on this list is that the allocation of runways is primarily based on reducing noise loads for surrounding urban areas.

This was not the first time that Schiphol had to deal with such allegations. On Christmas Eve 1997, a Boeing 757 landed at the side of the runway at Schiphol. Air line pilots told the press that this aircraft should never have landed on that runway under the heavy crosswind of that time, and that the pilot should have been directed to a runway with a more favorable direction under those wind conditions.

Aircraft noise load is a subject of concern for Schiphol, and together with other companies and institutes they seek a solution to reduce this problem. Adjustments to the operational flight procedures of Schiphol were proposed resulting in a reduction of the noise load contours. But before the implementation of these procedures could take place the civil aviation authority demanded a "proof of safety".

This is where the first problem pops up. Aviation safety is barely quantifiable, it is the result of an enormous amount of factors in a highly complex system. Until now the 'aviation safety level' was monitored with the calculation of risk, which can be calculated reasonably good and quite easy, compared to the quantification of the ambiguous safety level itself.

This report presents an exploratory study on a potential quantification method of the operational safety of flight procedures. A first design of such a quantification method is presented based on the limitations of the pilot as a human being.

From this point of view it is very promising to look at the relationship between pilot workload and safety, but here the second problem arises, because pilot workload is a very vague term. If safety is to be quantified using a pilot workload quantification technique as a basis, the vagueness around workload should be eliminated. An attempt will be made by laying down the first steps towards a model for pilot workload assessment.

The next chapter of this report presents an overview of aviation safety in general, concentrating on the ever increasing need for new safety improvements and the place of this report in the framework of aviation safety research. This chapter also contains a brief discussion on the problems that arise from the quantification of safety.

Safety of flight procedures is the subject of chapter 3. First the approach procedures will be defined, i.e., the reference procedure and the proposed adjustments to this procedure for noise load reductions. Secondly, the background of this study is presented in a more detailed fashion, after which a summation of potential safety assessment techniques for flight procedures is presented.

Chapter 4 presents the author's ideas on the quantification of airport safety as the big picture of this study, based on the quantification of pilot workload. From then on, a further zoom is made into the human factors field of research, concentrating on establishing a well-defined model of the pilot task, making a distinction between flight management, manual control, scanning & monitoring, and ATC-related tasks. Subsequently, pilot workload will be introduced officially and the problems of its definition shall be discussed briefly. After that,
the basic ideas behind the relationship between pilot task, pilot workload and operational safety are discussed in an extensive discussion.

In chapter 5 a workload assessment technique for the flight management task of the pilot is proposed, by using the resource metaphor from the psychology field of workload research. First the theories behind the resource metaphor shall be explained extensively, before an encapsulated summation of empirical and analytical workload assessment techniques is presented. These techniques are then used in the design of a flight management task workload assessment technique.

Chapter 6 contains the description of a workload assessment technique for the manual control task. The theories behind this technique, originated from the field helicopter flying qualities research, will be discussed, after which an attempt is made to translate this theory to fixed-wing aircraft. This is followed by the description of a computer simulation program called ASINOP, Approach Simulation and Noise Program, that was used for the calculation of the manual control workload of the different approach procedures. The results of this experiment are then presented, right after a more detailed explanation of the calculation method that was used to arrive at these results.

Two engineering pilots of the KLM Royal Dutch Airlines gave the author the opportunity to validate the workload predictions with the use of simulator data. To a certain extent a validation could be made. The results are presented in chapter 7.

Finally, chapter 8 will finish with a summation of the conclusions and recommendations of this report.
2.1. Introduction
2.2. The Need for Aviation Safety Improvements
2.3. Quantification of Aviation Safety
2.1. Introduction

Since the beginning of the commercial jet age, aviation industry has developed a large amount of complex systems and procedures, often as a result of bitter experience, to ensure the operational safety. Many of the changes have resulted from the meticulous investigation of aircraft accidents and incidents. As a result, aviation has long been, and continues to be, the leader in the field of transportation safety. Most of the lessons learned can be used in the other modes of transportation: road, railroad, marine, underground, and hazardous materials transport. There is even exchange of safety knowledge between the fields of aviation safety and medicine.

But what do we mean by safety? According to ref. 18, the description of safety can take different shapes:

- the safety at a specific place (the risk);
- a safe feeling, certainty (the experience with safety);
- protection against deliberate, unsafe actions (security);
- regulation and supervision in search for safety deficiencies (administration and inspection).

The intuitive component of safety is very important. The fact that people feel unsafe can be enough to label a situation as unsafe. Safety as such is not or hardly quantifiable, but the qualitative side can be assessed reasonably well.

This next section treats aviation safety in general, the ever increasing need for new safety improvements, and sets the general framework of aviation safety research. The last section explains the quantification of aviation safety, and presents a quick overview of other aspects of this subject.

2.2. The Need for Aviation Safety Improvements

An aircraft accident usually results in a large number of fatalities. Highly sensational photographs are then spread over the entire world, giving the impression that flying is dangerous. Nevertheless, flying is one of the safest means of transportation. Every week more people are killed worldwide in road accidents than the total number of aircraft accident fatalities in one year.

The public only sees the accidents and incidents that occur. In other words they are confronted with the media attention of the unsafe side of aviation safety. Although this report is about the safe side, or the prevention of accidents and incidents, it is nevertheless necessary to introduce aviation safety with the use of the more familiar unsafe side of safety.

First some proper definitions should be given. An aircraft accident is defined as an unsafe occurrence with an aircraft in operation with at least one fatality, or with the aircraft substantially damaged. An aircraft incident should be interpreted as all unsafe occurrences with an aircraft in operation that are not an accident.

Aviation safety uses a variety of mainly statistical parameters, giving an indication of the 'aviation safety level'. For example: the number of crashes per flight hour, the percentage of accidents that happened during the final approach phase, the number of crashes per million departures, the number of fatalities per million departures, or the absolute number of crashes per year. According to these parameters there is still a lot of work to be done,
before it can be said that air travel equals a safe way of future transport. This can be explained using figures 2.1 and 2.2.

![Figure 2.0.1: Accident rate. (Source: Ref. 22)](image)

This figure shows a steep decline in the number of accidents per million departures, simply named the accident rate, between 1960 - 1970, leveling out to a more or less constant rate. However, this constant safety level has been reached two decades ago and safety now remains stable in a long term plateau. It is often argued that with a stable accident rate and the prediction that air traffic will grow to twice its present size by 2010 - 2015, the total number of accidents will double to approximately 50 accidents per year, see figure 2.2. Public reactions, already sensitive to the absolute number of aircraft accidents, could rapidly require safety improvements.

![Figure 2.0.2: The need for safety improvements. (Source: Ref. 22)](image)

The situation could also worsen because of the future economical climate. On the one side, better cost-effectiveness and efficiency are required to survive in an extremely competitive environment. On the other hand, the deregulation process associated with these

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1 Only accidents resulting in hull loss were used for this statistical survey. Hull losses are accidents where the accident aircraft is declared total loss.
economical challenges has a high probability of introducing new safety hazards, which are not so easily recognized. The airline Valujet is an extreme example of this, the company had three major accidents within a short time. The U.S. National Transportation Safety Board concluded that these three accidents could all be associated with a sluggish compliance on the airline-management level to the FAA-regulations.

Maybe it is not possible to further improve the accident rate. In any case it is not certain, because no other highly technical transportation system has reached a better level. But there is no doubt that the present safety level can and may not worsen. This is known as the 'Stand-Still Philosophy'. Even this last objective seems an immense challenge for all the parties in the aviation community and will ask for innovative concepts.

It is the author's opinion that on this line of reasoning the general target of aviation safety research can be set as follows: the continuing search for safety improvements in all areas of the aviation community, in order to lower the absolute number of aircraft accidents.

There are two kinds of safety research:
- reactive research, investigating accidents and incidents after they occur, and;
- proactive research, concerned with the prevention of air 'unsafety' occurrences.

Nowadays all accidents and incidents are thoroughly investigated by the appointed authorities, but these organizations are also getting more and more proactive, trying to find the safety deficiencies in the aviation system before these deficiencies find them.

The study described in this report is a proactive one, and treats pilot workload theoretically during a flight procedure as part of flight safety. The validation of proactive studies can be problematic, because there is no 100% certainty that the study improves safety or introduces new safety hazards.

A well-known distinction within the aviation safety community is the difference between internal and external safety. Internal safety stands for the risk of the crew and passengers on board of the aircraft. In other words, it stands for the possibility that something goes wrong with the operating aircraft and its payload. External safety is the term used for the possibility that an aircraft accident can result in third party fatalities. A major investigation of the external safety of AAS can be found in ref. 7.

2.3. Quantification of Aviation Safety

Numerous technical branches in industry have the wish to make safety in general more visible and quantifiable for reasons such as insurance, risk calculation, or determination of the consequences resulting from different accident scenarios. Some of these companies or institutes have already developed calculation methods, for example in the petrochemical industry or the transport of dangerous goods. Some of these methods are already used by regulatory bodies and insurance companies. For example, a standard calculation-method for quantification of safety at technical installations situated in or nearby urban areas, such as an ammunition factory, an oil refinery, or a chemicals depot, is written down in European legislation.

However, in the aviation industry no unambiguous calculation-method has been developed to assess safety in such a way, that the results are 100% comparable with the results of the same processes in for example other locations or with different airplanes. Some examples: a flight safety assessment of a Boeing 747-300 compared to a 747-400 or a Fokker 100; a general aviation safety assessment of one country compared to other countries; or an
operational safety assessment of the take-off and landing procedures in the often busy airspace around Amsterdam Airport Schiphol compared to the even busier airspace at John F. Kennedy Airport in New York.

All these examples have four problems:

1. They play in an area where *multiple disciplines* act together, and it seems almost impossible to include all of these disciplines in a calculation-method.

2. The predictive assessment of safety is based on a highly *theoretical* description of a very turbulent and unpredictable process.

3. The product of the predictive safety assessment should be *validated* before application. The problem is that there is no practiced method for the validation of safety.

4. A lot of *skepticism* shall originate, because of the extremely conservative nature of the aviation community, and the fact that the effects of proactive research on safety are often not directly visible.

In recognition of these problems, it is clear that every attempt to quantify safety shall receive a lot of criticism on the assumptions that are made, the unpredictability of safety and its contributing factors, and the inability to validate.

One institute excels in proactive aviation safety research. This institute is BASI, the Bureau of Air Safety Investigations from Australia. They are one of the first who started with the quantification problem of safety, and asked themselves how they could measure the effects of the introduction of new safety regulations. They came up with the idea known as the 'Aviation Safety Indicators' (ref. 3), giving 22 indicators which provide a broad view of the national aviation system and its operation. At a later date the program INDICATE (ref. 9) was launched and tested. In this program the safety of an airline is tested on a managerial level with the aim directed towards finding out the gaps in safety defenses.

The work of BASI intrigued the Dutch government. The Dutch Aviation Authority, the RLD, plans to implement the aviation indicators for the Netherlands in order to design a preliminary measurement method of the aviation safety level.
3

Safety of Flight Procedures

3.1. Introduction
3.2. The Reference Final Approach Procedure
3.3. The Proposed TOMS Approach Procedure Adjustments
3.4. The 'Safety Proof'
3.5. Operational Safety Assessment of Flight Procedures
3.1. Introduction

The enormous growth in civilian air travel is a problem most airports have to deal with. These problems are not only in terms of airport facilities and capacity, but with the higher level of environmental consciousness of the people, also in terms of environmental issues. Two of these environmental issues receive a lot of attention, namely the emission of exhaust gases and aircraft noise emission.

The nuisance of aircraft noise emission is a subject of ever increasing importance since the public has accepted air travel as a 'normal' and efficient means of transportation. The amount of complaints on aircraft noise levels from people living in the residential areas around an airport is at this moment the most important parameter to 'measure' the nuisance. Figure 3.1 shows the number of complaints in the years 1982 to 1996 of Amsterdam Airport Schiphol.

There is no specific reason for the enormous increase in complaints since 1990, as the number of people living within the 35 Ke-contour remained approximately the same. There is much to say that this parameter reflects the public reaction on the planned growth of AAS. However, it does not matter for what reason people are complaining about, the large number of complaints is real, and something has to be done about it.

Another problem for AAS is that the number of aircraft movements is limited by the Dutch Parliament, which is a result of the enormous amount of complaints. In the first year that these limits were imposed on AAS, they were exceeded and from that moment on the aircraft noise problem became a national problem, which received an enormous amount of media attention.

A lot of work is and has been done to find a consensus for this problem. One of the studies, which was started by AAS and the Royal Dutch Airlines (KLM), is TOMS, or Technical Operational Measures Schiphol. One of the goals of this project was to look into the possibilities of reducing the aircraft noise emission as a result of adjustments to the dictated flight procedures for arrival and departure. The most promising adjustments were used in noise load calculations (ref. 10).

This chapter provides the basis of the study described in this report. First of all a description of the present approach procedure is given, which shall be used as a reference procedure.

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2 The Ke-contour stands for the noise load contours around AAS, calculated by the Kosten-eenheid (Ke).
Secondly a selection of the proposed TOMS-adjustments to this reference procedure is presented. These procedures are used for the first step in quantifying the operational safety of flight procedures, so a profound definition is quite useful. The third section treats the actual reason behind this study, the demand of safety proof by the civil aviation authorities.

### 3.2. The Reference Final Approach Procedure

The aircraft used in this study is the Boeing 747-400 with a Landing Weight of 240,000 kg. The choice for this aircraft was made at the beginning of the thesis assignment, and was justified by the possibility of a simulator session in a B747-400 simulator, which eventually took place at the end of the thesis. The Landing Weight of 240,000 kg is the same as used in the calculations for the noise contour plots for the B747-400 (ref. 10).

In this report the standard final approach procedure will be used as the reference procedure to which all results shall be compared. Figure 3.2 shows this procedure for the Boeing 747-400 in a three-dimensional plot.

![Figure 3.2: The reference final approach procedure for the Boeing 747-400.](image)

Although the study presented in this report only treats the final, two-dimensional part of this procedure, this figure shows the 3D-final approach procedure to give the reader a better understanding of the boundaries made in this study. The information for this procedure was extracted from ref. 1, in which a description was given of this standard KLM-procedure.

The aircraft starts at a point 2 km sideways of the runway threshold at 3000 ft altitude with a flap setting of 5 degrees and gear up, flying in the opposite direction of the runway with a speed of 180 knots. This is the downwind leg. From that point the aircraft descends to an altitude of 2000 ft and decelerates to 160 knots. During the turn to final with a radius of
approximately 1 to 2 km at circa 19 km from the runway threshold, the ILS-Localizer is intercepted and a flap setting of ten degrees is selected.

At the end of the 180 degrees turn the aircraft is flying aligned with the centerline of the runway at a constant altitude of 2000 ft. When the moment of Glide Slope (GS) interception is near, and the ILS-GS-pointer reads ‘one dot up’ a flap setting of 20 degrees is selected and the airplane should be decelerated to 150 knots. Upon GS-interception the aircraft must follow the glide slope of the ILS and Gear Down (GD) is selected, which produces just enough extra drag to adjust the airplane to a descent with a 3 degrees approach angle. When gear is down, the landing flaps are selected (30 degrees) and the aircraft must be decelerated to the reference speed $V_{REF} = 140$ knots. Touchdown takes place at a short distance after flying over the runway threshold.

The reference speed $V_{REF}$ equals 1.23 $V_{Stall}$ (1g) and is derived from table 3.1 from the KLM Aircraft Operations Manual (ref. 1), and the maneuvering speeds $V_{MAN}$ as indicated by the flap speed marks on the speed scale are derived from table 3.2 also from ref. 1.

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<thead>
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<th>Landing Weight (x 1000 kg)</th>
<th>$V_{REF 25}$</th>
<th>$V_{REF 30}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>132</td>
<td>127</td>
</tr>
<tr>
<td>210</td>
<td>135</td>
<td>130</td>
</tr>
<tr>
<td>220</td>
<td>139</td>
<td>133</td>
</tr>
<tr>
<td>230</td>
<td>142</td>
<td>137</td>
</tr>
<tr>
<td>240</td>
<td>146</td>
<td>140</td>
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<tr>
<td>250</td>
<td>149</td>
<td>143</td>
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<tr>
<td>260</td>
<td>152</td>
<td>146</td>
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<tr>
<td>270</td>
<td>155</td>
<td>149</td>
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<tr>
<td>280</td>
<td>158</td>
<td>152</td>
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<tr>
<td>290</td>
<td>161</td>
<td>155</td>
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<tr>
<td>300</td>
<td>164</td>
<td>157</td>
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<td>310</td>
<td>167</td>
<td>160</td>
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<td>320</td>
<td>170</td>
<td>163</td>
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<td>330</td>
<td>173</td>
<td>166</td>
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<tr>
<td>340</td>
<td>176</td>
<td>168</td>
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<tr>
<td>350</td>
<td>178</td>
<td>171</td>
</tr>
<tr>
<td>360</td>
<td>181</td>
<td>174</td>
</tr>
<tr>
<td>370</td>
<td>184</td>
<td>177</td>
</tr>
<tr>
<td>380</td>
<td>187</td>
<td>179</td>
</tr>
</tbody>
</table>

Table 3.1: $V_{REF}$ as a function of the Landing Weight. (Source: ref. 1)

<table>
<thead>
<tr>
<th>Flap Setting</th>
<th>Flap Speed Marks. $V_{REF 25}$ selected</th>
<th>$V_{MAN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP</td>
<td>UP</td>
<td>$V_{REF 25} + 80$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$V_{REF 25} + 60$</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>$V_{REF 25} + 40$</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>$V_{REF 25} + 20$</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>$V_{REF 25} + 10$</td>
</tr>
<tr>
<td>25</td>
<td>REF</td>
<td>$V_{REF}$</td>
</tr>
</tbody>
</table>

Table 3.2: Maneuvering speeds at different flap settings. (Source: ref. 1)
With the definition of the reference approach procedure for the Boeing 747-400 we are now ready to look further into the proposed TOMS-adjustments to this procedure. It should be noted that when the word aircraft or airplane is used, actually the B747-400 is meant. Other aircraft have different procedures and should be treated differently.

The approach procedures described in the next section shall be compared to the reference procedure. The choice for the "2000 ft, 3°, normal flaps & gear"-procedure as the reference procedure was made with the knowledge that this is the most common procedure.

3.3. The Proposed TOMS Approach Procedure Adjustments

The product of TOMS is a set of recommendations about possible noise reduction techniques. The recommendations can be divided into three different fields:

- proposed adjustments on approach procedures;
- proposed adjustments on departure procedures, and;
- a study on the use of runways in combination with noise load contours calculations.

The study in this report considers only the proposed adjustments made on the approach procedures:

1. Approach altitude from 2000 to 3000 ft.
2. Reduced flap setting and delayed gear down.
3. Steeper approach angle.
4. Combination of measures.
5. The present KLM-Approach procedure.

These adjustments are now described more in detail:
1. Approach altitude from 2000 to 3000 ft.

In the current standard procedure aircraft fly 'horizontally' at an altitude of 2000 ft towards the ILS-GS-interception point during daytime. By night this approach altitude is already set at 3000 ft. The proposed adjustment is to set the approach altitude to 3000 ft also during daytime hours. This higher trajectory is graphically depicted in figure 3.3.

*Figure 3.3: Procedure with ILS-intercept altitude at 3000 ft.*
2. Reduced flap setting and delayed gear down.

Figure 3.4 contains a picture of the approach procedure with reduced flap setting and delayed gear down. The B747-400 is certified to land with a reduced flap setting of 25 degrees instead of 30 degrees, resulting in a considerable drag reduction during the approach phase. This means that the engines can be set at a lower thrust level, resulting in a noise emission reduction. As can be seen, the only difference with the reference procedure is that after gear down a flap setting of 25 degrees is chosen instead of 30 degrees.

In the reference procedure the command for GD is given at the interception of the Glide Slope signal of the ILS, and the extra drag is used to slow down and position the airplane on the glide slope trajectory. With delayed gear down this action is performed when the aircraft flies over the Outer Marker (OM) at 1200 ft on the glide slope, and again, the drag reduction results in a noise emission reduction.

Figure 3.4: Procedure with reduced flaps and delayed gear down.
3. Steeper approach angle.

Another measure that results in a higher approach trajectory was found in a steeper approach angle, see figure 3.5. At almost every airport in the world, this approach angle is set at 3 degrees within the metric of the ILS. As can be seen further on in this report, steeper approach angles are theoretically a very interesting subject with respect to the operational safety, because the same things happen in less time, at a faster pace. However, there is a practical limit to this measure: the Flight Management System of the B747-400 is only certified to land at a maximum approach angle of 3.25 degrees. A further increase in the approach angle will require a separate certification of aircraft types and airports, and therefore this measure is not really an option. Nevertheless, for the sake of visualization, approach angles larger than 3.25 degrees shall be used in the theoretical experiment performed in this study.

![Diagram of approach angles](image)

Figure 3.5: Procedure with different ILS Glide Slope angles.
4. Combination of measures.

It is also possible to fly an approach procedure with a combination of the measures described above. Figure 3.6 gives an impression of the flight path of such a procedure with an approach altitude of 3000 ft, an approach angle of 3.25 degrees, and delayed gear down:

![Graph showing the comparison between the reference and the combined procedure.](image)

*Figure 3.6: Comparison between the reference and the combined procedure.*
5. The Present KLM-Approach procedure.

By January 1998 the KLM implemented a new approach procedure for the B747-400. This procedure shows a lot of resemblance with some of the TOMS adjustments (see figure 3.7). It has reduced flaps as well as delayed flaps, but gear is lowered upon GS-interception. This means that landing flaps of 25 degrees are selected when the aircraft flies over the OM instead of the moment after gear down.

![Diagram showing KLM-Approach procedure](image)

Figure 3.6: The KLM-procedure.

The noise reduction calculations of the TOMS-adjusted procedures are described in ref. 10 and shall not be mentioned here. All that is said about the link between noise emission and approach procedures is that we can intuitively 'feel' that less noise reaches urban areas on the ground when:

1. the aircraft approaches on a higher trajectory, and;
2. drag is reduced, resulting in lower engine settings, with lower noise emission.
The differences between the two-dimensional GS-interception characteristics of all of the described procedures are summarized in table 3.3.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Approach Altitude (ft)</th>
<th>ILS-path angle (deg)</th>
<th>Gear Down</th>
<th>Landing Flaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>2000</td>
<td>3</td>
<td>on GS-intercept</td>
<td>30, when gear = down</td>
</tr>
<tr>
<td>3000 ft appr. alt.</td>
<td>3000</td>
<td>3</td>
<td>on GS-intercept</td>
<td>30, when gear = down</td>
</tr>
<tr>
<td>Reduced flaps delayed gear</td>
<td>2000</td>
<td>3</td>
<td>on OM</td>
<td>25, when gear = down</td>
</tr>
<tr>
<td>Steeper</td>
<td>2000</td>
<td>3.25</td>
<td>on GS-intercept</td>
<td>30, when gear = down</td>
</tr>
<tr>
<td>Combination</td>
<td>3000</td>
<td>3.25</td>
<td>on OM</td>
<td>25, when gear = down</td>
</tr>
<tr>
<td>KLM-Procedure</td>
<td>2000</td>
<td>3</td>
<td>on GS-intercept</td>
<td>25, on OM</td>
</tr>
</tbody>
</table>

Table 3.3: A summary of the differences between the two-dimensional final approach phase characteristics of approach procedures.

3.4. The 'Safety Proof'

The primary function of the TOMS-recommendations is to seek possible aircraft noise emission reductions with operational measures. Aviation safety was not the main objective in this project. However, the RLD demanded proof that the adjusted procedures were safer than or at least as safe as the present procedure. The question is how this proof can be given.

The first answer to this question is to look at the present approach procedure, and find out how this procedure received its 'safety proof'. The conclusion should be that this proof was given because of the many years of experience with the procedure.

Nowadays it is not desirable to postpone the acquisition of the 'safety proof' until the operational phase of a flight procedure. It is clear that again the proactive nature of the present aviation safety research should be used to obtain this 'safety proof'. Some of the methods that can be used to obtain some kind of safety proof are described in the next section.

3.5. Operational Safety Assessment of Flight Procedures

Operational safety should be interpreted as the internal safety, or the safety of the airplane with its crew and passengers (or cargo), while flying a well-defined procedure. The consequences of an accident or incident for third party people or properties are not taken into account, this is called external safety. The main question within an operational safety assessment is: "When and why are the crew's and passengers' safety or the safety of the aircraft at risk?".
Numerous techniques have been or are still being designed to obtain a prediction of certain aviation safety aspects. The most promising techniques for the assessment of operational safety of flight procedures around an airport, can be summed as follows:

1. Statistical parameters.
2. Interviews and brainstorm sessions with pilots and experts
3. Simulations.
5. Handling Qualities.

A more profound description of these safety assessment techniques is given below:

**1. Statistical parameters.**

With the use of statistical parameters it could be possible to introduce a set of safety indicators. These indicators should be calculated yearly and will then represent the safety level. Ref. 3 gives a preliminary concept on these parameters. Some of these safety indicators are given below:

*Flying Activity Indicators:*
- The average hours flown by the pilots, who attempt a landing at the airport.
- The average number of times that the pilot flew a specific procedure.

*Aviation Industry Indicators:*
- Total number of aircraft landings at the airport.
- Load factor percentage.
- Number of different pilots landing at the airport.
- Number of pilots landing for the first time during that year at the airport.
- Number of Licensed Aircraft Maintenance Engineers working at the airport.

*Accident Indicators:*
- Total number of accidents at the airport.
- The Accident Rate of the airport.

*Incident Indicators:*
- Number of reported Violations of Controlled Airspace.
- Number of reported Runway Incursions Incidents.
- Number of reported Loss of Separation Standards.

This list of possible statistical safety indicators is far from complete, but is mentioned here just to give the reader an impression of a technique that can be used to tackle the problem statistically.

The use of statistical parameters should not take place without some restraints. One accident for example, can give an abnormal high fatality rate for the year in which the accident occurred, while in all other years the fatality rate was nearly zero. Caution should be applied if one tries to draw conclusions from the statistical safety indicators.

**2. Interviews and brainstorm sessions with pilots and experts.**

This method is a subjective and qualitative technique to identify the possible difficulties in the design of a new flight procedure. Brain storm sessions are to be held with highly experienced pilots and experts on all different fields in the aviation world, such as ATC, human factors, environmental issues, certification, aircraft performance, etc. During the session they all give their opinion on the proposed changes to the flight procedure. It is important that this session is structured according to some kind of brain storm technique.
The product is a list of advantages and disadvantages, which can then be used in the decision for further investigation in the operational measure.

3. Simulations.

The flight procedures around an airport can be simulated with the use of a computer program. After identification of certain safety parameters such as the vertical speed at touchdown, or the lateral deviation of the dictated flight path, the model could then be randomized with the use of statistical distribution functions. The randomized simulation program should then be run a large number of times, saving the data of the safety parameters. The result is a theoretical distribution of the safety parameters, indicating a certain safety level.

This technique uses a so-called 'Monte Carlo'-simulation and is only as accurate as can be built into the software program. A validation with real data from the airport under study is necessary in order to say anything about the use of this technique. An example of this technique is presented in ref. 6.

4. Workload Assessment.

As we shall see in later chapters, it is possible to assess pilot workload using empirical or analytical prediction techniques. Using workload assessment techniques, the bottlenecks in pilot performance can be identified. At every time-step the pilot workload is predicted, resulting in a workload-profile versus time. Whenever the workload nears or exceeds the maximum workload a potential hazardous situation can originate, because the pilot is very liable to make errors in such an 'overload condition'. More important, when workload is high, but does not result in an overload condition, it is thought that the pilot has a reduced capability to react to random technical failures, sudden unfavorable environmental conditions, ATC-instructions, etc.

A much more elaborate description of this theory and the usable workload assessment techniques is given in chapters 4 and 5.

5. Handling Qualities.

Handling qualities, also called flying qualities, can be measured with the use of Subjective Rating Scales. The pilot judges the quality of the pilot-aircraft system handling during a well-defined flight procedure according to a structured decision-scale. Refs. 8 and 17 present studies of the use of these handling qualities for safety quantification purposes. In this reference a data-set of pilot handling quality ratings is gathered and analyzed statistically. The product of this assessment technique is the probability of Loss-Of-Control.

Another method which uses handling qualities as an indication of flight safety is presented in ref. 18. The method described in this reference is not designed for the quantification of safety, but for the quantification of pilot workload. However, if a relationship can be found between pilot workload and flight safety, a technique can be designed to quantify flight safety with the use of handling qualities. A more detailed description of this technique can be found in chapter 6, and a description of the relationship between workload and safety is contained in the next chapter.

All of these safety assessment techniques can be used for a specific safety problem, and will result in valuable information on possible underlying safety deficiencies. However, if the safety quantification problem is to be dealt with in a bigger picture (for example the entire multi-disciplinary field), it is the author's opinion that eventually a combination of these techniques should be adopted.
4
Basic Proposal of the Pilot Workload Index

4.1. Introduction
4.2. The Airport Safety Index
4.3. The Pilot Task
4.4. The Definition and Use of Pilot Workload
   4.4.1. Defining Pilot Workload
   4.4.2. Using Workload
4.5. From Pilot Task to Workload
4.6. From Workload to Safety
4.7. Discussion
4.1. Introduction

This chapter contains the basic framework of the proposed workload metric, the Pilot Workload Index. However, this cannot be done without a proper introduction on a more complete view of the position of the workload index in a bigger picture, which is the desired quantification of the operational safety at an airport. This chapter functions as a link to every aspect of this final thesis assignment.

The author's ideas on an overall Airport Safety Index will be presented in the next section. The calculation method of this safety index shall be aimed at a model of the operational safety with the human factor at the basis of a proposed calculation method. Numerous assumptions have to be made in order to comply to most of the uncertainties concerning safety and human performance.

A safety index can be compared to the theoretical predictive calculation of noise load around airports. In such calculation methods certain assumptions are made to get around the unpredictable processes that can take place, such as deviations from the ideal flight paths (assumed as a normal distribution) and actual altitude-profiles (taken as a fixed profile).

However, the product of a safety index differs from such theoretical noise load calculation methods. A reference situation should be set to 100%, and proposed advancements can be calculated in the same way and then compared to this reference situation. For example, the data on the situation of Amsterdam Airport Schiphol in 1997 can be taken as the reference situation, and the situation of another year will show an increase or a decline of the index with respect to the reference year.

The basis of which the safety index is a proposal for a human performance calculation technique, but before we can actually treat this subject some structure should be created in the diversity of all the tasks the pilot has to carry out to achieve her or his goal, which is a safe and efficient operation of the aircraft. Section 4.3 contains a description of the structured pilot task system.

The term pilot workload has been used without a proper introduction. Section 4.4 deals with the problem of definition and discusses the areas of importance for workload research.

Now we are ready to design the Pilot Workload Index, using different workload prediction techniques for the different sub-tasks of the pilot. This is described in section 4.5. However, one question remains unanswered: "How is workload connected to safety?". Section 4.6 presents the proposed concept to be used to set this connection. And finally, section 4.7 concludes with some remarks on the practicability of the Airport Safety Index and the Pilot Workload Index.

4.2. The Airport Safety Index

Reducing the quantification of aviation safety to a mere calculation is an almost impossible task. The main reasons for this are that there is no exactly defined boundary between safe and unsafe, and that the multi-disciplinary environment imposes an almost infinitive amount of different parameters that have a link with safety.

It is therefore of no surprise that every attempt to calculate safety leads to a highly incomplete calculation method with a large number of assumptions. The value of such
safety calculations in the real world is low, but can be used for comparison between almost similar situations. Furthermore a lot of criticism can be expected to originate from the conservative aviation community. Most of this criticism will contain remarks on the assumptions made, and will probably be correct. The comments made should be used for further improvements in the development of a predictive safety calculation method.

In recognition of these problems concerning the design of an 'Airport Safety Index' (ASI), the reconnaissance study in this section continues in a very broad way, before a more explored view is created further on in this chapter.

The first step in the design of an ASI is to set the main objective. Which is to satisfy the wishes of civil aviation authorities in their demand for a safety proof. But there is more to it. If an ASI indeed works as a safety quantification tool, it can be used to inform the public (including the paying passengers), to inform airline companies, or to perform a payoff-study into new safety-items or procedures.

The second step is to set up the design requirements. The most important one is that an ASI cannot represent an absolute safety quantification. With an ASI only relative safety quantification compared to a reference situation such as the present situation, given an index of 100%, is possible. The reason for this is the relative nature of safety, there is no absolute point of zero safety. Furthermore, since safety is mostly about the comparison of two different situations, therefore a relative index is a very well-known and useful solution in these kind of comparison problems.

Another design requirement of an ASI should be that the calculation method can be split up into contributions of all the different fields such as ATC, maintenance, airline management, etc. These contributions must be, if possible, calculated separately because the ASI must be used for all kinds of different situations compared to the reference airport situation. So, besides new approach and landing procedures, it must be possible to use the ASI also for a prediction of the effects of, for example, the implementation of a confidential incident reporting system, or the introduction of 'Tunnels-in-the-Sky' as an operational landing navigation service. It is a lot easier to calculate the ASI, if the concerned component of the total calculation method can be changed separately from all the other components. A systematic approach is very much needed in the disorderly amount of different aspects.

A calculation method of the ASI is a very theoretical representation of the real world. It is a model which relatively quantifies the relationship of the operational safety and the contributing factors. However, one important factor is left out, namely the unpredictability of certain factors, more commonly known as chaos. This factor on its own can disturb the reality value of the ASI. Further on in this chapter an example is presented of this chaos-problem within the Pilot Workload Index.

It is the author's opinion that a first set-up of the Airport Safety Index should be consistent with the diagram in figure 4.1.

All rectangles in this figure represent a contributing factor in the operational safety. A relationship between two factors is thought present when two rectangles overlap each other. Furthermore if a rectangle lies in the layer above another rectangle it means that the upper factor is more important for the operational safety than the lower one.

The pilot has the final operational responsibility, but must listen to the ATC-controller, hence the marked overlap. However, it is the pilot who makes the flight a safe flight, he or she has the final responsibility for the internal safety of the aircraft.

The pilot is the operator of the aircraft and has to comply to the regulations of the airline and government. The airline in its turn has to comply to the regulations of the airport and
government. ATC is also subject to government regulations. It should be clear that the government regulates all aspects of aviation, and has the final public responsibility of safe aviation. However, the Dutch government administers a supervisor-philosophy (ref. 16), which means that the aviation industry has the responsibility of the safe execution of flights according to governmental regulations. The supervisor-philosophy also means that governmental bodies only intervene in cases with suspected safety deficiencies. This passive role places government as a contributing factor of operational safety at a lesser degree of importance.

![Airport Safety Index](image)

*Figure 4.1: Diagram of the first set-up of the Airport Safety Index (ASI).*

On every level in the diagram of figure 4.1 people perform the job they are assigned to do, such as the pilot, the air traffic controller, the airline manager, the government inspector, the fuel-truck driver, etc. All these people contribute to the safety climate, and make decisions for safer and more efficient operations. However, people make mistakes by definition. This is where we enter the field of Human Factors (HF).

Human factors can be a very good starting-point in the overall design of a safety index. The major players in the field of HF are the pilot as the operator of the aircraft, and the air traffic controller as the surveyor of the aircraft operation.

If the workload of pilot and controller is known through time, it is possible to calculate the probability of the occurrence of overload conditions. It is thought that in such an overload condition the pilot or controller is no longer able to control the situation completely and he or she is extremely liable to make mistakes or when the pilot or controller nears the onset of an overload condition he or she is less capable to cope with unpredictable factors. This probability can be calculated for an approach and landing, or a take-off maneuver, within the framework of a very clear-cut calculation method.

This probability is calculated for a single approach and landing or take-off maneuver, depending on the aircraft-type and the atmospheric conditions. Factors should subsequently be added, giving penalties or rewards for matters such as:

Equipment of the **aircraft**, such as:
- GPWS, Ground Proximity Warning System
- windshear detection system
- two, three, or four engines
- flaps & slats
- air-brakes
- etc.
Factors concerning airline-data, such as:
- average skill and training-level of the pilots
- average number of flight hours on an aircraft-type per pilot
- the economic status of the company
- average skill and training-level of the maintenance engineers
- average salary of the pilots
- average age of the fleet
- etc.

Factors concerning airport-data, such as:
- equipped with ILS, in what category?
- equipped with MLS
- airport capacity
- etc.

Factors concerning ATC-data, such as:
- number of aircraft in holding
- the busyness of the Controlled Terminal Area
- redundancy of the radar equipment
- etc.

Factors concerning the government, such as:
- economical climate
- inspection strategy
- regulation philosophy of the aviation authorities
- Gross National Product (GNP)
- etc.

These factors are named here, just to give the reader an indication of the applied approach. The list is by no means complete. A more elaborate discussion about factors that play a role in aviation safety can be found, for example in ref. 21, where a relational database is developed based on airline timetables. This database consists of a huge amount of different factors that can play a role in safety.

Application of this calculation method for every approach and take-off maneuver that takes place in one year, and a summation of all the results, delivers the outcome of the ASI: the probability of the occurrence of an unsafe operation.

The first steps that should take place in the design of the ASI should be the addition of all the components to the basic framework as presented in this report. But not before a thorough evaluation of the calculation method itself is performed, giving an answer to the following question: "Is this the right way to tackle the problem of quantification of operational safety?". This evaluation should be carried out by a project group, consisting of experts in safety science, human factors, ATC, government regulations, aircraft operations, airport operations and aircraft engineering.

The remaining sections of this chapter contains a more in-depth view of the ASI, concentrating on the quantification of pilot workload.

### 4.3. The Pilot Task

Where does the mental workload of the pilot come from? This question is crucial in order to obtain an useful representation of the mental workload of a pilot. In this thesis, workload
shall be assumed to be directly related to pilot performance, which in its turn is a result of performing the pilot task, see figure 4.2.

First of all, some insight is needed in order to model the task of a pilot of a large commercial airliner. The Pilot Flying (PF) has the responsibility of the efficiency and safety of the flight. This is the pilot task in very general terms.

The Pilot-Not-Flying (PNF) checks the PF-performance and carries out specific tasks, such as the control of the flaps and the landing gear. This study assumes that the aircraft is flown by only one person, the PF, who carries out the pilot task. The reason behind this is twofold:

1. As a first step towards workload quantification it is desirable to keep the simplicity of the pilot task low in order to concentrate on the real problem, the quantification of workload/safety.

2. The boundary between the tasks carried out by the two pilots is quite vague. A solution for this problem can be found by means of a detailed investigation of pilots flying procedures for real or in a simulator, concentrating on the covert cognitive side of all tasks.

In order to say anything on the modeling of the pilot task, the system level has to be changed to a lower level, so a further zoom into the pilot task is needed to acquire a more detailed description.

On this lower system level the pilot carries out a large variety of different tasks, such as: flying the aircraft manually, controlling the Auto-Throttle or Auto-Pilot when the aircraft is not in manual control mode, talking to ATC, scanning for other traffic, attending the on-board systems, navigating, talking to and checking with the copilot, etc. It is not very practical to calculate the workload for every task separately, therefore some sort of structured model must be made first. According to refs. 11 and 23 a distinction can be made between discrete and continuous tasks.

Discrete tasks are tasks that are carried out at a certain time, with a specific time-length. Some examples: the calculation of the LW, receiving a clearance of ATC, selecting a new flap setting, doing the landing checklist, etc. All these tasks have a limited duration of time, and impose an extra workload on the pilot during that time-span.

Continuous tasks are, as the name already says, carried out continuously, and impose a 'full-time' workload on the pilot. For example: manually controlling the aircraft, scanning the flight instruments, monitoring the aircraft state, etc.

With this distinction in mind, a schematic division of the pilot task is created:

1. The Flight Management Task - This is the name for the collection of all the discrete tasks that have to be carried out during the procedure, except the discrete ATC-related tasks.

2. The Manual Control Task - Flying the procedure manually is a continuous task. Pilots must have the ability to fly the aircraft manually, therefore the control task is taken as a manually performed task. There is also much to say that flying the aircraft on A/P and/or A/T, or replacing the manual control task by an intensive continuous monitoring task, reduces workload. This is a less interesting situation as we are interested in overload
conditions. Anyway, pilots must have the ability to control the aircraft manually in case the A/P is out of order.

3. The Scanning & Monitoring Task - This is the task of the perception of information on the state of the aircraft. Scanning means the acquisition of data and understanding it, while monitoring stands for the guarding-function of the pilot with respect to the aircraft-state. This task is assumed to be continuously present.

4. The Air Traffic Control Task - All ATC-related tasks are considered in this category of tasks, including the obvious communication tasks with ATC and the less obvious tasks imposed by the consequences of ATC-dictated altitudes and speeds, different from the procedure prescribes. This shall be explained in section 4.5. The assumption is made that these tasks can be sub-divided in continuous and discrete tasks.

A combination of these four sub-tasks results in a structured task system, representing the pilot task as a whole (figure 4.3). The challenge now is to translate this structured task system into pilot workload.

![Diagram of the pilot workload calculation method, using a structured task system.](image)

Figure 4.3: Diagram of the pilot workload calculation method, using a structured task system.

4.4. The Definition and Use of Pilot Workload

Until now pilot workload was mentioned, without properly introducing its concept. It is imperative to understand what pilot workload actually means before using it. This section deals with the problem of defining workload, and should give the reader an impression of the role of workload modeling in aviation research.
4.4.1. DEFINING WORKLOAD

How can pilot workload be defined? There is no unambiguous answer to this question, in fact the simple fact of the matter is that nobody seems to know what workload really is. Numerous definitions have been proposed, and many of them seem complete and 'intuitively right'. But all of these definitions failed the test of widespread acceptance.

However, a very general definition, on which most people shall agree to, can be given as follows: ‘Workload is the amount of mental effort a human being has to deliver in order to perform a task.’ This is a very loose and flexible definition, therefore people can customize their own boundaries within the definition and shape it in the way they want to use it.

The philosophical considerations over the possible underlying concepts of workload are much more useful in explaining the workload concept, especially when the final product of these discussions should be an inflexible definition of workload. The four most important workload modeling concepts derived from these discussions, the corner-stones, are given below in order to give a more practical view on workload (ref. 12):

"I. Workload reflects relative, rather than absolute individual states. It depends on both the external demands and the internal capabilities of the individual. This relativity exists qualitatively as well as in dimensions of quantity and time.

II. Workload is not the same as the individual’s performance in the face of work or tasks, nor is it synonymous with our way of measuring performance.

III. Workload involves the depletion of internal resources to accomplish work. High workload depletes these resources faster than low workload.

IV. Individuals differ qualitatively and quantitatively in their response to workload. There are several different kinds of task demands and corresponding internal capabilities and capacities to handle these demands. Persons differ in the amount of these capabilities which they possess, and their strategies for employing them."

With these four corner-stones mentioned and the acknowledgment of the 'vague' nature of workload, the problem of definition shall further be ignored in this report. The focus in this report is obviously on the modeling of workload, and not on an universally acceptable definition.

4.4.2. USING WORKLOAD

The concept of pilot workload is used in different areas and its use is often similar to the identification of bottlenecks in the overall pilot performance. For example in the performance of the pilot who has a variety of tasks simultaneously imposed; the process or nuclear plant controller who is trying to diagnose a fault and is simultaneously deciding, remembering, and scanning to acquire for new information; or the automobile driver who is trying to drive safely while operating a radio or reading a road map.

An impression of the more official role of pilot workload is given in Appendix A. The sections of FAR 25 (Federal Aviation Regulations for Transport Category Airplanes) where pilot workload is mentioned, are presented in this appendix. These regulations are rather qualitative than quantitative, which means that they are quite 'vague'. Despite these vagueness both designers and operators of (cockpit-)systems realize that it is very
Pilot Workload & Operational Aircraft Safety

important to consider the mental demands a task imposes on the operator's limited resources.

The more practical use and importance of research on pilot workload can be divided in three different areas:

- An assessment of workload imposed by equipment may be made to identify those bottlenecks in system performance in which resource demands momentarily exceed supply and performance breaks down. Measuring the pay-off of cockpit automation is also part of this category of workload research.

- Workload assessment is also used in Crew Resource Management (CRM) as a powerful tool for the determination of cockpit procedures. It is also used in the decision on the division of the different tasks between the Pilot Flying (PF) and the Pilot Not-Flying (PNF). Operator differences such as skill and training can be indicated by performance output, and then related to pilot workload.

- The prediction of workload before the actual system or procedure exists. This is a theoretical way to predict the demand of pilot resources in a new cockpit design, or a new cockpit- or flight procedure. The benefits of such predictions are high, because it takes place during the design phase where changes are more easily made with lower costs. The study in this report falls under this field of workload research and is about the prediction of pilot workload during slightly adjusted landing procedures.

There are many studies, in which pilot workload plays a role, as a matter of fact almost every single case study is a different field of workload research, but it would be out of the scope of this report to present the reader with an overview of these studies.

From all the work that has been done in this field, it should be concluded that the majority of this work uses pilot workload as a qualitative tool, and quantitative use of it is quite rare. This conclusion is mentioned here so directly because of the quantitative use of pilot workload further on in this report.

4.5. From Pilot Task to Workload

The pilot task system as defined in section 4.3 must be translated into pilot workload. This section contains a description of the method used for every task workload separately. The first two task workloads, Flight Management and Manual Control Workload, are briefly introduced, but shall be thoroughly treated in chapter 5 and 6 respectively. The other two task workloads, Scanning & Monitoring and ATC Workload, are only described here in a limited fashion, because of the limited time of the final thesis project.

A method for the combination of the four task workloads should be designed, resulting in the Pilot Workload Index. This is only possible after a detailed explanation of the calculation methods presented in chapters 5 and 6.

Flight Management Workload

From the engineering psychology certain theories exist to demystify the things that happen in the human brain. These theories often portray more of a belief than a scientific theory. They represent an answer to questions such as: "How does a human being make a decision?" or "Which parts of the brain processes the commands for the execution of a task?". For the outsider, all the theories seem right in an intuitive way, but for the engineering psychology expert the details are subject to discussion.
However, there exists a lot of consensus on one of the theories on the effects of task execution on the limited human capacities, using a resource metaphor. With the use of this metaphor, a system is assumed according to which the task performance of the human being uses the available resources. This theory, proposed by C.D. Wickens in ref. 23 assumes the available resources as a multidimensional space from which tasks demand their resources. This can lead to a good coexistence of, or a certain interference between simultaneous tasks.

Chapter 5 is devoted to the description of the background theory and presents a proposal for a calculation technique for Flight Management Workload.

**Manual Control Workload**

Translation of the manual control task to workload is done by using the ideas of G.D. Padfield. In his textbook (ref. 18), the first steps are taken towards a calculation method for manual control workload of helicopter pilots flying a well-defined slalom-maneuver. Data of certain performance-parameters versus time are the input of the calculation technique. This data can be taken from real flight-data, flight simulator-data, or from output-data of a computer-simulation.

After transformation of this data from the time-domain to the frequency-domain, a measure for the applied energy can be created. The final product of the calculation technique is the total amount of energy applied during the flight maneuver, which represents the pilot workload. Chapter 6 covers a more detailed description of this calculation technique.

**Scanning and Monitoring Workload**

The calculation method for scanning and monitoring workload result from the previously described scanning and monitoring task. The execution of this task presents a source of arousal for new tasks within the entire task system. For example, the pilot finds that airspeed is a little bit high, corrections shall take place in the manual control task to reduce airspeed.

The assumption was made that the scanning and monitoring task is a continuous task. The basic fundamentals of this assumption lie in the fact that the pilot needs to possess an overall knowledge of the state of the aircraft and its environmental conditions at every point in time. The task consists basically of the scanning cycle of the pilot on the instruments in the cockpit, including the monitoring of other traffic.

A workload model of this task can be derived from the technique as described for the flight management task. The only difference is that we are dealing with a continuous task consisting of mainly cognitive actions. It is the author’s opinion that in a first set-up of the pilot workload index the scanning and monitoring task should be modeled as an underlying task, with a constant demand of available resources.

More insight in the cognitive side of this task is needed in order to give a better calculation technique. This knowledge should be obtained in a detailed investigation in the task system and its covert cognitive side.

**Air Traffic Control Workload**

This task workload consists of the more problematic side of the execution of a landing procedure. Without ATC-intervention, a single aircraft would fly the landing and approach procedure exactly as is ideally dictated in the concerned documents. ATC is the primary cause of the fact that this does not happen. The ATC-controllers are responsible for the safe operation of aircraft with respect to other aircraft and as such they tell the pilot to deviate from the ideal flight path procedure, for example to maintain separation minima.
The workload modeling of the ATC-related tasks leads to two different components, a continuous and a discrete task workload. The continuous task is a result of the listening task. A pilot listens constantly to the ATC-frequency and is triggered if the identifier of the aircraft is mentioned. This task is more a part of the scanning and monitoring task, but because of the unpredictability of the exact time when the aircraft identifier is mentioned, it is grouped under the ATC-task.

The second component of the ATC-related tasks are the discrete ones, such as the communication with the tower, asking for or receiving a clearance. Regularly, pilots are asked to fly at a higher speed or altitude to a specific point in the airspace, thus deviating from the ideal flight path. The task system is structured with respect to a distinct flight procedure, so when ATC asks to deviate from this procedure, tasks will become different from the modeled task system. For example, task times and task intensities for the flight management task will change, and manual control of the aircraft takes place along a new desired flight path.

Obviously the main characteristic of the ATC-related tasks is the unpredictability of these tasks, resulting in a unique task system for every single approach and landing procedure. The problem with these tasks is that the other tasks in the task system are also affected, and an entirely different procedure is created.

In order to model this problematic task into the task system the assumption must be made that workload from ATC results from the following two tasks:

- The continuous listening task to the ATC-frequency.
- Receiving ATC-clearances at certain pre-determined times in the procedure, derived from a very close investigation into the unpredictability of ATC-tasks.

In the future it should be possible to introduce randomizing functions for the ATC-dictated flight path to approximate the unpredictability. But in order to do that a further investigation into these dictated flight-paths should be performed, giving an answer to the question if there are standard-decisions of flight-path deviations based on weather condition and air traffic situation.

Another possibility is to use fuzzy logic for this problem. According to an introduction course laid down in ref. 4 fuzzy logic is a logic that allows values to be defined between Boolean evaluations such as: true/false, yes/no, etc. Notions like rather warm or pretty cold can be formulated mathematically in the programming of computers. With fuzzy logic an attempt is made to apply a more human-like unpredictability in the programming of computers. Applications of fuzzy logic vary from controlling a subway system comfortably, safety improvements for nuclear reactors, cruise-control for cars, recognition of hand-written symbols with pocket computers, flight aid for helicopters, and many other studies.

In reference 4 it is stated that the employment of fuzzy logic is commendable for very complex (highly non-linear) processes, when there is no simple mathematical model. This is the case for the pilot workload index.

4.6. From Workload to Safety

An aircraft accident never happens because of one safety deficiency on its own, there are always more factors contributing to the most probable cause. However there is one contributing factor that comes up with almost every accident or incident, that is the 'Human
Factor'. Note that this term is very broad, and includes every possible human action or judgment that played a role in the accident.

According to the statistical surveys the percentage of accidents where the human factor contributed to the probable cause lies between 70 and 80%. This does not mean that all of these accidents were the result of human error. They are probably caused by a combination of human and system/aircraft error or adverse weather conditions, but it was the pilot who deservedly or undeservedly\(^3\) played a major role in the so-called causal accident chain.

From the accident investigator's viewpoint it is thought that system errors and unfavorable flying conditions can be taken care of by the crew, after all they are trained to deal with situations like that. When the crew did not succeed in dealing successfully with these situations the most probable cause is set on 'human or pilot error'. From a pilot's point of view it is not always fair to set an accident's probable cause to human error, because the roots of the so-called causal accident chain are often found within the technical equipment or adverse weather conditions. A further discussion on this subject is not relevant in this report, but a certain precaution should be used when using the percentage of accidents that are probably caused by pilot error.

With the notion of this two-sided view on the pilot error percentage, it is still tempting to state that the larger part of all accidents is caused by human misjudgment or wrong actions. It means that if it is possible to quantify the human performance, or the pilot workload, a gate towards quantification of safety is opened with respect to the 70 - 80% pilot error accidents.

In ref. 18 Padfield gives a description of a possible method for quantification of pilot manual control workload. This reference also contains a short overview about the link between workload and safety. The workload of a helicopter-pilot flying a well-defined maneuver, such as a slalom maneuver, is thought to be dependent of flying qualities parameters such as aircraft and task bandwidths, generally called the aircraft stability and task complexity. The bandwidth parameter, and the Padfield's workload metric will be discussed in more detail in chapter 6.

One step beyond Padfield's ideas a theory on the relationship between workload and safety originated at the Section of Performance Theory of the Department of Aerospace Engineering, Delft University of Technology. This theory is explained using figure 4.4:

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\(^3\) The question of blame is a legal issue, closely related to the pilot actions during the few minutes before the accident took place. Nevertheless, it is of no importance in safety research, only the questions what happened and why it happened are important.
Figure 4.4: The complexity of the task system versus pilot workload. The available margin acts as an indicator of the 'safety level'.

The complexity of the imposed task system results in the bottom line which represents the actual workload. From this line it can be seen that when task complexity increases, the workload imposed by the task system, increases in an exponential manner. The upper line represents the maximum possible workload that can be imposed at a certain complexity of the task system. This line is called the boundary of saturation. In the case that workload exceeds this line, the person is defined as 'overloaded'.

The boundary of saturation depends on a lot of different factors, such as the experience of the pilot, the level of training, crew resource management, physical condition and mental state of the pilot, etc. This line is not a constant, but should be thought of as a sort of flexible resource. The reason for this is that when the complexity of the task system is low, the vigilance or guard-function of the pilot is assumed to be low too.

Another way of explaining this figure is by the use of one of the many definitions of workload:

\[ PWL = \frac{T_R}{T_A} \]

with:
- \( PWL \) = Pilot Workload
- \( T_R \) = Time Required
- \( T_A \) = Time Available

If this ratio exceeds 1, the person is considered overloaded. The time required to perform a task is in this case equal to or more than the time available for the task. This is visualized by the boundary of saturation.
The bottom line in figure 4.4 graphically depicts the time required for the task system. If task system complexity does not grow above the maximum 100%, this line lies by definition under the overloading condition, with the PWL-value between 0 and 1.

The simple task in figure 4.4 takes place at a time when the pilot has a low vigilance, for example during the cruise-phase of a commercial flight. The actual workload level at that moment is indicated by point A. When at this time an emergency situation occurs, this shall result in a sudden increase in pilot workload, represented in the graph by a movement towards point B. If workload exceeds point B, the person is in overload condition. The length of line AB corresponds to the available workload margin. However, the possibility exists that because of the emergency situation the complexity of the task system has grown, resulting in a shift of the available margin to the right. Figure 4.5 contains a graph of the available margin versus the complexity of the task system.

At first, the available margin will grow to approximately 70% at 50% task system complexity, but when the task system becomes more complex, the available margin will reduce, and shall eventually become equal to zero at 100% task system complexity.

The available margin is a measure for the amount of extra tasks that can be imposed on a pilot, depending on the complexity of the task system.

It is a fact that pilots during approach and landing find themselves in a high workload condition. Therefore we are only interested in the decreasing part of the available margin in figure 4.5.

If an emergency situation occurs the safety margin decreases very rapidly towards zero, an overload condition originates, and the pilot becomes more liable to make mistakes. Because of this characteristic, it is stated that the available margin indicates the safety level.

With the use of extensive engineering-psychology research the two lines in figure 4.4 could probably be quantified. However, there was no opportunity in the limited time of my thesis assignment to perform the first steps into that direction. Just to give the reader an idea of the to-be-applied metric, the task system is thought to be equal to 50% complexity. This percentage serves only as an indication.
4.7. Discussion

An airport is used by a large variety of different aircraft, from different airlines, from different countries. Every approach and landing differs from other approaches, because of the differences in weather conditions and ATC-intervention.

The design of an Airport Safety Index should include most of these differences. But in what degree should we include them in a first set-up of the safety index? It is the author's opinion that the unpredictable portion of these differences, such as weather conditions and ATC-intervention, should be implemented in a second design cycle.

In a first set-up the safety index should therefore not be used for the comparison of a single approach and landing, but for the variety of aircraft that use the airport concerned in a specific time period.

It is most important to understand that the ASI only represents a highly theoretical calculation of operational safety, not the actual situations that occur.

In section 4.3 it is assumed that the pilot task is a structured task system set together by four different tasks of the pilot, namely:

1. Flight Management Task;
2. Manual Control Task;
3. Scanning & Monitoring Task, and;

It is the opinion of the author that the whole pilot task can best be represented with the use of these four sub-tasks. However, an attentive reader should have noticed that another division of the pilot task was presented in the FAR Part 25 Regulations, contained in appendix A. In these regulations six different sub-tasks are defined as the 'basic workload functions':

1. Flight Path Control;
2. Collision Avoidance;
3. Navigation;
4. Communications;
5. Operation and Monitoring of Aircraft Engines and Systems, and;

The division of the pilot task with these workload functions is very practical if the task is viewed qualitatively, because tasks are grouped in categories with the same contents. If workload is to be viewed in a quantitative way tasks should be grouped in categories with the same modeling or prediction technique.

For example, the operation of the engines is part of the workload function "Operation and Monitoring of Aircraft Engines and Systems", but could be thought of as a part of "Flight Path Control" too. In this report the operation of the engines is only part of the "Manual Control Task" as it is used to fly and control the aircraft, however the scanning and monitoring of the engine systems is modeled in a different way and are part of the "Scanning & Monitoring Task".

There exist no usable theories on the link between workload and safety, it is only said that there is a (qualitative) link. Intuitively, high workload results in a greater threat on the safe environment.
People working in the field of pilot workload prediction may disagree by the somewhat simple relation between workload and safety as described in section 4.6. However, it should be noted that this theory has not been a subject of discussion yet, and therefore presents only an idea of a possible solution for this link.
5

Wickens' Multiple-Resources Theory
(Flight Management Workload)

5.1. Introduction
5.2. The Resource Metaphor
   5.2.1. The Single Resource Theory
   5.2.2. Time-Sharing
   5.2.3. The Multiple-Resources Theory
   5.2.4. Discussion
5.3. Workload Assessment Techniques
   5.3.1. Empirical Workload Assessment
   5.3.2. Analytical Workload Assessment
5.4. The Proposed Flight Management Workload Assessment Technique
5.5. Discussion
5.1. Introduction

Models that predict workload can be useful tools for engineers who are tempted to address human capabilities and limitations in the design of advanced systems or procedures. This chapter presents a workload assessment technique for the discrete tasks of the flight management part of the structured task system using such techniques.

The psychological approach of pilot workload is the main component of this chapter, as the underlying theories will be used in the proposed flight management workload assessment technique.

The next section explains the prevailing theory on workload, i.e., the resource metaphor, serving as a background for those who have no knowledge in this field. Section 5.3 deals with the assessment of pilot workload, with a division in empirical and analytical techniques. Section 5.4 presents the proposed workload assessment technique for the flight management task, after which some aspects will be discussed in the final section.

5.2. The Resource Metaphor

The theory behind the resource metaphor is concentrated on the assumption that a human being has a limited capacity of resources. Tasks imposed on a human being draw a certain amount of these resources for task performance as needed to comply with the task demands.

Section 5.2.1 will start with an explanation of the somewhat outdated single resource theory, presenting the reader with a quick overview of the concept of the resource metaphor. There is one thing that cannot be explained by the single resource theory, namely the well-known fact that some tasks can be time-shared perfectly and some cannot. Section 5.2.2. contains a short overview of the theories underlying the concept of time-sharing. The multiple-resource theory presents a solution for this problem, and is explained in section 5.2.3. However, the multiple-resource theory has also problems to explain certain phenomena that can occur in the execution of tasks. This is contained in section 5.2.4.

5.2.1. THE SINGLE RESOURCE THEORY

The single resource theory assumes that there is one reservoir of resources out of which imposed tasks can draw their resources for the efficient and safe execution of the tasks. There is one reservoir for all tasks. Figure 5.1 contains a schematic diagram of the single resource theory.
Figure 5.1: Schematic diagram of the single resource theory. (source: ref. 23, slightly adjusted)

From this diagram the relationship between capacity demands, the level of arousal, and performance can be derived. This figure also shows that the human being is a limited system concerning the available resources. The higher the workload gets, the more resources are needed, the closer one gets to the ultimate limit of the available capacity. To give a good impression of the relation between the input and the output of this system, figure 5.2 represents a graph of the resources supplied to the task versus the demanded resources by the task.

Figure 5.2: Hypothetical relationship between resources demanded with increasing task difficulty, and resources supplied. (Source: ref. 23)
This figure explains the concept of a flexible resource and determines the amount of available capacity to process tasks. When more resources are demanded, the supply of these resources increases too. There are three different system functions described in figure 5.2:

- A perfect system can always satisfy the resources demand imposed on the system, and supplies the same amount of resources as demanded. This system cannot be used for the modeling of the resources of a human being, simply because we, human beings, have a limited amount of resources that can be used at the same time.

- The fixed-capacity system was the first theory to include the limited resources concept in a model. Although it is a rough approximation, the model is capable to describe a human-like demand-supply system.

- Human performance lies somewhere in between, because people have no fixed capacity, and no perfect system too. The line drawn in figure 5.2 shall eventually reach a maximum, which means that 100% of all resources are supplied, and the demand of resources cannot be fulfilled.

The single resource theory is a very useful tool in explaining how the resource metaphor works. The theory however has one major deficiency, which has all to do with time-sharing.

### 5.2.2. Time-Sharing

The operator carries out tasks in two ways: serial and parallel. A serial task imposes a workload on the operator after the previous task is performed successfully. A parallel task is performed simultaneously with another task, using the available resources at the same moment.

Many of the tasks involved in aircraft operation can be described as automated or highly practiced activities that demand little attention. The danger of high workload does not lie in the execution of such single tasks, it lies in the variety of tasks that must be carried out simultaneously, or more concretely the execution of parallel tasks. There is a possibility that there are not enough resources available in the reservoir to comply to all of these tasks. In this case some of the tasks must be carried out at a later point in time, of course an extra workload can originate because a mental priority list must be made of all the tasks that have to be carried out.

Figure 5.3 shows the performance-resource function (PRF), which represents the performance of a certain task versus the allocated resources. The effects of task difficulty and operator experience are visualized in this figure too.
In this figure, line A represents a task with high complexity and/or low operator experience, line B represents a task with low complexity and/or high operator experience. If 0% of the available resources is allocated to task A or task B, both tasks normally result in 0% performance. In the same way, when 100% of the available resources are allocated to task A or B, it is thought that 100% performance can be reached in both tasks. If 25% of the available resources is allocated to task A, only 30% performance is reached, while task B results in approximately 85% performance.

Until now, only the execution of a single task has been taken into account. According to this figure it is assumed that the simultaneous execution of two tasks using the same resources reservoir can have negative effects on the actual performance of both tasks. For example, 25% of the available resources are allocated to task B, resulting in 85% task B performance according to the previous paragraph. This means that 75% of the available resources are free to use for other tasks, like task A. When 75% of the available resources are allocated to task A, task A performance results in approximately 80%. The amount of interference between two tasks is determined by the form of the two PRF's. This is the concept of time-sharing.

It is assumed that the operator makes the decision on the allocation of the available resources flexibly between tasks in any proportion desired. This assumption is based on psychological research studies discussed in ref. 23, where two tasks are time-shared, and the subject is asked each time to adopt a different allocation strategy. It is possible to cross-plot the task performance of these experiments in a single figure (5.4).
This graph is called the Performance Operating Characteristic, or POC, and is constructed with the two PRF's of both tasks. The POC has proven to be a useful way of summarizing a number of characteristics of time-shared tasks.

1. Single task performance is shown by the lines AP and BP. The intersection of these lines at point P corresponds with perfect time-sharing.

2. There is a "cost of concurrence" when 100% resources are allocated to a task, while time-sharing 0% resources with task B (point C in figure 5.4), the difference with the single task performance is equal to this cost of concurrence.

3. The time-sharing efficiency is the minimal distance from point P to the curve. The closer the curve lies to the single task performance lines, the more efficient the dual task performance.

5.2.3. THE MULTIPLE-RESOURCE THEORY

The disadvantage of the single resource theory is that it is impossible to explain the well-known fact that some tasks can be time-shared perfectly. For example, driving a car and having a conversation with a passenger results in almost no interference, while driving a car and reading a road map simultaneously is almost impossible. Wickens has proposed a solution for this deficiency of the single resource theory in ref. 23 with the multiple-resource theory: "... instead of one single supply of undifferentiated resources, people have several different capacities with resource properties. Tasks will interfere more and difficulty-performance trade-off will be more likely to occur, if more resources are shared." Figure 5.5 contains the basic ideas of the multiple-resource theory.
Figure 5.5: Wickens' structure of processing resources as a multidimensional resource space. (Source: ref. 23)

According to Wickens (ref. 23) this figure is "... a representation of a space in which task demands can be placed according to whether they are verbal or spatial, their input from visual or auditory, and their output from manual or vocal. The closer together two tasks or interface channels are in this space, the more they draw on the same attentional resources and therefore, the more difficult they are to time-share."

The left side of the multidimensional resource space is the input-side, the right side the output-side. Note that the problem of what really happens within the mind, or the central processing of tasks, is evaded, and tasks can be typified with the use of their input and output characteristics.

5.2.4. DISCUSSION

Although the resource metaphor seems capable of describing some of the mysteries that happen in the brain while performing a task, it is not necessarily the best method. Scientists in this kind of research are divided into groups with different beliefs.

Human factors experts, engineering psychologists, doctors, engineers, and lots of other people have written an impressive, but primarily abundant, stack of literature on this subject, and there was simply not enough time within this final thesis assignment to go through all of this literature, although all of the theories and models described in literature are probably intuitively correct. For this reason it could be possible that other theories on how workload acts within a human being have been constructed, and perhaps they represent an even better model.

Clearly the multiple-resource theory gives a very good idea of what happens when tasks are performed simultaneously. In any case it is a very useful extension of the single resource theory.
However, some aspects still cannot be explained by the multiple-resource theory. The limitation is in the amount of information that can be processed simultaneously in the different mechanisms.

5.3. Workload Assessment Techniques

The big question now is how pilot workload can be measured. After all, our main concern lies in the quantification of pilot workload. There are numerous techniques for doing this, and none of them is universally known as the right technique. This section contains the description of a limited number of assessment techniques, which does not mean that other methods are less usable.

First of all, a division is made between empirical and analytical assessment techniques, for no other reason than to differentiate between techniques which require that an operator interacts with a system from those that do not. Obviously, this report is mainly concerned with the analytical assessment techniques. However, the empirical techniques are also presented in this section for the sake of completeness, and of course for further investigation into a possible validation method. Further on in this chapter it is suggested to use empirical techniques for the translation of an analytical workload assessment technique from helicopters to fixed-wing.

5.3.1. Empirical Workload Assessment

Although we are mainly interested in the analytical ways of assessing workload, and the empirical techniques were never used in this study, we shall nevertheless pay some attention to this subject. This is done in order to present the reader with the fact that workload just cannot be measured directly, and to give a well-structured background for some of the recommendations further on in this report.

Empirical assessment of pilot workload is the closest thing to the measurement of actual workload, because data can be gathered directly from the ‘operator-in-the-loop’. These empirical assessment techniques use this ‘real data’ gathered from the users of the system (pilots, air traffic controllers) as input. This data consists either of physiological data, subjective opinion, dual task data or (human and/or machine) performance data.

Physiological Assessment

The manifestations of high workload and resource depletion on certain physiological parameters can be recorded, representing a good estimation of the actual human performance level. Table 5.1 contains a list of physiological parameters that can be measured and used as an indication of the amount of workload.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relation with task performance and workload</th>
</tr>
</thead>
<tbody>
<tr>
<td>heart-rate variability</td>
<td>Variability decreases when workload increases.</td>
</tr>
<tr>
<td>pupil diameter</td>
<td>Diameter varies with imposed (cognitive) workload.</td>
</tr>
<tr>
<td>pupil blink-rate</td>
<td>Blink-rate decreases with increasing task difficulty.</td>
</tr>
<tr>
<td>magnitude and frequency of respiration</td>
<td>Respiration becomes more regular and more intense with higher demands.</td>
</tr>
<tr>
<td>etc.</td>
<td></td>
</tr>
</tbody>
</table>

*Table 5.1: Physiological workload measurement techniques.*

It should be considered that all of these physiological measurement techniques have one constraint, this is the interference of the measurement equipment with the task at hand. This can result in a certain annoyance, irritation, and frustration level of the operator, and may impose an extra workload. It is imperative to understand what is actually measured with these physiological assessment techniques.

**Subjective Opinion**

Numerous subjective rating scales have been proposed to measure the effort required to perform a task. Two of the multidimensional resource scales will be presented in this section, the NASA TLX scale and the SWAT technique.

Subjective rating scales are used to present the pilot some general directions in her or his judgment of how demanding a certain task or maneuver was, or how well the performance of the pilot-aircraft was. One of the first subjective rating scales was the Cooper-Harper Handling Quality Rating Scale (ref. 5). The pilot arrives at a handling quality rating by means of a series of decisions: controllable or uncontrollable, adequate performance or not, and then satisfactory performance or not.

Other rating scales specified on pilot workload followed the example of the Cooper-Harper HQR-Scale, resulting in a large number of different pilot judgment rating scales. Only the two most interesting pilot workload scales shall be named here.

The first is the NASA TLX (Task Load Index) rating scale where the pilot is asked to judge six different terms on a 7-point scale. The definitions of the terms are given in table 5.2.
### Table 5.2: The NASA TLX Scale: The rating scale definitions. (Source: ref. 23)

The second scale is called the SWAT technique (Subjective Workload Assessment Technique), which measures workload on three 3-point scales, see table 5.3.

<table>
<thead>
<tr>
<th>Time load</th>
<th>Mental effort load</th>
<th>Stress load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Often have spare time. Interrupts or overlap among activities occur infrequently or not at all.</td>
<td>1. Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.</td>
<td>1. Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.</td>
</tr>
<tr>
<td>2. Occasionally have spare time. Interrupts or overlap among activities occur frequently.</td>
<td>2. Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention required.</td>
<td>2. Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.</td>
</tr>
<tr>
<td>3. Almost never have spare time. Interrupts or overlap among activities are very frequent, or occur all the time.</td>
<td>3. Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.</td>
<td>3. High to very intense stress due to confusion, frustration, or anxiety. High to extreme determination and self-control is required.</td>
</tr>
</tbody>
</table>

### Table 5.3: The SWAT Scale. (Source: ref. 23)

Both scales present the engineering psychologist with a subjective way to assess workload, and yield approximately the same results. However, the rating on itself is not very valuable without the comment of the pilot, giving an explanation how he or she arrived at the rating.
Dual Task Techniques

Imposing a secondary task on the operator while performing the primary task, can be a measure of the available residual workload. The performance of the secondary task is thought to reflect the demand of resources by the primary task.

For example, the operator is asked to tap a constant rhythm with her/his foot or hand while performing the primary task, e.g. flying an aircraft. Tapping variability increases as primary-task workload increases. Another secondary task is for example random number generation, where the operator is asked to generate a series of random numbers. As primary-task workload increases, the degree of randomness decreases, and more repetitiveness originates in the number generation. A secondary task with resemblance to an R/T task is the Sternberg memory search task, where the operator is presented with a letter and must respond with yes or no whether this letter is part of a pre-memorized set of two to four letters. To do so, the operator must search through her or his working memory, resulting in interference with the cognitive side of the primary task, and therefore presenting us with a measure for cognitive primary-task workload.

Performance Data

Comparison of man/machine performance data of two slightly different situations can be used to obtain an indication of the workload effects of the new situation. In this study, performance data will be used to calculate a measure of delivered energy by the pilot, giving an indication on the workload, according to the method described in chapter 6.

5.3.2. ANALYTICAL WORKLOAD ASSESSMENT

This section contains the description of a limited amount of analytical workload assessment techniques. Because of the large number of possible techniques, only those that are used in the proposed flight management workload assessment technique shall be named here: Timeline Task Analysis, the McCracken-Aldrich approach, and the Workload Index W/INDEX.

Timeline Task Analysis

Timeline Task Analysis is one of the very first approaches on workload evaluation. It is a simple method, where the task sequence of the pilot is investigated. A disadvantage of this technique is that it does require extensive labor. In the early days it was only used to investigate the mission profile, and the accompanying tasks. Nowadays its use is far more widespread, ranging from the investigation of the cognitive resource demands of one small task to an analysis of a structured task system, which is of importance to this study.

In a traditional timeline task analysis, tasks are analyzed in relation to the behavioral responses that must be made to carry out the task, emphasizing on the target performance and task-related knowledge. The product of such an analysis is more insight in certain characteristics of the task, such as how long does it take to perform the task, or the demanded intensity of the task on the operator. Ref. 11 contains valuable information on carrying out a timeline task analysis, specifying a set of basic rules the experimenter should comply with. In the same reference some examples are given of the application of task analysis in high workload environments, such as the control chamber of a nuclear power station.

Since the early eighties a newer version of task analysis exists, the Cognitive Task Analysis, or CTA. According to ref. 20: “CTA identifies and describes the cognitive structures (e.g.,
knowledge base organization and representational skills) and processes (e.g., attention, problem solving, and decision making) underlying job expertise or human-systems interactions.". CTA is a technique that is complementary to a traditional timeline task analysis.

One of the easiest methods of CTA is to have the pilot provide a running commentary describing what he sees, what he is doing, and why he does it. This commentary can then be recorded by audio or video tape, for later analysis. Reasonably good insight can be acquired into the cognitive processes based on this pilot commentary.

**McCracken-Aldrich Approach**

The McCracken-Aldrich approach presents us with a way of quantifying workload. According to ref. 12, this approach "... involves performing mission and task analyses that generate a timeline of tasks which are divided within three categories: flight control, support, and mission. It is assumed that tasks within each category would be performed sequentially, but tasks across categories could be performed concurrently. It is also assumed that a flight control task would be performed at all times. These tasks are sub-divided into performance elements which, based on system characteristics, are used to generate workload estimates on five behavioral dimensions comprising cognitive, visual, auditory, kinesthetic, and psychomotor."

The sub-division of pilot workload into five different dimensions clearly represents the implementation of Wickens' multiple-resources theory. The imposed pilot workload of a task can be estimated in each of the five workload components according to pre-defined rating scales. An example of such scales can be found in appendix B. The scales are taken from ref. 2, which describes a Mission/Task/Workload Analysis of the UH-60A helicopter.

The rating values of the workload component scales can be derived from empirical research, for example using a physiological workload measurement technique in a laboratory environment, combined with the subjective commentary of the pilot.

The high level of detail of the component workload rating scales allows the tasks to be split up into very basic sub-tasks, such as pushing or turning a button, checking a status on a display, etc. From a library of such sub-tasks with accompanying intensities as rated according to the workload component rating scales, a task can be built up, such as the selection for a new flap setting. All of these basic sub-tasks then receive a specific duration of time within the overall task and most can then be related to a subsystem in the cockpit.

By placing the tasks on a time-scale according to the results of a timeline analysis, an overlap of tasks can occur, imposing a demand on the same resources at the same time, therefore resulting in a total component workload that can be calculated by the summation of the component workloads of the separate tasks.

The products of the McCracken-Aldrich approach are the four overload indices (ref. 2):

- A **component overload** occurs whenever the sum of the ratings assigned to a given workload component (i.e., visual, auditory, kinesthetic, cognitive, or psychomotor) for concurrent tasks equals "8", or higher. Thus as many as five component overloads may occur for two or more concurrent tasks. A value of "8" was chosen as the criterion for an overload because it exceeds the maximum value on any of the workload component rating scales.

- An **overload condition** occurs whenever a component overload, as defined above, occurs in at least one component of the concurrent tasks. In theory as many as five component
overloads (i.e., visual, auditory, kinesthetic, cognitive, or psychomotor) may occur within a single overload condition.

- **Overload density** is the percentage of time during a mission segment that a component overload occurs. It is calculated by dividing the number of timelines with component overloads by the total number of timelines in the segment.

- The term **subsystem overload** is used to describe the relationship between a component overload and a subsystem. It is computed by tallying the number of times each subsystem is associated with a component overload."

The overload density is a potential measure of workload in the execution of a sequence of tasks, while the other three indices present measures that are primarily concerned with the simultaneous execution of concurrent tasks.

**Workload Index (W/INDEX)**

W/INDEX is a workload assessment technique which can be used to predict workload according to Wickens' multiple-resources theory. It uses the information of a timeline task analysis as input. Ref. 15 contains a more elaborate description of the technique, and also describes some of the software implementations of W/INDEX.

For every second or half a second the attentional demands on the different resources are summed, after which the characteristics of time-sharing and the multidimensional resource space are added, by using a conflict-matrix.

This conflict matrix specifies the degree of workload penalty that results when the operator must attend to multiple input or output channels simultaneously, and could give us more understanding of the bottleneck areas of high workload in a flight procedure.

Table 5.4 shows a prototype conflict matrix that is taken from ref. 15, and presents the reader with a good idea of the meaning of these time-sharing penalties.
### Table 5.4: Prototype Conflict-Matrix, used to provide conflict levels based on resource category. (Source: ref. 15)

The values in the conflict matrix are derived from laboratory experiments and should be interpreted as indicative values. Peak values in workload are mainly caused by the high conflict areas within the variety of tasks imposed on the pilot, for example the execution of two verbal tasks at the same time is impossible. These tasks have to be carried out as serial tasks.

#### 5.5. The Proposed Flight Management Workload Assessment Technique

Now that the analytical workload assessment techniques and its underlying theories are described, we can start designing the proposed flight management workload assessment technique.

First a traditional (behavioral) timeline task analysis should be performed, resulting in the determination of certain discrete tasks such as making a flap selection, checking the engine status, etc. A first division into the structure of each task with respect to its basic sub-tasks can also be made using this task analysis. A further breakdown of the discrete tasks into
basic sub-tasks, concentrating on the very important cognitive aspects of each task, is made by using a cognitive task analysis.

After this study into all the tasks, which should result in a profound insight into the variety of the sub-tasks, we are ready to quantify these sub-tasks in terms of workload. The application of the McCracken-Aldrich approach provides this quantification, and makes it possible to define all of the sub-tasks in a database or library. But first a thorough investigation into the component rating scales is required, in order to use them correctly for civil airliner pilots. This has not been done in the study described in this report.

As can be seen in figure 5.6 the horizontal phase in the design of the flight management workload assessment technique represents these preparations for the actual assessment technique. The library of sub-tasks can now be used to define the tasks through time for a specific approach procedure.

![Diagram of the flight management workload calculation method.](image)

Figure 5.6: Diagram of the flight management workload calculation method.

By performing a timeline analysis of all the discrete tasks, the required information on the duration of certain discrete tasks is acquired. Another question can also be answered with such a timeline analysis, and that is when all the tasks according to the procedure have to be carried out. Now we are ready to place all the tasks on a timeline and sum the component workload for every time interval. This is exactly what is required for the calculation of the overload density.

However, one thing has not been taken into account yet, and that is the penalty of time-sharing of two or more concurrent tasks. Implementation of the W/INDEX conflict matrix at this point presents a solution for this boundary in human performance. At every time interval the contributions of each task is looked at, and penalties are issued for conflict situations, resulting in a possible higher component workload.

The final product is a quantification of flight management workload versus time, using a predictive and reproducible assessment technique.
5.6. Discussion

The list of workload assessment techniques, as presented in section 5.3, is by no means complete. There is a large amount of empirical techniques, especially of the subjective pilot workload rating scales. Only the two most interesting and most promising rating scales were shown. In the description of the analytical techniques, only those techniques are described which are used in the proposed flight management workload assessment technique. The interested reader is referred to ref. 12, which contains the description of numerous other workload modeling techniques.

A remark should be made on the question whether the McCracken-Aldrich approach is a subjective or a quantitative workload assessment technique, as the values of the workload components rating scales are derived from empirical assessment techniques and are used to classify the tasks. These scales are actually a much more detailed version of the subjective pilot workload rating scales presented in section 5.3.1.

However, the very high detail level of the component scales allows the tasks to be split up into very basic sub-tasks, such as pushing or turning a button, checking a display, etc. From a library of such sub-tasks with accompanying intensities as rated according to the workload component rating scales, a model of the task can be built up consisting of these sub-tasks. The basic sub-tasks receive at that point a specific duration of time within the overall task. So, every task can be modeled with a combination of the basic sub-tasks.

The tasks are looked into with such a zoom, that the basic elements of the task are recognized. Quantification of these basic elements in terms of workload, with the objective of quantifying the task workload, is a very precise and difficult job. It is the author’s opinion that when this job is carried out correctly and verified with reality, the McCracken-Aldrich approach should be called a workload quantification method, and not a subjective rating scale.

It is possible that the proposed workload assessment technique as described in section 5.5, is not the best technique to quantify flight management workload. There exist numerous other techniques, and combinations of techniques, to arrive at the same results or maybe even better. In most cases there was simply no opportunity to obtain more specific information on the techniques. Especially information on workload modeling computer software was hard to come by.

Nevertheless, the technique presented in this chapter can be used for the problem of modeling the discrete tasks of the flight management task. There is only one disadvantage, and that is the labor-intensive nature of the timeline task analyses.
6

The 'Padfield' Experiment
(Manual Control Workload)

6.1. Introduction
6.2. Background Theory
6.3. Application of the Theory
6.4. The Simulation Program ASINOP
  6.4.1. Adjustments on ASINOP
  6.4.2. Output Results
6.5. Calculation of Manual Control Workload
6.6. Manual Control Workload Results
6.7. Discussion
6.1. Introduction

Manual aircraft control imposes a continuous demand on the pilot, who watches certain control parameters closely, such as pitch angle and airspeed, and tries to keep them within limits. Padfield states in his textbook on helicopter modeling (ref. 18) that the response signals of certain control inputs can be used as a measurement of the actual pilot workload.

This next section contains a short description of these ideas and presents the basic framework, that Padfield suggests as a potential technique for the assessment of manual control workload. Section 6.3 contains a description of the translation of these ideas to fixed-wing aircraft.

Section 6.4 gives a description of the simulation program ASINOP. This program produced the performance data that was used as input for the calculation technique.

Section 6.5 presents the calculation method for the workload parameter, of which the results are presented in section 6.6. The results are then discussed in section 6.7.

6.2. Background Theory

Padfield states in reference 18 that in many cases there is a close correlation between pilot control activity, task difficulty and the Handling Quality Rating, or HQR, and in such cases the level of control activity can be related to pilot workload. This correlation is quite obvious: a more complex pilot control task shall increase the task difficulty, increasing the demanded pilot control activity, which in turn demands more of the pilot's attention, thus increasing the pilot workload.

Before we can go further into the ideas of Padfield, the term Handling Quality Rating should be explained more elaborately. According to ref. 5 handling qualities are defined as "... those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required of an aircraft role.". In reference 17 Padfield gives another definition for flying quality: "Flying 'Quality' can be further interpreted as the synergy between the internal attributes of the air vehicle and the external environment in which it operates. The internals consist typically of the air vehicle (airframe, powerplant and flight control system) response characteristics to pilot inputs (handling qualities) and disturbances (ride qualities), and the key elements of the pilot/vehicle interface, e.g., cockpit controls and displays."

Figure 6.1 presents a visualization of this definition with the external factors as the mission, with its individual mission task elements, the required levels of task urgency, and the external natural environment.

![Figure 6.1: The synergy of Flying Qualities. (Source: Ref. 17)](image-url)
Figure 6.2 shows the Cooper-Harper Handling Qualities Rating Scale. This scale is used by pilots to assign ratings to the flying qualities of aircraft in well-defined flight procedures or maneuvers. The pilot is led through a series of decisions to arrive at a numerical rating for the flown maneuver. Ratings better than 1 or worse than 10 are not possible. The military uses the three levels shown to make decisions on the acceptability of the aircraft. The Cooper-Harper Rating Scale is designed for the subjective assessment of handling qualities and should not be used to assess pilot workload during the evaluated maneuver.

Figure 6.2: The Cooper-Harper handling qualities rating scale. (Source Ref. 5)

Figure 6.3: Time histories of lateral cyclic in a lateral slalom mission task element. (Source: Ref. 18)

Now let us go back to the helicopter experiment of Padfield. Figure 6.3 shows the time histories of the lateral cyclic in a lateral slalom maneuver in an experiment, described by Padfield in reference 18. The experiment was carried out on the advanced flight simulator of the DRA (Defense Research Agency). As aggression is increased, the HQR level in figure 6.3 degrades from 1 to 2.

Pilot control activity can also be represented in the frequency domain. Figure 6.4 contains the power spectral density function for the lateral cyclic showing the amount of control 'energy' applied by the pilot at the different frequencies. The increase in effort for the higher aggression case is evident. Padfield states that "There is evidence that one of the critical parameters as far
Pilot Workload & Operational Aircraft Safety

as the pilot workload is concerned is the ratio of aircraft bandwidth to task bandwidth." (ref. 18).

Before we go on with a description of Padfield's ideas, a good definition of this bandwidth parameter should be given first. The bandwidth is the frequency beyond which closed loop stability is threatened. The frequency at which instability takes place is commonly referred to as the crossover frequency, and the bandwidth frequency corresponds to some lower value that provides an adequate stability margin.

Figure 6.5 shows conceptually the expected trend according to Padfield. "A workload metric, e.g., rms. of control activity or frequency at which some proportion of the activity is accounted for, is plotted against the bandwidth ratio. As the ratio increases one expects the pilot's task to become easier, as shown. Conversely, as the ratio reduces, either through reduced aircraft bandwidth or increased task bandwidth, then workload increases."

This figure actually shows the basis of the theory behind the relationship between pilot workload and safety, as described in section 4.6. It also shows the 'region of strong workload increase', rapidly leading to a possible overload condition with increasing task system complexity.

6.3. Application of the Theory

The theory described in the previous section is now used as a workload prediction technique for the manual control task in the structured task system as described in section 4.3, but how can we use this for a pilot, flying an approach procedure with a fixed-wing aircraft?

First, the cyclic signal of the helicopter pilot in the previous section should be translated to a fixed-wing aircraft control signal. According to ref. 13 several state variables can be selected as the controlled variables of a feedback control system. For the longitudinal control of an aircraft the following three motion variables, or rather their deviation from reference values, should be considered:

- pitch angle \( \theta \)
- angle-of-attack \( \alpha \)
- airspeed \( V \)
For the control of these variables the following control elements are available in principle:

- pitching-moment control element, effected by moment-producing aerodynamic surfaces
- normal-force control elements, effected by lift-producing aerodynamic surfaces
- longitudinal-force control element, effected by thrust-producing engines

The pilot has to perform two functions with these control elements during approach and landing:

1. stabilization of the aircraft, and;
2. providing the means for maneuvering of the aircraft.

He or she delivers good performance when these two functions are kept within their limits, or rather when they satisfy the criteria for flying qualities.

It can be roughly said that it is possible to translate these functions to the pilot's continuous minimization of the aircraft's speed and flight path error between actual and reference values. Based on this information a simulation program can now be used to arrive at the necessary performance data for further processing.

The pilot uses two manipulators for the longitudinal control of the aircraft, the engine throttle and the elevator part of the steering column. As we are interested in pilot workload, the variability of the settings of these manipulators for the control of the aircraft state give an indication of the efforts of the pilot, and are specified now as the required performance data for our theoretical experiment.

In the next section a simulation program is presented called ASINOP. This program was used as a tool for the acquisition of the required performance data. Among the output of this program are engine setting and pitch angle versus time. Although the pitch angle is not the same as the deflection of the steering column or the elevator angle, for an exploratory study like this, it is a representative variable for the control input of the pilot.

The data of these two parameters are then transformed from the time-domain to the frequency-domain using the Fourier transform. Subsequently the power spectral density function is deduced of both parameters representing the amount of control 'energy' applied by the pilot at the different frequencies, as was done for the helicopter experiment in figure 6.4. The rms. of this amount of control energy applied by the pilot can now be used as a workload metric. Figure 6.6 presents a diagram of the manual control task workload calculation method.

6.4. The Simulation Program ASINOP

In stead of real flight performance data, the manual control workload assessment technique uses data derived from a simulation program of approach and landing procedures. This simulation data is used because of the relative nature of a workload index. We want to compare two different procedures with each other theoretically. However, the real flight performance data will consist of certain unique anomalies, which makes the calculation method unusable, because of the lack of
reproducibility. Obviously, real flight performance data or data from a simulator session must be used for validation purposes.

The simulation program is written in the programming language Matlab, and is called ASINOP, or Approach Simulation and Noise Program. Designed at the Delft University, Department of Performance Theory, by Ir. N. Münninghof, ASINOP presents the possibility to analyze takeoff or approach procedures. Adjustments to approach procedures such as

![Diagram showing an example of the implementation of an approach procedure in ASINOP. In this case the procedure with reduced flaps and delayed GD is displayed.]

Figure 6.7: An example of the implementation of an approach procedure in ASINOP. In this case the procedure with reduced flaps and delayed GD is displayed.

described in section 4.3, can easily be implemented in the software.

Figure 6.7 depicts a graphical representation of the implementation of the reduced flaps and delayed GD approach procedure. The procedure is divided into segments marked by their endpoints. The information at the endpoints contain the values for the desired variables. Table 6.1 contains the matching values of the endpoints in figure 6.6.

<table>
<thead>
<tr>
<th>No.</th>
<th>Trigger</th>
<th>s [m]</th>
<th>H [ft]</th>
<th>$\gamma$ [$^\circ$]</th>
<th>flaps [$^\circ$]</th>
<th>$V$ [kts]</th>
<th>$u_c$ [1=GD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>s</td>
<td>-22000</td>
<td>2000</td>
<td>0</td>
<td>10</td>
<td>$V_{REF25} + 20$</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>&quot;1 dot up&quot;</td>
<td>ilsdot-routine*</td>
<td>2000</td>
<td>0</td>
<td>10</td>
<td>$V_{REF25} + 20$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>ILS-intercept</td>
<td>-11632</td>
<td>2000</td>
<td>0</td>
<td>20</td>
<td>$V_{REF25} + 10$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Outer Marker</td>
<td>-7270</td>
<td>2000</td>
<td>$s\tan(3^\circ)$**</td>
<td>-3</td>
<td>$V_{REF25} + 10$</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Gear = Down</td>
<td>6 sec after no. 4***</td>
<td>$s\tan(3^\circ)$**</td>
<td>-3</td>
<td>20</td>
<td>$V_{REF25} + 10$</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>$s = 0$</td>
<td>0</td>
<td>0</td>
<td>$s\tan(3^\circ)$**</td>
<td>-3</td>
<td>25</td>
<td>$V_{REF25}$</td>
</tr>
</tbody>
</table>

Table 6.1: The segment points of the approach procedure with reduced flaps and delayed GD.

* The ilsdot-routine is a routine that calculates the distance from the runway threshold as a function of the approach altitude, the ILS-angle and the number of "dots up".
** The conversion factor between feet and meters should be taken into account.
*** The duration of the extension of the landing gear is assumed to be 6 seconds.

ASINOP uses the input of the endpoints of the segments to define the procedure that is to be simulated. All of the triggers are converted to distance from runway threshold (symbol s). If the aircraft finds itself between two of these endpoint values of s in the simulation, the program can read out the accompanying values of flap setting, desired speed, etc.
Only two-dimensional procedures can be simulated with ASINOP. The simulation therefore does not start at the point where the aircraft flies into the airport's airspace, but starts at the final two-dimensional part of the flight-path along the extended centerline of the runway, just before glide-slope interception.

Two feedback control loops are implemented in the simulation program to simulate pilot control. The control of the desired pitch attitude is a so-called PID controller (Proportional Integrating Differentiating):

$$\theta_{\text{desired}} = \theta_{\text{ref}} + K_{\theta,P}(H_{\text{desired}} - H) + K_{\theta,D}(V_{\text{desired}} \sin \gamma_{\text{desired}} - V \sin \gamma) + K_{\theta,I} \int H$$

with:
- $\theta_{\text{ref}}$ the initial pitch angle;
- $H, H_{\text{desired}}$ altitude, desired altitude;
- $V, V_{\text{desired}}$ airspeed, desired airspeed;
- $\gamma, \gamma_{\text{desired}}$ path angle, desired path angle;
- $\int H$
- $K_{\theta,P}, K_{\theta,D}, K_{\theta,I}$ respectively the Proportional, Differential, and Integrating gain.

The control of the desired setting of the engines is a PI-controller and can be written as follows:

$$\tau_{\text{desired}} = \tau_{\text{ref}} + K_{\tau,P}(V_{\text{desired}} - V) + K_{\tau,I} \int V$$

with:
- $\tau_{\text{ref}}$ the initial engine setting at the beginning of a segment;
- $\int V$
- $K_{\tau,P}, K_{\tau,I}$ respectively the Proportional and Integrating gain.

Every time the program-loop passes these two control loops, new values are calculated for the desired pitch angle and the desired engine setting.

At every discrete point in time the state of the aircraft is calculated, resulting in a differential equation, which is then solved using the Runge-Kutta routine from Matlab. This routine does not need a fixed time interval, but determines itself which time intervals to use until the desired accuracy is reached.

The output of ASINOP is performance data versus time and was originally used to calculate noise load contours. On discrete time steps the following data is stored:

- Calibrated Air Speed $V$;
- path angle $\gamma$;
- altitude $H$;
- distance from runway threshold $s$;
- pitch angle $\theta$, and;
- engine setting $\tau$. 


6.4.1. ADJUSTMENTS ON ASINOP

Before these parameters are graphically depicted, some remarks must be made on the adjustments that have been made to ASINOP.

First of all, the program was converted to a newer version of Matlab. Version 5 has a number of advantages compared to Matlab 4, e.g., a user-friendly editor for the Matlab language and better signal processing tools, which will be used further on in this chapter.

However, there is one major disadvantage, and that is that the two versions of Matlab are not completely compatible with each other. If you are dealing with a complex Matlab program such as ASINOP, which has a large number of parameters, and consists of a lot of sub-programs, the version change is not easily implemented.

The most important reason behind the conversion of ASINOP to a newer version lies in the fact that Matlab 5 possesses a Runge-Kutta differential equation routine with the option to write output data away on constant time-intervals. This was needed because part of the manual workload calculation method takes place in the frequency domain.

A number of adjustments were proposed to implement in the simulation program, but proved to take more time to program than was available for this thesis assignment. Among these adjustments were:

- The implementation of the delays between actual throttle setting and engine response. Engine response cannot become less than "approach idle", which is circa 36% RPM. If an engine in this setting receives a sudden increase in throttle setting, a delay in engine response of circa 10 seconds may occur.

- Instead of pitch attitude, the feedback control loop might present us with better results if the elevator angle is controlled by a PID-controller. The elevator angle is also a better representation of the effort the pilot has to deliver in order to perform the manual control task than pitch attitude.

- The model in ASINOP handles flap deflections and landing gear extension as step functions. In other words, the assumption is made that flaps and gear extensions do not take time, but happen instantaneously.

The problem of the implementation of these adjustments lay in the poor debugging information ASINOP and Matlab return as a reaction on such an adjustment. For example, modeling a linear flap deflection resulted in erroneous output because of the almost impregnable and user-unfriendly structure of the numerical differential equation routine of Matlab.
6.4.2. OUTPUT RESULTS

Figure 6.8 presents the output of the simulation program ASINOP graphically depicted versus time. In order to compare two different procedures, both the reference and the KLM procedure are displayed.

![Graph showing Airspeed, Path angle, Altitude, Pitch angle, N1 versus Time](image)

*Figure 6.8: The performance data from ASINOP of the reference and the KLM procedure.*

Two remarks concerning this figure:

- During the approach phase, the pilot has to decelerate the aircraft to $V_{REF}$, while descending towards the runway threshold along the ILS-GS-signal. The minimal possible engine setting for the B-747-400 in the approach phase is 'approach idle' and corresponds 36% N1 speed, which is the speed of the engine-compressor in % RPM. From the N1-graph it can be seen that in the reference procedure the engine setting was at this lower limit for a
short period just after GS-interception. For the KLM-procedure however, the setting stays at this limit until the end of the simulation, while airspeed never reaches the desired values after GS-interception.

- The altitude profiles of both procedures seem very different, although both procedures have the same altitude-profile. This can be explained by the time-axis. Both procedures start at the same time and place, but the KLM-procedure has a higher speed-profile, therefore this line reaches the GS-interception earlier and seems to descent steeper than the reference procedure. The same graph versus the distance from runway threshold is presented in figure 6.8. Obviously, the two altitude-profiles overlap each other perfectly.

![Graph showing altitude vs. distance from runway threshold.](image)

Figure 6.9: The altitude profiles of the reference and the KLM-procedure versus the distance from runway threshold.

In conclusion it can be said that at first sight the performance data of both procedures looks quite realistic. However, the minimal engine setting causes the airspeed to deviate from its desired values.

### 6.5. Calculation of Manual Control Workload

A Matlab-program has been written for the calculation of manual control workload according to the ideas of Padfield. A listing of this program with detailed commentary is contained in appendix C.

The Fast Fourier Transform routine within Matlab was used to translate the performance data of pitch and engine setting from the time-domain to the frequency-domain. Power spectral densities were calculated according to the method described in reference 14, and are presented in figure 6.10 for the reference and the KLM procedure.
Figure 6.10: The pilot control activity in the frequency-domain.

As Padfield suggests in ref. 18 the rms. of these spectral densities give an indication of the manual control workload.
Table 6.2 shows the absolute and relative results for the reference and the KLM procedure.

<table>
<thead>
<tr>
<th></th>
<th>WL Pitch</th>
<th>WL Engine</th>
<th>% WL Pitch</th>
<th>% WL Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>44.9</td>
<td>756</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>KLM-Procedure</td>
<td>31.6</td>
<td>643</td>
<td>70.38</td>
<td>85.05</td>
</tr>
</tbody>
</table>

Table 6.2: The absolute and relative results of the manual control workload calculation.

6.6. Manual Control Workload Results

The numeric results for all procedures are presented in table 6.3.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>WL Pitch</th>
<th>WL Engine</th>
<th>% WL Pitch</th>
<th>% WL Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>44.9</td>
<td>756</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>1750 ft approach</td>
<td>49.8</td>
<td>746</td>
<td>110.91</td>
<td>98.68</td>
</tr>
<tr>
<td>Reference</td>
<td>44.9</td>
<td>756</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>2250 ft approach</td>
<td>40.2</td>
<td>765</td>
<td>89.53</td>
<td>101.19</td>
</tr>
<tr>
<td>2500 ft approach</td>
<td>35.6</td>
<td>774</td>
<td>79.29</td>
<td>102.38</td>
</tr>
<tr>
<td>2750 ft approach</td>
<td>31.2</td>
<td>783</td>
<td>69.49</td>
<td>103.57</td>
</tr>
<tr>
<td>3000 ft approach</td>
<td>27.0</td>
<td>790</td>
<td>60.13</td>
<td>104.50</td>
</tr>
<tr>
<td>2.5 deg approach</td>
<td>41.0</td>
<td>840</td>
<td>91.31</td>
<td>111.11</td>
</tr>
<tr>
<td>2.75 deg approach</td>
<td>43.1</td>
<td>794</td>
<td>95.99</td>
<td>105.03</td>
</tr>
<tr>
<td>Reference</td>
<td>44.9</td>
<td>756</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>3.25 deg approach</td>
<td>46.0</td>
<td>724</td>
<td>102.45</td>
<td>95.77</td>
</tr>
<tr>
<td>3.5 deg approach</td>
<td>45.7</td>
<td>698</td>
<td>101.78</td>
<td>92.33</td>
</tr>
<tr>
<td>4 deg approach</td>
<td>41.0</td>
<td>697</td>
<td>91.31</td>
<td>92.20</td>
</tr>
<tr>
<td>4.5 deg approach</td>
<td>39.7</td>
<td>711</td>
<td>88.42</td>
<td>94.05</td>
</tr>
<tr>
<td>5 deg approach</td>
<td>40.1</td>
<td>722</td>
<td>89.31</td>
<td>95.50</td>
</tr>
<tr>
<td>5.5 deg approach</td>
<td>40.9</td>
<td>731</td>
<td>91.09</td>
<td>96.69</td>
</tr>
<tr>
<td>6 deg approach</td>
<td>41.9</td>
<td>738</td>
<td>93.32</td>
<td>97.62</td>
</tr>
<tr>
<td>reduced flaps</td>
<td>33.4</td>
<td>643</td>
<td>74.39</td>
<td>85.05</td>
</tr>
<tr>
<td>delayed GD</td>
<td>35.3</td>
<td>663</td>
<td>78.62</td>
<td>87.70</td>
</tr>
<tr>
<td>reduced flaps &amp; delayed GD</td>
<td>26.0</td>
<td>643</td>
<td>57.91</td>
<td>85.05</td>
</tr>
<tr>
<td>Combination</td>
<td>11.1</td>
<td>614</td>
<td>24.72</td>
<td>81.22</td>
</tr>
<tr>
<td>KLM-Procedure</td>
<td>31.6</td>
<td>643</td>
<td>70.38</td>
<td>85.05</td>
</tr>
</tbody>
</table>

Table 6.3: The absolute and relative results of the manual control workload calculation for all procedures.
The influence of the approach altitude on pitch and engine workload is graphically depicted in figure 6.11.

![Approach Altitude vs. Pilot Workload](image1)

*Figure 6.11: The influence of the approach altitude on the calculated pitch and engine manual control workload.*

Figure 6.12 shows the influence of the ILS-approach angle on the calculation of the manual control workload.

![ILS-Approach Angle vs. Pilot Workload](image2)

*Figure 6.12: The influence of the ILS-approach angle on the calculated pitch and manual control workload.*
Finally, the results of the manual control workload calculation of all of the practicable approach procedures are shown in figure 6.13.

![Graph showing pilot workload and engine workload for different approach procedures](image)

Figure 6.13: The manual control workload results for all of the practicable approach procedure adjustments.

6.7. Discussion

For higher altitudes the manual pitch control workload decreases with increasing altitude. Manual engine control workload remains approximately the same as the reference value.

The results for steeper approaches seem to be invalid for ILS-approach angles of 3.5 degrees and higher. This is caused by the simulation program ASINOP as a direct consequence of the 'approach idle' setting of the engines, which remains a constant when the desired airspeed cannot be reached. A constant control setting in the frequency domain results in no frequency at all at which control takes place, therefore the workload metric for manual engine setting control results in lower values. However, the approach angle of interest is 3.25 degrees, and it seems that manual pitch control workload increases by 2% and engine control workload decreases with 4%.

All of the other approach procedures result in a lower workload following the calculation technique as described in this chapter. The biggest question we have now is whether the data ASINOP delivers is correct data compared with the reality. In the next chapter we shall see that some of the assumptions that are made are not completely realistic.
7

The Simulator Session

7.1. Introduction
7.2. Performance Data
7.3. The Flight Management Task
7.4. Manual Control Workload Results
7.1. Introduction

Two engineering pilots of the KLM Royal Dutch Airlines gave the author the opportunity to validate some of the manual control workload predictions with the use of simulator data. The main objective of this experiment was to perform workload calculations on performance data with a pilot-in-the-loop. The secondary objective was simply to gain more insight in what happens in the cockpit during the approach phase.

As described in the previous chapter, the manual control workload calculation uses performance data with the requirement that the time-interval is constant, because of the transformation of the data to the frequency-domain. Performance data acquisition took place by a computer linked up with the simulator.

An audio recording of the pilots in action was made in order to process the pilot's running commentary and the sequence of tasks at a later time.

Six different approach procedures were flown:

1. The reference procedure.
2. The reference procedure with an approach altitude of 3000 ft.
3. The KLM-procedure.
4. The reference procedure with 20 kts downwind.
5. The KLM-procedure with 20 kts downwind.
6. An approach procedure with two engines out at one side.

Section 7.2 discusses the performance data of the six simulated approaches. Section 7.3 deals with a first timeline analysis of the six approach procedures, and contains some of the subjective remarks the two pilots made during the session. Finally, in the last section the simulator performance data is used to calculate manual control workload according to the method described in the previous chapter.

7.2. Performance Data

The following parameters were stored during the simulated approach procedures:

- latitude;
- longitude;
- N1 compressor speed;
- pitch angle;
- roll angle;
- heading, and;
- Calibrated Air Speed.

Because the approach procedures as used in this report are two-dimensional only the longitudinal parameters were of importance, i.e., N1 compressor speed, pitch angle and CAS. The three-dimensional parameters were recorded for another research project that took place during the same simulator session.

Because tabular data was not available, the longitudinal parameters were measured manually from the graphs that were produced by the data acquisition unit. Appendix D contains the resulting graphs. The altitude parameter was not stored by the data acquisition unit during the session, which is too bad, because altitude is the best parameter to match ASINOP- and simulator-data in a graphical representation. However, the reference
procedure is overlaid with the ASINOP-performance data and as can be seen in figure D.1 it is very hard to compare these data-sets.

7.3. The Flight Management Task

This section is divided into two parts. The first part is an initial step into the direction of a task analysis, the second part consists of a selection from the subjective commentary of the two pilots.

The conversation in the simulator was recorded by a hanging microphone above each pilot's head. Commands and checks can be heard clearly on the recording, and it is possible to measure the time in between tasks with a stopwatch. The result of this very crude task breakdown is a general timeline analysis, presented in figure 7.1.

![Timeline Analysis Diagram](image)

**Figure 7.1: A first step towards a timeline analysis.**

On the vertical axis of this figure are the six simulated approach procedures, the horizontal axis represents the cumulative time. The legend besides the graph is the sequence of events, which is always the same in every approach procedure. Above the task lines a thick black line is drawn, representing the time that it takes from the command of 'Landing Checklist' to the statement of the PNF 'Landing Checklist completed'. The small triangle above a task line indicates the point in time when the aircraft flew over the Outer Marker (OM).

All of the measurements start with the command of the PF to the PNF to select a **flap setting of 20**, after which approx. 9 seconds later the command **speed 20 mark** is given. Upon glide slope intercept, ca. 5 seconds later the command **gear down** is given to the PNF, after which, depending on the procedure (normal or delayed), **landing flaps** are selected, and the PF asks to set a speed mark on **Vref + 5**. Somewhere around this time, the PF orders the **landing checklist**, but there is no specific point in time when that happens. At 1200 ft the **OM** is passed. Between the OM and the next event, where a computer voice (CV) calls out: "**500 ft**", it is required for KLM-pilots to have the aircraft stabilised, after which the PNF should look visually for the **runway**, and the decision can be
made to make a landing. The next event is the CV counting down from "100" to "10 ft". After touchdown the thrust reversers are put into work, and speed decreases. The PNF calls out the ground speed from "100 ground speed" to "50" or lower.

As can be seen from figure 7.1 the reference procedure gives the pilots the most time to perform their tasks. However, there is reason to believe that the 3000 ft approach procedure is even less time-pressing, but no task data could be measured, because the simulator was set on 'freeze' by the data acquisition unit in the middle of a simulation run.

As expected the KLM-procedure results in shift of some tasks, such as the landing flaps setting, and completing the landing checklist, to a later point in the procedure. As the extension of the landing gear and the selection of a new flap setting results in an alteration of the aircraft's stability, the time between the configuration change and the 500 ft approach stability may become short.

No conclusions should be drawn from figure 7.1 because the data comes from a session during which the pilots where also giving a constant commentary. For example the reason of the long time between start of the landing checklist and completing it in the fifth run (KLM-procedure, 20 kts downwind), is a direct result of the PNF who wanted to finish his commentary.

Important subjective remarks by the pilots:

- The PF watches the following parameters closely during the final approach phase: the position of the aircraft with respect to centerline of the runway, airspeed, pitch and roll. But the hardest task in the approach phase is to stabilize the airspeed.
- The aircraft is said to be stable when the speed/thrust ratio feels right.
- The extension of the landing gear at intercept altitude results in enough drag to pitch the aircraft on the ILS-GS.
- The decision for a go-around is ultimately made when the aircraft flies over the runway threshold.
- The 500 ft call by a computer voice obligates the PF to make a decision on the stability of the aircraft, because the PF has to clear this call.
- The PNF continually watches the PF and checks his performance. The PNF is the pilot who talks to ATC. When there are high winds, the PNF also monitors the wind-changes in speed and direction.
- The assumption throughout the study in this report is made that the approach speed is \( V_{\text{REF}} \). In reality this speed is \( V_{\text{REF}} + 5 \) in ideal weather conditions.
- In general, stability is already reached at an altitude of 800 ft with the KLM-procedure. It takes approximately 500 ft to stabilize from a landing gear extension, therefore the delayed gear procedure can become a difficult one to fly.
- There is a lot of time for performing all of the tasks in the 3000 ft approach procedure. At an early point on the Glide-Slope all tasks are already done, and no configuration changes will take place before touchdown.
- In the KLM-procedure a lot of tasks are concentrated in a short time period at 1200 ft. at the OM.
- All of the approach procedures, including the procedure with two engines inoperative, are designed so, that the sequence of events remains the same.
- In the "Two Engines Out"-approach a lot of attention of the PF is required to constantly trim the rudder at a new engine setting. However, at 700 ft altitude the trim is set to zero, so that the PF feels the forces on the rudder during the final phase and touchdown. For this approach, landing clearance is needed, before the landing gear is extended.
7.4. Manual Control Workload Results

In conclusion, the performance data of the simulator session was used to assess manual pilot control workload according to the calculation method as described in the previous chapter. Table 7.1 contains the absolute and relative workload values. The reference procedure is taken as run 1.

<table>
<thead>
<tr>
<th></th>
<th>Pitch WL</th>
<th>Engine WL</th>
<th>Pitch WL</th>
<th>Engine WL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>2865</td>
<td>853757</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3000 ft.</td>
<td>5070</td>
<td>101000</td>
<td>176.94</td>
<td>118.30</td>
</tr>
<tr>
<td>KLM</td>
<td>4370</td>
<td>677000</td>
<td>152.51</td>
<td>79.30</td>
</tr>
<tr>
<td>Ref wind</td>
<td>3100</td>
<td>832000</td>
<td>108.19</td>
<td>97.45</td>
</tr>
<tr>
<td>KLM wind</td>
<td>4320</td>
<td>597000</td>
<td>150.77</td>
<td>69.93</td>
</tr>
<tr>
<td>&quot;2 Engines Out&quot;</td>
<td>4190</td>
<td>1360000</td>
<td>146.23</td>
<td>159.30</td>
</tr>
</tbody>
</table>

Table 7.1: The absolute and relative manual control workload levels of the simulator session.

Table 7.1 is depicted graphically in figure 7.2.

![Figure 7.2: Manual control workload levels of the approaches from the simulator session.](image)

The performance data and resulting workload calculations of the 3000 ft approach procedure is probably incorrect due to a sudden freeze of the simulator by the data acquisition unit in the middle of the simulated approach.
The approaches were flown only once by only one pilot. It should be clear that the dataset for the workload calculations is therefore not a dataset that reflects the reality in a good manner. Hence the calculations should be viewed at as an initial calculation of the pilot workload with a highly subjective nature.
8

Conclusions & Recommendations

8.1. Conclusions
8.2. Recommendations
8.1. Conclusions

Operational measures for the reduction of noise load may lead to a reduction in flight safety, but could just as well increase the safety level. Nowadays it is not desirable to postpone the acquisition of the 'safety proof' until the operational phase of a new flight procedure. In this report techniques were explored for an operational aircraft safety quantification method that may give an answer on how to obtain this safety proof. The following general conclusions are drawn:

- The proactive nature of the present aviation safety research should be used to obtain this safety proof.
- Quantification of operational aircraft safety is a proactive calculation, reflecting a highly theoretical description of a very turbulent and unpredictable process that takes place in an area where multiple disciplines act together.
- There are five techniques for the assessment of the operational safety of flight procedures. These are: statistical analysis of aircraft accident and incident data, structured interviews and brainstorm sessions with pilots and experts, 'Monte Carlo' simulation, pilot workload assessment, and pilot-aircraft system performance assessment. These assessment techniques are interrelated with each other and none of them guarantees to be the best usable technique.
- There is no practiced method for the validation of a safety quantification method.

The results of this exploratory investigation were laid down in the first steps towards an Airport Safety Index, based on the limitations of the users in the aviation system (the pilot and the air traffic controller). The following conclusions are drawn with respect to the proposed safety index:

- It is possible to assess the internal safety of aircraft flying well-defined take-off and landing procedures with the use of such a safety index.
- The safety level of a pilot flying an aircraft can be connected to the pilot’s residual workload capacities called the safety margin. This safety margin has the ability to intercept part of the extra workload resulting from unpredictable emergency situations, and is defined by the difference between actual workload as a result of the complexity of the imposed task system, and the boundary of saturation, or workload limit, beyond which a so-called overload condition occurs.
- Pilot workload cannot be defined completely, depends on a large variety of parameters, and has a direct link with the pilot’s ability to maintain or reach a desired performance level.
- By dividing the pilot task into four sub-tasks, being the Flight Management Task, the Manual Control Task, the Scanning & Monitoring Task, and ATC-Related Tasks, we can comply to the different predictive workload modeling technique for each task separately.
- Without ATC-intervention, a single aircraft would fly the approach procedures exactly as is ideally dictated in the concerned documents. ATC is the primary cause of the fact that this does not happen for real, because ATC-controllers are responsible for the safe operation of aircraft with respect to other aircraft and as such they tell the pilot to deviate from the ideal flight path procedure. When, how and why this happens cannot be predicted.
Of the four sub-tasks only the Flight Management Task and the Manual Control Task were considered in the study in this report. A predictive workload assessment technique for the discrete flight management tasks is proposed, which consists of existing techniques based on Wickens’ multiple-resources theory. Workload that results from the Manual Control Task is calculated according to a technique suggested by Padfield. It can be concluded that:

- The proposed flight management task workload assessment technique is a very detailed and time-consuming technique, which might present a good quantification of pilot workload that results from discrete tasks.
- Both predictive workload assessment techniques present a solution to eliminate the 'vagueness' of pilot workload.

Several adjustments to the reference approach procedure were considered. These were: higher ILS-interception altitudes, steeper approaches, reduced flaps and delayed gear down, a combination, and the KLM-procedure (reduced and delayed flaps). The manual control workload was calculated for these approach procedures using a simulation program called ASINOP. Some of approach procedures were flown in a simulator session. The following conclusions are drawn:

- Higher approach altitudes cause a longer duration of time in which all of the tasks, such as selecting new flap settings and landing gear extension, have to be performed. Also the workload resulting from manual pitch control reduces considerably according to the manual control workload calculation technique. This adjustment to the approach procedure could promise to be profitable for operational safety.
- The steeper approach procedure with an ILS-path angle of 3.25 degrees shows almost no difference with respect to the reference procedure.
- The analytical results of the manual control workload calculations of the reduced flaps, delayed gear down, the combination, and the KLM-approach procedure result in a very low workload, while much higher values were expected. The cause for this peculiarity was found in the limitations of the simulation program ASINOP, which was used for the production of performance data.
- The differences between the performance data from ASINOP and the simulator session are considerable. First of all the approach procedures in the simulator are flown with a higher speed-profile. Secondly, the variations in the control signal result in a high control activity of the pilot in the simulator, whereas the simulated pilot in ASINOP controls the aircraft probably too perfect. The cause for this is that ASINOP reacts on small and large deviations of the desired aircraft state in the same manner.
- The KLM-procedure of the simulator session shows a higher manual pitch workload with respect to the reference procedure, probably caused by the more aggressive control in order to stabilize the aircraft above 500 ft.

8.2. Recommendations

→ The recommendations in this section are sorted in chronological order as their subjects were presented in the report. The final two recommendations serve a more general purpose.

It is recommended that an extensive analysis of the available operational safety assessment techniques for flight procedures is performed. The product of such an analysis would be a list of advantages and disadvantages of the various techniques.

One of the potential operational safety assessment techniques was a statistical analysis of the present safety level, based on accident and incident data, such as flying activity data, etc. Such a study has been performed in Australia, with very positive results. It is
recommended to perform such a study for the Netherlands aviation system too, as one of the first steps towards measurable safety levels.

A thorough evaluation of the Airport Safety Index calculation method should be performed, giving an answer to the following question: "Is this the right way to tackle the problem of quantification of operational safety?". This evaluation should be carried out by a project group, consisting of experts in safety science, human factors, ATC, government regulations, aircraft operations, airport operations, and aeronautical engineering.

A study into possible workload modeling techniques for the Scanning & Monitoring and the ATC-related tasks is recommended, as this was not carried out in the study of this report.

A solution for the unpredictability-problem of the ATC-tasks and the effects on the rest of the task system may be found in the introduction of randomizing functions or in fuzzy logic for example.

Further psychological research is recommended in order to quantify the maximum workload and actual workload as a function of the complexity of the task system in order to quantify the theory on the relationship between pilot workload and operational safety.

The component workload scales of the McCracken-Aldrich approach as used in the proposed quantification technique for the Flight Management Task workload needs a translation from military helicopters to large commercial fixed-wing aircraft.

Although a proposal was made for a flight management task workload assessment technique, no experiments were performed. It is recommended to carry out such an experiment in order to evaluate the proposed technique.

An initial timeline cognitive task analysis technique could be to divide all the discrete tasks of the pilot into the distinction as presented in ref. 19, where task performance is thought to be skill-based, rule-based, or knowledge based, thus concentrating on the cognitive side of tasks.

Adjustments should be made to the simulation program ASINOP in order to produce more realistic performance data, including delayed engine response, a PID-controlled elevator angle, and flap/gear extensions that take time. It is also recommended to implement three-dimensional aircraft control in order to expand the longitudinal approach phase with the three-dimensional part of the approach procedure.

Other landing simulation programs than ASINOP should be evaluated for their use for pilot workload calculations.

→ General recommendations:

Other aircraft than the Boeing 747-400 should be investigated.

It might be possible to validate the highly theoretical technique as described in this report and to gain more insight into the actual workload of pilots during the final approach procedure if a large data-set can be created of empirical workload assessments in real flight. For example, a large number of flights are made with the Cessna Citation Flying Classroom of the Faculty of Aerospace Engineering. If the pilots where asked to wear a heart-rate meter during approach procedures this large data-set can be created.
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Appendices

A: The Role of Pilot Workload in the FAR Part 25 Regulations
B: An Example of the Pilot Workload Component Scales of the McCracken-Aldrich Approach
C: The Matlab-Program Code of Workload.m
D: Longitudinal Performance Data of the Simulator Session
Appendix A: The Role of Pilot Workload in the FAR Part 25 Regulations

Airworthiness Standards: Transport Category Airplane

SEC. 25.771 PILOT COMPARTMENT.

(a) Each pilot compartment and its equipment must allow the minimum flight crew (established under Sec. 25.1523) to perform their duties without unreasonable concentration or fatigue.

(b) The primary controls listed in Sec. 25.779(a), excluding cables and control rods, must be located with respect to the propellers so that no member of the minimum flight crew (established under Sec. 25.1523), or part of the controls, lies in the region between the plane of rotation of any inboard propeller and the surface generated by a line passing through the center of the propeller hub making an angle of five degrees forward or aft of the plane of rotation of the propeller.

(c) If provision is made for a second pilot, the airplane must be controllable with equal safety from either pilot seat.

(d) The pilot compartment must be constructed so that, when flying in rain or snow, it will not leak in a manner that will distract the crew or harm the structure.

(e) Vibration and noise characteristics of cockpit equipment may not interfere with safe operation of the airplane.


SEC. 25.1523 MINIMUM FLIGHT CREW.

The minimum flight crew must be established so that it is sufficient for safe operation, considering:

(a) The workload on individual crewmembers;

(b) The accessibility and ease of operation of necessary controls by the appropriate crewmember; and

(c) The kind of operation authorized under Sec. 25.1525.

The criteria used in making the determinations required by this section are set forth in Appendix D.

APPENDIX D TO PART 25

Criteria for determining minimum flight crew. The following are considered by the Agency in determining the minimum flight crew under Sec. 25.1523:

(a) **Basic workload functions.** The following basic workload functions are considered:
   1. Flight path control.
   2. Collision avoidance.
   5. Operation and monitoring of aircraft engines and systems.

(b) **Workload factors.** The following workload factors are considered significant when analyzing and demonstrating workload for minimum flight crew determination:
   1. The accessibility, ease, and simplicity of operation of all necessary flight, power, and equipment controls, including emergency fuel shutoff valves, electrical controls, electronic controls, pressurization system controls, and engine controls.
   2. The accessibility and conspicuity of all necessary instruments and failure warning devices such as fire warning, electrical system malfunction, and other failure or caution indicators. The extent to which such instruments or devices direct the proper corrective action is also considered.
   3. The number, urgency, and complexity of operating procedures with particular consideration given to the specific fuel management schedule imposed by center of gravity, structural or other considerations of an airworthiness nature, and to the ability of each engine to operate at all times from a single tank or source which is automatically replenished if fuel is also stored in other tanks.
   4. The degree and duration of concentrated mental and physical effort involved in normal operation and in diagnosing and coping with malfunctions and emergencies.
   5. The extent of required monitoring of the fuel, hydraulic, pressurization, electrical, electronic, deicing, and other systems while en route.
   6. The actions requiring a crewmember to be unavailable at his assigned duty station, including: observation of systems, emergency operation of any control, and emergencies in any compartment.
   7. The degree of automation provided in the aircraft systems to afford (after failures or malfunctions) automatic crossover or isolation of difficulties to minimize the need for flight crew action to guard against loss of hydraulic or electric power to flight controls or to other essential systems.
   8. The communications and navigation workload.
   9. The possibility of increased workload associated with any emergency that may lead to other emergencies.
   10. Incapacitation of a flight crewmember whenever the applicable operating rule requires a minimum flight crew of at least two pilots.

(c) Kind of operation authorized. The determination of the kind of operation authorized requires consideration of the operating rules under which the airplane will be operated. Unless an applicant desires approval for a more limited kind of operation. It is assumed that each airplane certificated under this Part will operate under IFR conditions.

[Amdt. 25-3, 30 FR 6067, Apr. 29, 1965]
Appendix B: An Example of the Pilot Workload Component Scales of the McCracken-Aldrich Approach.

This appendix contains the pilot workload component scales of a mission/task/workload analysis of the UH-60A helicopter, as described in ref. #.#.#.

<table>
<thead>
<tr>
<th>Scale Value</th>
<th>Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual-Unaided (Naked Eye)</strong></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>Visually Register/Detect (Detect occurrence of image)</td>
</tr>
<tr>
<td>3.7</td>
<td>Visually Discriminate (Detect visual differences)</td>
</tr>
<tr>
<td>4.0</td>
<td>Visually Inspect/Check (Discrete inspection/static condition)</td>
</tr>
<tr>
<td>5.0</td>
<td>Visually Locate/Align (Selective orientation)</td>
</tr>
<tr>
<td>5.4</td>
<td>Visually Track/Follow (Maintain orientation)</td>
</tr>
<tr>
<td>5.9</td>
<td>Visually Read (Symbol)</td>
</tr>
<tr>
<td>7.0</td>
<td>Visually Scan/Search Monitor (Continuous/serial inspection, multiple conditions)</td>
</tr>
<tr>
<td><strong>Visual-Aided (Night Vision Goggles [NVG])</strong></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>Visually Register/Detect (Detect occurrence of image) with NVG</td>
</tr>
<tr>
<td>4.8</td>
<td>Visually Inspect/Check (Discrete inspection/static condition) with NVG</td>
</tr>
<tr>
<td>5.0</td>
<td>Visually Discriminate (Detect visual differences) with NVG</td>
</tr>
<tr>
<td>5.6</td>
<td>Visually Locate/Align (Selective orientation) with NVG</td>
</tr>
<tr>
<td>6.4</td>
<td>Visually Track/Follow (Maintain orientation) with NVG</td>
</tr>
<tr>
<td>7.0</td>
<td>Visually Scan/Search Monitor (Continuous/serial inspection, multiple conditions) with NVG</td>
</tr>
<tr>
<td><strong>Auditory</strong></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>Detect/Register Sound (Detect occurrence of sound)</td>
</tr>
<tr>
<td>2.0</td>
<td>Orient to Sound (General orientation/attention)</td>
</tr>
<tr>
<td>4.2</td>
<td>Orient to Sound (Selective orientation/attention)</td>
</tr>
<tr>
<td>4.3</td>
<td>Verify Auditory Feedback (Detect Occurrence of Anticipated Sound)</td>
</tr>
<tr>
<td>4.9</td>
<td>Interpret Semantic Content (Speech)</td>
</tr>
<tr>
<td>6.6</td>
<td>Discriminate Sound Characteristics (Detect Auditory Differences)</td>
</tr>
<tr>
<td>7.0</td>
<td>Interpret Sound Patterns (Pulse Rates, Etc.)</td>
</tr>
<tr>
<td><strong>Kinesthetic</strong></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>Detect Discrete Activation of Switch (Toggle, Trigger, Button)</td>
</tr>
<tr>
<td>4.0</td>
<td>Detect Preset Position or Status of Object</td>
</tr>
<tr>
<td>4.8</td>
<td>Detect Discrete Adjustment of Switch (Discrete Rotary or Discrete Lever Position)</td>
</tr>
<tr>
<td>5.5</td>
<td>Detect Serial Movements (Keyboard Entries)</td>
</tr>
<tr>
<td>6.1</td>
<td>Detect Kinesthetic Cues Conflicting with Visual Cues</td>
</tr>
<tr>
<td>6.7</td>
<td>Detect Continuous Adjustment of Switches (Rotary Rheostat, Thumbwheel)</td>
</tr>
<tr>
<td>7.0</td>
<td>Detect Continuous Adjustment of Controls</td>
</tr>
<tr>
<td><strong>Cognitive</strong></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>Automatic (Simple Association)</td>
</tr>
<tr>
<td>1.2</td>
<td>Alternative Selection</td>
</tr>
<tr>
<td>3.7</td>
<td>Sign/Signal Recognition</td>
</tr>
<tr>
<td>4.6</td>
<td>Evaluation/Judgment (Consider Single Aspect)</td>
</tr>
<tr>
<td>5.3</td>
<td>Encoding/Decoding, Recall</td>
</tr>
<tr>
<td>6.8</td>
<td>Evaluation/Judgment (Consider Several Aspects)</td>
</tr>
<tr>
<td>7.0</td>
<td>Estimation, Calculation, Conversion</td>
</tr>
<tr>
<td></td>
<td>Psychomotor</td>
</tr>
<tr>
<td>---</td>
<td>-------------</td>
</tr>
<tr>
<td>1.0</td>
<td>Speech</td>
</tr>
<tr>
<td>2.2</td>
<td>Discrete Actuation (Button, Toggle, Trigger)</td>
</tr>
<tr>
<td>2.6</td>
<td>Continuous Adjustable (Flight Control, Sensor Control)</td>
</tr>
<tr>
<td>4.6</td>
<td>Manipulative</td>
</tr>
<tr>
<td>5.8</td>
<td>Discrete Adjustable (Rotary, Vertical Thumbwheel, Lever Position)</td>
</tr>
<tr>
<td>6.5</td>
<td>Symbolic Production (Writing)</td>
</tr>
<tr>
<td>7.0</td>
<td>Serial Discrete Manipulation (Keyboard Entries)</td>
</tr>
</tbody>
</table>

Table B.1: Pilot workload component scales for the UH-60A Mission/Task/Workload analysis. (Source: Ref. 2)
Appendix C: The Matlab-Program Code WORKLOAD.M

The following Matlab-code is used to calculate spectral density functions and Workload-levels.

% This program calculates and plots the power spectral density
% function of pitch and engine control.
% This program also calculates the root mean square (rms) of
% control activity of both controlled parameters, giving an
% indication of the accompanying workload level.

deltat = 0.10; % Definition of the time interval
t_end = 290; % Last point in time
fs = 1/deltat; % Definition of the sample rate
N = t_end*fs; % Number of data points
t = [deltat:deltat:t_end]; % Definition of the time-axis

% Load data-file containing performance data
cd results;
load refproc;
cd ..;

y = x(:,0); % Define y as all engine setting data points
x = x(:,7); % Re-define x as all pitch data-points

X = fft(x); % Fast Fourier Transform of x
Sxx = X.*conj(X)/N; % Calculate power spectral density of x

% Define frequency-axis and prepare power spectral densities ...
% ... for pitch control as a function of frequency.
f = fs*(0:N/2-1);
for i=1:N/2
    fg(i) = -f(N/2+1-i);
    Sx(i) = Sxx(N/2+1-i);
end
f = [fg f]; % Frequency-axis
Sxx = [Sx (Sxx(1:N/2))']; % Power spectral density values

Y = fft(y); % Fast Fourier Transform of y
Syy = Y.*conj(Y)/N; % Calculate spectral density of y

% Prepare power spectral densities for engine control ....
% ... as a function of frequencey.
for i=1:N/2
    Sy(i) = Syy(N/2+1-i);
end
Syy = [Sy (Syy(1:N/2))'];

WLtheta = 0; % Initialize pitch workload parameter
WLtau = 0; % Initialize engine workload parameter
% Calculation of the rms of control
for i=1:N/2
    WLTtheta = WLTtheta + ((Sxx(1,i))^2);
    WLTau = WLTau + ((Syy(1,i))^2);
end

WLTtheta = sqrt(WLTtheta/(N/2)); % rms of pitch control
WLTau = sqrt(WLTau/(N/2)); % rms of engine control

% Save Workload-values
WL = [WLTtheta WLTau];
cd results;
save WL.txt WL -ascii;
cd ..;

% Plot power spectral density of pitch control
figure(1);
loglog(f(N/2:N-1),Sxx(N/2:N-1));
xlabel('frequency [Hz]');ylabel('Sxx');
title('Power Spectral Density THETA (Loglog Scales)');

% Plot power spectral density of engine control
figure(2);
loglog(f(N/2:N-1),Syy(N/2:N-1));
xlabel('frequency [Hz]');ylabel('Syy');
title('Power Spectral Density TAU (Loglog Scales)');

% END OF PROGRAM
Appendix D: Longitudinal Performance Data of the Simulator Session

Figure D.1: The Reference Procedure.
Figure D.2: The Reference procedure with 3000 ft approach altitude.
Figure D.3: The KLM-procedure.
Figure D.4: The reference procedure with 20 kts downwind.
Figure D.5: The KLM-procedure with 20 kts downwind.
Figure D.6: "Two Engines Out".