UNIVERSITY OF SÃO PAULO

A comparison between qualitative pilots' opinion and quantitative flight data on potential loss of control in flight conditions

João Paulo Costa Antunes de Macedo

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SÃO CARLOS SCHOOL OF ENGINEERING

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To all those who have devoted their time
to teach me something.

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ABSTRACT

MACEDO, J. P. C. A. **A comparison between qualitative pilots' opinion and quantitative flight data on potential loss of control in flight conditions**. 2021. Thesis (Master's in Mechanical Engineering) – São Carlos School of Engineering, University of São Paulo, São Carlos, 2021.

Loss of Control in Flight (LOC-I) is the most lethal type of air accidents in recent aviation history; however, its characteristics are still not well understood, especially from the perspective of the human pilot. This research analysed whether (and to which extent) a quantitative LOC-I detection criterion correlates with subjective pilots' opinions on the controllability of an aircraft. Six flight test pilots flew a Boeing 777 in four scenarios (different combinations of typical LOC-I precursors) in a flight simulator, and performed 13 manoeuvres specifically designed to assess different aspects of controllability. The aircraft controllability category was determined from the pilots' qualitative opinions for each manoeuvre, via the so-called Cooper-Harper Rating Scale (CHR), and from recorded flight data, according to the Quantitative Loss of Control Criteria (QLC). Statistical correlation tests determined the degree of correlation between the approaches. A positive weak statistically significant correlation was found between the controllability categories resulting from both CHRs and QLC, thus revealing a lack of clear connection between the understandings of a LOC-I by human pilots and quantitative engineering metrics. The outcomes suggest LOC-I detection criteria should be revised towards including qualitative pilots' opinion, i.e., human-related factors must be given proper attention prior to the introduction and spread of potential "LOC-I solutions" solely based on quantitative metrics.

Keywords: Loss of control in flight. Cooper-Harper scale. QLC. Controllability. Flight simulator. Flight safety. Aircraft dynamics. Human-machine interaction. Flight test.

RESUMO

MACEDO, J. P. C. A. **Um comparativo entre percepção de pilotos humanos e parâmetros de voo em potenciais condições de perda de controle em voo**. 2021. Dissertação (Mestrado em Engenharia Mecânica) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2021.

A Perda de Controle em Voo (LOC-I) é o tipo de acidente aéreo mais letal na história recente da aviação, mas suas características ainda não são bem compreendidas, especialmente sob a perspectiva do piloto humano. Esta pesquisa analisou se (e em que medida) um critério quantitativo de detecção de LOC-I correlaciona-se com a percepção subjetiva de pilotos humanos acerca da controlabilidade de uma aeronave. Em um simulador de voo, seis pilotos voaram um Boeing 777 em quatro cenários LOC-I (diferentes combinações de precursores típicos) e realizaram um conjunto de 13 manobras projetadas especificamente para avaliar diferentes aspectos de controlabilidade. Para cada manobra, a categoria de controlabilidade da aeronave foi determinada a partir da opinião qualitativa do piloto, por meio da chamada Escala de Classificação Cooper-Harper (CHR), e dos dados de voo, por meio do Critério de Perda Quantitativa de Controle (QLC). Testes de correlação estatística foram executados para determinar o grau de correlação entre as abordagens. Encontrou-se correlação positiva fraca estatisticamente significativa entre as categorias de controlabilidade decorrentes do CHRs e do QLC. Dada a fraca correlação, conclui-se que não há clara conexão entre o que os pilotos humanos entendem como LOC-I e o que as métricas de engenharia quantitativas sinalizam ser. Os resultados sugerem que os critérios de detecção de LOC-I devem ser revisados para incluir a opinião qualitativa de pilotos, ou seja, antes de introduzir e difundir potenciais "soluções LOC-I" unicamente baseadas em métricas quantitativas, fatores humanos devem ser considerados em sua devida atenção.

Palavras-chave: Perda de controle em voo. Escala Cooper-Harper. QLC. Controlabilidade. Simulador de voo. Segurança de voo. Dinâmica da aeronave. Interação humano-máquina. Ensaio em voo.

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AA Adverse Aerodynamics envelope

AGL Above Ground Level

AoA Angle of Attack

CAST Commercial Aviation Safety Team

CFIT Controlled Flight Into Terrain

CG Centre of Gravity

CHR Cooper-Harper Rating

CICTT Commercial Aviation Safety Team/ICAO Common Taxonomy Team

DOF Degree of Freedom

DPC Dynamic Pitch Control envelope

DRC Dynamic Roll Control envelope

EASA European Aviation Safety Agency

EGPWS Enhanced Ground Proximity Warning System

EICAS Engine Indicating and Crew Alerting System

FAA Federal Aviation Administration

FADEC Full Authority Digital Engine Control

FBW Fly-by-Wire

FCS Flight Control System

FDR Flight Data Recorder

FMS Flight Management System

GARTEUR Group for Aeronautical Research and Technology in Europe

GS Glideslope

HRC High-Risk Occurrences Categories

IATA International Air Transport Association

ICAO International Civil Aviation Organization

ILS Instrument Landing System

IVP Initial Value Problem

KSFO San Francisco International Airport

LDG Landing Gear

LOC Loss of Control, Localizer

LOC-I Loss of Control in Flight

MAC Mean-Aerodynamic Chord

MCAS Manoeuvring Characteristics Augmentation System

MTOW Maximum Takeoff Weight

NASA National Aeronautics and Space Administration

NLR Netherlands Aerospace Centre

NTSB National Transportation Safety Board

OEI One-Engine Inoperative

PAPI Precision Approach Path Indicator

PFD Primary Flight Display

PID Proportional-Integral-Derivative

PIO Pilot-Induced Oscillation

QLC Quantitative Loss of Control Criteria

RE Runway Excursion

RMS Root Mean Square

RQ Research Question

RS Runway Safety

SD Standard Deviation

SERFI Safety Enhancements Reserved for Future Implementation

SI Structural Integrity envelope

TAWS Terrain Awareness and Warning System

UA Unusual Attitude envelope

UPRT Upset Prevention and Recovery Training

US United States of America

LIST OF SYMBOLS

Roman letters

b	Wingspan
$\overline{c}$	Mean aerodynamic chord
c_D	Drag coefficient
c_L	Lift coefficient
$c_{\mathcal{L}}$	Rolling moment coefficient
c_M	Pitching moment coefficient
c_N	Yawing moment coefficient
c_{ref}	Chord reference length
c_Y	Lateral-force coefficient
$c_{D_0}, c_{L_0}, c_{M_0}$	Base coefficients (null incidence)
$c_{D_u}, c_{L_u}, c_{M_u}$	Stability derivatives with respect to Δu
$c_{D_\alpha}, c_{L_\alpha}, c_{M_\alpha}$	Stability derivatives with respect to α
$c_{D_{\delta_a}}, c_{\mathcal{L}_{\delta_a}}, c_{N_{\delta_a}}, c_{Y_{\delta_a}}$	Stability derivatives with respect to δ_a
$c_{D_{\delta_e}}, c_{L_{\delta_e}}, c_{M_{\delta_e}}$	Stability derivatives with respect to δ_e
c_{L_q}, c_{M_q}	Stability derivatives with respect to q
$c_{L_{\dot\alpha}}, c_{M_{\dot\alpha}}$	Stability derivatives with respect to $\dot\alpha$
$c_{L_{\delta_{th}}}, c_{M_{\delta_{th}}}$	Stability derivatives with respect to Δth
$c_{\mathcal{L}_p}, c_{N_p}, c_{Y_p}$	Stability derivatives with respect to p
$c_{\mathcal{L}_r}, c_{N_r}, c_{Y_r}$	Stability derivatives with respect to r
$c_{\mathcal{L}_\beta}, c_{N_\beta}, c_{Y_\beta}$	Stability derivatives with respect to β
$c_{\mathcal{L}_{\delta_r}}, c_{N_{\delta_r}}, c_{Y_{\delta_r}}$	Stability derivatives with respect to δ_r
D	Drag force
$\mathbf{F}$	Force vector
$mag(\cdot)$	Magnitude of envelope excursion

$\mathbf{F_b}$	Net force vector
F_x, X	Longitudinal force component
F_y, Y	Lateral force component
F_z, Z	Normal force component
$\mathbf{I}$	Inertia matrix
I_{xx}, I_{yy}, I_{zz}	Moment of inertia
$I_{xy}, I_{xz}, I_{xz}, I_{yz}$	Product of inertia
L	Lift force
$\mathcal{L}$	Rolling moment
m	Mass
$\mathcal{M}$	Pitching moment
$\mathbf{M_b}$	Net moment vector
n	Normal load factor
$\mathcal{N}$	Yawing moment
o_E	Origin of an inertia reference frame
o_b	Origin of a body reference frame
p	Roll rate; Statistical *p-value*
$\mathbf{p}$	Linear *momentum*
q	Pitch rate
r	Yaw rate
r_{bisR}	Biserial rank correlation coefficient
S_{ref}	Surface reference area
$time(\cdot)$	Time interval of envelope excursion
T	Thrust force
u	Longitudinal velocity transient perturbation component
v	Lateral velocity transient perturbation component
V_E	Equivalent airspeed
V_{FE}	Maximum operating equivalent airspeed for flaps-down configuration

V_{MO}	Maximum operating equivalent airspeed for flaps-up configuration
V_{neg}	Normalised negative airspeed
V_{NORM}	Normalised airspeed
V_{pos}	Normalised positive airspeed
V_{SW}	Stall warning equivalent airspeed in 1-g flight
$\mathbf{V_{0_b}}$	Total linear velocity vector
w	Vertical velocity transient perturbation component
W	Weight
x_b, y_b, z_b	Axes names in a body reference frame
x_E, y_E, z_E	Axes names in an inertia reference frame

Greek letters

α	Angle of attack; Statistical significance level
α_{NORM}	Normalised angle of attack
α_{pos}	Normalised positive angle of attack
α_{SW}	Angle of attack for stall warning activation
β	Sideslip angle
β_{neg}	Normalised negative sideslip angle
β_{NORM}	Normalised sideslip angle
β_{MDXW}	Sideslip for non-crabbed approach in the maximum demonstrated crosswind for takeoff or landing
β_{pos}	Normalised positive sideslip angle
δ_a	Aileron deflection
δ_{ctrl}	Normalised position of a control device
δ_e	Elevator deflection
δ_r	Rudder deflection
δ_{th}	Trust variation
γ	Goodman and Kruskal's correlation coefficient
ϕ	Bank angle

ϕ'	Dynamic roll attitude
ϕ_c	Cramer's V correlation coefficient
τ_b	Kendall's tau-b correlation coefficient
θ	Pitch angle
θ'	Dynamic pitch attitude
ψ	Yaw angle
ρ	Air density; Spearman's rank correlation coefficient
$\omega_{\mathbf{0_b}}$	Total angular velocity vector

CONTENTS

INTRODUCTION

1 INTRODUCTION

THE increasing numbers of air passengers and competition have caused the maintenance of safe and affordable air travel to be challenging. According to IATA – International Air Transport Association –, only in 2016, aircraft transported more than three billion passengers, which represents a 7% increase in comparison to the previous year, thus surpassing the agency's growth forecasts. Among other reasons, this fact is intrinsically associated with low-cost policies strengthened in both Europe and the United States of America.[1]

Although economically positive for those who profit from aviation, the greater number of people crossing the air, on the other hand, may cause instabilities in the balance between *economic viability* and *safety of the activity*, which reinforces the importance of consolidating flight safety as an element inseparable from the aerial activity. ICAO (2017, p.2)[2] – International Civil Aviation Organization –, the main civil aviation body, claims its primary goal is:

> Improving the safety of the global air transport system is ICAO's guiding and most fundamental strategic objective. The Organization works constantly to address and enhance global aviation safety through coordinated activities and targets.

Accidents have vast social-economic impacts such as expenses, credibility of vehicles and the transportation system, and, mainly, negative consequences for people's lives. In early years of aviation, incidents and even accidents were considered normal and not given proper attention. In fact, only after World War II, when commercial aviation had been boosted, the first concerns about accidents and the importance of determining their causes for avoiding future similar situations came to light, thus resulting in several enhancements, such as the FDR – Flight Data Recorder –, in 1958, an accident-proof flight data recording device that could help investigation teams identify probable causes of accidents.[3]

In the subsequent years, and regardless of some safety-oriented efforts, air crashes continued to occur, accounting for several deaths. In 1996, the growth projections of aviation and, mainly, the society's confidence in air transport encouraged the US government to create an authority called White House Commission on Aviation Safety and Security.[4] Led by the US vice-president, the governing body had high representativeness and urged aeronautical industries and the FAA — Federal Aviation Administration — to develop a strategic plan for the monitoring and guidance of flight safety progress,[5] thus giving rise to CAST — Commercial Aviation Safety Team —, a working group dedicated to the safety of commercial aviation.

The initial studies conducted by CAST revealed the existence of several isolated flight safety efforts; however, the body pointed they were of least purpose, since all aviation stakeholders should work together towards similar safety purposes.[6] Consequently, CAST and ICAO joined and founded a third body called CICTT – Commercial Aviation Safety Team/ICAO Common Taxonomy Team –, involving the participation of aeronautical industries, certification authorities, government bodies, and international aviation monitoring agencies.[7] The team established all safety issues would not be tackled concomitantly, since such a strategy would delay the flight safety progress, and prevention efforts should be concentrated on topics of greatest benefits to both aerial activity and society. Such a prioritisation should be based on quantitative analyses and support the development of a safety strategic plan.[6]

In 1997, the White House Commission on Aviation Safety and Security's report revealed two types of accidents had been responsible for over 70% of deaths in US aviation in the five previous years.[8] The disasters were classified as *Loss of Control in Flight* – LOC-I – and *Controlled Flight Into Terrain* – CFIT –, and shaped the list of priorities to be debated already in that year.[6]

Towards a more effective guidance of prioritisation of prevention efforts, a new concept was developed, i.e., both frequency of occurrence of a particular type of accident and exposure of those onboard the aircraft to the risk of death (known as *fatality risk*[i]) were considered, thus shaping the concept of High-Risk Occurrences – HRC.[9]

According to the new metric, the following three categories were given the HRC status: runway safety related events (RS), CFIT, and LOC-I. The former shows high repeatability, expressly by virtue of a specific event known as runway excursion (RE), whereas CFIT and LOC-I are relatively less frequent, although posing very high fatality risks.[10] The scenario is corroborated by IATA studies conducted between 2012 and 2016, whose results are summarised in Figure 1,[11] where the diameter of the circumferences is proportional to the number of fatalities (the absolute number is shown with the taxonomies). It is inferred that RE accidents account for more than 20% of the total occurrences registered in the period of the study, whereas CFIT and LOC-I do not exceed 10%. However, regarding fatalities, the numbers are reversed, since runway accidents claimed 14 lives, CFIT was responsible for 259 deaths, and 949 passengers deceased due to LOC-I. The numbers ratify the higher fatality risks associated with CFIT and LOC-I (0.07 and 0.12, respectively, as in Figure 1).

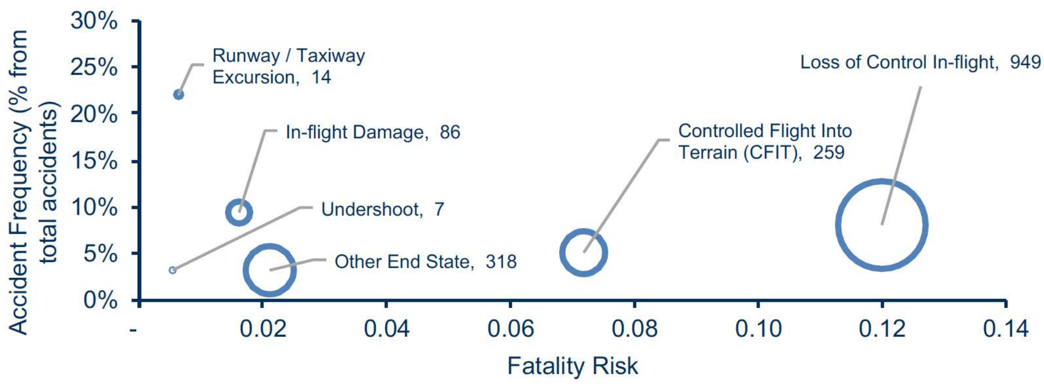


Figure 1: Relation between frequency of accidents and fatality risk for accidents occurred between 2012 and 2016.
[Source: IATA (2017)[11]]

Since 2013, ICAO has established the mitigation of HRCs as a global priority, since the studies conducted by the agency have claimed high-risk accidents had remained the same

i It is a number that ranges from 0 to 1; the nearer the unity, the greater the exposure to risk since 2006.[10] Recent data have corroborated the 1990s findings of the White House Commission on Aviation Safety and Security, i.e., despite the significant progress achieved from the efforts devoted to flight safety over the past decades, CFIT and LOC-I still figure as accidents that pose the highest risks to society.

1.1 Technological context

CFIT and LOC-I are relatively uncommon accidents; however, their frequencies of occurrence darken serious hazards, since they almost invariably result in deaths – from 2012 to 2016, 84% of CFIT occurrences were fatal, whilst 90% of LOC-I accidents yielded casualties[11] –, justifying the highest fatality risks associated with such accidents (see Figure 1).

According to Boeing,[12] from 2007 to 2016, 1347 deaths were recorded as a consequence of 16 LOC-I events in commercial aviation[ii], whereas 13 CFIT occurrences accounted for 654 lives, i.e., together, the two categories represented 68% of deaths associated with air accidents in a recent ten-year period, which is almost identical to the percentage reported by the US government in the 1990s (Figure 2 shows details).

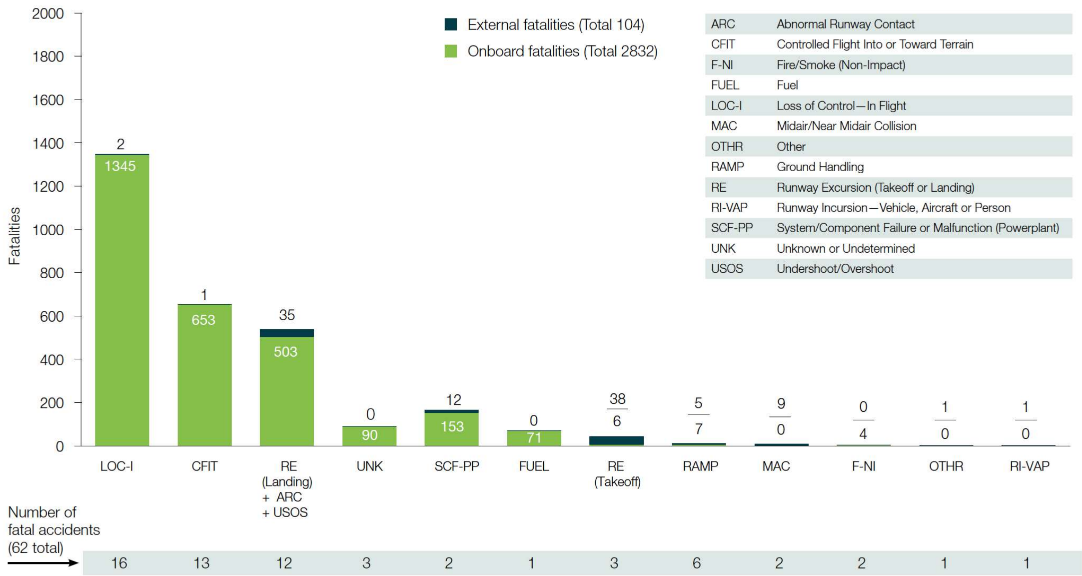


Figure 2: Fatalities recorded in aeronautical accidents between 2007 and 2016. [Source: The Boeing Company (2017)[12]]

Airbus, also attentive to the subject, conducted a survey on the evolution of the ten-year moving average of HRC accident rates (per million flights) in the last 20 years. The results (see Figure 3) showed the rates of CFIT accidents had been significantly reduced. However, despite a large decrease regarding LOC-I occurrences in the 1997-2007 decade, the historical evolution of the series remained practically constant, showing a punctual and slight reduction between 2013 and 2015, but reaching higher levels in the following year.[13]

ii Jets heavier than 60,000 lb MTOW – Maximum Takeoff Weight

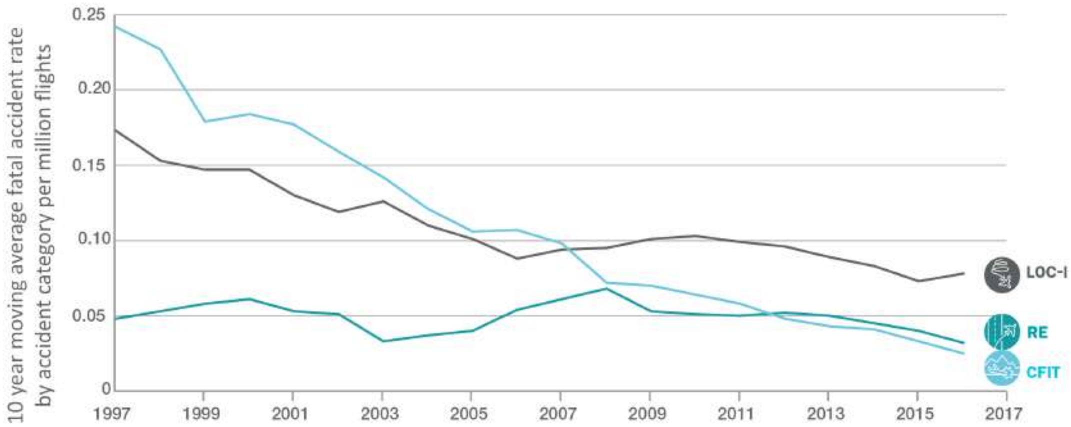


Figure 3: Ten-year moving average of HRC accident rates from 1997 to 2007.
[Source: Airbus (2017)[13] – legend modified by the author]

The implementation of safety recommendations towards mitigating LOC-I and CFIT caused LOC-I casualties to exceed those from CFIT accidents, i.e., actions oriented to CFIT were more efficient than those on LOC-I.[9] It must be highlighted that safety recommendations consider the characteristics of each event. Figure 4 shows the statistical distribution of CFIT and LOC-I accidents according to the phases of flight[iii], and based on the clear predominance of CFIT occurrences during the approach phase, still in 1997, the White House Commission recommended the improvements in ground proximity warning systems among the actions on the strategic plan towards reduction of CFIT accidents.[6] Consequently, technologies like EGPWS — Enhanced Ground Proximity and Warning System —, TAWS — Terrain Awareness and Warning System —, and ILS — Instrument Landing System — categories II and III, were developed and widely diffused into commercial aviation, which explains the reductions observed in Figure 3.[13]

LOC-I accidents, however, permeate all phases of flight, and cannot be associated with a distinguished aircraft configuration, or the pilot workload level, since, as shown in Figure 4, approach and cruise, for example, accounted for almost identical percentages of accidents (18% and 19%, respectively), regardless of the massive differences in both the aerodynamic configuration and crew workload in such phases of flight.

Snow (2015, p.1)[14] claimed LOC-I "is not as monolithic in its causes and outcomes as some of the other accident categories like midair collision or CFIT. Therefore, it doesn't lend itself as well to one alerting system that's going to solve the accident". The development of LOC-I-oriented prevention technologies has faced such profound difficulties that the industry has not been able to incorporate a widespread strategy for the mitigation of those occurrences[15] or, in the words of Belcastro and Jacobson (2010, p.3),[16] "due to the complexity of aircraft LOC[-I] events, [currently] no single intervention strategy can be identified to effectively prevent them".

In such a context, CAST has developed the Safety Enhancement Plan, i.e., a comprehensive conjunction of most promising safety enhancements (in terms of technologies, training, procedures etc.) together with their implementation procedures. Whereas some developments have already been completed (e.g., TAWS), others are classified as *Safety Enhancements Reserved*

[iii] Data retrieved from IATA annual Safety Reports – editions 2013, 2014, 2015 and 2016

for Future Implementation – SERFIs.

A closer look into SERFIs reveals technologies and procedures that would help prevent LOC-I. Most of them address mechanisms to increase crew situational awareness, e.g., enhancements in the Primary Flight Display (PFD) such that an arrow is displayed showing the pilot the action to be taken for high bank angles. However, according to Snow (2015, p.1),[14] "some of the selected technologies might not be certified for this purpose or widely implemented until 2035".

The apparent "delay" in the implementation process is, in fact, necessary, since any technology to be introduced in aircraft, especially those potentially altering the crew´s perception of the vehicle dynamics, must be thoroughly assessed prior to operation, which must include the pilot's opinion on the candidate technology. The re-certification of the Boeing 737 MAX is a good example of how time-consuming an evaluation of new (or even existing) technologies can be.[17]

However, the current lack of dedicated pilot-aiding LOC-I prevention devices is mainly due to a still uncompleted understanding of human-machine interaction mechanisms, especially in off-nominal flight conditions. Under such circumstances, flight deck systems provide limited and sometimes confusing information,[16] which, added to non-effective pilot training, results in crews typically stricken by startle and surprise, thus limiting their capacity to properly respond to LOC-I events.[18]

In 2009, FAA and EASA set new standards for flight simulator devices motivated by the Colgan Air 3407 accident in that same year and towards enhancing pilot training, essentially requiring improvements in aircraft dynamic models for off-nominal flight conditions.[19,20] The proposal was to make simulators more representative of real conditions and use the equipment to train pilots to avoid (and also recover from) off-normal conditions.[21] Such a training was called UPRT – Upset Prevention and Recovery Training –.[22,23] Groen (2008)[24] extensively investigated

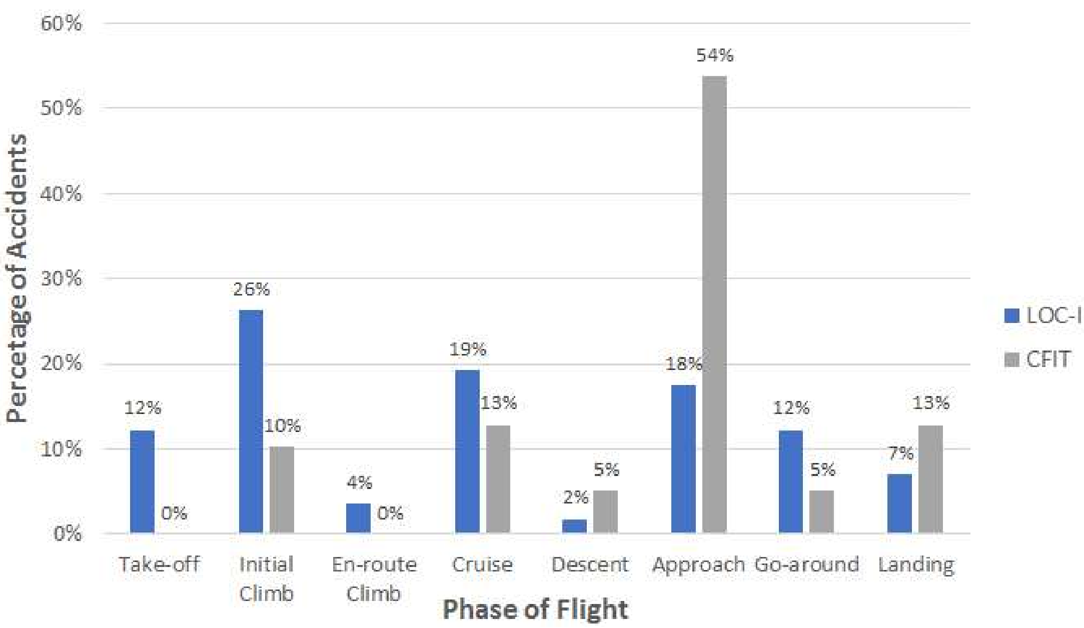


Figure 4: CFIT and LOC-I percentage distribution per phase of flight (period: 2009 to 2016). [Source: The author]

features simulators should display in order to accurately simulate upset conditions given the need of presenting pilots with g-loads compatible with those of real conditions.

Although benign, UPRT alone is not sufficient to mitigate LOC-I,[16] since such accidents display several components, from human behaviour to aircraft systems, particularly in most modern vehicles with FBW – Fly-By-Wire – technology and various autoflight system modes. The LOC-I accidents Lion Air Flight 610 (2018) and Ethiopian Airlines Flight 302 (2019), both involving Boeing 737 MAX, show the complexity of a LOC-I, since initial findings revealed a system called MCAS – Manoeuvring Characteristics Augmentation System[iv] – was not cited in MAX's flight manuals, impeding pilots to fully understand the characteristics of the aircraft when in particular circumstances of high angles of attack.[25,26] Such an example is didactic as shows some of the current challenges for the development of LOC-I defences, namely: **(i)** poor crew situational awareness, particularly regarding autoflight system modes; **(ii)** subtle changes in aircraft dynamics towards conditions for which pilots are not properly trained; and **(iii)** confusing information on the flight deck about the actual condition of the aircraft.

Due to such a panorama, NTSB — National Transportation Safety Board –, a reference body in air crash investigation, included LOC-I in its list of priorities (called *Most Wanted List*) for the 2017-2018 biennium, understanding it is both significant in impact and ripe for action[27] and still occur at an unacceptable rate.[28] An accurate description of the LOC-I phenomenon, especially in the light of the growing automatism and worn-out pilot-aircraft relationship, is vital for a flight safety evolution.

1.2 Scientific context

The *academia*, in this context understood as a scientific community, i.e., universities and research institutes, plays a major role in the development of studies with strict rigour typically oriented to the underlying foundations of flight safety issues, including LOC-I. Since it usually does not produce an "end of the chain" solution, the role of researchers and institutions may not be so apparent and, therefore, renegade; however, the relevance of scientific projects must be reinforced. The list below is an overview of the main most recent/ongoing studies on LOC-I:

- Bromfield and Gratton (2008)[29] investigated factors that affected LOC-I of general aviation aircraft, spotting differences among the dynamic behaviours of some widely diffused aircraft from flight schools;
- Everett et al. (2018)[30] discussed the possibility of incorporation of an angle of attack — AoA — indicator in the cockpit, since they concluded the observation of such a parameter is a key to prevent and recover from a LOC-I;
- Bromfield and Landry (2018)[31] worked on the definition of the LOC-I phenomenon understanding it could not be "solved" until it had been well characterised; their study resulted in a qualitative re-definition of the accident;
- Pfifer; Venkataraman and Seiler (2017)[32] also worked on the definition of LOC-I accidents,

[iv] MCAS is a software integrated into MAX's FCS – Flight Control System – to mimic the behaviour of Boeing 737NG (its predecessor) at low-speed and high angles of attack

and suggested adaptations to a quantitative LOC-I criterion for incorporating aircraft particularities and failure conditions;
- Richards et al. (2017)[33] conceived an upset recovery system that identified the LOC-I condition, assessed a recovery strategy, and displayed recommended inputs in the aircraft instrumentation. The system still lacks validation and certification approval;
- Zhao and Zhu (2017)[34] used the bandwidth adaptation technique to design an automatic flight control system capable of dealing with severe wind variability, one of the LOC-I contributing factors, and reducing the chances of an accident; and
- Samaili et al. (2017)[35] proposed an "intelligent flight control system" that reconfigures itself under adverse flight conditions, and would evaluate and adjust envelope protections in real-time, depending on the aircraft condition.

The methodologies and strategies employed to study LOC-I are plural, since some of them tend to concentrate on adaptive control strategies and fault-tolerant control systems, whereas others try to (re-)characterise the phenomenon, and others suggest the incorporation of new flight instruments. Although positive, such a plurality also reveals a lack of consensus on the best way to tackle the issue. In fact, Belcastro and Jacobson (2010, p.3)[16] claimed "there are currently no coordinated or integrated [...] research efforts for addressing aircraft LOC[-I]".

To date, despite the existence of GARTEUR – Group for Aeronautical Research and Technology in Europe –, a collaborative research program among Old Continent countries that, although not LOC-I-specific, has achieved promising results, especially those from NLR – Netherlands Aerospace Centre – and Delft University of Technology,[36] the only current systematic research program that addresses LOC-I is coordinated by C. Belcastro in NASA – National Aeronautics and Space Administration. The program has originated the first and most relevant research on the topic.

Briefly speaking, the first LOC-I-oriented studies were developed in mid-2000s with an investigation on a manner to translate qualitative aspects into a quantitative LOC-I characterisation,[37] which resulted in a method called Quantitative Loss of Control Criteria (QLC), detailed in Section 2.1.2.

Still in NASA, since LOC-I, as any other accident, results from several contributing factors combined in a unique manner,[38,39] Belcastro and Foster (2010)[40] mapped LOC-I precursors and presented them as worst-case combinations and temporal sequences. Such a thorough characterisation was a big step towards the study of LOC-I, since it led Belcastro (2012)[41] to develop 60 LOC-I test scenarios that combined and sequenced typical contributing factors, and could be reproduced in flight simulators to research on potential LOC-I prevention technologies and test their effectiveness. The scenarios are detailed in Section 2.3.

Finally, an important study dates back to the 1960s, when the NASA engineers Cooper and Harper (1969)[42] conceived a methodology to confidently and reliably assess aircraft handling qualities from pilots' perspective and that culminated in the well-known Cooper-Harper scale. Although not LOC-I-oriented (in fact, term "LOC-I" did not even exist at that time), the scale provides valuable insights regarding such a type of accident, since it also takes into account human's perception on aircraft controllability. The scale is detailed in Section 3.3.

1.3 Hypothesis

As addressed elsewhere, the efforts for tackling LOC-I are diverse, and, to date, none of the "solutions" proposed have been effective in mitigating the event. Indeed, such evidence have revealed a lack of understanding of the phenomenon and triggered the question: *what is LOC-I?*

"Solutions" will never be effective with our current meager understanding of the accident, and we foresee that we still have not fully understood LOC-I because the phenomenon has never been simultaneously characterised from the perspectives of its two protagonists, namely human pilots **and** aircraft. Although independent methods are adopted for qualitatively (e.g., the Cooper-Harper scale) and quantitatively (e.g., the QLC) characterising the accident, the hypothesis of this research project is there is no clear correspondence between such LOC-I-definition methods, i.e., between what pilots understand as a LOC-I and the criteria engineers use to quantitatively classify an event as such.

This lack of correspondence hampers aviation progress and is a gap that must be overcome for safer aeronautics. Therefore, this study aims to deepen the characterisation of the LOC-I phenomenon simultaneously investigating it from the two aforementioned approaches. Its primary goals include:

- selection of LOC-I test scenarios of statistical representativeness regarding number of accidents and fatalities;
- design of simulation tasks to evaluate aircraft controllability;
- performing pilot-in-the-loop simulations;
- collection of aircraft variables of motion during the simulations for application of the QLC;
- collection of handling qualities ratings via the Cooper-Harper scale for each simulated task; and
- assessment of the correlation between the qualitative and quantitative controllability assessment methods.

The results are expected to bring new insights towards the characterisation of LOC-I, envisioned to help the development of more effective defences to the accident, whether in the form of pilot training, renewed aircraft instrumentation, systems and alerts, or their combination.

1.4 Document outline

Chapter 1 offers an aviation safety panorama through a brief historical overview and its current scenario. The most critical occurrences are highlighted, raising attention to the ongoing situation of LOC-I. Facts concerning both Technological and Scientific contexts have shown LOC-I lacks better characterisation, which slows the development of defences and increases the dangers posed by the event. The motivation for and objectives of the research are addressed in the Hypothesis section.

Chapter 2 provides the current most accepted qualitative and quantitative LOC-I definitions and a discussion on the contributing factors of such accidents, considering their combinations and temporal sequencing. LOC-I test scenarios, i.e., comprehensive sets of precursors that led to real accidents, are also presented.

Chapter 3 introduces the equations of motion of an aircraft, fundamental for the understanding of the QLC, which is also detailed. Considerations on the Cooper-Harper scale and the way it is applied in flight test campaigns are included.

Chapter 4 presents the methodology employed for the accomplishment of the research objectives, and the flight simulator used in the experiments, aircraft model, selection of the LOC-I test scenarios, tasks performed, information on the participating pilots, simulation procedures, and data processing and analysis.

Chapter 5 reports results from the simulations with six flight test pilots, including a task by task analysis of their "average" actuation and the way it impacted on the classifications provided by the controllability assessment methods, results of numerical correlation tests between variables related to the Cooper-Harper scale and QLC, and discussions on the findings.

Chapter 6 provides conclusions on key research questions and recommendations for future studies on the LOC-I topic.

LOC-I REVIEW

2 LOC-I REVIEW

A clear and objective definition for LOC-I is paramount for the development of safety measures. It is well known that LOC-I is a highly complex accident, however, its current definitions are limited.[31] This chapter provides insights on current qualitative and quantitative LOC-I descriptions, together with contributing factors to the accident, and test scenarios for the reproduction of loss of control conditions towards the evaluation of possible defences.

2.1 LOC-I Definition

LOC-I is a situation in which neither the crew, nor the autoflight systems can control the aircraft flight path. Regarding human pilots, the crew´s knowledge of the flight is often insufficient to make them regain control, whereas in the case of autopilot systems, the flight trajectory in a LOC-I is typically outside the tolerances accepted by the flight guidance systems, leading to a degradation of flight protection modes or even to a sudden autopilot switch off. Whichever the case, LOC-I is essentially a dynamic-and-control problem, since the aircraft assumes a dynamic often uncontrollable for both the crew and autoflight systems[43] [i].

Given the mentioned characteristics, how to define a LOC-I? Hereinafter, two approaches are provided: from a *qualitative* point of view and from a *quantitative* perspective.

2.1.1 Qualitative approach

Among several documents provided by aircraft manufacturers, the so-called *Flight Envelope* is a quick reference on the capabilities of an aircraft in terms of multiple parameters (airspeed, load factor, altitude, "turn rate" etc). It is a valuable tool, since it reports tested and published aircraft limitations, therefore, respecting and remaining inside the envelopes is synonymous with *safety*.[44]

Situations may occur, and the aircraft departs from its usual flight condition, possibly entering a regime called *outside the envelope*, which potentially leads to dangerous consequences (e.g., structural damage) due to a combination of factors, such as component failures, pilot's misjudgements, maneuverability near critical points, and adverse environmental conditions. A major design concern is the prediction of abnormal situations and creation of standardised emergency procedures towards bringing the aircraft to the inside of the flight envelope boundaries, at least minimising the consequences of an unusual event.

Expanding those concepts, Wilborn and Foster (2004, p.3)[37] qualitatively described LOC-I as motion that is:

[i] Not every LOC-I ends in an accident, as in some cases control is eventually regained. In any case, however, LOC-I is always a serious safety threat since, at least for a while, control has been lost

- outside the normal operating flight envelopes;
- not predictably altered by pilot control inputs;
- characterized by nonlinear effects, such as kinematic/inertial coupling, disproportionately large responses to small state variable changes, or oscillatory/divergent behavior;
- likely to result in high angular rates and displacements;
- characterized by the inability to maintain heading, altitude, and wings-level flight.

However, issues arise when attempts to distinguish between similar events are made. For example, why do some stalls become an accident, while hundreds of others are safely performed in the certification campaign of an aircraft? Both stalls match the just mentioned definition, although their consequences are highly different.[37]

Crew training in stall recognition and recovery, situational awareness, and the altitude at which manoeuvres are performed help explain the different outcomes and, therefore, should be part of a LOC-I definition. Noticing this gap, Bromfield and Landry (2018)[31] conceived a qualitative LOC-I re-definition based on "triggers" (factors potentially leading to a LOC-I) and "recovery factors" (aspects related to a possibly successful recovery), and concluded a LOC-I "may be recoverable if recognized by the crew (situation awareness), given: sufficient height above terrain and sufficient pitch, roll and yaw control authority (controllability) for recovery within the airplane's structural design limits" [31, p.5].

Although such a re-definition incorporates crucial elements for a better understanding of a LOC-I, any qualitative definition thoroughly addresses the phenomenon. Indeed, engineers do depend on non-subjective metrics to propose defences to the accident, which has motivated the search for a quantitative definition for LOC-I.

2.1.2 Quantitative approach

Towards the conception of a quantitative definition, NASA has identified that the multiple factors justifying different consequences for similar events directly affected the following flight dynamic parameters:

- *angle of attack* (α);
- *sideslip angle* (β);
- *bank angle* (ϕ);
- *pitch attitude* (θ);
- *equivalent airspeed* (V_E);
- *normal load factor* (n);
- *pitch control deflection* (δ_e);
- *pitch rate* (q);
- *roll control deflection* (δ_a);
- *roll rate* (p).

Once identified, the engineers observed the ten parameters through a parametric approach (instead of a traditional time history analysis) for effectively conceiving a quantitative definition. By mapping pairs of related variables, they constructed five graphs, each of which individually referring to flight dynamics, aerodynamics, structural integrity, and lateral and longitudinal flight control use.[37]

Additionally, the NASA engineers identified the minimum/maximum expected values for each of the ten variables under regular flight conditions, including eventual emergencies foreseen in the aircraft manuals. Based on such limits, they plotted the so-called "normal flight envelope" on the graphs. Figure 5 shows the parametric envelopes.

Finally, the quantitative LOC-I definition, also called *Quantitative Loss of Control Criteria* – QLC –, was based on the number of envelopes extrapolated:

> [...] normal operational maneuvers, even if aggressive, usually do not exceed more than one envelope [, while] a maneuver that exceeds only two envelopes is a borderline LOC-I condition [and] a maneuver that exceeds three or more QLC envelopes can be classified as LOC-I. [It] seems to be a good working definition" [37, p.10].

To date, QLC has been the only quantitative method that determines whether a given event can be considered a LOC-I.

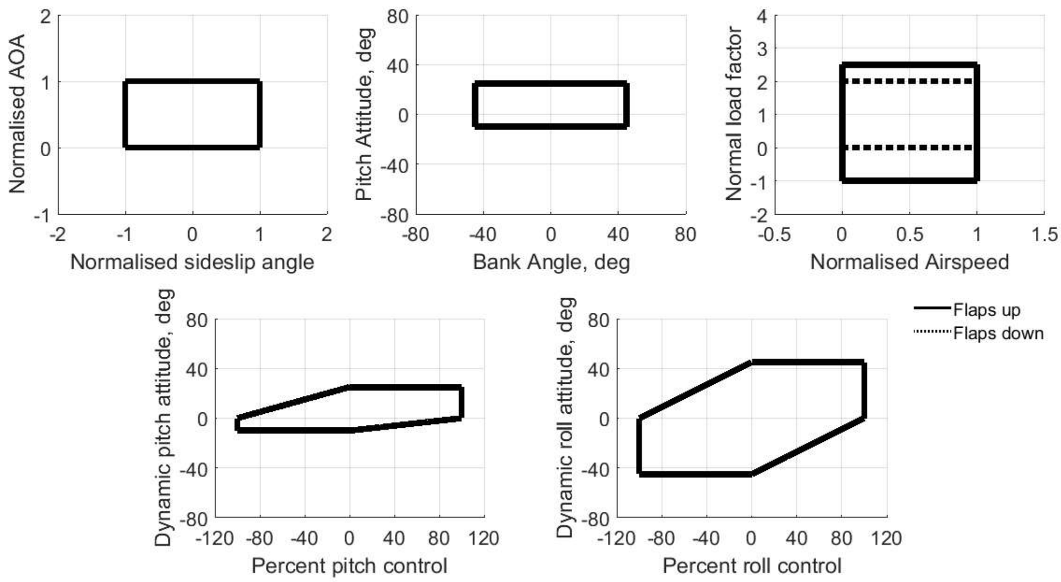


Figure 5: Parametric envelopes.
[Source: Adapted from Wilborn and Foster (2004)[37]]

2.2 Contributing factors

The classification of events is not sufficient for the design of holistic strategies for the prevention of accidents; they also require the understanding of the way an aircraft leaves regular flight conditions and flies into unforeseen situations.

Accidents and even the entrance into an "outside the flight envelope condition" do not happen from single causes, but are the outcome of a particular combination of many contributing factors of different natures,[38,39] which also verifies for LOC-I according to Belcastro and Foster (2010, p.2):[40]

> "no single [contributing factor] category is solely responsible for loss of control accidents [, they] occur when combinations of breakdowns happen across human and engineering systems, and often in the presence of threats posed by the external environment."

Any type of LOC-I-oriented defence must tackle (and interrupt) the chain of events that lead to an accident. According to Belcastro and Foster (2010),[40] historically, the LOC-I contributing factors are grouped into the following three main categories:

- **adverse onboard conditions**, related to *vehicle problems*, such as system faults, airframe/engine damages, and improper vehicle loading, and *inappropriate crew response*, like aggressive manoeuvres. Due to the huge number of factors, they can be split into two major subgroups, namely, *adverse vehicle conditions* and *inappropriate crew response*);
- **external hazards and disturbances**, related to unfavourable weather conditions, atmospheric disturbances, and abrupt manoeuvring to avoid obstacles; and
- **vehicle upset conditions**, which involve abnormal flight conditions, such as inappropriate attitude, airspeed, roll rate, among others.

After the identification of the contributing factors, worst-case combinations and the way precursors sequence in time for the occurrence of a LOC-I should be analysed.

2.2.1 Worst-case combinations

Towards visualizing the combinations of LOC-I contributing factors, Belcastro and Foster (2010)[40] proposed a three-dimensional scatter graph whose axes represent the precursor categories and their related factors. A sphere is placed at the corresponding intersection of precursors for each combination of factors that lead to a LOC-I. The larger the number of accidents in a given combination, the bigger the sphere. Figure 6 shows the results of a survey of 126 LOC-I accidents (the colours of the spheres refer to a categorisation of the number of fatalities).

According to Figure 6, the worst-case combinations are: **(i)** crew action and vehicle upsets, **(ii)** system faults either alone, or together with vehicle upsets, and **(iii)** vehicle impairment, icing and stall.

2.2.2 Worst-case temporal sequences

Figure 7 shows the most frequent first, second and third LOC-I contributing factors in the chains of precursors that lead to an accident – see Belcastro and Foster (2010).[40]

Two facts must be highlighted from Figure 7: **(i)** LOC-I is normally composed of at least three contributing factors, i.e., it is rarely an accident in which control is suddenly lost, instead, it degrades; and **(ii)** the "inappropriate crew response" precursor is typically present in LOC-I accidents, either as the first, second or third factor in the sequence of events.

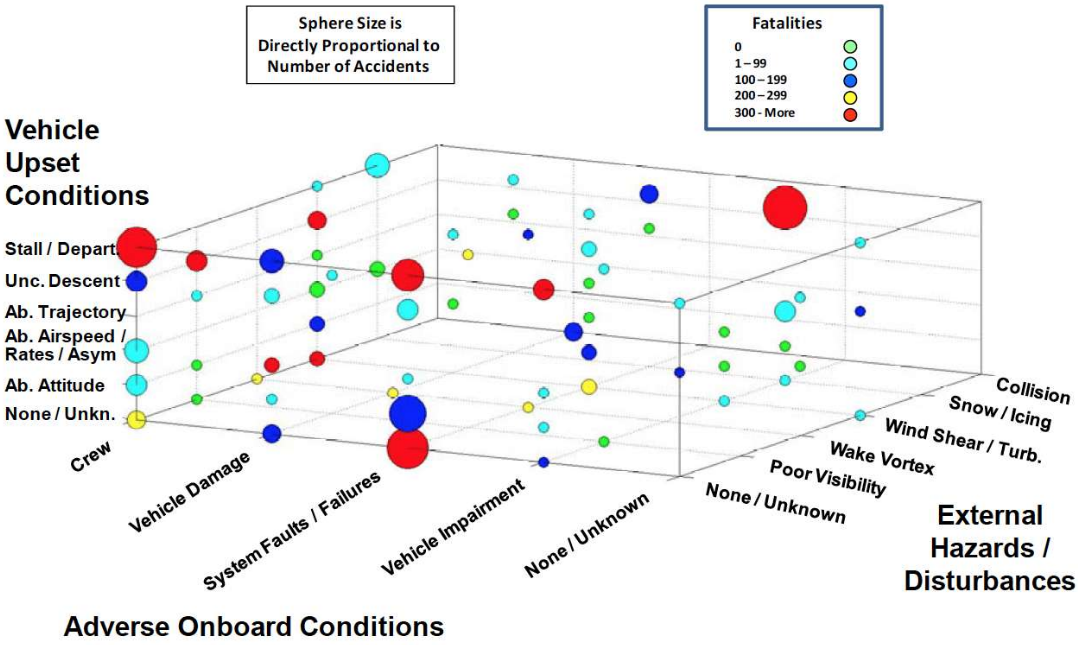


Figure 6: Combinations of LOC-I precursors for accidents between 1979 and 2009.
[Source: Belcastro and Foster (2010)[40]]

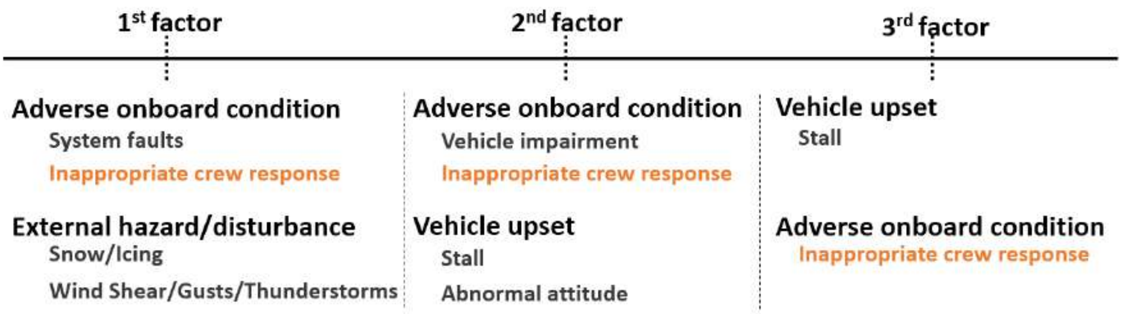


Figure 7: LOC-I worst-case temporal sequences.
[Source: The author]

2.3 LOC-I test scenarios

Based on the identification of the LOC-I contributing factors and on the way they combine and sequence in time, Belcastro (2012)[41] gave a step forward and designed a set of 60 LOC-I test scenarios. Instead of conceiving them in terms of generic precursors (inappropriate crew response, e.g.), Belcastro, C. translated the contributing factors into actionable terms (delayed pilot response, e.g.). Consequently, the scenarios gained realism and could be systematically reproduced in a controlled environment, a big leap towards the better characterisation of the accident and validation of possible LOC-I mitigation technologies.

As further discussed in Section 4.3, the simulation scenarios used in this research were designed based on the scenarios proposed by Belcastro (2012).[41] The 60 test scenarios are presented in their integrity in Annexe A.

THEORETICAL FOUNDATION

3 THEORETICAL FOUNDATION

During the few hundred years of aviation, humans have remained practically constant, whereas machines have rapidly evolved. Such a "mismatch" has substantially affected the way humans interact with machines, especially in highly complex environments, such as a flight deck.

Towards safer aviation, the gaps that inevitably arise from that constantly changing relationship between humans and machines must be overcome. From a controllability viewpoint, it means aircraft should display characteristics that can be interpreted and handled by an average pilot, regardless of the level of technology the machine would incorporate,[45] i.e., controllability is not a feature of pilots or aircraft; instead, it is an asset of a "team" called *pilot-aircraft system*.

This chapter presents the concepts used in this research for the understanding of how humans and machines interact, aiming at the characterisation of the LOC-I phenomenon. It includes the equations of motion of an aircraft, details about the QLC, and explanations on the principles and use of the Cooper-Harper scale.

3.1 Physical state of an aircraft

The physical state of an aircraft is characterised by its orientation and position in space, and its linear and angular velocities.[46] In mathematical terms, equations of motion can describe the dynamics of an aircraft at any given time, and this section is devoted to their derivation.

Firstly, a reference frame is defined according to the following two usual options:

- **inertia reference frame:** for flight dynamics purposes, the inertial frame, hereinafter called $o_E x_E y_E z_E$, is a right-handed orthonormal system in which the $o_E x_E y_E$ plane is horizontal and parallel to the surface of the planet, the $o_E z_E$ axis points downwards and the $o_E x_E$ axis points to the direction of flight. The origin of the system is at the atmosphere and is coincident with the origin of the body-fixed axes; and
- **body reference frame:** hereinafter called $o_b x_b y_b z_b$, this set of axes is fixed to a convenient and notable reference point, i.e., the centre of gravity (CG) of the aircraft. It is a right-handed orthonormal system fixed to the aircraft and constrained to move with it. In normal flight attitudes (in a commercial aviation sense), the $o_b y_b$ axis points to the right wing, while the $o_b x_b$ axis points to the direction of flight. In a particular case of body axes, the $o_b x_b$ axis is parallel to the total velocity vector of the aircraft, i.e., it is rotated by the body incidence angle in relation to $o_E x_E$; the axes in such a particular orientation are known as *stability axes*[i].

Although the choice of frame is arbitrary, working with body frames tends to be easier, and was, therefore, selected for our study.

[i] In what follows, unless otherwise stated, the system defined by $o_b x_b y_b z_b$ is *stability axes*

The motion of an aircraft is mathematically described by resolving forces, moments, attitude, and linear and angular velocities in a chosen reference frame system. Under equilibrium conditions (also called *trimmed equilibrium*), i.e., steady non-accelerating flight, the net forces and moments acting on the vehicle sum zero. However, when the aircraft is disturbed from such a condition, the equilibrium does not hold anymore, and the sum of forces and moments is different from zero until the trimmed equilibrium has been restored. The transient motion between two equilibrium states is described by quantities known as *motion variables*[ii].[46] Figure 8 shows the variables (some of them are extensively used in this research, especially those required by the QLC).

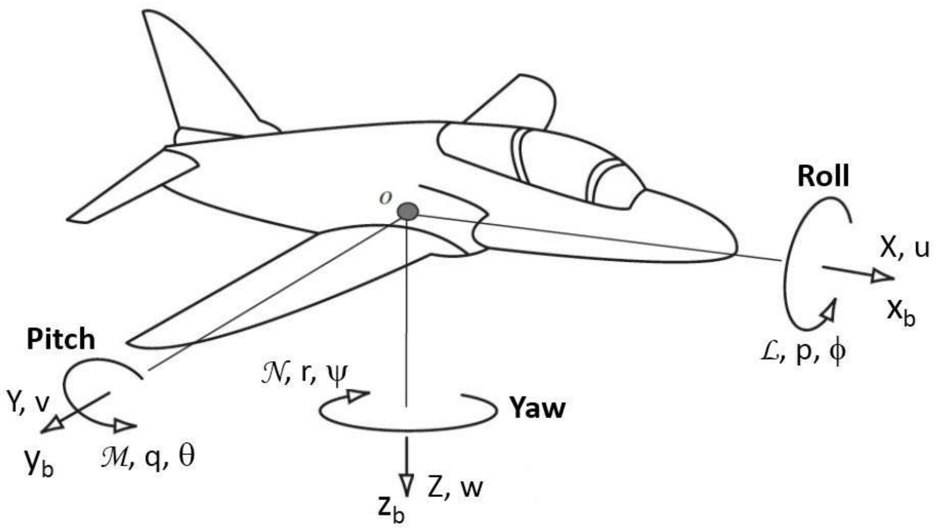


Figure 8: Motion variables.
[Source: Adapted from Cook (2007)[46]]

Based on the motion variables and bearing in mind both position and attitude of an aircraft are also necessary for a full characterization of its state, we have defined a state vector containing the parameters of interest:

$$\mathbf{X} = [x_\mathrm{E}, y_\mathrm{E}, z_\mathrm{E}, u, v, w, p, q, r, \phi, \theta, \psi]^\mathrm{T} \tag{3.1}$$

The equations of motion are then derived in terms of the aircraft state vector, as detailed in the sequence.

Linear velocity components

According to Newton's second law applied for the translational motion,

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} \tag{3.2}$$

where $\mathbf{p}$ represents the quantity *momentum*.

For a body-axes reference frame and an object of constant mass, Equation 3.2 becomes

$$\mathbf{F_b} = m\left[\frac{d\mathbf{V_{0_b}}}{dt} + \omega_{\mathbf{0_b}} \times \mathbf{V_{0_b}}\right] \tag{3.3}$$

[ii] Also called *perturbation variables*

where $\mathbf{V_{0_b}}$ is the total velocity vector with respect to (wrt) the body reference frame, i.e., $\mathbf{V_{0_b}} = [u, v, w]^\intercal$ and $\omega_{\mathbf{0_b}}$ is the total angular velocity vector wrt the same body reference frame, i.e., $\omega_{\mathbf{0_b}} = [p, q, r]^\intercal$.

The derivative of the total velocity vector can be computed by the Coriolis Theorem:

$$\frac{d\mathbf{V_{0_b}}}{dt} = (\frac{du}{dt}\hat{\mathbf{i}} + \frac{dv}{dt}\hat{\mathbf{j}} + \frac{dw}{dt}\hat{\mathbf{k}}) + \omega_{\mathbf{0_b}} \times \mathbf{V_{0_b}} \tag{3.4}$$

Solving Equation 3.4 in Equation 3.3 for the translational acceleration yields:

$$\begin{aligned} \dot{u} &= \frac{F_x}{m} + vr - wq \\ \dot{v} &= \frac{F_y}{m} + wp - ur \\ \dot{w} &= \frac{F_z}{m} + uq - vp \end{aligned} \tag{3.5}$$

$\mathbf{F_x}$, $\mathbf{F_y}$ and $\mathbf{F_z}$ are the components of the net force vector acting on the CG of the aircraft wrt the body reference frame, i.e., $\mathbf{F_b} = [\mathbf{F_x}, \mathbf{F_y}, \mathbf{F_z}]^\intercal$ and such forces can be expressed in terms of aerodynamic, gravitational, and propulsive contributions.

Angular velocity components

Regarding rotational motion, Newton's second law enforces an equality between the net moment acting on the CG of the aircraft wrt a body reference frame ($\mathbf{M_b}$) and the rate of change of its angular momentum. Towards easing the modelling, the net moment is decomposed around the body axes, resulting in components known as rolling, pitching, and yawing moments, i.e., $\mathbf{M_b} = [\mathcal{L}, \mathcal{M}, \mathcal{N}]^\intercal$. The angular momentum, on the other hand, is computed as the product between the total angular velocity ($\omega_{\mathbf{0_b}}$) and the moment of inertia matrix ($\mathbf{I}$).

Strictly speaking, the inertia properties of an aircraft vary over time because of its moving parts (propellers, control surfaces etc.; however, their influence is small, and the vehicle can be modelled as a rigid body.[47] Due to the symmetry of an aircraft, the products of inertia I_{xy} and I_{yz} are null, thus simplifying the inertia matrix to:

$$\mathbf{I} = \begin{bmatrix} I_{xx} & 0 & -I_{xz} \\ 0 & I_{yy} & 0 \\ -I_{xz} & 0 & I_{zz} \end{bmatrix}$$

Such considerations and application of the Coriolis theorem for rotational motion (analogously to the translational case) lead to

$$\mathbf{M_b} = \mathbf{I}\Big[(\frac{dp}{dt}\hat{\mathbf{i}} + \frac{dq}{dt}\hat{\mathbf{j}} + \frac{dr}{dt}\hat{\mathbf{k}}) + \omega_{\mathbf{0_b}} \times \omega_{\mathbf{0_b}}\mathbf{I}\Big] \tag{3.6}$$

Solving Equation 3.6 for the rate of change of the angular velocity components, we have:

$$\dot{p} = \frac{-I_{xz}[\mathcal{N} + q(I_{xx}p - I_{xz}r) - I_{yy}pq]}{I_{xz}^2 - I_{xx}I_{zz}} - \frac{-I_{zz}[\mathcal{L} + q(I_{xz}p - I_{zz}r) + I_{yy}qr]}{I_{xz}^2 - I_{xx}I_{zz}}$$
$$\dot{q} = \frac{-[p(I_{xz}p - I_{zz}r) - \mathcal{M} + r(I_{xx}p - I_{xz}r)]}{I_{yy}} \tag{3.7}$$
$$\dot{r} = \frac{-I_{xx}[\mathcal{N} + q(I_{xx}p - I_{xz}r) - I_{yy}pq]}{I_{xz}^2 - I_{xx}I_{zz}} - \frac{-I_{xz}[\mathcal{L} + q(I_{xz}p - I_{zz}r) + I_{yy}qr]}{I_{xz}^2 - I_{xx}I_{zz}}$$

Position in space

An observer on the Earth's surface naturally describes the position of an aircraft wrt a frame on the planet's surface, which is mathematically equivalent to performing the so-called "axes transformation", i.e., transforming relevant motion variables from the body reference frame fixed to the aircraft to an inertia frame fixed to the Earth (considering the planet is indeed an inertial frame).[46]

Figure 9 shows different sets of axes, where oy_0z_0 and oy_3z_3 can represent, respectively, an inertia frame and a generalised body frame – not necessarily a stability frame. Such frames are related through the ϕ, θ and ψ angles, known as Euler angles. Basically, an axes transformation is the rotation of the variables of interest around specific axes and in a strictly defined order. Details are provided in Cook (2007).[46]

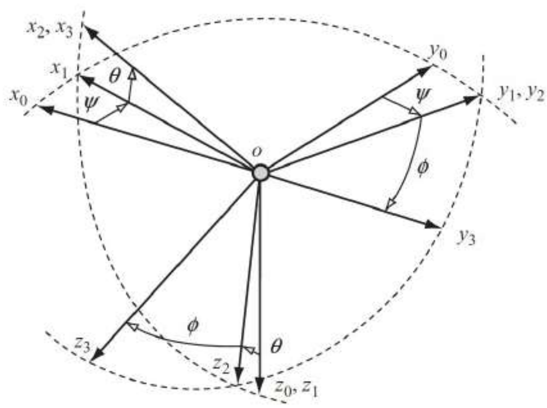


Figure 9: Axes transformation and Euler angles.
[Source: Adapted from Cook (2007)[46]]

For our purpose, we transformed V_{0_b} components from the body to the inertia frame, and obtained the linear velocity components of the aircraft wrt the Earth's surface:

$$\dot{x_E} = (cos\psi\ cos\theta)u + (cos\psi\ sin\theta\ sin\phi - cos\phi\ sin\psi)v + (sin\phi\ sin\psi + cos\theta\ cos\psi\ sin\theta)w$$
$$\dot{y_E} = (cos\theta\ sin\psi)u + (cos\phi\ cos\psi + sin\theta\ sin\psi\ sin\phi)v + (cos\phi\ sin\psi\ sin\theta - cos\psi\ sin\phi)w \tag{3.8}$$
$$\dot{z_E} = (-sin\theta)u + (cos\theta\ sin\phi)v + (cos\phi\ cos\theta)w$$

Orientation in space

The orientation (or attitude) of an aircraft is typically given by the Euler angles,[46] obtained from Equation 3.9, calculated from the transformation of ω_{0_b} components from a body to an inertial reference frame.

$$\begin{aligned}\dot{\phi} &= p + q(sin\phi\ tan\theta) + r(cos\phi\ tan\theta)\\ \dot{\theta} &= q\ cos\phi - r\ sin\phi\\ \dot{\psi} &= q\frac{sin\phi}{cos\theta} + r\frac{cos\phi}{cos\theta}\end{aligned} \tag{3.9}$$

Equations 3.5, 3.7, 3.8 and 3.9 are the so-called *equations of motion*, whose solutions provide time-dependent expressions for all components of the state vector – Equation 3.1 –, and enable a full characterisation of the motion of an aircraft at any given instant of time. For instance, the computers of flight simulators find solutions to the equations at every fraction of a second for reproducing the vehicle dynamics. Several alternatives can solve the equations of motion; however, regardless of the alternative, they invariably hinge on the determination of the forces and moments acting on the vehicle, and imposition of boundary conditions to the equations.

As addressed elsewhere, regarding the forces, the net force vector has components in the ox_b, oy_b and oz_b directions, i.e., $\mathbf{F_b} = [\mathbf{F_x}, \mathbf{F_y}, \mathbf{F_z}]^\intercal$, and due to their difficult direct calculation, a typical strategy is to write them in terms of "aeronautical forces", whose calculation is extensively covered in the literature.[46,48,49]

The forces emerging from the interaction of the aircraft with the atmosphere, wrt stability axes, are known to decompose into the following four components, also shown in Figure 10:

- one pushing the vehicle upwards/downwards, i.e., L or lift force, perpendicular to the velocity vector;
- one pushing the vehicle forward, i.e., T or thrust force, assumed purely parallel to the velocity vector and pointing forward;
- one opposed to the movement of the aircraft, i.e., D or drag force, parallel to the velocity vector and pointing backwards;
- a sideward one, i.e., Y, acting on the oy_b direction.

Therefore, F_x, F_y and F_z can be written as

$$\begin{aligned}F_x &= T - D(cos\alpha\ cos\beta) + L\ sin\alpha + Y(cos\alpha\ sin\beta) - W\ sin\theta\\ F_y &= -D\ sin\beta + Y\ cos\beta + W(cos\beta\ sin\phi)\\ F_z &= -D(sin\alpha\ cos\beta) - L\ cos\alpha - Y(sin\alpha\ sin\beta) + W(cos\theta\ cos\phi)\end{aligned} \tag{3.10}$$

where α and β are the angle of attack and the sideslip angle, respectively, defined as:

$$\alpha = \arctan\frac{w}{u} \tag{3.11}$$

$$\beta = \arcsin \frac{v}{\|\mathbf{V_{0_b}}\|} \tag{3.12}$$

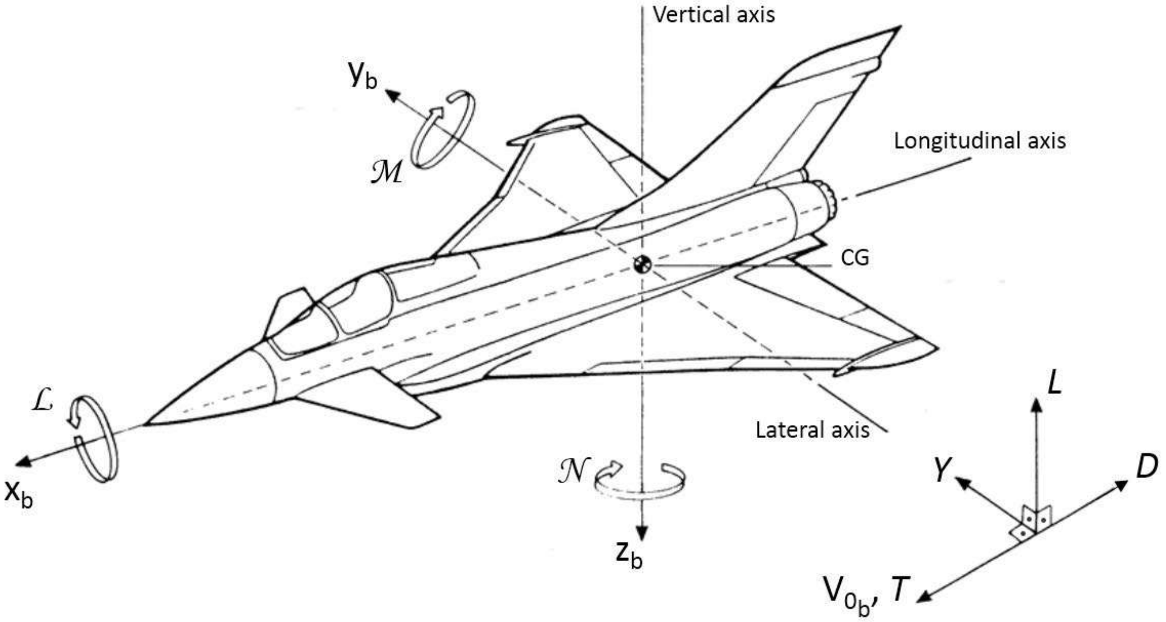


Figure 10: Aerodynamic Forces and Moments.
[Source: Adapted from Lucoveic et al. (2015)[50]]

The aerodynamic forces – L, D, T, Y – and moments – $\mathcal{L}$, $\mathcal{M}$, $\mathcal{N}$ – can be calculated with the use of the so-called *stability derivatives*, i.e., transfer functions that measure the way changes in the flight parameters – angle of attack, airspeed, altitude, load factor, control surface deflections etc. – disturb the motion variables.[49] The most relevant derivatives are typically combined into a single non-dimensional coefficient for each force and moment, as in the following simplified formulation:[48]

$$\begin{gathered}
c_L = c_{L_0} + c_{L_\alpha}\alpha + (c_{L_{\dot\alpha}}\dot\alpha + c_{L_q}q)\frac{\bar{c}}{2\|\mathbf{V_{0_b}}\|} + c_{L_{\delta_e}}\delta_e + c_{L_u}\Delta u + c_{L_{\delta_{th}}}\Delta th \\
c_D = c_{D_0} + c_{D_\alpha}\alpha + c_{D_{\delta_e}}\delta_e + c_{D_u}\Delta u + c_{D_{\delta_a}}\delta_a \\
c_Y = c_{Y_\beta}\beta + (c_{Y_p}p + c_{Y_r}r)\frac{b}{2\|\mathbf{V_{0_b}}\|} + c_{Y_{\delta_a}}\delta_a + c_{Y_{\delta_r}}\delta_r \\
c_{\mathcal{L}} = c_{\mathcal{L}_\beta}\beta + (c_{\mathcal{L}_p}p + c_{\mathcal{L}_r}r)\frac{b}{2\|\mathbf{V_{0_b}}\|} + c_{\mathcal{L}_{\delta_a}}\delta_a + c_{\mathcal{L}_{\delta_r}}\delta_r \\
c_M = c_{M_0} + c_{M_\alpha}\alpha + (c_{M_{\dot\alpha}}\dot\alpha + c_{M_q}q)\frac{\bar{c}}{2\|\mathbf{V_{0_b}}\|} + c_{M_{\delta_e}}\delta_e + c_{M_u}\Delta u + c_{M_{\delta_{th}}}\Delta th \\
c_N = c_{N_\beta}\beta + (c_{N_p}p + c_{N_r}r)\frac{b}{2\|\mathbf{V_{0_b}}\|} + c_{N_{\delta_a}}\delta_a + c_{N_{\delta_r}}\delta_r
\end{gathered} \tag{3.13}$$

where $\bar{c}$ and b are, respectively, the wing mean aerodynamic chord and the wingspan, δ_e, δ_a and δ_r are, in that order, the deflections of the elevator, ailerons, and rudder[iii], and δ_{th} is the variation of thrust.

[iii] By convention, a positive control surface displacement produces a negative aircraft response. For example, δ_e positive means elevator trailing edge down, which results in a nose down attitude (negative)

Finally, the forces and moments can be calculated by Equation 3.14:

$$\begin{aligned} Force &= \frac{1}{2}\rho\Big(\|\mathbf{V_{0_b}}\|\Big)^2\ S_{ref}\ c_{force} \\ Moment &= \frac{1}{2}\rho\Big(\|\mathbf{V_{0_b}}\|\Big)^2\ S_{ref}\ c_{ref}\ c_{moment} \end{aligned} \tag{3.14}$$

where c_{force} and c_{moment} represent the aerodynamic coefficients associated with the force/moment of interest, c_{ref} and S_{ref} are reference lengths (usually, wing mean aerodynamic chord and wing area, respectively), and ρ is the density of air.

The computation of the forces and moments emerging from the interaction of the aircraft with the atmosphere and the establishment of initial conditions for Equations 3.5, 3.7, 3.8 and 3.9 lead to the so-called *Initial Value Problem* – IVP –, whose solution describes the motion of an aircraft. As mentioned elsewhere, several techniques are available to find solutions for IVPs (e.g. numerical methods and a state-space approach), and in this research, we have used a flight simulation software (explored in Section 4.1). Therefore, instead of detailing such solution methods, in the next section, we have focused on the way the QLC uses some motion variables to determine whether an event is a LOC-I.

3.2 Quantitative Loss of Control Criteria

Briefly introduced in Section 2.1.2, QLC is currently the only mechanism based on quantitative variables that classifies an event as a LOC-I. Given the importance of the method to this research, this section details the five QLC envelopes and discusses how the criterion – number of envelopes crossed – has been established. See Wilborn and Foster (2004)[37] for further information.

3.2.1 *Adverse aerodynamics envelope – AA*

This envelope plots normalised angle of attack (α_{NORM}) versus normalised sideslip angle (β_{NORM}). The normalisation is defined in Table 1, i.e., α_{NORM} depends on the angle of attack that activates the stall warning system (α_{SW}), whereas β_{NORM} is related to the sideslip angle for a non-crabbed approach in the maximum demonstrated crosswind for takeoff or landing (β_{MDXW}). Since the boundaries of the AA envelope are based on stall attitudes, the graph shows stall conditions in both pitch and yaw. Figure 11 depicts the AA envelope.

Table 1: Normalisation of α and β for the AA envelope.
[Source: Adapted from Wilborn and Foster (2004)[37]]

$\alpha_{NORM} =$	0	at	$\alpha =$	$0°$
$\alpha_{NORM} =$	1	at	$\alpha =$	α_{SW}
$\beta_{NORM} =$	-1	at	$\beta =$	$-\beta_{MDXW}$
$\beta_{NORM} =$	+1	at	$\beta =$	$+\beta_{MDXW}$

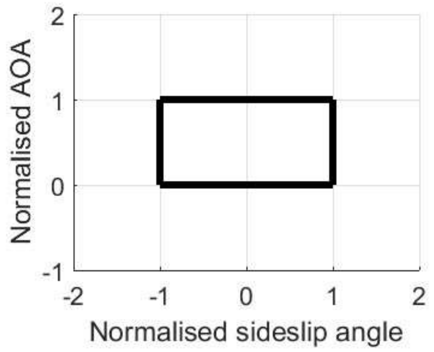


Figure 11: QLC Adverse Aerodynamics (AA) envelope.
[Source: Adapted from Wilborn and Foster (2004)[37]]

3.2.2 *Unusual attitude envelope – UA*

The UA envelope plots pitch attitude angle (θ) versus bank angle (ϕ), and plays a major role, since θ and ϕ are the flightpath parameters pilots are constantly looking at, especially when attempting to recover from upsets. As suggested by Wilborn and Foster (2004),[37] its boundaries are the typical industry-accepted limits for usual attitude. Table 2 shows the values for both positive and negative attitudes. In case of an excursion of usual attitudes, the analysis of the UA envelope can reveal the axis of origin of the upset, key information for the application of the appropriate recovery technique. Figure 12 displays the graph.

Table 2: General definition of *usual attitude*.
[Source: Adapted from Wilborn and Foster (2004)[37]]

-45°	$\leq$	ϕ	$\leq$	+45°
-10°	$\leq$	θ	$\leq$	+25°

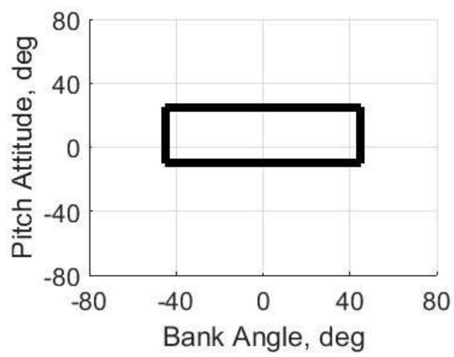


Figure 12: QLC Unusual Attitude (UA) envelope.
[Source: Adapted from Wilborn and Foster (2004)[37]]

3.2.3 *Structural integrity envelope – SI*

The SI envelope plots vertical load factor (n) and normalised airspeed (V_{NORM}), indicating overspeed and structural overload. Regarding its boundaries, the load factor limits reflect FAA requirements for structural design[iv], whereas in terms of airspeed, the normalisation depends on the flap configuration of the aircraft:

- **Flaps up**

$$V_{NORM} = \frac{V_E - V_{SW}}{V_{MO} - V_{SW}} \tag{3.15}$$

where V_{SW} is the stall warning equivalent airspeed in 1-g flight and V_{MO} is the maximum operating equivalent airspeed for flaps up;

- **Flaps down**

$$V_{NORM} = \frac{V_E - V_{SW}}{V_{FE} - V_{SW}} \tag{3.16}$$

where V_{FE} is the maximum operating equivalent airspeed for flaps down.

Figure 13 shows the SI envelope in detail.

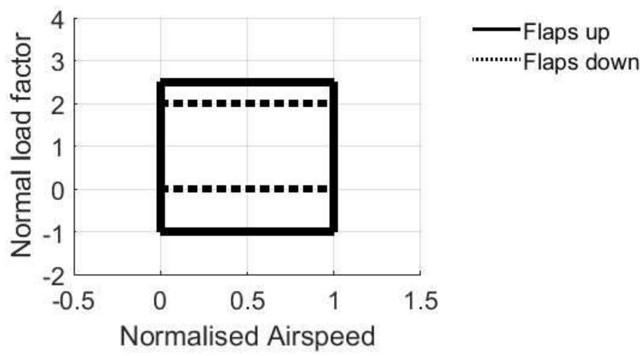


Figure 13: QLC Structural Integrity (SI) envelope.
[Source: Adapted from Wilborn and Foster (2004)[37]]

3.2.4 *Dynamic pitch control envelope – DPC*

DPC (Figure 14) plots dynamic pitch attitude (θ') versus pitch control percentage usage. θ' is the sum of current pitch (θ) and its expected change (i.e., its derivative in time) after one second ($\dot{\theta}$) – Equation 3.17. Concerning boundaries, the percent pitch control authority varies from -100% (fully pushing the yoke) to +100% (fully pulling the yoke), and θ' inherits θ limits for usual attitudes (see Table 2). Therefore and physically speaking, the dynamic pitch attitude establishes a trade-off between current and predicted aircraft longitudinal attitudes.

$$\theta' = \theta + \dot{\theta} \tag{3.17}$$

The DPC envelope reflects whether pilot pitch inputs are consistent with the aircraft dynamic trend. If pilots and aircraft are in harmony, DPC "allows" the maximum level of adversity in pitch; otherwise, the "allowable" adversity level is reduced according to the control authority

iv The limits vary according to the aircraft category and its flight configuration. For Part 25: -1.0 g's to +2.5 g's for flaps-up operation and 0.0 g's to +2.0 g's for flaps-down operation;[51] for Part 23: -1.52 g's to +3.8 g's for flaps-up operation and 0.0 g's to +2.0 g's for flaps-down operation[52] still available. Such a distinction leads to "squared" (harmony case) and "tapered" (disharmony case) quadrants – see Figure 14.

Due to its dynamic characteristic, DPC helps the visualisation of longitudinal dynamic events, e.g., pitch axis PIO – Pilot-Induced Oscillation – and large inappropriate control inputs. Such conditions can be distinguished by the concentration of data in the graph, e.g., in case of a PIO, data tend to predominantly be displayed in the "tapered" quadrants, since pilots "battle" the aircraft.

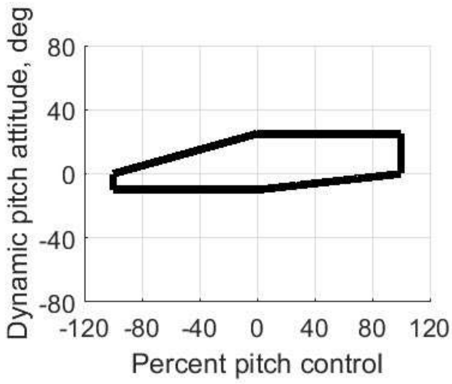


Figure 14: QLC Dynamic Pitch Control (DPC) envelope.
[Source: Adapted from Wilborn and Foster (2004)[37]]

3.2.5 *Dynamic roll control envelope – DRC*

DRC is analogous to DPC for the lateral case; therefore, it plots dynamic roll attitude (ϕ') versus roll control percentage usage. The definition of dynamic roll attitude is similar to that of dynamic pitch attitude, i.e., summation of the current roll angle (ϕ) and its derivative with time ($\dot{\phi}$) after one second – Equation 3.18.

$$\phi' = \phi + \dot{\phi} \tag{3.18}$$

The boundaries of ϕ' are the same of those of the usual roll attitude – Table 2 –, whilst the percent roll control authority varies from -100% (yoke fully left) to +100% (yoke fully right). The consistency of pilot lateral inputs and aircraft roll response is again expressed via "squared" and "tapered" quadrants. Figure 15 shows the DRC envelope.

The QLC classifies an event based on the number of envelopes crossed, i.e., after data from such an event have been plotted in the five QLC graphs, the following classification possibilities arise:

- **Normal condition:** an event is "normal" when no more than one envelope has been crossed;
- **Borderline LOC-I condition:** the event is a near-LOC-I situation when two QLC envelopes have been crossed; and
- **LOC-I condition:** the event is a LOC-I if three or more QLC envelopes have been crossed.

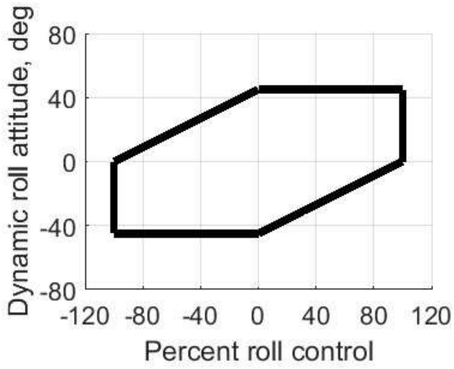


Figure 15: QLC Dynamic Roll Control (DRC) envelope.
[Source: Adapted from Wilborn and Foster (2004)[37]]

Figure 16 shows data from three different events plotted according to the QLC graphs. Based on the classification possibilities, the QLC states the three events are a LOC-I.

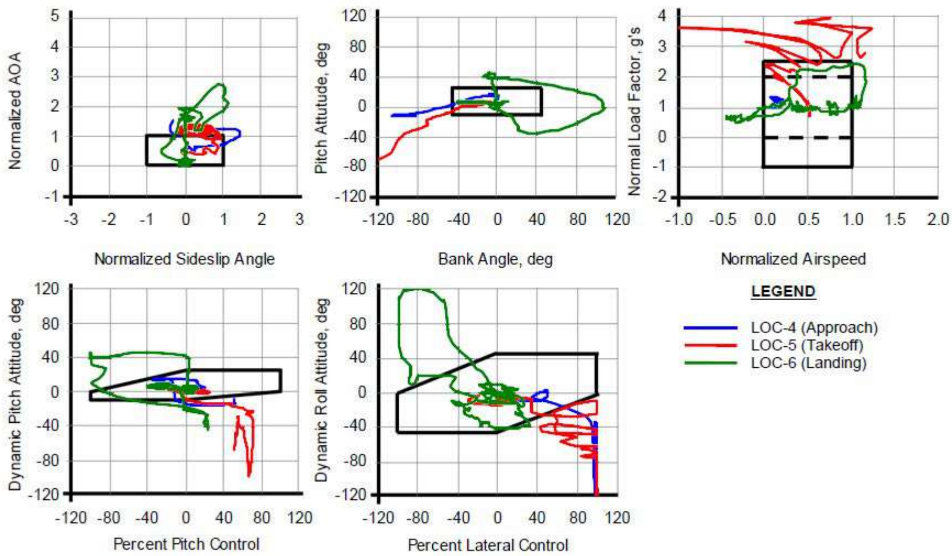


Figure 16: Flight data and QLC graphs.
[Source: Adapted from Wilborn and Foster (2004)[37]]

Despite the clearness of the parametric methodology supporting the QLC, Wilborn and Foster (2004)[37] did not explore the reasons for selecting the number of envelopes crossed as the parameter defining the quantitative criterion. They only stated "generally speaking, if a maneuver crosses three or more envelopes, it will be classified even by experimental test pilots as 'out of control.' This then seems to be a good working definition" [37, p.6].

In fact, the QLC has never been validated,[32] although its parametric methodology is feasible and can potentially provide paramount information for the characterisation of LOC-I occurrences from the perspective of the aircraft dynamics. However, given the participation of human pilots in the events, information must be assessed from their point of view, as performed in this research via the Cooper-Harper Rating Scale – explored in the sequence.

3.3 Assessment of Handling Qualities

Aircraft must display qualities and characteristics that enable humans to easily and precisely perform required tasks. At the end of the 1960s, Cooper and Harper (1969)[42] coined the term "handling qualities" for such characteristics.

If human pilots did not exist anymore and aircraft were flown exclusively by automated systems, handling qualities would not even exist, since they essentially depend on the presence of a human operator in the flight deck. However, to date, especially in off-normal situations, human pilots have been paramount to guarantee the safety of a flight, and good qualities can be differential for them to avoid an accident. Numerous and highly integrated factors comprise "handling qualities" (e.g., aircraft stability characteristics, type of propulsion system, control sensitivity, among others), and, the best way to assess them is asking a human pilot[v].

The handling qualities assessment process is an art somewhere in between Engineering and Psychology. Pilots report and explain whether they consider the aircraft controllable, and, if so, the way they perceive their action.[45] The mapping of the most important factors considered by pilots is difficult in such a complex analysis, especially because they may be influenced by the pilots' flight experience, training, motivation, ability, stress, interaction with the machine, input gains etc.

Handling qualities rating scales (e.g., Cooper-Harper Rating Scale, Cornell Aeronautical Laboratory Scale, Cranfield Aircraft Handling Qualities Rating Scale etc.) were conceived for the establishment of a "common language" and for engineers to more effectively discuss and address the outcomes of an assessment process[vi]. The basic in-common idea among those scales is to group handling qualities into categories, and divide them into subcategories associated with qualitative descriptions and numerical ratings.[42] Among some options, the Cooper-Harper Rating Scale stands out. Although introduced by G. Cooper and R. Harper in 1969, it is still extensively used in flight test activities, partially because the authors proposed a methodology, as opposed to "only" a scale, as discussed in what follows.

3.3.1 Cooper-Harper scale

According to G. Cooper and R. Harper, the handling qualities of an aircraft should be assessed in the context of tasks assigned to pilots. Under such conditions, they propose the evaluation of qualities based on the *performance-workload* binomial. *Performance* refers to both **(i)** *pilot performance* – a pilot´s efficiency in moving the controls towards accomplishing a given task –, and **(ii)** *pilot-vehicle performance* – the accuracy and precision of the pilot-aircraft system in accomplishing a given task. *Workload* measures the mental and physical efforts of pilots for attaining a given level of performance during a task.[42]

However, *performance* and *workload* are strongly connected, and cannot be characterised

[v] Handling qualities can also be predicted by computational tools, but software programs lack accurate models to represent the adaptive behaviour of a human being and their use is limited[45]

[vi] As further clarified in this section, a handling qualities assessment process involves much more than only the use of a scale

independently. To indirectly measure such parameters, Cooper and Harper (1969)[42] defined an additional and independent variable called *compensation*, which is "the measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics"[42, p.17]. The word "additional" is paramount, since it states the total workload to perform a task is comprised of the compensation **plus** the workload due to the task itself. The authors formulated a strategy according to which pilots observe *performance* and *compensation* to evaluate the aircraft handling qualities; however, they are in fact analysing *performance* and *workload*, the actual characteristics of interest.

The strategy was shaped in a handling qualities assessment tool in the form of the scale shown in Figure 17, i.e., the so-called Cooper-Harper scale. At a first glance, we see ratings varying from 1 to 10, accompanied by textual descriptions and grouped into four levels, according to a decision tree structure. Except for ratings (hereinafter called Cooper-Harper Rating – CHR) *8* to *10*, the textual explanations clearly show the *performance-compensation* binomial. In a more careful reading, *performance* can be either "adequate" or "desired", whereas *compensation* ranges from "not a factor" to "maximum tolerable".

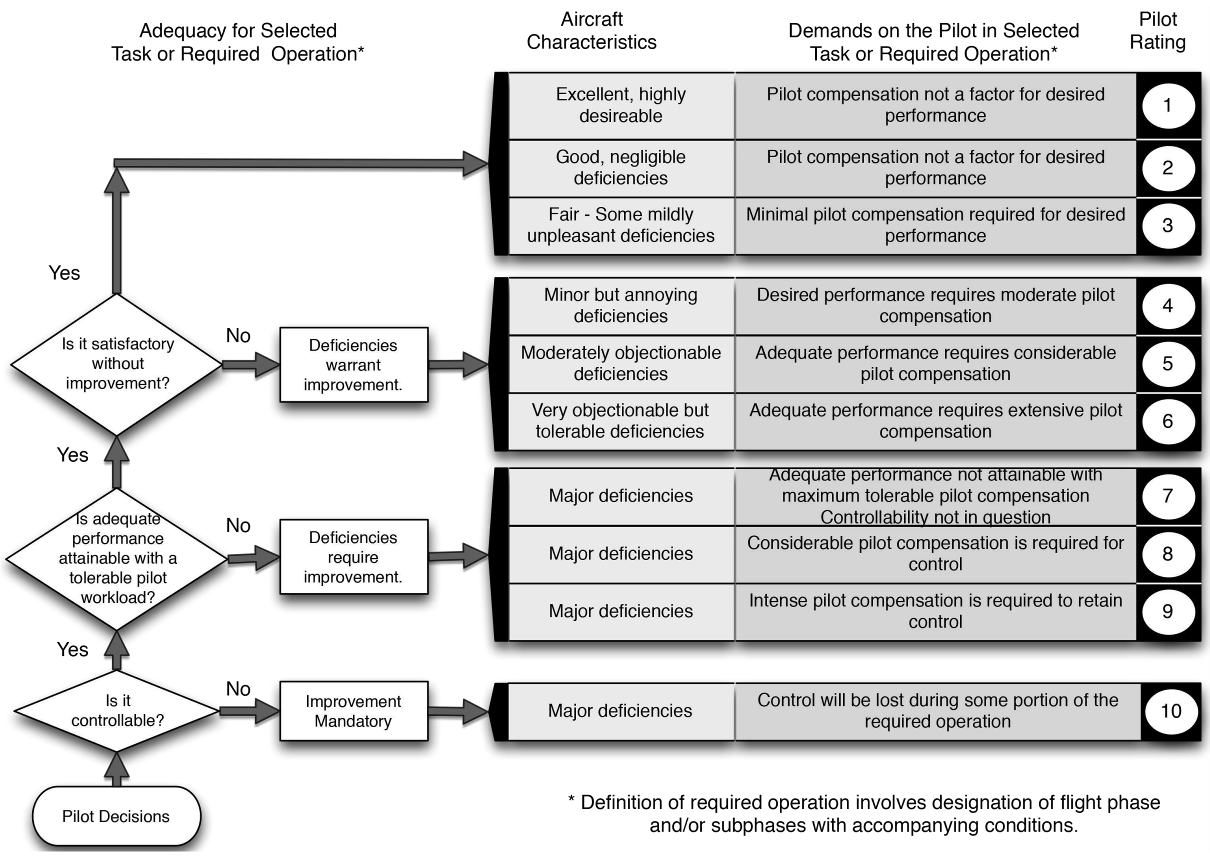


Figure 17: Cooper-Harper rating scale.
[Source: Adapted from Cooper and Harper (1969)[42]]

Levels of performance or degrees of compensation can be assessed only in the context of a task. In simple words, *task* is the work pilots are assigned to, and typically consists of a manoeuvre and definition of parameters under evaluation, e.g., climbing 1,000 ft while maintaining heading and airspeed, or varying heading in 45° maintaining airspeed and altitude.

In a task, levels of performance refer to tolerances around the parameters under evaluation. Broader tolerances are the "adequate" level, and stricter limits represent the "desired" level, e.g., climbing 1,000 ft while maintaining 100° heading (± 2.0° for adequate or ± 1.0° for desired) and 250 kts airspeed (± 10 kts for adequate or ± 5 kts for desired), or varying the heading in 45° maintaining 300 kts airspeed (± 4 kts for adequate or ± 2 kts for desired) and 7,000 ft altitude (± 300 ft for adequate or ± 150 ft for desired).

When performing a task, pilots are aware of the parameters under evaluation and their tolerances, so that they can adjust their control approach towards meeting them. Naturally, the control efforts are associated with a workload, which, in turn, depends on both task and degree of compensation. Although engineers can help pilots determine whether the "adequate" or "desired" level of performance has been achieved, only pilots are able to assess the degree of compensation.

For such an assessment, firstly, pilots must clearly distinguish between workload originating in the task ("non-additional workload") and in the deficiencies of the aircraft ("additional workload", i.e., "compensation"), which demands considerable experience[vii]. Towards avoiding the infinite possibilities pilots can use to describe "compensation", Cooper and Harper (1969)[42] proposed seven different adjectives to describe it, namely "not a factor", "minimal", "moderate", "considerable", "extensive", "intense", and "maximum tolerable".

Regarding tasks, although such wording is meaningful, it is quite subjective, thus potentially biasing the handling qualities assessment. Towards reducing subjectivity, the aforementioned authors adopted two strategies. Firstly, they associated the adjectives with levels of performance, an objective parameter, conceiving *performance-compensation* pairs related to the CHRs. This is clearly shown by the textual descriptions of the ratings (see Figure 17). Secondly, they conceived four levels of ratings based on a decision tree structure, i.e., instead of simply "choosing" a rating, pilots and engineers must answer specific dichotomous questions towards reaching a certain handling qualities level. Pilots decide on a final CHR based on the textual descriptions in the levels, typically composed of three ratings. Therefore, instead of seven "compensation" adjectives, they distinguish between two or three qualifiers for their final decision, considerably reducing subjectivity.

The decision structure of the Cooper-Harper scale is comprised of three questions (see Figure 17). Although simple in wording, their meaning is complex, since they are connected to a broader context and human limitations. The first question ("Is it controllable?") does not mean controllability as only a control authority or predicted outputs to certain inputs; instead, it asks pilots whether they must provide their undivided attention to be able to make the pilot-aircraft system accomplish an assigned task.[42,48,53] Therefore, a negative answer, or a CHR *10*, does not mean the aircraft will certainly crash; on the contrary, it represents a condition in which pilots must fully focus on controlling the vehicle, and cannot afford other actions/thoughts, such as trying to understand the behaviour of the aircraft and experimenting with control strategy alternatives. However, the aircraft can demonstrate enough control authority/predictability to divert to another task.[48,53]

vii As addressed elsewhere, this separation is necessary because *compensation*, as opposed to *workload*, is an entry to the scale

The second question ("Is adequate performance attainable with a tolerable pilot workload?") is comprised of two others: **(1)** "is adequate performance attainable?" and **(2)** "if attainable, is the pilot workload tolerable?".[53] In case of a negative answer for any of them, pilots must decide whether controllability is marginal (CHRs *8* and *9*) or not (CHR *7*), thus reflecting on whether their attention and efforts are fully directed to control the aircraft and accomplish the task, or on whether they can accept a given request (reach of certain performance).

The third and last question ("Is it satisfactory without improvements?") is related to pilots feeling "annoyed" by compensation. If they understand the deficiencies of the aircraft are disturbing, improvements are mandatory, and they must choose between CHRs from *4* to *6*. Again, differences in levels of performance and degrees of compensation help pilots decide on one of those ratings. Conversely, if compensation is negligible or the least possible ("minimal"), CHRs *1* to *3* are made available. To a practical extent, the possibility of choosing CHRs level 1 (*1* to *3*) means the aircraft can be accepted (certified) as it is, since its deficiencies, if existent, are very small, and (practically) require no additional workload.

According to all considerations, CHRs can be rearranged from the perspective of controllability, the topic of major concern in this research, bearing in mind the application of the Cooper-Harper scale is always associated with the context of given tasks and their design should be based on (but not bounded by) demands of the real-world, i.e., tasks must display a “necessity" component[viii].[42,53] Consequently, the ratings can be rearranged into the following controllability categories:

- CHR *10*: LOC-I condition;
- CHRs *8* and *9*: borderline LOC-I condition; and
- CHRs *1* to *7*: normal control condition.

The Cooper-Harper scale can be then read in terms of qualitative subjective pilot´s opinion on the controllability of the aircraft and not on handling qualities, thus enabling comparisons with the outcomes of the QLC. However, CHRs are the final outcome of the handling qualities assessment process, i.e., they do not convey opinions in their integrity. Towards bringing such information to light and effectively understanding how pilots perceive controllability, we must go beyond the CHRs, which is explored in the following section.

3.3.2 Beyond the printed scale

Despite the practicality of working with numbers, an appropriate handling qualities assessment campaign involves much more than analyses of CHRs. Numbers oversimplify a pilot’s opinion, since they do not tell *how* and *why* pilots decided on a rating; in fact, only words can do that.[42,53]

Engineers depend on this information to identify reasons for pilots’ approvals/disapprovals, and a way to capture a thorough pilot’s feedback is to use an "open-questionnaire" during the debriefing of each task. The questionnaire, typically called *comment car* – two examples are given

[viii] There is no reason, for example, for designing a task like "capturing a 20° pitch angle in two seconds" for a Cessna 150

in Figure 18 –, consists of a list of items for which pilot comments are desired.[45] Instead of highly specific questions, comment cards should stimulate pilots to reflect on causes and consequences of the general piloting characteristics of the aircraft, raising discussions and providing information not captured by the Cooper-Harper scale. Besides, engineers should be flexible to explore deviations of the original questions and obtain the most out of pilots' perception, i.e., they should use the cards as a guideline rather than a checklist.

Well-conducted comment sections usually result in open and long pilot answers; therefore, their recording is suggested for a proper post-processing.[42] Additionally, debriefing sections report whether the objectives of an experiment have been accomplished, whether the terms on the Cooper-Harper scale have been accurately interpreted, and whether the tasks have been well-interpreted and executed.

Approach and Landing Pilot Comment Card

Facility:	**Card No.:**	**Flight No.:**
Config.:	**Pilot:**	**Date:**

1. Pitch Attitude and Bank Angle Control and Tracking Capability? (Easy, Fair, Difficult)
2. Predictability of Pitch and Roll Response to Pilot Inputs? (Satisfactory, Abrupt, Sluggish)
3. Did you see any PIO Tendencies in the Pitch or Roll Axis? _____ Yes _____ No
   If Yes, did you have to reduce pilot gain to continue task or did you have to abandon the task to keep from diverging?
   Any special control techniques required?
4. Ability to Control Flight Path? (Easy - Fair - Difficult)
5. Ability to Control Airspeed (autothrottle OFF)? (Easy - Fair - Difficult)
6. Centerstick Force and Displacement Characteristics? (Desirable - Satisfactory - Unsatisfactory)
7. Was Pitch/Roll Harmony Satisfactory?
8. Rudder Pedal Force and Displacement Characteristics (if did not use, indicate so)? (Desirable - Satisfactory - Unsatisfactory)
9. Flare and Touchdown - Any problems with runway line-up, sink rate control, tendency to float, lowering the nose?
10. Approach vs. Landing - Which was more difficult and why?
11. Effects of Wind/Turbulence?
12. Summary (brief) - Good/Bad Features.

Segment	***Cooper-Harper rating***	***Long. PIO rating***	***Lat-Dir PIO rating***
Approach			
Landing Flare			

Performance Definitions for Cooper-Harper Ratings	
Desired	***Adequate***
No Pilot-Induced Oscillations (PIOs)	
Touchdown within 5 feet of centerline	Touchdown within 25 feet of centerline
Touchdown within ±250 ft of aimpoint	Touchdown within –250, +750 ft of aimpoint
Approach airspeed maintained within ±5 knots	Approach airspeed maintained within –5 knots/+10 knots
Touchdown airspeed within ±3 knots of target speed with less than 3 ft/second sink rate	Touchdown airspeed within ±5 knots of target speed with less than 9 ft/second sink rate

(a)

Pilot Comment Card -- Task ID: [ ] 4020 [ ] 4069 [ ] 3115

Pilot: ________________**Configuration:**____________ **Date:**____________

1. Adequacy of Roll Control Power? (Desirable - Satisfactory - Unsatisfactory)

2. Ability to Control and Track Flight Path? (Easy - Fair - Difficult)
   Bank Angle? (Easy - Fair - Difficult)

3. Predictability of Response to Pilot Inputs in
   Pitch? (Desirable - Satisfactory - Unsatisfactory)
   Roll? (Desirable - Satisfactory - Unsatisfactory)

4. Were there any PIO tendencies in Pitch or Roll? _____ Yes _____ No
   If Yes, was the task: _____ continued (with reduced pilot gain), or
   _____ abandoned (to prevent divergence)

5. Response Characteristics of the Pitch/Roll Inceptor and Rudder Pedals (indicate if used):
   • Force and Displacement Characteristics? (Desirable - Satisfactory - Unsatisfactory)
   • Pitch and Roll Sensitivity? (Desirable - Satisfactory - Unsatisfactory)
   • Pitch/Roll Harmony? (Desirable - Satisfactory - Unsatisfactory)

6. Any problems in Pitch or Roll during Glideslope or Localizer tracking/ capture?

7. Any problems in Pitch or Roll during Offset Corrections?

8. Any problems in Pitch or Roll during Flight Director Tracking (if applicable)?

9. Any problems during Flare and Touchdown?
   • Runway Line-Up, Sink Rate Control, Tendency to Float

10. Approach vs. Landing - Which was more difficult and why?

11. Effects of Wind/Turbulence?

12. Were the problems noted in questions 6-11 (if any) primarily a result of:
    (Vertical Vibrations - Lateral Vibrations - Both - Neither - Can't Specify)

13. Summary - Good/Bad Features. Any special control techniques required?

08-Sept-97 DLR

(b)

Figure 18: Example of comment cards.
[Source: (a) Hodgkinson (1999);[54] (b) Bailey (2000)[55]]

3.3.3 Classification variability

Humans are an inseparable part of handling qualities assessment campaigns – in fact, they are their reason – and, naturally, have different opinions; therefore, variability is expected in tests. Substantial disagreements are indicative of serious misunderstandings, but slight variations are acceptable and even positive for the overall result of a campaign.

Pilot rating variability is divided into two groups, namely **(a)** intrapilot and **(b)** interpilot. The former refers to an individual pilot that cannot reliably repeat her/his assessments, and the latter is related to differences between two given human beings.[56] Although neither type can be fully eliminated, variability can be minimised with the use of proper techniques – e.g., the solid methodology proposed by Cooper and Harper (1969).[42]

The importance of the proper use of the Cooper-Harper scale must be reinforced; it includes the clarification of its wording for both pilots and engineers and assurance of the use of its decision tree structure. In some campaigns, participants tend to dismiss the comment section and even ignore the questions of the scale, disregarding crucial reflections. Consequently, ratings are "chosen", not analysed, and variability (intra and inter) significantly increases.[45,56]

Another cause of variability (more specifically, intrapilot variability) is the "learning effect" pilots are subjected to in an assessment campaign. Naturally, the more the pilots familiarise with the aircraft, its condition and the assigned task, the more proficient they tend to become. This effect can considerably impact on the results, and can be reduced by a consistent application of an evaluation technique, i.e., use of either *short-look* or *long-look* evaluation techniques (and not mixing them up). The basic difference between the strategies is the time during which pilots fly the aircraft between the briefing and the start of the task. *Long-look* evaluations tend to be associated with less variability, since pilots have more time to "study" the condition and optimise their control technique, minimising the learning effect,[56] and should be preferred in research studies not limited by costs. However, over the past 50 years, the industry has preferred *short-look* evaluations due to the high costs involved in test flights.[53] Each technique has its pros and cons, and flight test teams must be aware of them. Both options lead to the same results, provided they have been consistently used throughout the whole assessment campaign (i.e., techniques are not interchangeable in a campaign).

Rating variability (interpilot, in this case) also originates from the fact each pilot is a different human being, i.e., their abilities, decisions and perceptions vary. To a practical extent, it represents differences in not only the control strategies adopted by each pilot, but also in the way they interpret the wording of the Cooper-Harper scale.[56] Due to the peculiarity of the matter, McDonnell (1968)[57] demonstrated that, psychologically speaking, the *degree of compensation* is a nonlinear variable. Such differences in human perception can be reduced through the selection of pilots with similar backgrounds (training, experience, and total flight hours).

Moreover, the greater the number of pilots in a campaign, the lesser the interpilot variability and the higher the confidence in the results. However, flights are costly and campaigns have deadlines, i.e., a "magic" number of participating pilots that balances the expenses of the flight campaign and provides reliable results must be found. According to Figure 19, campaigns with more than six pilots (provided tests are well-designed and executed)[58] promote no significant gain of confidence in the results. Six is, therefore, the minimum number of pilots and a logical cutoff that guarantees an acceptable pilot rating variability.[56]

Below is a summary of some of the best practices for reducing variability in handling qualities experiments:

- clear definition of the program objectives;
- maximum maintenance of constancy of all external variables (aircraft, flight condition, environment etc.) throughout the campaign;
- design of tasks and definition of levels of performance based on real-world demands;
- selection of at least six pilots with similar backgrounds;
- instruction to pilots and engineers on their choice and use of a single evaluation technique

(short- or long-look) throughout the campaign;
- assurance that pilots and engineers understand the wording of the Cooper-Harper scale;
- assurance that the pilot comment section is held; and
- assurance of the proper use of the Cooper-Harper scale.

In the wake of a rapidly changing aviation, human-related matters are sometimes ignored, thus leading to catastrophic consequences, since the number of accidents with human contribution increases. While human pilots are in the cockpits, the assessment and understanding of the way they interact with the aircraft will continue to be imperative. From the new understanding given to CHRs, the Cooper-Harper scale can enable analyses of controllability issues from a pilot´s point of view, whereas QLC contributes from the perspective of the aircraft dynamics to investigations on whether (and to which extent) such methods correlate. The next chapter presents and details the way such methods have been used in this research.

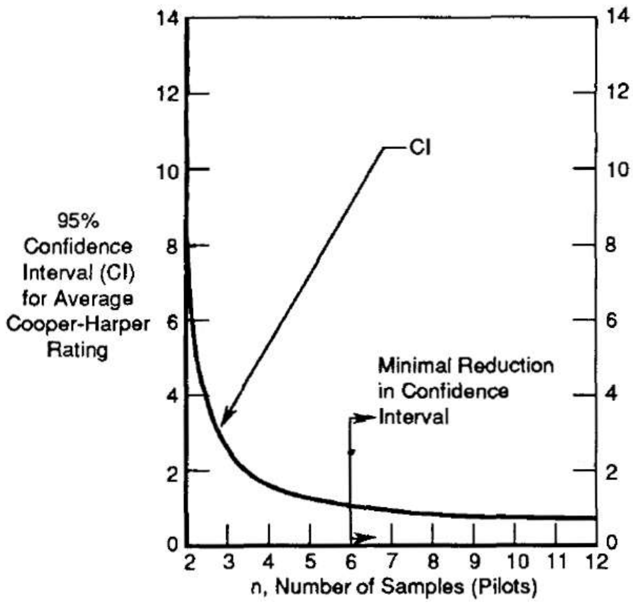


Figure 19: Confidence intervals and sampling size.
[Source: Adapted from Wilson and Riley (1989)[56]]

METHODOLOGY & MATERIALS

4 METHOD

Pilot-in-the-loop simulations were performed to collect data for investigations on the correlation between pilot's opinions and flight data under LOC-I conditions. Debriefing comments constitute qualitative data, whereas CHRs and aircraft parameters represent quantitative ones. Several intermediate steps such as selection of representative test scenarios, choice of an aircraft model, design of proper tasks, and establishment of simulation procedures were taken prior to the experiments. This chapter details all such steps, as well as the data post-processing methods adopted in the research.

4.1 Apparatus

The experiments were performed in the EB#2 research flight simulator at the São Carlos School of Engineering (EESC-USP), in Brazil. The simulator features a 6DOF (Degree of Freedom) hydraulic hexapod motion system (Stewart platform), a 50-inch screen for the out-the-window scene, a 24-inch screen for the aircraft panel, an audio system (for both communication and simulation sounds), and a regular set of controls[i]. A black cover "wraps" the cockpit to prevent pilots from capturing references from the external environment. Figures 20 and 21 show, respectively, the exterior and the interior of EB#2.

A Proportional-Integral-Derivative (PID) controller and a washout filter were used for motion cueing.[59,60] For safety reasons, saturation thresholds were programmed to limiting the motion of the platform, resulting in the capabilities shown in Table 3. An open-source flight simulator software called FlightGear emulated the visual scenes, sounds and aircraft model.

Switches were properly configured for the elevator trim, flaps, spoiler/speedbrake and toe-brakes. Although the equipment had been designed by Thrustmaster® and was based on a real aircraft, it provided no force feedback, but only weighted supporting bases (except for the rudder pedals). Since the sensitivity of the controls (surface deflection for control displacement) intrinsically depends on the aircraft type, they were adjusted for the aircraft model selected for the experiments (details in Section 4.2). The same equipment has already been used in previous studies.[61–63]

4.2 Aircraft model

Although LOC-I accidents occur in all aviation categories, most fatalities and the biggest social impact are detected in commercial aviation; therefore, such a segment was selected as the focus of this research. From 1970 to 2019, the commercial aviation fatal accident rate showed a 16 factor decrease[64] due to more reliable engines and structures, standardisation of maintenance

[i] Sidestick on the left-hand side, pedestal with engines, flaps and spoilers/speedbrakes controls on the right side, and rudder pedals

(a) With no black cover

(b) With black cover

Figure 20: EB#2 simulator exterior.
[Source: The author]

Table 3: EB#2 motion limits (relative to the central position of the platform).
[Source: The author]

Degree of Freedom	Displacement
Longitudinal	-370 mm $\leq$ x $\leq$ 400 mm
Lateral	-400 mm $\leq$ y $\leq$ 400 mm
Vertical	-275 mm $\leq$ z $\leq$ 275 mm
Roll	-15° $\leq \phi \leq$ 15°
Pitch	-15° $\leq \theta \leq$ 15°
Yaw	-15° $\leq \psi \leq$ 15°

and operation procedures, better management of the airspace and, unquestionably, introduction of a plurality of embarked systems.

The systems, well-evidenced by the four aircraft generations shown in Figure 22, have inevitably shifted the role of the human pilot from an active participation in the aircraft control loop to a “high-order” automation manager. Apart from tasks and the way pilots interact with the aircraft, the spread of technical advances have also changed the set of cognitive abilities required from a pilot,[65] i.e., flexibility to rapidly switch between mental models, quick filtering of information and enhanced judgement skills to solve problems and make decisions, sustained attention despite monotonicity, and emotional self-regulation to cope with occasional startle and surprise.

(a) Out-the-window-view and instrument panel

(b) Set of controls and instrument panel

Figure 21: EB#2 simulator interior.
[Source: The author]

Fourth generation aircraft have naturally increased in number, and, according to Airbus (2017, p.16),[13] "[such jets have] added a 75% reduction in fatal LOC-I accidents compared to the third generation", mainly due to the incorporation of FBW systems and flight envelope protection. However, the spreading of this same technology is accompanied by an increase in the frequency of misunderstandings between pilots and autoflight systems,[66] evidenced by episodes like Turkish Airlines 1951 (2009), Air France 447 (2009), Asiana Airlines 214 (2013), Lion Air 610 (2018), Ethiopian Airlines 302 (2019), among others.

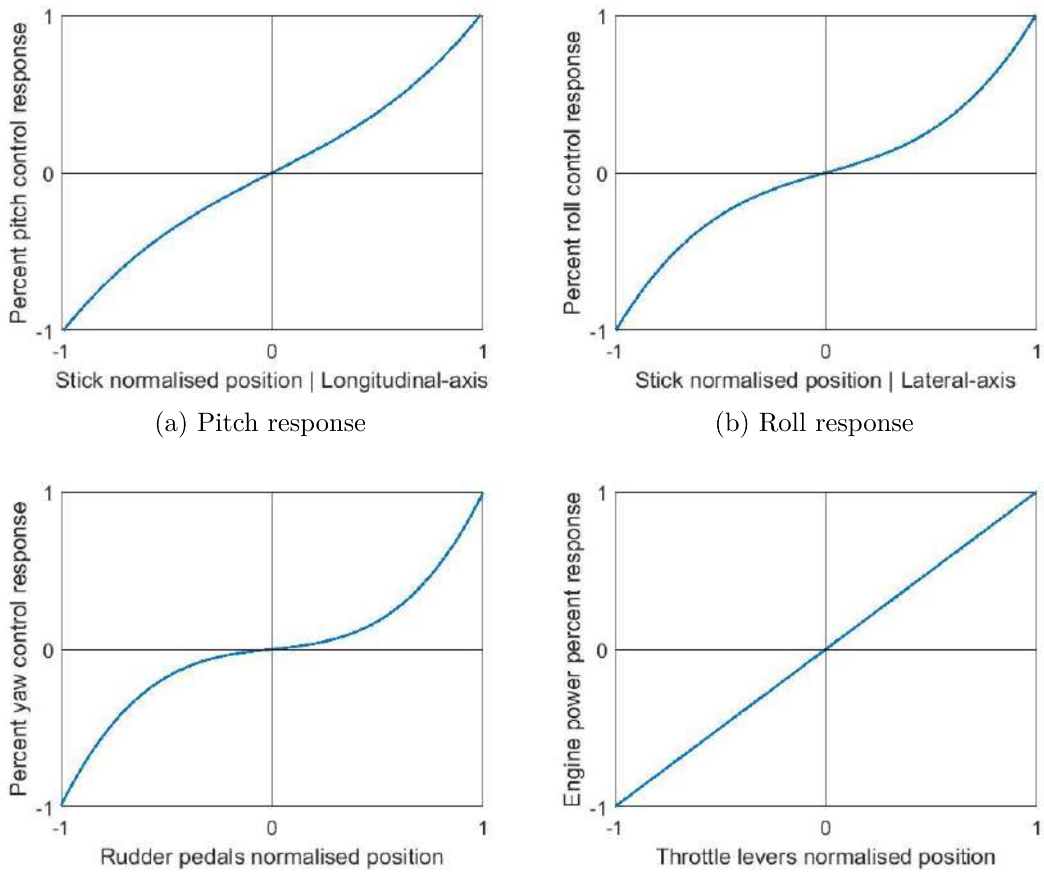
Figure 22: Generations of aircraft.
[Source: Airbus (2017)[13]]

Given such a panorama and deadlines of this research, a fourth generation aircraft was chosen for the simulations. A non-linear aerodynamic model of a Boeing 777-200ER officially developed by FlightGear and that provides failure and additional configuration options was used. It is a consolidated 350 pax (average) commercial fourth generation long-range wide-body twin-engine turbofan. The -200ER version is one the variants of the Boeing 777 programme, a family whose development dates back to the mid-1990s and that currently responds to more than 14 million flight hours worldwide.[67] Boeing 777 has one of the best aviation safety records, since, in more than 25-year operation, it has been involved in only 28 occurrences,[68] among which the following controllability-related events[ii]:

[ii] Most occurrences involved the -200ER

1. Malaysia Airlines Flight 124 (2005) serious incident involving fault instrument indications and an upset triggered by the autopilot;[40]
2. British Airways Flight 38 (2008) no-fatal accident in which engines failed to respond to human and autopilot inputs, thus resulting in an uncontrolled descent;[40]
3. Delta Airlines Flight 18 (2008) serious incident related to an uncommanded loss of thrust in one of the engines at high altitude[iii];
4. Asiana Airlines Flight 214 (2013) fatal accident after a non-stabilised final approach resulting from a poor interaction between human pilots and the controls;[71] and
5. Emirates Flight 521 (2016) fatal landing due to windshear activity and a frustrated go-around procedure.[72]

After the selection of the aircraft model, two professional pilots adjusted the control sensitivity curves to being as close as possible to a real aircraft, and after several simulations and discussions, they agreed the curves shown in Figure 23 adequately represented the response of the controls of a fully operational Boeing 777.



(a) Pitch response (b) Roll response

(c) Yaw response (d) Throttle levers

Figure 23: Normal controls response curves (stick & pedals + throttle inputs).
[Source: The author]

The two invited pilots also assessed relevant instrument indications, resulting in the panel

[iii] Investigations later showed the ice crystals clogging the fuel-oil heat exchanger were the main cause of both British Airways 38 and Delta Flight 18[69,70]

shown in Figure 24. From left to right: pitch trim bar indication, a PFD, and an EICAS – Engine Indication and Crew Alerting System –; the aileron trim bar was placed just above the PFD[iv]. All other switches and buttons exerted a null action and were not used in the experiments.

Figure 24: Panel of instruments used during the simulations.
[Source: The author]

Given the dependence of the aircraft performance and controllability characteristics on the vehicle's weight and CG location, the experiments were performed for a relatively light and rear CG condition, since this is the combination in which performance tends to be privileged in detriment to controllability,[48] i.e., a preferable condition for the objectives of this research. Consequently, a Boeing 777-200ER at 460,000 lb @ 44% MAC[v] was used in the experiments, and the condition was in accordance with the aircraft operation manual.[73] Moreover, the simulations were performed in the so-called *direct mode*, i.e., the FBW system was bypassed and pilot inputs effectively moved the control surfaces with no filtering.[74] This choice aimed at promoting a more active pilot participation in the aircraft control loop.

It is important to bear in mind that any flight simulator has its limitations, and we cannot state EB#2 simulated a real Boeing 777-200ER. In any case, the purpose of this research is to deepen the understanding of the LOC-I phenomenon, rather than to address conditions specific for an aircraft. Therefore, the experiments must be consistently performed with the same aircraft, which was enabled by EB#2.

4.3 Test scenarios

Section 2.3 discussed the development of 60 LOC-I test scenarios from a study of 126 real LOC-I accidents. The choice of the scenarios for the research was based on their statistical

[iv] Some tasks performed in the research (details in Section 4.4) required additional information to be displayed in the panel of instruments, e.g., 37.5° bank angle markers – yellow dashes in the bank angle arch in Figure 24 –, and ILS indicators – purple diamonds in the vicinities of the PFD, also shown in Figure 24

[v] Via FlightGear, the configuration was frozen for every pilot, test scenario and task

significance in terms of number of accidents and fatalities.

On average, each of the 60 scenarios covers 1.52% of the 126 accidents and 1.43% of the 6087 associated fatalities. A more detailed analysis revealed 21 scenarios overcame the average accident coverage, whereas another 21 combinations exceeded the regular mean fatality coverage. The intersection of such "above average" groups showed 13 test scenarios that together account for 45.20% of the accidents (56 occurrences) and 54.25% of the fatalities (3302 lives) – Figure 25. Due to its statistical meaning, this relatively small sum of 13 scenarios certainly carries valuable information on LOC-I events, and was selected for the research.

According to Belcastro, C. (2012, p.1),[41] "aircraft LOC[-I] can result from a wide spectrum of hazards, often occurring in combination, which cannot be fully replicated during evaluation"; therefore, discussions on possible simulations of the selected scenarios based on the available resources and research goals are mandatory, which is addressed in the sequence.

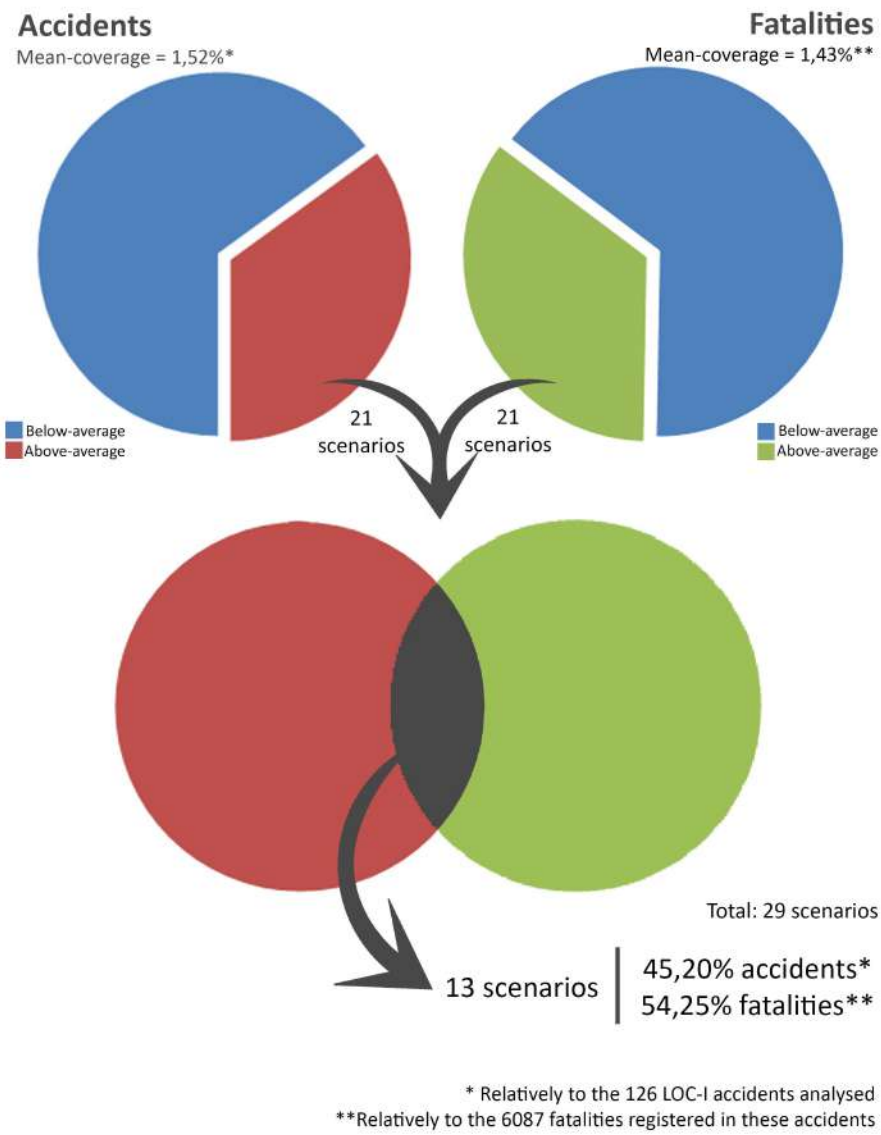


Figure 25: Statistical selection of test scenarios.
[Source: The author]

4.3.1 Test scenarios in EB#2

Belcastro (2012)[41] provided multiple options of contributing factors and phases of flight to simulate each of the LOC-I test scenarios, e.g., in Scenario 41 in Annexe A, **(i)** a night flight, turbulence or thunderstorm activity can simulate external hazards, **(ii)** pilot inactivity or exacerbating inputs can represent inappropriate crew response, **(iii)** spiral dive, stall or varying attitude/velocity can serve as a vehicle upset, and **(iv)** the scenario can be run for takeoff, cruise or approach conditions, i.e., a given scenario can be simulated in many different ways.

Only the most critical contributing factors and phase of flight were chosen for each of the 13 scenarios selected for the experiments due to deadlines. Bromfield and Landry (2019, p.1)[31] stated "the majority of [LOC-I] previous studies have concentrated on fatal events only [, i.e.,] a missed opportunity" to learn from the non-fatal occurrences; therefore, the "most critical contributing factors" were selected from a flight safety perspective, i.e., instead of picking factors that would most likely lead to catastrophes, we selected combinations of precursors consistent with the current aviation reality and that can potentially contribute to flight safety.

Below are the 13 test scenarios selected and considerations for their simulations. Discussions involved **(i)** EB#2 capabilities, **(ii)** most feasible and real safety threats, and **(iii)** principles governing the use of the Cooper-Harper scale and QLC. Towards easing the debates, the sets were renumbered and presented in an ascending order, starting from 'Scenario 1', rather than keeping the original scenario identification number, as in Annexe A.

Scenario 1

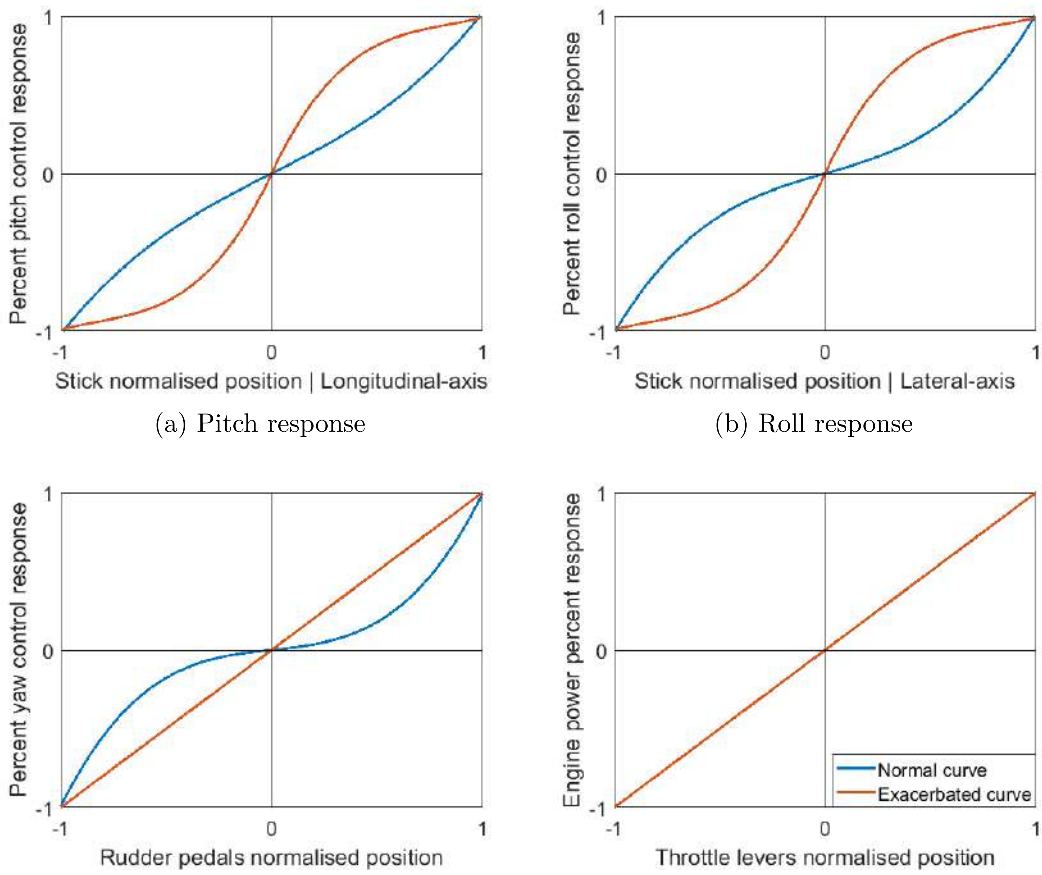
This scenario, number 3 in Annexe A, simulates a single engine failure and accounts for 3.97% of the accidents and 3.12% of the fatalities. The most critical condition for testing is the total loss of thrust, regardless of the engine, during takeoff, since the maximum of the engines is required in the procedure. Scenario 1 was easily reproduced in the simulation campaign by switching off engine 2, arbitrarily chosen.

Scenario 2

This scenario, number 2 in Annexe A, simulates the failure of a control surface actuator and accounts for 1.59% of the accidents and 1.49% of the fatalities. For simulation purposes, the total loss of any given primary control surface significantly increases the chances of an accident, and does not represent the redundancies of a fourth-generation aircraft well; therefore, a 75% reduction was selected for the experiments. Moreover, a failure of the elevator is more critical, in comparison to failures of rudder and ailerons, regardless of the flight condition.

In real-life, the failure of a control surface would probably be followed by high-gain inputs, at least in a first moment. Since exacerbated inputs can be an important contributing factor, such a precursor was addressed in the simulations by changing the control response curves to make them more sensitive, i.e., when pilots displaced the stick in normal magnitudes, the aircraft responded as it had been inputted by larger displacements – Figure 26 shows a comparison of normal and exacerbated control curves[vi].

Regarding the infrastructure of EB#2, the simulation of Scenario 2 was relatively simple, i.e., the exacerbated curves were transmitted to the aircraft dynamics via FlightGear and the software was configured for a 75% reduction in the elevator effectiveness.



(a) Pitch response (b) Roll response

(c) Yaw response (d) Throttle levers

Figure 26: Comparison between normal and exacerbated control response curves (stick & rudder + throttle inputs).
[Source: The author]

Scenario 3

This scenario, number 9 in Annexe A, simulates an uncontained engine failure with vehicle damage consequences, and accounts for 1.59% of the accidents and 1.82% of the fatalities. According to Belcastro (2012),[41] structural damages affect engines, lift surfaces, control surface actuators, and other underlying systems. However, the extension of damages resulting from uncontained engine failures are difficult to be predicted and, to date, simulation models to reproduce those events are still unrealistic. For such reasons and because FlightGear does not offer options for simulating structural damages, Scenario 3 was discarded.

[vi] Although arbitrary, the changes in the control curves attended the objective of representing excessive control inputs

Scenario 4

This scenario, number 20 in Annexe A, simulates unresponsive engine(s) followed by vehicle upset(s), and accounts for 2.38% of the accidents and 2.48% of the fatalities. Since in fourth-generation aircraft, the probability of a simultaneous failure of all FADEC – Full Authority Digital Engine Control – systems[vii] of all engines is virtually zero, the unresponsiveness of one engine was chosen as the condition to be simulated (it is critical and also connected to reality).

Since pilots are not usually trained to deal with unresponsive engines, non-normal inputs are naturally expected in such events. However, the presence of this additional precursor changes the original combination of factors into the one addressed by scenario 34 in Annexe A (unresponsive engine + inappropriate crew response + vehicle upsets). This new combination also corresponds to one of the 13 LOC-I test scenarios initially selected for the research and is detailed in Scenario 8 of the current list.

Scenario 5

This scenario, number 25 in Annexe A, simulates an icing impairment that leads to abnormal attitudes and/or stall, and accounts for 14.29% of the accidents and 8.74% of the fatalities.

Ice accretion mechanisms are complex and highly specific to the aircraft type, i.e., wind tunnel experiments are mandatory for the development of representative models of such conditions. FlightGear provides no icing simulation options, and the literature reports no study on ice accretion on Boeing 777. However, in general, icing is known to reduce the effectiveness of lifting and control surfaces and engines.[41]

Towards the simulation of this scenario, the following changes were made to the source code of the FlightGear Boeing 777-200ER aircraft model [viii]:

- sooner and more abrupt stalls for wing and horizontal stabiliser;
- reduction in the effectiveness of ailerons and elevator, i.e., the deflection of the surfaces produced less lift and more drag increments than in a usual condition; and
- reduction in the response speed and output power of engine 2, i.e., when the corresponding lever was moved, the engine required longer time to reach the solicited power and provided less power than that demanded for such a lever position.

The "icing" aircraft model used in this research may not fully represent the behaviour of a Boeing 777-200ER in ice events, however, the changes made followed the suggestions of Belcastro (2012)[41] and the known ice accretion effects.

Inappropriate pilot actions are expected in ice events, since aviators are not trained for such a condition. This precursor was addressed in the simulations through the introduction of a delay between sidestick inputs[ix] and vehicle response. More precisely, the delay was provided by

[vii] There is usually more than one FADEC per engine

[viii] Appendix A presents the "normal" and "icing" aircraft .XML FlightGear model configuration files used in the research and details the parameters of the "icing" model

[ix] There were no delays for pedals and throttle levers

a 60 Hz to 1 Hz reduction in the sampling rate of the EB#2's sidestick position[x].

Scenario 6

This scenario, number 27 in Annexe A, simulates windshear profiles and/or different levels of turbulence resulting in abnormal trajectory and/or stall, and accounts for 1.59% of the accidents and 4.11% of the fatalities.

Although this is a relatively simple combination of contributing factors to be simulated – FlightGear provides several wind profile options –, the presence of a meteorological event limits the applicability of the Cooper-Harper scale. Recalling the scale defines "pilot compensation" as the additional workload due to aircraft deficiencies (Section 3.3), inclement weather demands extra pilots' attention, affecting their degree of compensation and, consequently, biasing their qualitative assessment towards higher CHRs. Since the Cooper-Harper scale is not appropriate for evaluations of handling qualities when distinct meteorological phenomena (e.g. windshear) are present, Scenario 6 was rejected.

Scenario 7

This scenario, number 33 in Annexe A, simulates the failure of flight instruments (altitude, airspeed or attitude indicators) while the autothrottle or/and autopilot is/are engaged, followed by inappropriate crew inputs and a consequent low-speed stall. It accounts for 2.38% of the accidents and 3.25% of the fatalities.

Although relatively simple to be simulated, this combination of precursors, particularly the faulty instrument indication, violates the principles of application of the Cooper-Harper scale, since pilots/engineers would not be able to monitor aircraft performance (Section 3.3). Therefore, Scenario 7 was rejected.

Scenario 8

This scenario, number 34 in Annexe A, simulates an unresponsive engine together with inappropriate pilot actuation and consequent upset(s) (abnormal angular rates and/or stall). It accounts for 2.38% of the accidents and 1.74% of the fatalities.

For simulation purposes, the unresponsive engine precursor was addressed through the locking of engine 2 output power at 50%[xi] of the total available thrust and the switching off of communication between its corresponding throttle lever and FlightGear. Regardless of the position of the lever, engine 2 always provided half of its maximum power. Pilots were not allowed to shut the engine down.

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x In tests prior to the experiments, pilots reported perceiving delays when the sampling rate dropped to below 5 Hz

xi Belcastro (2012)[41] provided no clue on such a number; however, since engines work at approximately half their powers during cruise, 50% was considered a representative number

Regarding the "inappropriate pilot actuation" precursor, exacerbated and delayed inputs were, respectively, simulated by the response curves of Figure 26, and by a 60 Hz to 3 Hz reduction in the sampling rate of the sidestick.

Scenario 9

This scenario, number 40 in Annexe A, simulates pilot spatial disorientation leading to vehicle upsets. It accounts for 7.14% of the accidents and 7.10% of the fatalities.

Artifices like clouds or night flight can simulate spatial disorientation; however, a proper use of the Cooper-Harper scale requires pilots focus on instrument indications while performing the tasks, which, in practice, prevents a spatial disorientation. Therefore, Scenario 9 was rejected.

Scenario 10

This scenario, number 42 in Annexe A, simulates wind shear and/or turbulence together with inappropriate crew actuation, which result in upsets, such as overspeed, stall and/or rapid descent. It accounts for 1.59% of the accidents and 2.46% of the fatalities. A meteorological disturbance in this combination of precursors limits the applicability of the Cooper-Harper scale, as in Scenario 6; therefore, Scenario 10 was rejected.

Scenario 11

This scenario, number 47 in Annexe A, simulates meteorological and vehicle adverse conditions leading to upsets. It accounts for 1.59% of the accidents and 3.75% of the fatalities. For the same reasons of Scenarios 6 and 10, Scenario 11 was rejected.

Scenario 12

This scenario, number 49 in Annexe A, simulates a crew failing to properly configure high-lift devices during takeoff and approach (with and without go-around) and the aircraft enters an abnormal trajectory. It accounts for 1.59% of the accidents and 2.50% of the fatalities.

The simulation of Scenario 12 depended on improperly configuring the aircraft without the pilots noticing it, which was not possible in EB#2 because of aural configuration alarms and EICAS messages automatically triggered by FlightGear that prevented pilots from the surprise effect. Moreover, a proper use of the Cooper-Harper scale requires pilots be aware of the aircraft condition, which would not be the case if they had been deceived. For such reasons, Scenario 12 was rejected.

Scenario 13

This scenario, number 50 in Annexe A, simulates an inadvertent deployment of thrust reverser during takeoff or approach, leading to abnormal attitudes in pitch/roll, loss of airspeed, and a stall. It accounts for 3.17% of the accidents and 11.68% of the fatalities.

A highly publicised accident resulting from this combination of precursors occurred with TAM flight 402 in Sao Paulo, in 1996. Since then, protections against in-flight inadvertent thrust reversal deployment have been mandatory for commercial aircraft.[75] Boeing 777-200ER features such protections; therefore, Scenario 13 was rejected.

Four out of the 13 scenarios initially selected met the simulation criteria[xii], and account for 24.61% of the 126 LOC-I accidents and 17.57% of the associated 6087 casualties analysed by Belcastro and Foster (2010),[40] which are representative numbers. Towards avoiding nomenclature confusion, the four remaining scenarios were renumbered, as shown in Table 4, along with their short descriptions.

Table 4: Summary of the simulation scenarios.
[Source: The author]

Scenario ID	Summary	Precursors	
01	Single engine failure	100% thrust reduction in engine 2	
02	Loss of control surface effectiveness together with exacerbated crew inputs	Loss of 75% of the elevator effectiveness	Exacerbated crew control inputs
03	Unresponsive engine together with exacerbated and delayed crew inputs	Engine 2 unresponsive and locked at 50% of the total available thrust	Exacerbated and delayed crew control inputs
04	Icing impairment together with delayed crew inputs	Icing accumulation (sooner stall, less effective control surfaces, thrust asymmetry)	Delayed crew control inputs

4.4 Tasks

Assessment tasks should be representative of real-life operation and push pilots into the aircraft control loop towards bringing the actual handling qualities of an aircraft to light.[45,53] Since this research is focused on potential controllability issues, tasks were designed to assess the two most fundamental characteristics of controllability, namely capacity of **(i)** changing and **(ii)** maintaining the aircraft attitude. They also concentrated on the aircraft stability axes to capture the way controllability degrades, i.e., they were either **(i)** more longitudinally demanding, **(ii)** more lateral-directionally demanding, or **(iii)** demanding in all three axes. Consequently, the tasks were grouped into the following five objectives:

1. maintenance of longitudinal attitude;
2. maintenance of lateral-directional attitude;
3. change of longitudinal attitude;
4. change of lateral-directional attitude; and
5. combination of control actuation in all three axes.

Additionally, Belcastro (2012)[41] suggested the test scenarios should be simulated in different flight phases, therefore, at least two tasks were designed for a same assessment objective. Table 7

[xii] Since Scenarios 4 and 8 ("old nomenclature") were very similar, we can say five scenarios met the criteria

shows the descriptions and objectives of the tasks.

Still regarding the design of the tasks, towards using the Cooper-Harper scale, the performance criteria parameters were determined considering the instrument panel's data and objective of each task, whereas their tolerances – *desired* and *adequate* – were determined from an "iterative reverse engineering" process.

The process consisted in a test pilot performing the tasks of Table 7 in a fully operational Boeing 777-200ER. Flight data parameters were recorded and a debriefing session was conducted for the assessment of whether the task objectives could be achieved during the proposed manoeuvres and definition of provisional performance tolerances around the parameters under evaluation. In a new iteration, the pilot fine-tuned the tolerances and the process continued until both the pilot and the experimenter agreed the tolerances guaranteed the pilots participation in the aircraft control loop, at the same time that were not overly strict to disconnect the tasks from reality.

Each task was performed again and the aircraft handling qualities were assessed towards the validation of the tolerances, which were accepted only if CHRs level 1 (CHR *1*, *2* or *3*) were assigned[xiii]. Any other rating would mean the aircraft had deficiencies and required improvements, which would not be realistic, since a fully operational Boeing 777 model, i.e., a certified aircraft, was used for the tests.

Since the tolerance-defining process was carried out for a fully operational aircraft, and the simulation scenarios introduced vehicle deficiencies, the resulting tolerances were broadened by at least 50% to be used in the research. Figure 27 displays a flowchart of the tolerance-defining procedure and Table 8 shows the parameters and tolerances adopted for the performance evaluation[xiv].

The initial conditions of each task (i.e., aerodynamic configuration, altitude, airspeed, bank angle, and heading) were established to ensure reproducibility of the manoeuvres and equal conditions for every pilot[xv]. Tables 5 and 6 show, respectively, the tasks undertaken in each simulation scenario and their preferred order of execution – to the maximum possible extent, the order was respected for all participants. Appendix B provides a summary of the tasks.

Table 5: Tasks performed in each scenario.
[Source: The author]

Tasks	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**4b**	**5**	**6a**	**6b**	**7a**	**7b**
Sc 01	×	×	×	✓	✓	×	×	✓	×	×	×	×	×
Sc 02	✓	×	✓	×	✓	×	✓	×	✓	×	×	×	×
Sc 03	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓
Sc 04	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

xiii If this was not the case, a new iteration was initiated

xiv Despite the lack of rules for the distance between the levels of performance, *desired* tolerances are usually half of the *adequate* ones. According to Mitchell (2019),[53] this separation is psychologically important for pilots, and contributes to their awareness of margins of errors

xv In Table 7, the * sign denotes small differences in the initial conditions/manoeuvres of certain tasks, depending on the simulation scenario

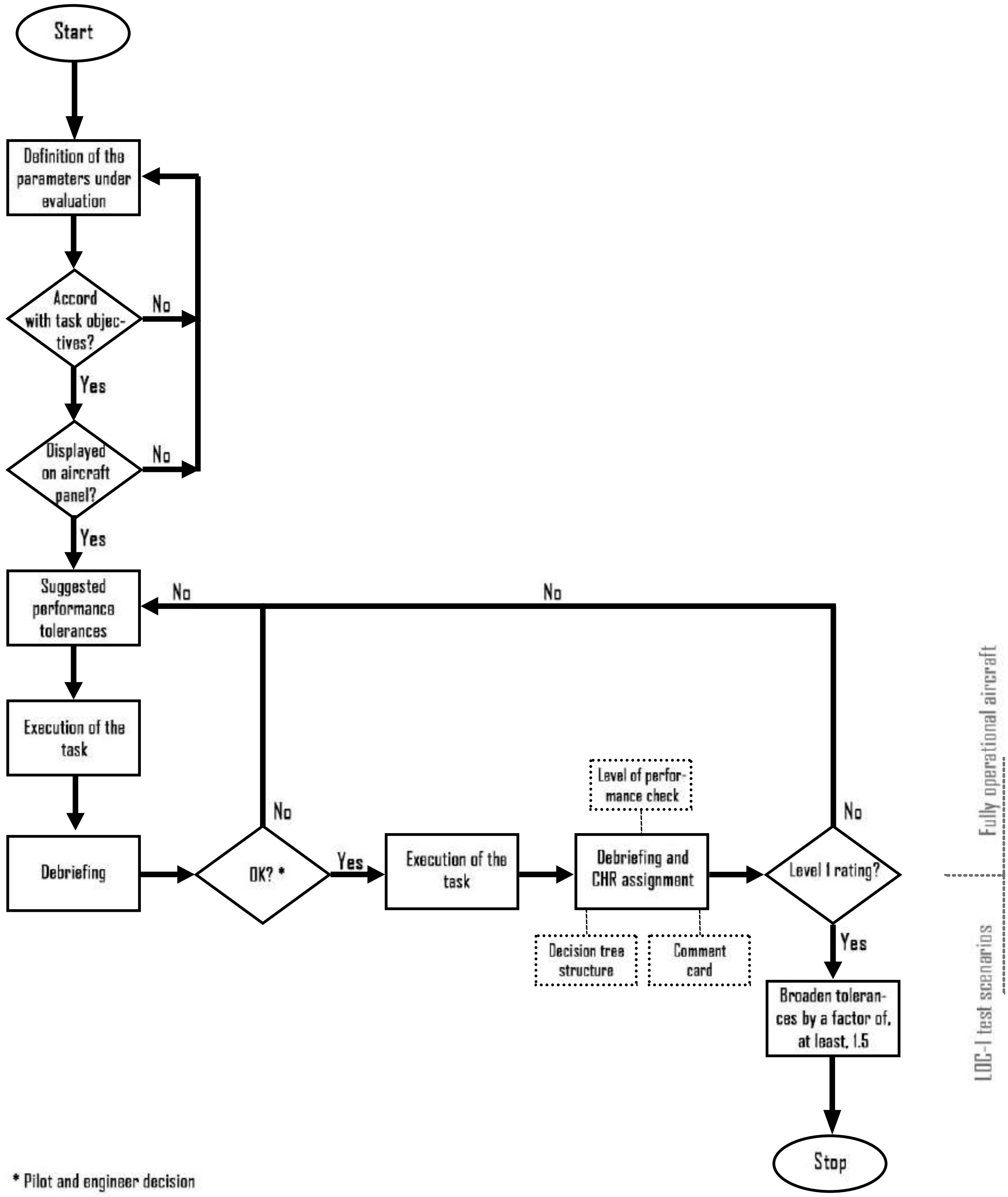

Figure 27: Flowchart of procedures to define performance tolerances.
[Source: The author]

Table 6: Preferred order of execution of the tasks.
[Source: The author]

Fisrt part				Second part		
	2b				1a	
Sc 01	4b	↓			2a	↓
	3a				4b	
	4a				2b	
	2a				4a	
Sc 02	3a	↓			7b	↓
	1a		**Resting pause**	**Sc 04**	3b	
	5				1b	
	6b				6b	
	7a				7a	
Sc 03	6a	↓			3a	↓
	7b				6a	
	5				5	

Table 7: Tasks performed in the research.
[Source: The author]

Task ID	Objective	Description
1a*	Maintain longitudinal attitude (climb)	Reach θ = 12.5° and attain it until completing a 3,000 ft climb. Maintain heading and airspeed within the required performance bands. No over- or undershoots.
1b*	Maintain longitudinal attitude (descent)	Reach θ = -5.0° and attain it until completing a 3,000 ft descent. Maintain heading and airspeed within the required performance bands. No over- or undershoots.
2a	Maintain lateral attitude (right turn)	Reach ϕ = 30° and attain it until completing a 90° turn (cross it with 30° bank). Maintain altitude and airspeed within the required performance bands. No over- or undershoots.
2b	Maintain lateral attitude (left turn)	Reach ϕ = -30° and attain it until completing a 90° turn (cross it with -30° bank). Maintain altitude and airspeed within the required performance bands. No over- or undershoots.
3a*	Change longitudinal attitude (climb)	Reach θ = 12.5° as quickly and precisely as possible. Maintain heading and airspeed within the required performance bands. No over- or undershoots.
3b	Change longitudinal attitude (descent)	Reach θ = -5.0° as quickly and precisely as possible. Maintain heading and airspeed within the required performance bands. No over- or undershoots.
4a	Change lateral attitude (right turn)	Reach ϕ = 37.5° as quickly and precisely as possible. Maintain altitude and airspeed within the required performance bands. No over- or undershoots.
4b	Change lateral attitude (left turn)	Reach ϕ = -37.5° as quickly and precisely as possible. Maintain altitude and airspeed within the required performance bands. No over- or undershoots.
5	Perform an ILS approach	Intercept and follow glideslope and localizer from 2,500 ft altitude up to 500 ft AGL. Maintain altitude and airspeed within the required performance bands.
6a	High gain simultaneous actuation on all three axes (high airspeed)	From level flight, turn right and reach ϕ = 37.5°. Turn left up to ϕ = -37.5° and then go back to level flight. No over- or undershoots. Be as quick and precise as possible.
6b*	High gain simultaneous actuation on all three axes (low airspeed)	From level flight, turn left and reach ϕ = -37.5°. Turn right up to ϕ = 37.5° and then go back to level flight. No over- or undershoots. Be as quick and precise as possible.
7a*	Low gain simultaneous actuation on all three axes (low airspeed)	Climb 2,000 ft and turn right for a 120° heading change. Return to a level flight and start a 2,000 ft descent and left turn to return to the beginning point. No over- or undershoots in altitude and heading.
7b*	Low gain simultaneous actuation on all three axes (high airspeed)	Descend 2,000 ft and turn left for a 120° heading change. Return to a level flight and start a 2,000 ft climb and right turn to return to the beginning point. No over- or undershoots in altitude and heading.

Table 8: Parameters under evaluation and levels of performance.
[Source: The author]

Task ID	Lateral-directional performance		Longitudinal performance		Timing performance	
	Desired	**Adequate**	**Desired**	**Adequate**	**Desired**	**Adequate**
1a	Heading ± 4°	Heading ± 8°	$\theta \pm 2°$ Speed ± 5 kts	$\theta \pm 4°$ Speed ± 10 kts	—	—
1b	Heading ± 4°	Heading ± 8°	$\theta \pm 2°$ Speed ± 5 kts	$\theta \pm 4°$ Speed ± 10 kts	—	—
2a	$\phi \pm 3°$	$\phi \pm 6°$	Altitude ± 100 ft Speed ± 5 kts	Altitude ± 200 ft Speed ± 10 kts	—	—
2b	$\phi \pm 3°$	$\phi \pm 6°$	Altitude ± 100 ft Speed ± 5 kts	Altitude ± 200 ft Speed ± 10 kts	—	—
3a	Heading ± 4°	Heading ± 8°	$\theta \pm 2°$ Speed ± 5 kts	$\theta \pm 4°$ Speed ± 10 kts	Δt $\leq$ 3 sec	Δt $\leq$ 6 sec
3b	Heading ± 4°	Heading ± 8°	$\theta \pm 1.5°$ Speed ± 8 kts	$\theta \pm 3°$ Speed ± 15 kts	Δt $\leq$ 3 sec	Δt $\leq$ 6 sec
4a	$\phi \pm 3°$	$\phi \pm 6°$	Altitude ± 100 ft Speed ± 5 kts	Altitude ± 200 ft Speed ± 10 kts	Δt $\leq$ 5 sec	Δt $\leq$ 8 sec
4b	$\phi \pm 3°$	$\phi \pm 6°$	Altitude ± 100 ft Speed ± 5 kts	Altitude ± 200 ft Speed ± 10 kts	Δt $\leq$ 5 sec	Δt $\leq$ 8 sec
5	LOC offset ± 1 *dot* No PIO	LOC offset ± 2 *dots* No PIO	GS offset ± 1 *dot* Speed ± 8 kts No PIO	GS offset ± 2 *dots* Speed ± 15 kts No PIO	—	—
6a	$\phi \pm 3°$	$\phi \pm 6°$	Speed $\leq$ 330 kts	Speed $\leq$ 330 kts	—	—
6b	$\phi \pm 3°$	$\phi \pm 6°$	Speed $\geq$ 200 kts	Speed $\geq$ 200 kts	—	—
7a	$\phi \pm 3°$	$\phi \pm 6°$	Altitude ± 200 ft Speed $\geq$ 200 kts	Altitude ± 400 ft Speed $\geq$ 200 kts	—	—
7b	$\phi \pm 3°$	$\phi \pm 6°$	Altitude ± 200 ft Speed $\leq$ 330 kts	Altitude ± 400 ft Speed $\leq$ 330 kts	—	—

4.5 Participants

The characteristics of the research required pilots experienced in engineering flight testing and handling qualities assessment, who, unfortunately, correspond to a very restricted group. With the help of Embraer, seven experienced test pilots were called up to participate in the simulations [xvi]. Table 9 shows a summary of their experience and background.

Table 9: Background of the evaluation pilots.
[Source: The author]

Pilot	Initial Formation	Type Ratings	Flight Hours
01	Civilian	A310; A319; A320; A330; A350 B737-200/-300/-400; F-100; MD-11	19000
02	Military	E145; E170; E390; E530	7500
03	Civilian	E145; E170; E390	6000
04	Military	AMX; E110; E120; E145; E170; E190; L500	7500
05	Military	AT-26; C-95; E145; E170; E190; F-5; HS-125; L500	7500
06	Civilian	E50P; E55P; E120; E145; E170; E190; E550	5800
07	Military	E120; E145; E170; E390; E530	6000
		Mean (SD)	8470 (4360)

4.6 Simulation Procedure

The simulations involved several variables, namely pilots, test scenarios, tasks, aircraft conditions, among others, which might affect the results if they were not given due attention, especially regarding the supply of equal conditions to all participants. The simulations were conducted with one pilot at a time and, aiming at the maximum maintenance of constancy of all external variables, a procedure was established and followed for every aviator. It consisted of **(i)** preflight briefing, **(ii)** execution of tasks, and **(iii)** manoeuvre debriefing and Cooper-Harper rating assignment, all detailed in what follows.

Preflight Briefing

Preflight briefing was the moment at which simulation objectives, procedures and conditions were presented to the pilots. Besides technical and operational aspects, the section also had a psychological component, since it was the first contact between the researcher and the evaluation pilot and the only opportunity for them to build mutual confidence and establish an environment where both felt comfortable and motivated.

Details are paramount for the establishment of such a relationship; therefore, the section was conducted as a conversation between the pilot and the experimenter seated side by side

[xvi] In fact, one of the pilots was not from Embraer, but was experienced in flight testing procedures

(instead of a presentation in which the pilot remains seated and the engineer stands in front of her/him). The pilot was encouraged to speak, demonstrating her/his experiences and providing the researcher with an opportunity to motivate the aviator to participate in the research by showing her/his importance to the experiments.

On the technical side, the preflight briefing led to discussions with the pilots on **(i)** the tasks they were required to accomplish, and **(ii)** the conditions under which the simulations were conducted. Concerning item **(i)**, the 13 tasks were presented in details to the pilot, and included objectives, starting and ending points, manoeuvres, parameters under evaluation, and tolerances that defined the levels of performance. Regarding item **(ii)**, pilots were made aware that certain conditions of simulation depended on the scenarios and tasks, whereas some did not (e.g., meteorology — daylight, no clouds, no wind, and no turbulence —, aircraft model and its loading condition, and execution of tasks in manual control mode and based on instrument indications). Concerning dependent conditions, the precursors of the simulation scenarios were presented, and pilots were encouraged to predict the behaviour of the aircraft under those conditions for avoiding eventual distractions during the execution of the manoeuvres caused by unknown vehicle characteristics.[35] They were also briefed on the aircraft configuration for each task.

Since the experimental section was forecast to last approximately five hours, pilots were made aware that a resting stop had been scheduled and that the session might be paused for additional resting at any time and discretion. They were instructed to use the *long-look* evaluation technique, and the engineer and the pilots agreed on a signal to mark the beginning and ending of the tasks[xvii]. Although all pilots were familiar with the Cooper-Harper scale, the assessment tool was detailed during the briefing towards a clear definition of its wording and establishment of equal understanding for all participants. Special attention was devoted to the adjectives defining "compensation", and pilots were instructed to consider the following definitions:[53,76]

- *Minimal:* the least possible;
- *Moderate:* tending towards the mean or average amount, avoiding extreme behaviour;
- *Considerable:* large in extent or degree;
- *Extensive:* of wide or considerable extent;
- *Intense:* marked by or expressive of great zeal, energy, determination, or concentration;
- *Maximum:* the greatest quantity or value attainable or attained; an upper limit allowable.

Pilots were presented the qualitative assessment procedure, with emphasis on the existence of a debriefing comment section and the fact the assignment of the CHR respected the decision tree of the scale. Since pilots were aware that the aircraft in the simulation scenarios had failures, they were briefed to assess controllability considering the aircraft they were flying ready to be produced and delivered to customers[xviii].

[xvii] Pilots shouted "TOP" to indicate they had just initiated/finished the task

[xviii] Test pilots usually know an aircraft very well, and the aviators invited to participate in the research knew a "normal" Boeing 777 would not behave as the aircraft models of the simulation scenarios. Consequently, they would tempt to take degradations into account, transforming the simulated aircraft into a "normal" one, and assign lower CHRs (towards level 1) because they knew they were flying a vehicle with failures, although performance and compensation were unacceptable[77]

The configuration of buttons and switches was shown to the pilots in a replica of the controls installed in the simulator, so that they could familiarise with EB#2. At the end of the preflight section, pilots were given a kneeboard containing a printed Cooper-Harper scale and a summary of the tasks, and invited to perform a familiarisation flight towards being more intimate with the controls, aircraft behaviour (low/high speeds, different control gains etc.), simulator response, and operational procedures.

Execution of the tasks

After the familiarisation flight with the fully-operational aircraft and the pilots reporting to be comfortable in the simulator, they proceeded to the execution of the tasks. Figure 30 displays a flowchart of the procedure, which basically consisted of the following steps:

1. configuration of FlightGear for a combination of precursors corresponding to a given simulation scenario;
2. positioning of the aircraft at 10,000 ft / 250 kts;
3. controls assumed by the evaluation pilot;
4. scenario familiarisation;
5. stabilisation of the aircraft under the initial conditions (altitude, heading, airspeed etc.) of a given task; and
6. execution (and repetition, when necessary) of the corresponding manoeuvre.

The "TOP" mark agreed in the preflight briefing guaranteed a precise definition of the beginning and ending of each task, which was important to clarify the period to which the qualitative assessment referred and for a precise monitoring and recording of the quantitative data. After the "TOP" mark given by the pilot, the experimenter triggered/stopped a MATLAB® script to record certain flight parameters that, besides being further plotted according to the QLC, were used to monitor the levels of performance. Such a procedure enabled the engineer to inform pilots during the qualitative assessment on the level achieved. Figure 28 shows the graphs automatically displayed to the engineer immediately after the execution of Task 2a – to wit, in that case, not even the adequate level of performance was reached –; the graphs were updated according to the task.

In-between tasks, pilots were required to fly the aircraft to the initial conditions of the next task, meaning the *long-look* evaluation technique was naturally used in the simulations[xix].

Task debriefing and CHR assignment

After each task, the simulation was paused for the initiation of the debriefing session, which consisted of a conversation between the experimenter and the pilot with use of the comment card shown in Figure 29 – questions were selected according to the task under evaluation. The

[xix] As opposed to the technique used in this research, the standard procedure in piloted experiments is to configure the simulation software to trim the aircraft in the condition of interest before the pilot assumes the controls, limiting her/his contact with the aircraft and privileging the use of the *short-look* technique

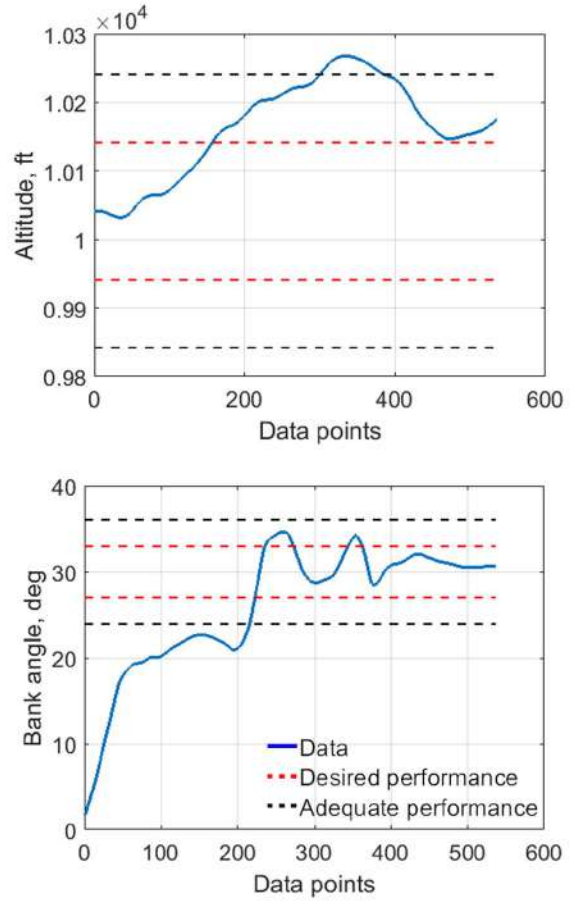

Figure 28: Example of the monitoring of a task performance.
[Source: The author]

questions of the Cooper-Harper scale were then accordingly posed to the evaluation pilot, who was concomitantly informed on the level of performance achieved in the manoeuvre; the process resulted in the assignment of a CHR. The session was recorded.

Besides its technical purposes, the debriefing also identified an occasional need of resting stops, since confined environments (e.g., a flight simulator) naturally cause people to lose engagement and concentration. Figure 30 displays a flowchart of the simulation and classification procedures, both strictly respected in the research.

PILOT COMMENT CARD

Pilot: _____ | **Task:** _____ | **Scenario:** _____

1. Pitch attitude control and track
   Easy | Fair | Difficult
2. Bank angle control and track
   Easy | Fair | Difficult
3. Predictability of pitch response to pilot inputs
   Desirable | Abrupt | Sluggish
4. Predictability of roll response to pilot inputs
   Desirable | Abrupt | Sluggish
5. Displacement of pitch control
   Small | Moderate | High
6. Displacement of roll control
   Small | Moderate | High
7. Frequency of use of pitch control
   Small | Moderate | High
8. Frequency of use of roll control
   Small | Moderate | High
9. Did Pitch/Roll harmony exist?
   Agree | Neutral | Disagree
10. Any PIO tendency in pitch or roll? *
    Yes | No
11. Displacement of rudder control
    Not used | Small | Moderate | High
12. Frequency of use of rudder control
    Not used | Small | Moderate | High
13. Ability to control airspeed
    Easy | Fair | Difficult
14. Level of physical workload
    Small | Moderate | High
15. Level of mental workload
    Small | Moderate | High
16. Any problems in pitch and/or roll during localizer capture and tracking? *
    Yes | No
17. Any problems in pitch and/or roll during glideslope capture and tracking? *
    Yes | No
18. Any special control technique required? *
    Yes | No
19. Summary – good/bad features

Cooper-Harper Rating: _____

* For positive answer, describe it (reverse side)

Figure 29: Pilot comment card used in the experiments.
[Source: The author]

4.7 QLC Normalisation Parameters

The airspeed and the angles of attack and sideslip must be normalised prior to the plotting of the QLC envelopes. Since normalisation data are not available in the literature, simulations were conducted in EB#2 using procedures similar to those of real flight test campaigns for the determination of the following parameters:

- angle of attack for stall warning activation – α_{SW};
- sideslip angle for non-crabbed approach in the maximum demonstrated crosswind – β_{MDXW};
- maximum operating equivalent airspeed for flaps-down configuration – V_{FE};
- maximum operating equivalent airspeed for flaps-up configuration – V_{MO}.
- stall warning equivalent airspeed in 1-g flight – V_{SW}.

Determination of α_{SW}

The angle of attack for stall warning activation depends mainly on the aircraft weight, the flight altitude, and the configuration of high-lift devices. In this research, the manoeuvres were performed at similar altitudes and under a constant aircraft loading condition; therefore,

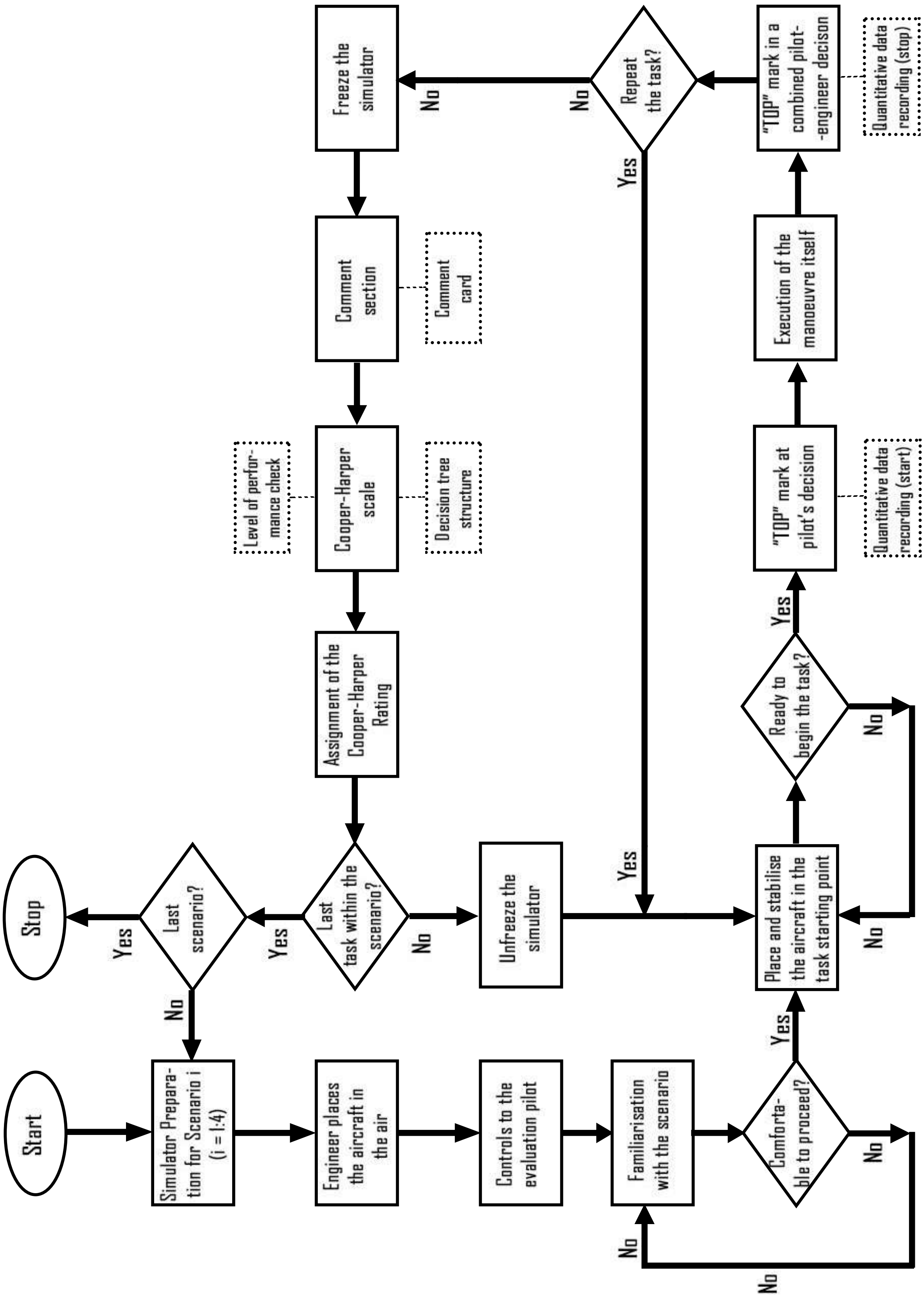

Figure 30: Flowchart of the simulation procedure.
[Source: The author]

α_{SW} was directly linked to the aerodynamic configuration and determined for both "clean" (flaps retracted, landing gear up) and "dirty" (flaps full, landing gear down) conditions.

Boeing 777-200ER (460,000 lb @ 44% MAC) was placed at 10,000 ft in the configuration of interest and a volunteer professional pilot was asked to trim the aircraft and then gently increase the angle of attack at a rate equivalent to the reduction of 1 knot per second up to the occurrence of the stall. The procedure was repeated several times and many flight parameters were recorded, including airspeed, angle of attack, roll rate, and others required for the calculation of the lift coefficient (c_L).

The angle of attack for stall warning activation was approximated as the angle corresponding to the beginning of the prestall region, which is a logical point for an alarm. Since the region is marked by aerodynamic nonlinearities and a nonzero roll rate tendency,[33] it was identified by 'c_L *vs* α' and 'p *vs* α' graphs. After three valid trials for each aircraft configuration, the mean α_{SW} values yielded 12.35° and 13.84° for the clean and dirty conditions, respectively. Appendix C provides the data collected in the tests, including airspeed and the aforementioned graphs.

Determination of β_{MDXW}

Differently from the angle of attack, the sideslip angle has a reduced dependence on the aircraft weight; however, it is strongly influenced by the number of operating engines, wind speed, and runway condition.

Wilborn and Foster (2004)[37] defined β_{MDXW} as the sideslip angle for non-crabbed approach (i.e., using rudder) in the maximum demonstrated crosswind for takeoff or landing, and, according to the Boeing 777 Flight Manual,[73] the maximum manufacturer's demonstrated takeoff/landing crosswind component is equal to 45 kts (dry runway and all engines operating). Therefore, β_{MDXW} was determined by simulating an approach with such a wind component (45 kts @ 194°) at KSFO 28R for a fully-operational Boeing 777-220ER (460,000 lb @ 44% MAC, full flaps, landing gear down). A volunteer pilot performed the simulations and was instructed to use the non-crabbed approach technique (also known as "sideslip technique"), i.e., to maintain the longitudinal axis of the aircraft aligned with the runway during the entire approach, as shown in Figure 31.

The approach was repeated three times; one of them was discarded due to unacceptable oscillation of the validation parameters, namely, indicated airspeed and glideslope/localizer deviations. Figure 32 shows the sideslip angle for the two valid approaches; the resulting β_{MDXW} mean-value was 7.4°. The angle obtained was small in comparison to typical β_{MDXW} values, since high wingspan aircraft, e.g. Boeing 777, do not perform non-crabbed approaches; instead, the crabbed technique (Figure 31) is recommended and usually results in greater angles. However, the non-crabbed technique was used in this research to conform with the QLC definition of β_{MDXW}.

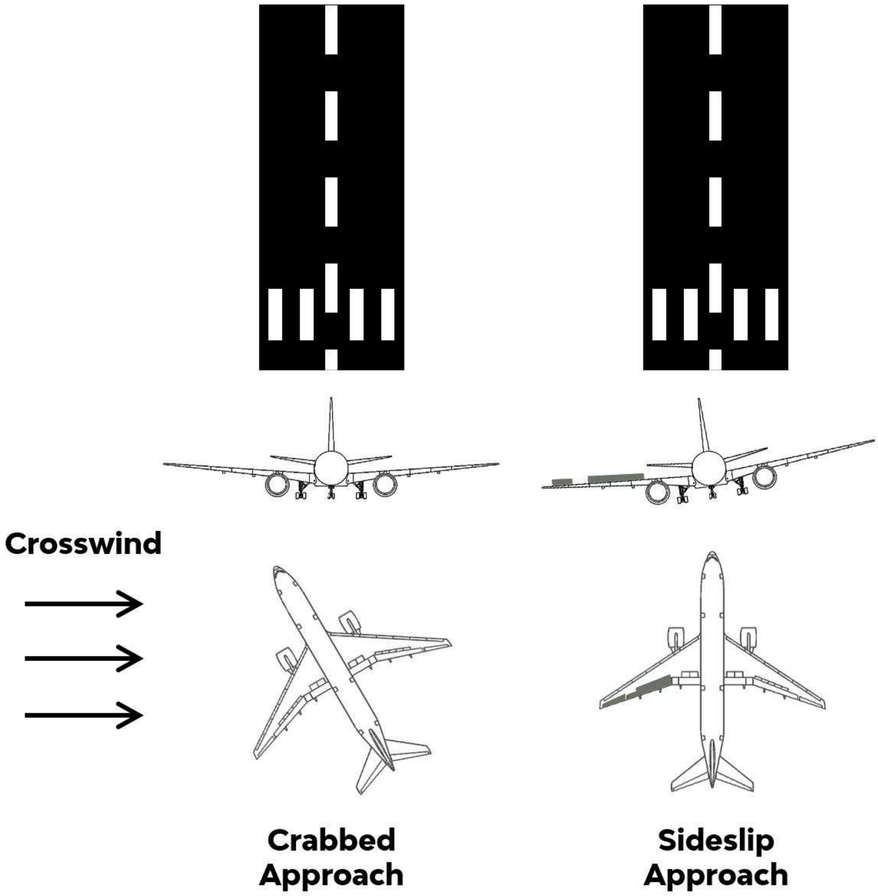

Figure 31: Crabbed and sideslip approach techniques.
[Source: Adapted from Airbus (2008)[78]]

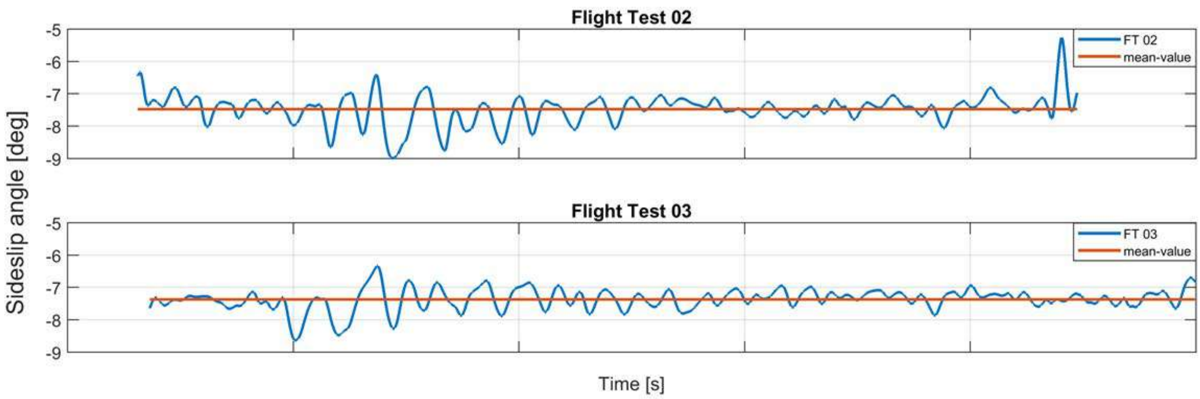

Figure 32: Sideslip angle in the tests for the determination of β_{MDXW}.
[Source: The author]

Determination of V_{MO} and V_{FE}

The maximum operating equivalent airspeed (V_{MO} and V_{FE} for flaps up and down, respectively) essentially depends on the flight altitude and the weight and structural resistance of an aircraft. Since it must not be exceeded, it is accordingly displayed in the airspeed indicator of Boeing 777-200ER by a red dashed line on the right side of the corresponding value.

Differences between *indicated* and *equivalent* airspeed are due to compressibility effects, and the higher and the faster the flight, the greater the differences. Since most of the tasks were executed at approximately 10,000 ft, i.e., a relatively low altitude, such effects were neglected, resulting in $V_{MO} = 330kts$ and $V_{FE} = 170kts$ for the aircraft loading condition used in the simulations.[73]

Determination of V_{SW}

The stall warning equivalent airspeed in 1-g flight (V_{SW}) basically depends on the aircraft weight, altitude, and aerodynamic configuration. The airspeed indicator of Boeing 777-200ER accordingly displays such information as a red dashed line on the right side of the speed tape. $V_{SW} = 200kts$, for flaps up and $V_{SW} = 120kts$, for flaps down, for the aircraft loading condition of the experiments; again, compressibility effects were neglected.

Table 10 shows a summary of the values used to normalise the angles of attack and sideslip (Table 1) and the airspeed (Equations 3.15 and 3.16) for the plotting of the QLC graphs and extraction of parameters of interest for the research. Details are provided in Section 4.8.

Table 10: Normalisation values for parameters of the QLC.
[Source: The author]

Aircraft Configuration	**Parameter**	**Value**
Flaps retracted LDG up	α_{SW} [deg]	12.35
	β_{MDXW} [deg]	7.40
	V_{MO} [kts]	330
	V_{SW} [kts]	200
Flaps full LDG down	α_{SW} [deg]	13.84
	β_{MDXW} [deg]	7.40
	V_{FE} [kts]	170
	V_{SW} [kts]	120

4.8 Data Processing and Dependent Variables

The independent variables of the experiments were the tasks and simulation scenarios, whereas the dependent ones were, mainly, the controllability categories resulting from both the Cooper-Harper scale and the QLC. During data processing, some dependent variables (those derived from the application of the QLC methodology, the controllability categories resulting from the CHRs, and pilot workload metrics) were treated as quantitative parameters, and others (pilots' comments) were considered qualitative data. This section describes the way such variables were processed in the research (Appendix D details statistical considerations involved in the data processing).

4.8.1 QLC Application

During each task, 53 flight data parameters – including the variables necessary for the QLC – were recorded from FlightGear at a sampling rate of 10 Hz (similar to that of FDRs[79]). MATLAB® plotted the five QLC graphs for each manoeuvre, and the following information was obtained:

- number of envelopes crossed;
- magnitude of excursion from normal flight conditions;
- time interval outside normal flight conditions;
- data concentration patterns;
- time interval between the crossings of successive envelopes; and
- envelope crossed.

32 dependent variables were derived from such information, and are detailed in what follows.

Number of envelopes crossed

This variable was obtained from the counting of the QLC envelopes extrapolated in a given task and treated as an ordinal variable that could assume values in the [0-5] interval.

Controllability categories resulting from the number of envelopes crossed (QLC)

As detailed in Section 3.2, the QLC establishes the controllability category of a given event according to the number of envelopes crossed. Therefore, the category of each simulated manoeuvre was determined, and the variable *controllability categories resulting from the number of envelopes crossed*, also called *QLC*, was treated as an ordinal one that could either assume the "Normal event", "Borderline LOC-I condition", or "LOC-I condition" value.

Magnitude of excursion from normal flight conditions

Provided that an envelope has been crossed, the magnitude of excursion – $mag(\cdot)$ – is the distance between a borderline of such an envelope and the most external corresponding data point. The bigger the magnitude of excursion, the more distant an aircraft from its nominal flight parameters. Consequently, it can indicate the severity of abnormal flight conditions. In this research, $mag(\cdot)$ was treated as a ratio variable that could assume values in the]0-∞] interval.

Since the QLC analyses a number of variables, each with its own physical significance, the magnitude of excursion was meaningful, hence, computed only for the following envelopes/variables[xx]:

[xx] For example, QLC normalises AoA in a way $\alpha_{NORM} < 0$ has no physical significance – Table 1 –, therefore, such a variable (and the derived ones) was not of interest in this research

- **AA envelope:** α_{pos}, β_{pos}, and β_{neg}. Since α and β are normalised in the envelope, their magnitudes of excursion, if any, were calculated by Equation 4.1

$$mag(\alpha_{pos}) = \frac{max(\alpha_{NORM})}{max(\alpha_{NORM_{pos}})} \tag{4.1}$$

  where $max(\alpha_{NORM})$ is the maximum normalised recorded α, and $max(\alpha_{NORM_{pos}})$ is the maximum normalised α predicted by the AA envelope, i.e., $max(\alpha_{NORM_{pos}}) = +1$. Adjustments were accordingly made to compute $mag(\beta_{pos})$ and $mag(\beta_{neg})$;

- **UA envelope:** θ_{pos}, θ_{neg}, ϕ_{pos}, and ϕ_{neg}. Since the parameters are not normalised in the UA envelope, their magnitudes of excursion were computed by Equation 4.2

$$mag(\theta_{neg}) = \frac{min(\theta) - min(\theta_{UA})}{min(\theta_{UA})} \tag{4.2}$$

  where $min(\theta)$ is the minimum recorded θ, and $min(\theta_{UA})$ is the minimum θ angle in the UA envelope, i.e., $min(\theta_{UA}) = -10°$). The same idea was applied to the other parameters;

- **SI envelope:** n_{pos}, n_{neg}, V_{pos}, and V_{neg}. The magnitudes of excursion were calculated by Equation 4.3

$$mag(n_{pos}) = \frac{max(n) - max(n_{SI})}{max(n_{SI}) - 1.0} \tag{4.3}$$

  where $max(n)$ is the highest load factor recorded, and $max(n_{SI})$ is the maximum load factor according to the configuration of the aircraft, i.e., $max(n_{SI}) = 2.5$, for flaps up, and $max(n_{SI}) = 2.0$, for flaps down. Equation 4.3 was accordingly adapted for the cases of negative load factor and airspeed.

Time interval outside normal flight conditions

The time an aircraft had remained outside its normal operating envelopes – $time(\cdot)$ – provides insights on the severity of abnormal circumstances and the extension of damages to the vehicle as a consequence of exceeded operational limits. Such a parameter was treated as a ratio variable in the]0-∞] interval and computed for the following envelopes/variables:

- **AA envelope:** α_{pos}, β_{pos}, and β_{neg}. For the longitudinal axis, $time(\alpha_{pos})$ was calculated as the longest continuous period during which $\alpha_{NORM} > +1.0$; for the directional axis, since a stall can occur in either direction, $time(\beta)$ was the longest continuous period between conditions $\beta_{NORM} > +1.0$ and $\beta_{NORM} < -1.0$;

- **UA envelope:** θ_{pos}, θ_{neg}, ϕ_{pos}, and ϕ_{neg}. Similarly to $time(\beta)$, $time(\theta)$ and $time(\phi)$ were computed as the longest continuous period during which an aircraft extrapolated the positive or negative limits of the respective parameters;

- **SI envelope:** V_{pos}, V_{neg}, n_{pos}, and n_{neg}. According to the QLC, a negative normalised airspeed means an aircraft was flying slower than its stall speed, and $time(V_{neg})$ was calculated as the longest continuous period during which $V_{NORM} < 0.0$, representing the duration of the stall condition. Excessive speed or load factor, on the other hand, represent situations in which the aircraft is exposed to more probable and extensive damages, and the crew to becoming incapacitated due to "g-force" effects. Damages or pilot incapacity do not vanish when an aircraft returns to the inside of the SI envelope; on the contrary, they are cumulative. Although an aircraft has returned to operational airspeed/load factor, if it exceeds those limits again, the new damages/incapacities are additive to the previous ones. Consequently, $time(V_{pos})$ was computed as the total time during which the positive airspeed limit was extrapolated, and, similarly, $time(n)$ was calculated as the total time during which positive or negative load factor limits were exceeded.

Figure 33 shows examples of the calculations of $mag(\cdot)$ and $time(\cdot)$.

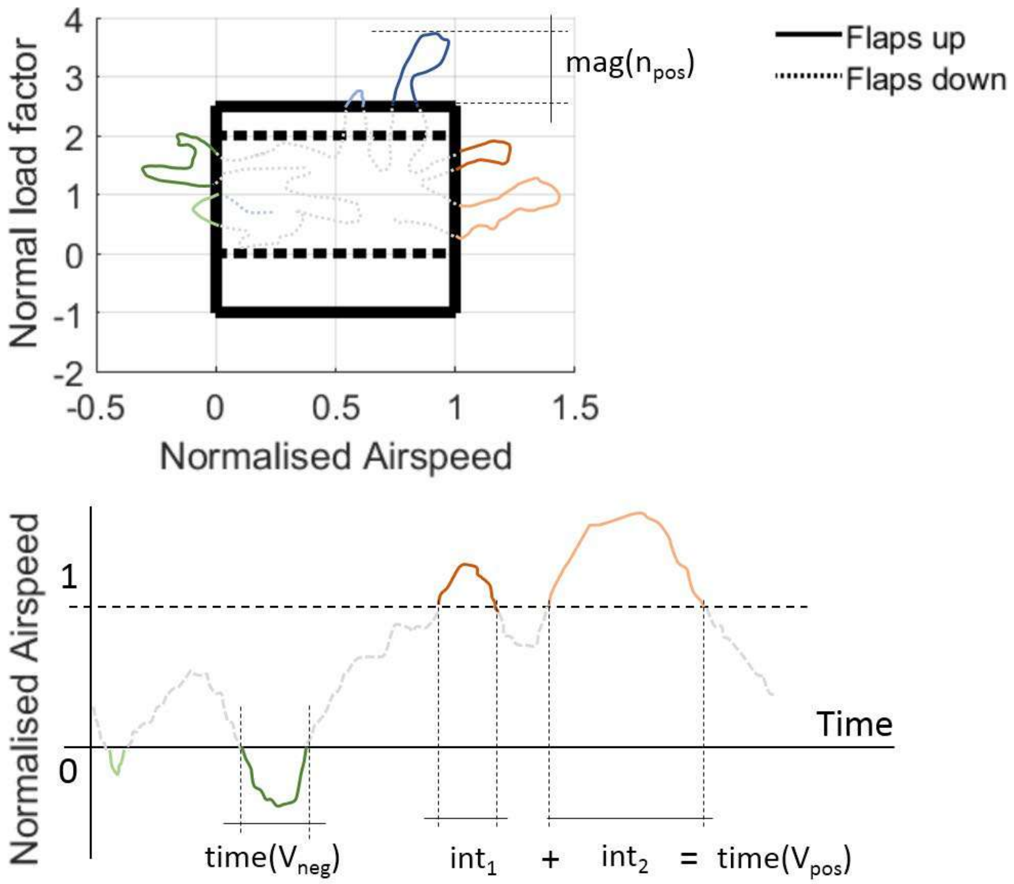

Figure 33: Example of the calculations of $mag(\cdot)$ and $time(\cdot)$. Fictitious data.
[Source: The author]

Data concentration patterns

The way data of a given event concentrated in the DPC and DRC envelopes was observed for investigations on whether pilot inputs agreed with the aircraft behaviour. The data concentration – $conc(DPC)$ and $conc(DRC)$ for DPC and DRC, respectively – was treated as a dichotomous variable that could assume either the "squared", or the "tapered" value. If more time had been spent on the "squared" quadrants, e.g., $conc(\cdot)$ assumed the value "squared", and vice-versa.

Crossing intervals of successive envelopes

Whenever two or more QLC envelopes have been crossed, the time interval between two successive extrapolations was calculated for capturing how fast an aircraft flew towards non-nominal conditions. Four possible independent crossing intervals were defined and statistically treated as ratio variables in the]0-∞] interval.

Critical window

Wilborn and Foster (2004)[37] defined *critical window* as the time interval between the instants of the extrapolations of the first and third envelopes. It was also computed in this research whenever the QLC had flagged a "LOC-I condition" and treated as a ratio variable in the]0-∞] interval.

Envelope crossed

Since each QLC envelope has its particular significance, a dichotomous variable was defined for each envelope for capturing whether it has been crossed ("yes") or not ("no") in a given manoeuvre.

Table 11 shows a summary of all parameters extracted from the application of the methodology on which the QLC is based and which were used in the correlation analyses performed – details in Section 4.9.

Table 11: Parameters extracted from the parametric methodology on which the QLC is based. [Source: The author]

QLC envelope					**Time-dependent parameters**	**Additional parameters**
AA	**UA**	**SI**	**DPC**	**DRC**		
$mag(\alpha_{pos})$	$mag(\theta_{pos})$	$mag(n_{pos})$	*Data concentration pattern*	*Data concentration pattern*	*Crossing intervals*	*Specific envelope crossed*
$mag(\beta_{pos})$	$mag(\theta_{neg})$	$mag(n_{neg})$				
$mag(\beta_{neg})$	$mag(\phi_{pos})$	$mag(V_{pos})$				*Number of envelopes crossed*
	$mag(\phi_{neg})$	$mag(V_{neg})$				
$time(\alpha_{pos})$	$time(\theta)$	$time(n)$			*Critical window*	*Controllability categories resulting from the number of envelopes crossed (QLC)*
$time(\beta)$	$time(\phi)$	$time(V_{pos})$				
		$time(V_{neg})$				

4.8.2 Pilot Workload

Pilot workload can be quantitatively measured by analyses of pilot control actuation. The magnitude and frequency at which pilots deflect the controls are directly related to their physical and mental workloads, respectively. Since pilot inputs are not constant in time, Lombaerts et al. (2009)[77] proposed the use of the root mean squares (RMS) of the control displacements (RMS_{ctrl}) and deflection rates ($RMS_{ctrl_{rate}}$) for determining the overall level of such workload shares during a certain task.

The normalised positions of the controls (δ_{ctrl}) – sidestick in pitch and roll, and rudder pedals – were recorded during the simulations and their rates (δ'_{ctrl}) were computed by a forward finite differences approximation,

$$\delta'_{ctrl} = \frac{\delta_{ctrl_{t+\Delta t}} - \delta_{ctrl_t}}{\Delta t}$$

Frequent movements in the controls, even if in small displacements, and supply of large control inputs, even if infrequently, were the piloting actions that mostly contributed to high deflection rates.

Finally, RMS_{ctrl} was calculated as

$$RMS_{ctrl} = \frac{||\delta_{ctrl}||_2}{\sqrt{n}} \tag{4.4}$$

where $||\delta_{ctrl}||_2$ is the Eucledian norm of the normalised position of a control, and n is the size of the data sample. $RMS_{ctrl_{rate}}$ was analogously calculated by Equation 4.4, substituting δ_{ctrl} for δ'_{ctrl}.

Central tendency (mean-value) and dispersion (standard-deviation) metrics were computed for both RMS_{ctrl} and $RMS_{ctrl_{rate}}$ for each task, considering all pilots participating in the research.

4.8.3 CHRs

The CHRs assigned at the completion of each simulated manoeuvre were also a dependent variable, and, based on the discussion made in Section 3.3, transformed into the variable *controllability categories resulting from the CHRs*, which is of greater interest for the analyses in this research. The parameter was treated as a quantitative ordinal variable and could assume either the "Normal event", "Borderline LOC-I condition", or "LOC-I condition" value.

4.8.4 Pilots' Comments

Although CHRs were treated as quantitative parameters for the use of correlation tests, they are the product of a qualitative assessment process, whose core is the pilots' comments recorded in the debriefing sessions and summarised in the answers of the comment card. Both comments and answers were qualitatively processed for each task and identified the most common pilots' control actuation techniques and perceptions on the controllability characteristics of the aircraft.

4.9 Data Analysis

Given the variety of data collected in the experiments and their multiple possibilities of analysis, this section presents the methods and software that scrutinised them for the obtaining of relevant results for investigations on the hypotheses raised. The data were analysed regarding **(i)** task-by-task pilot actuation, and **(ii)** correlation tests.

Task-by-task Pilot Actuation

The most common pilots' comments and comment card responses for each task were analysed together with the "average" pilot actuation, i.e., mean-value and standard deviation of RMS_{ctrl} and $RMS_{ctrl_{rate}}$ on the three control axes. The analyses revealed the way pilots typically used the controls, perceived the controllability of the aircraft in terms of control authority and predictability, their physical and mental efforts, and, ultimately, the influence of a conjunction of factors on both CHRs they assigned and number of QLC envelopes crossed. Bar graphs of RMS_{ctrl}, $RMS_{ctrl_{rate}}$, *CHRs* and *Number of envelopes crossed* supported the analyses and, whenever relevant, additional flight parameters collected during the simulations were plotted.

Correlation tests

The hypothesis of an association between the qualitative and quantitative controllability assessment methods was tested by bivariate and independent correlation tests, i.e., the tests were always related to variable *controllability categories resulting from the CHRs*, and applied in pairs, being the other parameter, one-by-one, the variables derived from the application of the methodology on which the QLC is based (Table 11).

Correlation coefficients indicate the direction and the strength of the association between given variables, and the selection of the proper correlation test hinges on the statistical type of such variables.[80] Table 12 shows the tests applied for each correlation pair[xxi] and the statistical type of the variables. The statistical significance level for the report of significant results was set at $\alpha = 0.05$ for all correlation tests.

Appendix D provides details on the statistical classification of variables and bivariate analyses, as well as all necessary checks for the use of the selected tests. The correlation analyses were performed in MATLAB® and IBM SPSS Statistics® software.

Table 12: Selected correlation tests.
[Source: The author]

Variable name	Type of variable	Selected correlation test
Controllability categories resulting from the CHRs [—]	Categorical | Ordinal	—
QLC [—]	Categorical | Ordinal	Kendall's tau-b
Number of envelopes crossed [—]	Categorical | Ordinal	Kendall's tau-b
Magnitude of excursion [—]	Continuous | Ratio	Kendall's tau-b
Time interval of excursion [s]	Continuous | Ratio	Kendall's tau-b
Crossing intervals [s]	Continuous | Ratio	Kendall's tau-b
Critical window [s]	Continuous | Ratio	Kendall's tau-b
Data concentration patterns [—]	Categorical | Dichotomous	Cramer's V
Envelope crossed [—]	Categorical | Dichotomous	Cramer's V

[xxi] The "Selected correlation test" in Table 12 is always related to the variable *controllability categories resulting from the CHRs*

RESULTS & DISCUSSION

5 RESULTS AND DISCUSSION

This chapter, which reports the results, is comprised of the following three parts: Section 5.1, which discusses, task-by-task, the controllability categories resulting from both the CHRs and QLC from the perspective of control strategies, Section 5.2, devoted to the measurement of the strength of the association between the qualitative and quantitative controllability assessment methods in terms of results and statistical significance of the correlation tests, and Section 5.3, which discusses the meaningfulness of the results towards deepening our current understanding of a LOC-I.

Although seven pilots participated in the experiments, the results were analysed and presented for six of them, since one aviator ('p07' in Table 9) was very sleepy during the simulations due to insomnia. Consequently, the tests were interrupted before the completion of the programme. Data were not recorded for 'p04' in Tasks 4a and 5 in Scenario 04 due to a mistake made by the experimenter; for such tasks, central tendency and dispersion metrics were not calculated, and the analyses were restricted to five pilots. Appendix E provides individual pilot's data, including RMSs of the control deflections and rates, CHRs, and number of envelopes crossed.

5.1 Task-by-task Pilot Actuation

In each task, pilots established and applied a control strategy they foresaw as the most appropriate for that situation. The workload unfolding from the strategy was proportional to their degree of compensation assessed by the Cooper-Harper scale, and their accuracy in evaluating the controllability characteristics of the aircraft impacted on the number of QLC envelopes crossed.

The "average" pilot control strategy was identified, task by task, by pilots' comments and the mean-value and standard deviation of RMS_{ctrl} – Figure 34 – and $RMS_{ctrl_{rate}}$ – Figure 35. CHRs and the number of envelopes crossed are plotted in Figure 36. The results are separately discussed for each task, according to the aforementioned figures; therefore, the reader is advised to consult them whenever necessary, and also Tables 4 and 7 to recap the simulation scenarios and tasks. Although some comparisons were made between the results of different tasks, the tasks compared were not necessarily performed in a sequence; instead, to the maximum possible extent, the sequence shown in Table 6 was respected for all pilots.

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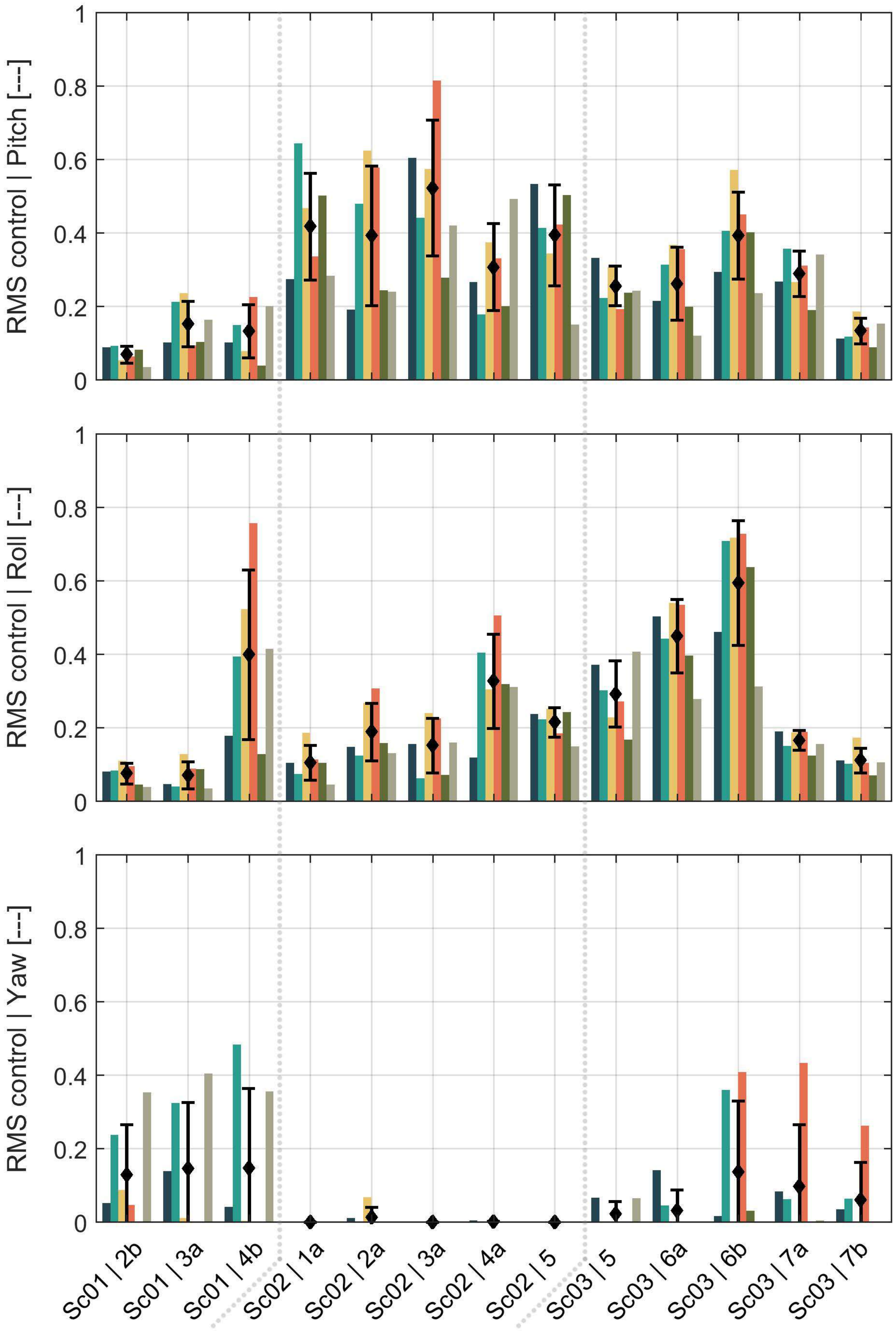

Figure 34: RMS of normalised control deflections.
[Source: The author]

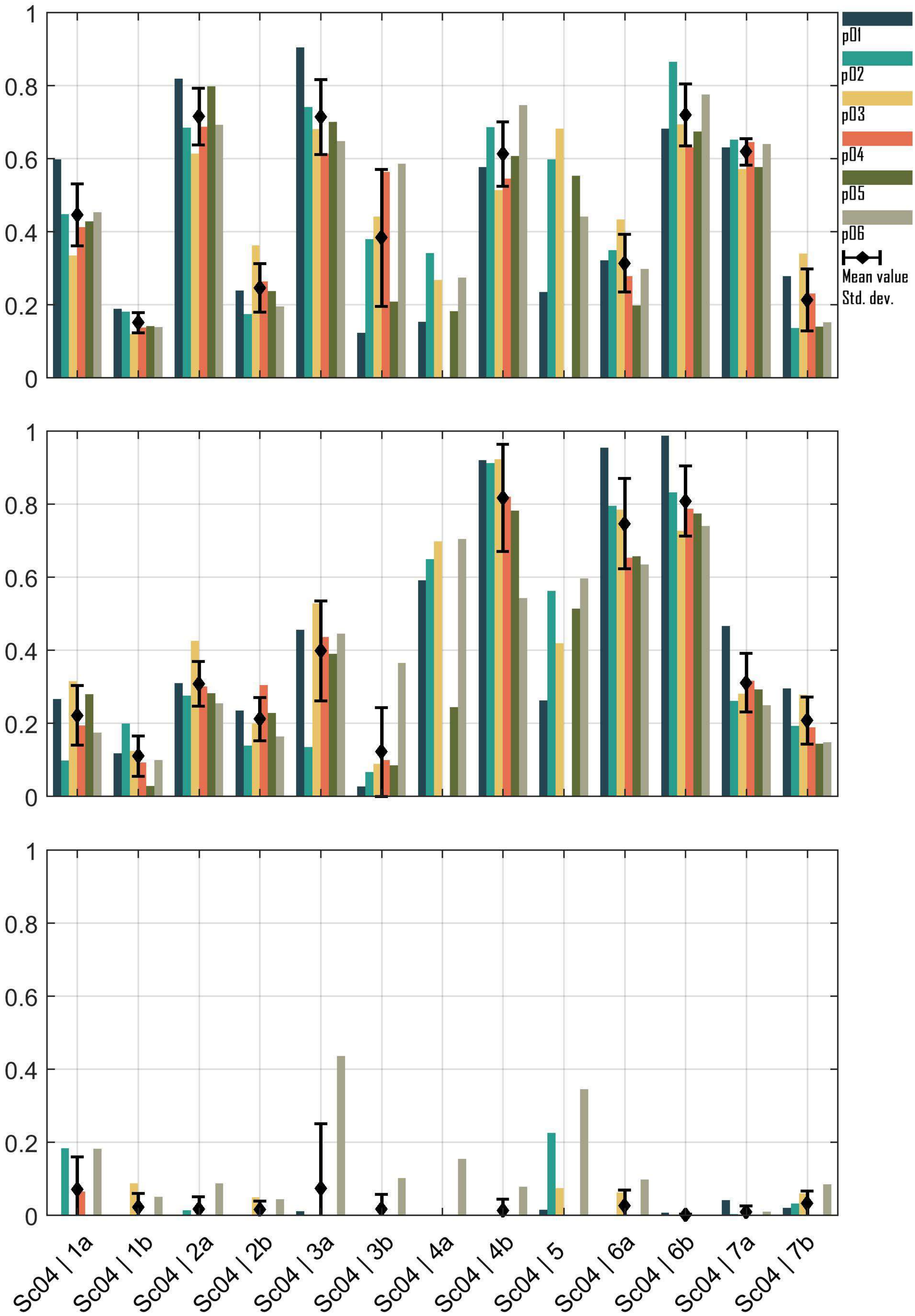

Figure 34: RMS of normalised control deflections, Continued.
[Source: The author]

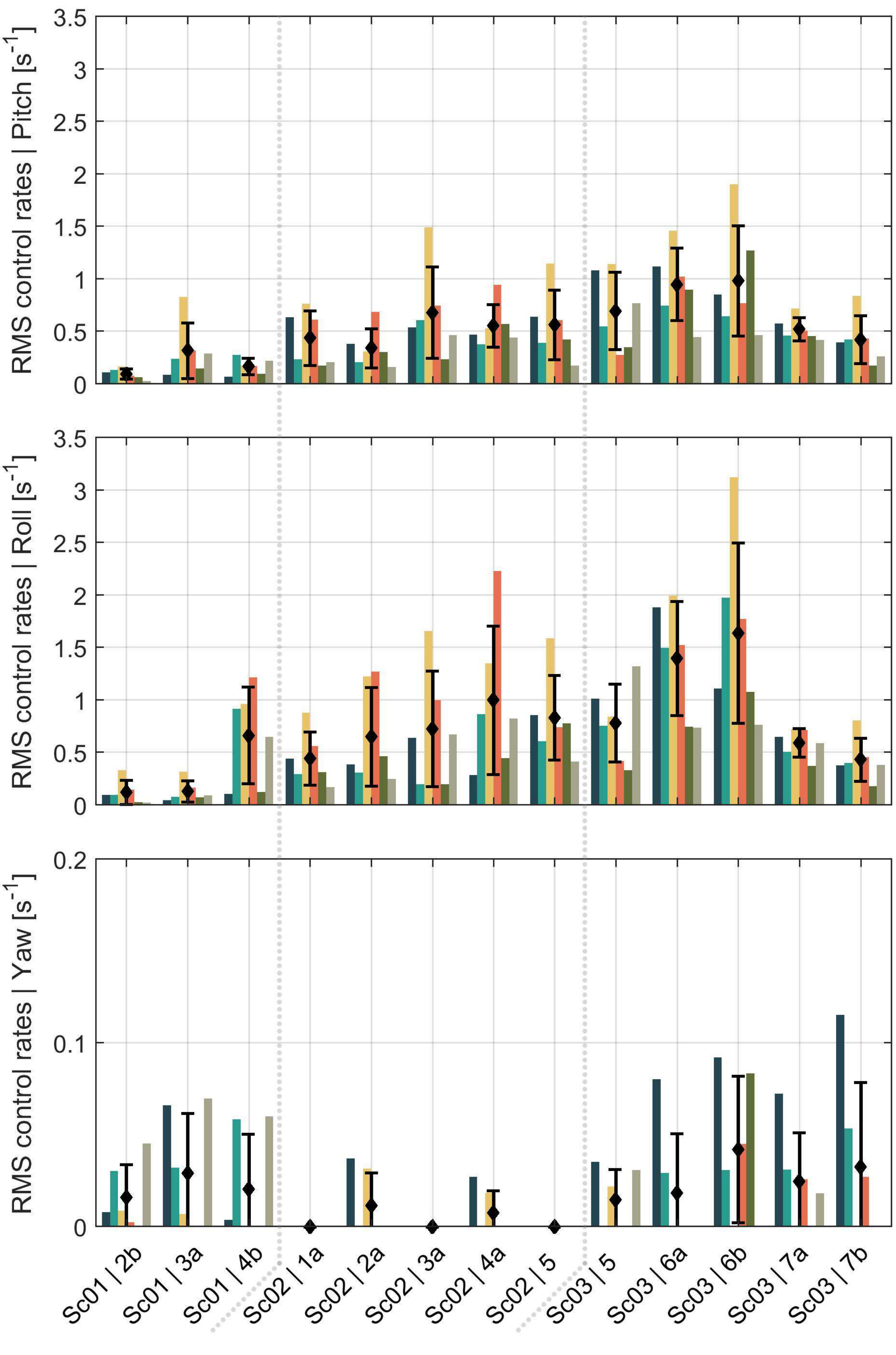

Figure 35: RMS of control deflection rates.
[Source: The author]

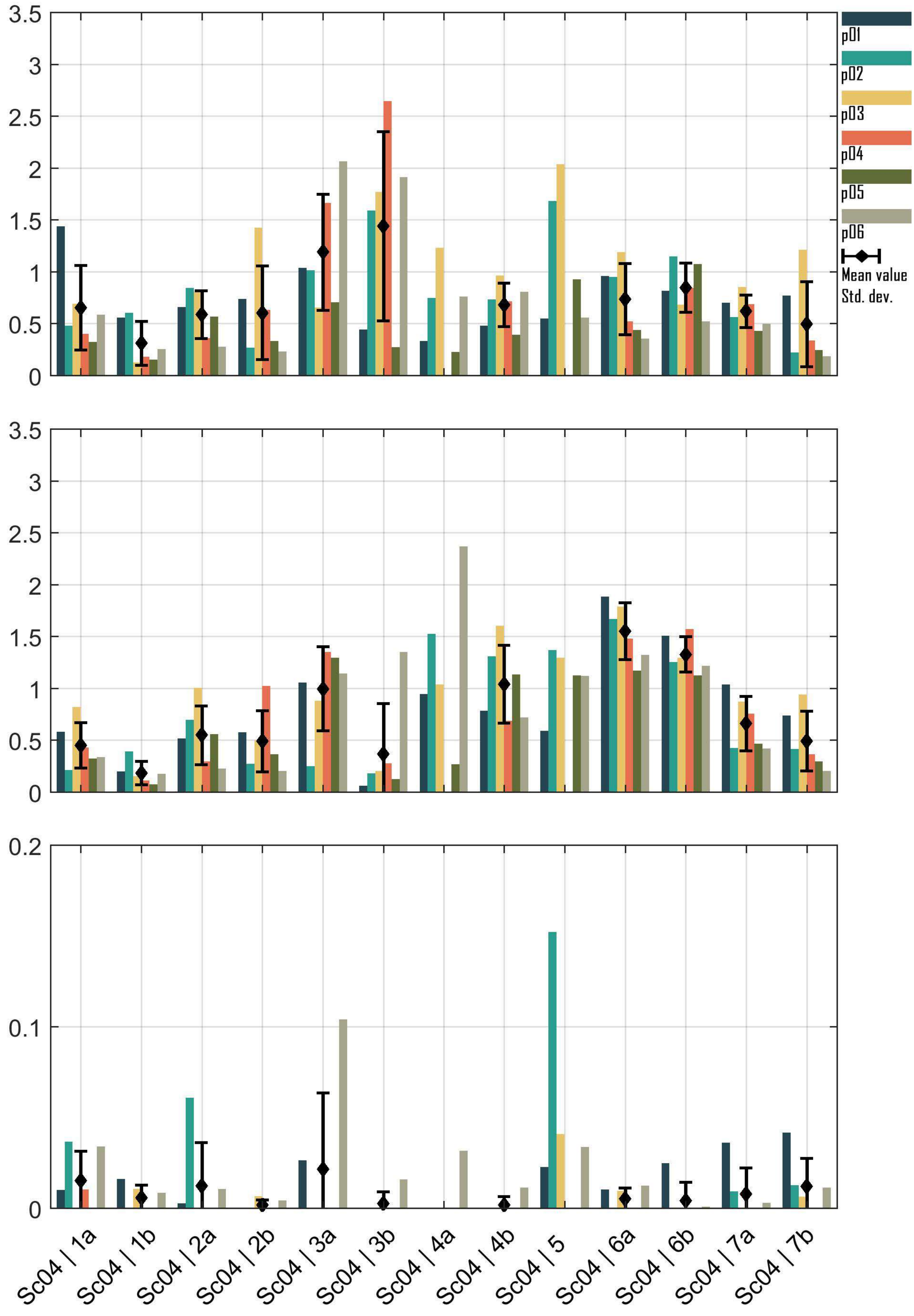

Figure 35: RMS of control deflection rates, Continued.
[Source: The author]

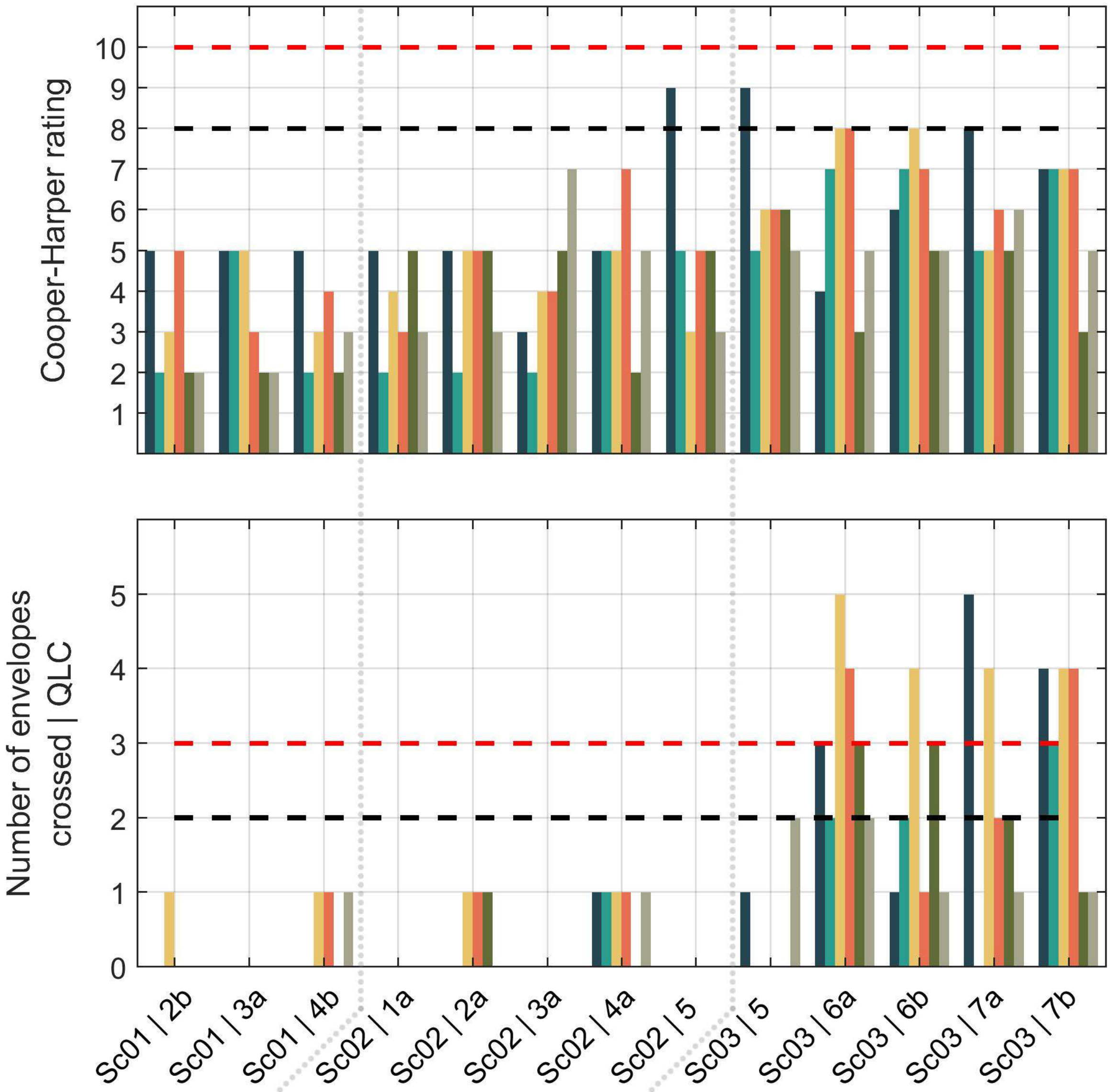

Figure 36: Cooper-Harper ratings and number of envelopes crossed.
[Source: The author]

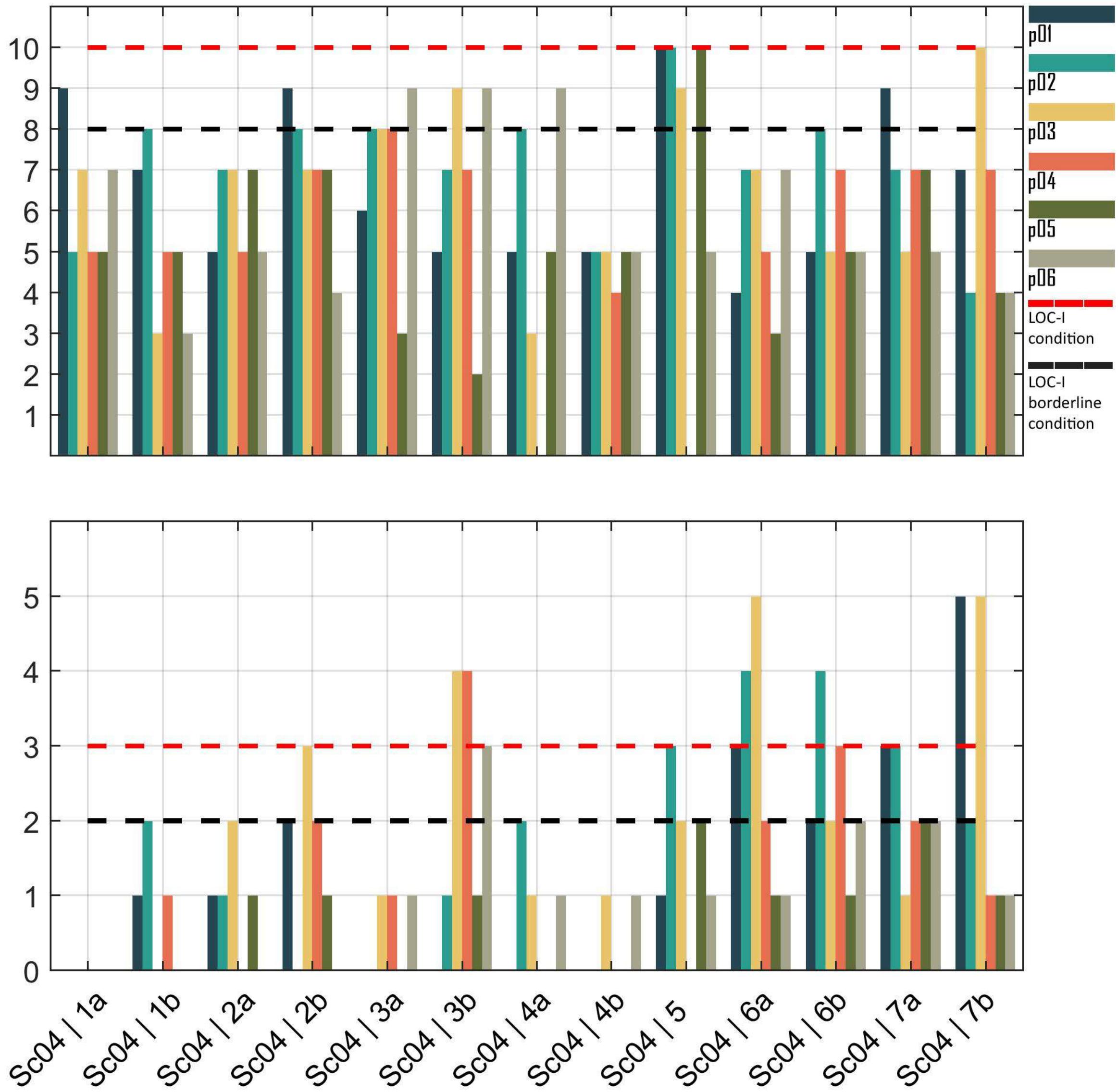

Figure 36: Cooper-Harper ratings and number of envelopes crossed, Continued.
[Source: The author]

Scenario 01 | Task 2b

This manoeuvre aimed at maintaining the lateral attitude in an OEI condition, and the turn was performed over the operating engine and at high speed. Pilots understood both pitch and bank controls were "easy" and required neither large displacements, nor frequent adjustments – the average displacement of the controls was below 20% for the three axes.

No pilot mentioned the use of special control techniques; instead, they reported harmony between longitudinal and lateral inputs, but also some discomfort with the rudder pedals due to the absence of force feedback. Regarding the use of such pedals, a divergent behaviour was displayed by the pilots. Four of them ('p01', 'p03', 'p04' and 'p05') hardly used them, due to their discomfort with the device, and because "the aircraft accepted yaw compensation only with the use of ailerons", according to one of them. 'p02' and 'p06' reported to have applied "moderate" and "small" pedal displacements, respectively, and kept them in a fixed position. Both RMS position – Figure 34 – and RMS rates – Figure 35 – confirm the comments, and show the different perceptions of 'p02' and 'p06' on the magnitude of the pedal displacement, since 'p06' displaced the pedals by greater magnitudes than 'p02'.

Regarding the workload associated with the manoeuvre, the pilots claimed the physical workload was "small", and the mental share ranged from "small" to "moderate". All pilots assigned CHRs within the "normal" controllability category, and the QLC also classified the event as "normal" for all pilots.

Scenario 01 | Task 3a

The RMS position and RMS rates show all pilots adopted similar control strategies regarding the use of the stick in the task, although 'p03' used the controls slightly more frequently, especially in pitch. The participants reported the control of the aircraft in both longitudinal and lateral axes was "easy", and required "small" and "infrequent" displacements; concerning the directional axis, the differences observed in Scenario 01 Task 2b were also identified in Task 3a. None of the pilots mentioned tendencies for a PIO, or use of special control techniques.

Two pilots expressed surprise on the power increase demanded by the aircraft to maintain its airspeed during the manoeuvre (the variation in the longitudinal attitude was relatively small, i.e., approximately 4° positive). However, four pilots considered the airspeed performance requirement "difficult" to accomplish, and the comments suggested the airspeed control was the reason why 'p01' and 'p03' rated the level of mental workload as "moderate". From the perspectives of both the Cooper-Harper scale and QLC, the event was of "normal" controllability for all pilots.

Scenario 01 | Task 4b

In this manoeuvre, the aircraft was at a high energy level and a quick turn was made over its operating engine. The pilots reached consensus that the aircraft control was "easy" in all axes; however, different strategies were identified. Whereas they all employed "small" and "infrequent" control displacements in pitch (the RMS of the normalised position showed it hardly exceeded 20%), ’p02’, ’p03’, ’p04’ and ’p06’ applied roll inputs significantly greater in magnitude and frequency than ’p01’ and ’p05’, which explains the high standard deviations in Figures 34 and 35 (especially due to the more aggressive actuation of ’p04’). No direct comments justified those differences – they may have originated from pilots’ individual interpretations on the task request ("$\phi = 37.5°$ should be reached as quickly and as accurately as possible"). The same considerations made for Scenario 01 Tasks 2b and 3a are valid for the directional axis, with an addition made by ’p02’, who reported having used a special control technique consisting of the application of "moderate" pedal displacements to reach the required bank angle "as fast as possible". It was evidenced in the RMS of the rudder pedals position and partially responsible for its considerable standard deviation.

All pilots reported no tendency for a PIO and agreed the aircraft showed desirable predictability and harmony in the stick controls. The words of ‘p06’ well-summarise their perception: "the controls were good and the aircraft stopped where I requested". Concerning performance criteria, the maintenance of airspeed demanded the closest attention from pilots, since, in the words of ’p04’, "the roll rate demanded an excessive and unexpected increase in traction [that] impacted on the control of airspeed". However, the difficulty in controlling the airspeed has been classified as "easy" to "intermediate". In terms of workload, all pilots understood both physical and mental shares were "small", except for ’p01’, who classified the latter as "moderate". The Copper-Harper scale and the QLC classified the event as of "normal" controllability for all pilots.

Scenario 02 | Task 1a

Although Task 1a was predominantly longitudinal and the elevator effectiveness in Scenario 02 was significantly impaired, the pilots reported the bank control was more difficult (from "easy" to "fair") than the pitch control ("easy"), since the aircraft response was less predictable in roll ("abrupt") than in pitch ("sluggish").

Despite nuances in the use of controls (e.g. ’p02’, ‘p03’ and ’p05’ used greater magnitudes of pitch control, and ’p01’ varied it in greater amplitudes than the others, even causing certain distortion in the standard deviation of $RMS_{pitch_{rate}}$), all pilots adopted the same control strategy, i.e., "small" and "frequent" stick displacements in roll, "moderate" and "infrequent" displacements in pitch, and no rudder pedals, as shown in Figures 34 and 35. The pilots classified the levels of physical and mental workloads between "low" and "moderate", and none reported tendencies for a PIO.

All aviators assigned CHRs in the "normal" controllability category, and the same classification was made by the QLC.

Scenario 02 | Task 2a

The pilots stated the bank angle demanded in the task required pitch inputs to maintain the altitude; however, the "sluggish" longitudinal response, associated with an "abrupt" or even "excessive" lateral response revealed the overall difficulty of the task was "fair". Roll displacements generally concentrated on the first fifth of the total control travel (except 'p04' and 'p05', who tended to apply greater magnitudes), whereas pitch displacements were significantly smaller for 'p01', 'p05' and 'p06' than for 'p02', 'p03' and 'p04'; reasons for such differences could not be identified. Concerning control rates, all pilots used the controls more frequently in roll than in pitch, which is especially visible for 'p04' and 'p05', who even caused some distortion in the standard deviation.

None of the pilots reported tendencies for a PIO, and classified the levels of physical and mental workload between "small" and "moderate". The event was "normal" for both the qualitative and quantitative assessment methods ('p02' and 'p06' assigned the lowest CHRs and did not cross any QLC envelope; as aforementioned, they applied a pitch control strategy different from that used by the other pilots).

Scenario 02 | Task 3a

Since this was an essentially longitudinal manoeuvre, pilots typically applied "moderate" pitch displacements. However, under the condition of a dynamic task (time was a performance parameter), the roll axis was inevitably excited during the climb, revealing some disharmony between the controls in such axes, which persisted up to the end of the task and "drove all types of compensation", as reported by one of the pilots. The longitudinal response was "sluggish" and did not demand special attention, and pilots concentrated most of their compensation work on the longitudinal axis, typically providing "small", but "frequent" inputs. The significant standard deviations in Figures 34 and 35 originated from differences between specific pilots ('p04' and 'p05' in the RMS_{pitch} case, and 'p03' and 'p04' in the $RMS_{roll_{rate}}$ case); however, pilots' comments revealed they all attempted to apply a same control strategy.

Pilots reported the aircraft disharmony, even if demanding, was restricted to the relationship between the longitudinal and lateral axes, i.e., there was harmony between inputs and aircraft response on each axis in isolation, and no tendencies for a PIO in the aviators' opinion; the physical and mental workloads were "moderate". The controllability of the event was "normal", from the perspective of both the Cooper-Harper scale and QLC; however, great discrepancies were observed between the assigned CHRs (from *2* to *7*), differently from the number of envelopes crossed (for all pilots, no envelope was crossed).

Scenario 02 | Task 4a

Overall, the pilots classified the difficulty of this task as "fair" to "high". Elevator inputs were necessary to compensate for the loss of altitude associated with the execution of the turn, and their magnitudes tended to concentrate between "small" and "moderate", as corroborated by RMS_{pitch}. Regarding the ailerons, the displacements concentrated on the first third of the total control travel, except for 'p01', who applied significantly smaller amplitudes.

Concerning the rates of use of the controls, there was good convergence among pilots in pitch (although 'p04' had applied more frequent/pronounced inputs), differently from the lateral axis, as shown by the sharp standard deviation of $RMS_{roll_{rate}}$. Figure 37 shows the explanation of the condition through three different pilots' behaviours: **(i)** 'p01' and 'p05' practically did not vary the position of the stick in roll and dislocated it smoothly (especially 'p05'), **(ii)** 'p02' and 'p06' provided smooth inputs, but used slightly more oscillatory and larger displacements, and **(iii)** 'p03' and 'p04' applied frequent and large stick displacements. Such groups of pilots, respectively, were associated with "low", "medium" and "high" $RMS_{roll_{rate}}$. Only 'p03' and 'p04' reported a slight tendency for a lateral PIO and the need for reducing gain inputs in the axis (this is more apparent for 'p03' in Figure 37); the other participants used traditional control techniques.

All pilots assigned CHRs in the "normal" controllability category, and most of them crossed one QLC envelope; therefore, the event was "normal" also for the quantitative method.

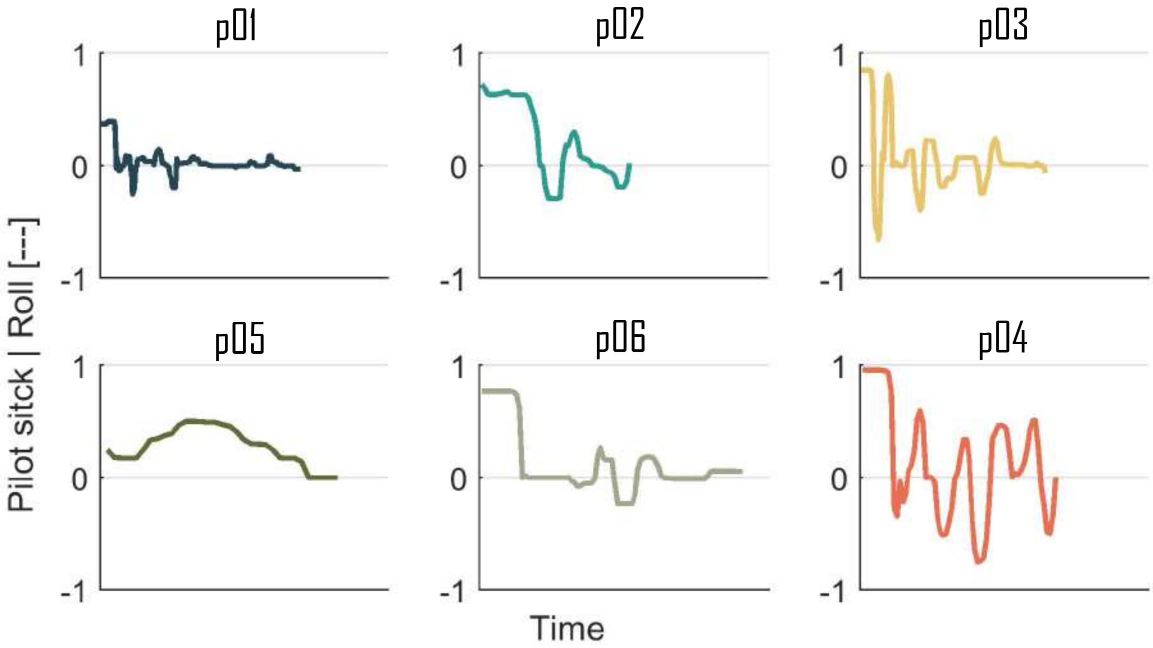

Figure 37: Scenario 02, Task 4a – Roll inputs.
[Source: The author]

Scenario 02 | Task 5

In this ILS approach manoeuvre, the pilots understood the difficulties of the control of the pitch and roll attitudes were equal ("fair" to "high"), although glideslope capture problems had been considerably more frequent than localizer capture; the control of airspeed ranged from "easy" to "fair". The levels of physical and mental workload were "moderate".

Most pilots applied "moderate" control amplitudes in pitch with "small" and "infrequent" variations (the only exception was 'p06', who applied much smaller displacements); in roll, the amplitudes were "small" and slightly more frequent (except for 'p03', who used the command at considerably higher rates); rudder pedals were not used at all.

Despite the convergence of $RMS_{control}$ and $RMS_{control_{rate}}$ in all three axes and the fact that none of the pilots reported tendencies for a PIO, some mentioned the use of special control techniques, e.g., ‘p02’ employed engine power variations to control both pitch attitude and airspeed due to the lack of elevator effectiveness, and ’p06’ used frequent pitch trim inputs to avoid large stick displacements in pitch (see Figure 38).

Concerning controllability categories, both methods classified the manoeuvre as "normal"; the only exception was ’p01’, who qualitatively assessed it as a "borderline LOC-I condition" and was the only pilot to report "high" physical and mental workloads during the task. Her/his comments revealed s/he had control over the aircraft; however, it did not follow her/his inputs and s/he was obliged to constantly reflect on the aircraft response; as a result, the workload was beyond her/his tolerable threshold. According to the comments, ’p01’ evaluated the condition differently from the other aviators due to her/his workload perceptions, rather than use of a particular control strategy.

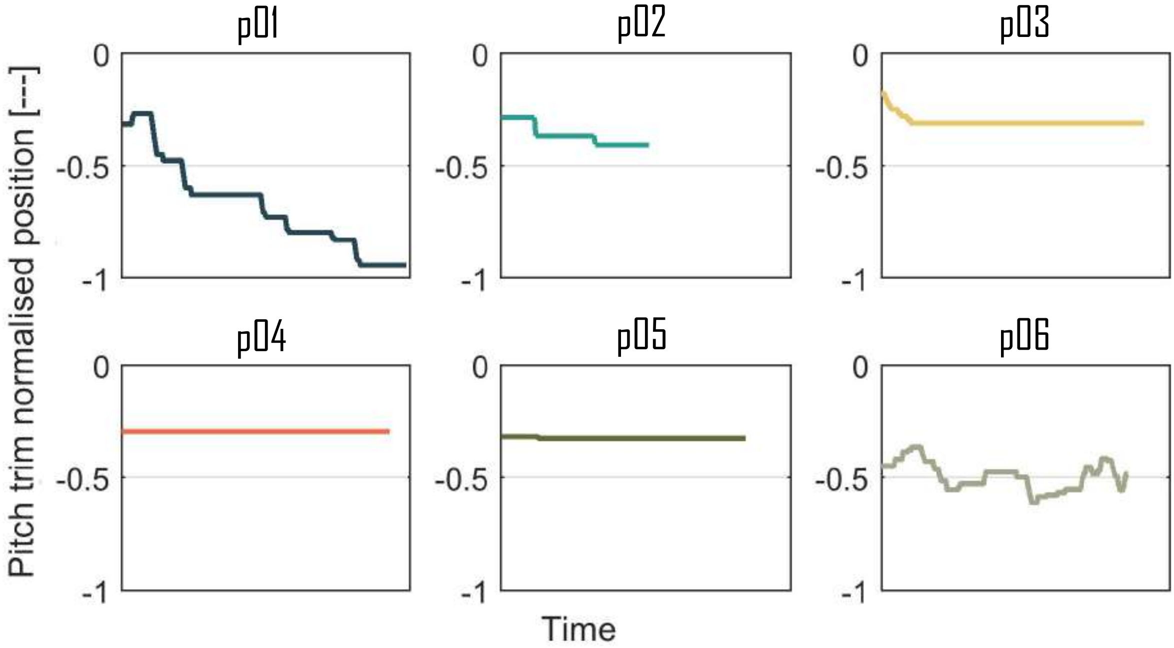

Figure 38: Scenario 02, Task 5 – Pitch trim inputs.
[Source: The author]

Scenario 03 | Task 5

An ILS approach was also performed in Scenario 03, and most of pilots reported a "fair" to "hard" control of the pitch attitude, as the glideslope was usually off by at least one dot at the end of the task. In contrast, only one pilot experienced difficulties in capturing the localizer, and the control of the roll attitude was, in general, "fair". Regarding airspeed, the difficulty in controlling it ranged from "fair" to "hard", due to the condition of engine 2.

Regarding the aircraft condition in Scenario 03, the delayed aircraft response was more demanding than the exacerbation of the control curves in this manoeuvre, since most pilots reported a slight tendency for a pitch PIO, and classified the aircraft response in both pitch and roll as "slow". In terms of control actuation, the significant standard deviations in $RMS_{control}$ and $RMS_{control_{rate}}$ hindered the visualisation of an in-common control strategy. However, during the comment sections, most pilots reported attempting to use "small" and "frequent" inputs in pitch (especially) and roll for mitigating a pitch PIO. Rudder pedals were not used.

Overall, the controllability of the aircraft was classified as "normal", except for 'p01', who understood the workload was beyond tolerable, and 'p06', who crossed two QLC envelopes; on such occasions, the event was classified as a "borderline LOC-I condition".

Scenario 03 | Task 6a

The pilots classified the overall difficulty of controlling both pitch and roll attitudes as "fair" to "hard" in the manoeuvre. The term "high gain" was used to assign the task to the pilots; although subjective, RMS_{roll} indicates that, on average, most aviators shared a same understanding of the term, and tended to use 50% of the total control travel to execute the task. Only 'p05' and 'p06' made a slightly divergent interpretation, since they had never applied stick displacements greater than 75%, as shown in Figure 39[i]. Moreover, 'p05' and 'p06' actuated more smoothly and less frequently on the lateral inputs (Figures 35 and 39), which is closely related to their reporting of no tendency for a lateral PIO in the manoeuvre, as opposed to 'p02', 'p03' and 'p04'. Concerning the longitudinal axis, Figure 39 shows the stick was dislocated by smaller amplitudes in comparison to the lateral case, although sometimes quite often (especially 'p02' and 'p03'). Such characteristics are shown in Figures 34 and 35.

'p02', 'p03' and 'p04' classified the workload between "moderate" and "high", whereas 'p01', 'p05' and 'p06' reported the physical share was "small" and the mental one ranged from "small" to "moderate". Such differences in perception correlated well not only with the pilots' understating on a possible PIO, but also with the CHRs, since the first and second groups tended to assign ratings in the "borderline LOC-I condition" and "normal condition" categories, respectively. From the quantitative perspective, the event was a "borderline LOC-I condition" for 'p02' and 'p06', and a "LOC-I" for the other participants.

Scenario 03 | Task 6b

Tasks 6a and 6b were similar; however, the aircraft had a lower energy level in the latter, and, consequently, demanded greater stick displacements in pitch and roll – see Figure 34, which also shows the standard deviations recorded for both tasks were similar, corroborating the fact that, although they were relatively high (especially in the lateral axis), they were caused by differences in individual pilots' understandings on the "be as quick as possible" requirement.

Regarding the rates of sidestick use, pilots who reported tendencies for a lateral PIO ('p02', 'p03' and 'p04') provided more frequent and oscillating inputs, especially in the lateral axis. 'p02' and 'p03' mentioned the use of a special control technique consisting of the application of smaller control gains after the capture of the 37.5° bank angle to avoid a PIO, and attempted

[i] The same behaviour was observed for other tasks (details in the sequence of this section), corroborating the hypothesis that 'p05' and 'p06' interpreted "high gain" differently from the other pilots

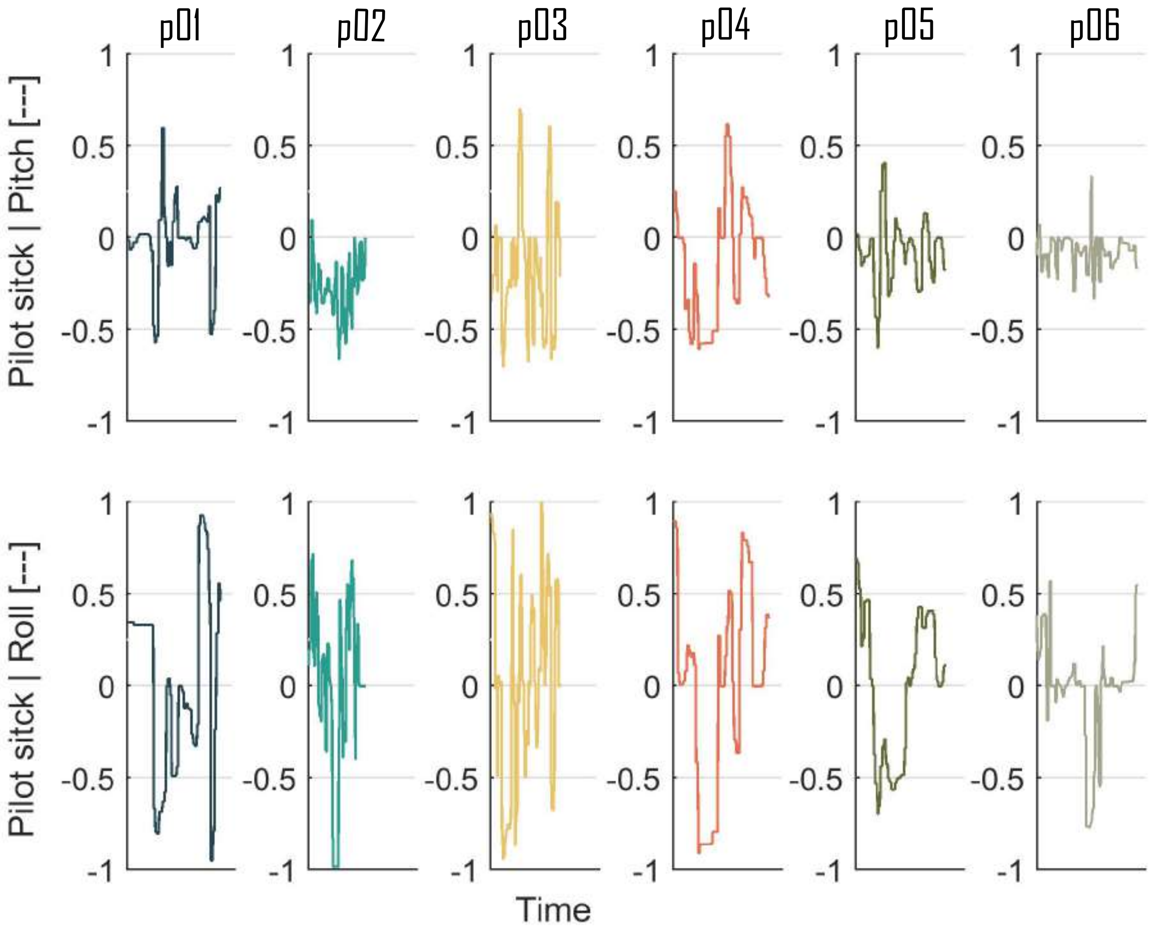

Figure 39: Scenario 03, Task 6a – Pitch and roll control inputs.
[Source: The author]

to not excite the aircraft in pitch. Only 'p02' and 'p04' used the rudder pedals in Task 6b, which did not cause significant changes in the aircraft behaviour.

As a result of the application of the Cooper-Harper scale, only 'p03' assigned a rating in the "borderline LOC-I condition" category. Although for 'p02' and 'p04' the workload was beyond tolerable, the controllability was not threatened, and the event was "normal" for the other pilots. The QLC was much less homogeneous and classified the event as a "LOC-I" for 'p03' and 'p05', a "borderline LOC-I condition" for 'p02', and as "normal" for 'p01', 'p04' and 'p06'.

Scenario 03 | Task 7a

All pilots reported more difficulty in controlling the longitudinal attitude of the aircraft than the lateral one in the manoeuvre, since the pitch command was "abrupt" and power variations directly affected the axis. Figures 34 and 35 show convergence of the control strategies on **(i)** the use of a third of the total stick travel in pitch, **(ii)** the application of lateral inputs of "small" amplitudes, generally below 20% of the total travel, **(iii)** similar rates of longitudinal and lateral inputs, and **(iv)** non-use of rudder pedals. Deviations from such a strategy were observed (to wit, the use of the pitch command by 'p05', and of pedals by 'p04'), however, they were punctual, and according to the comments, did not constitute a new control strategy.

Most pilots reported experiencing a slight tendency for a longitudinal PIO, which could be mitigated by the application of smoother and shorter inputs. The constant need for actuating on the controls was essential for pilots to classify the physical and mental workloads between "intermediate" and "high".

The qualitative method showed good convergence in classifying controllability as "normal" (only ’p01’ assigned a CHR in the "borderline LOC-I condition" category, but it was not possible to identify reasons for that in her/his comments), whereas the quantitative method was more divergent (two pilots in each controllability category).

Scenario 03 | Task 7b

Although the aircraft was at a higher energy level in Task 7b comparatively to Task 7a, the pilots understood it was equally difficult to exert longitudinal and lateral controls. Figures 34 and 35 show they adopted a control strategy based on the use of smaller control amplitudes in comparison to that of Task 7a, which was a direct consequence of the aircraft energy level. Again, the aviators reported tendencies for a longitudinal PIO during the manoeuvre.

Similarly to Task 7a, the event was "normal" according to the Copper-Harper scale; however, in general, the CHRs were higher in Task 7b, since some pilots understood they had faced a beyond tolerable workload. The comments revealed such an increase in workload was due to the control of airspeed, since the higher velocity at the beginning of Task 7b demanded more frequent pilots’ actuation on engine 1 for meeting the performance criterion of no overspeed; the need was not observed in such a degree in Task 7a, as shown in Figure 40. The QLC classified the event as a "LOC-I" on four occasions, and as "normal" on two.

Scenario 04 | Task 1a

Although Task 1a was geared towards the pitch attitude, the power asymmetry displayed by the aircraft in Scenario 04 referred to the pilots applying latero-directional inputs towards meeting the performance criteria, which led to the emergence of different control strategies. Whereas ’p01’, ’p03’ and ’p05’ used only ailerons to compensate for the asymmetry, ’p02’, ’p04’ and ’p06’ combined ailerons with rudder. Figure 34 shows such a distinction and the use of larger stick displacements by the pilots in the first group. In any case, the difference did not impact on the difficulty of exercising the lateral control, since pilots from both groups classified it between "easy" and "fair".

Concerning the longitudinal axis, RMS_{pitch} concentrated around 50% of the total control travel, and all pilots agreed tracking the pitch angle was "hard". The same reading was valid for airspeed control, since each variation of power led to "annoying" latero-directional disturbances.

The pilots diverged regarding a possible PIO: ’p02’, ’p04’ and ’p05’ reported no tendency, whereas ’p03’ and ’p06’ described a slight tendency for a longitudinal PIO, and ’p01’ stated the tendency was strong. Therefore, ’p03’ and ’p06’ adopted the techniques of "looking out to reduce

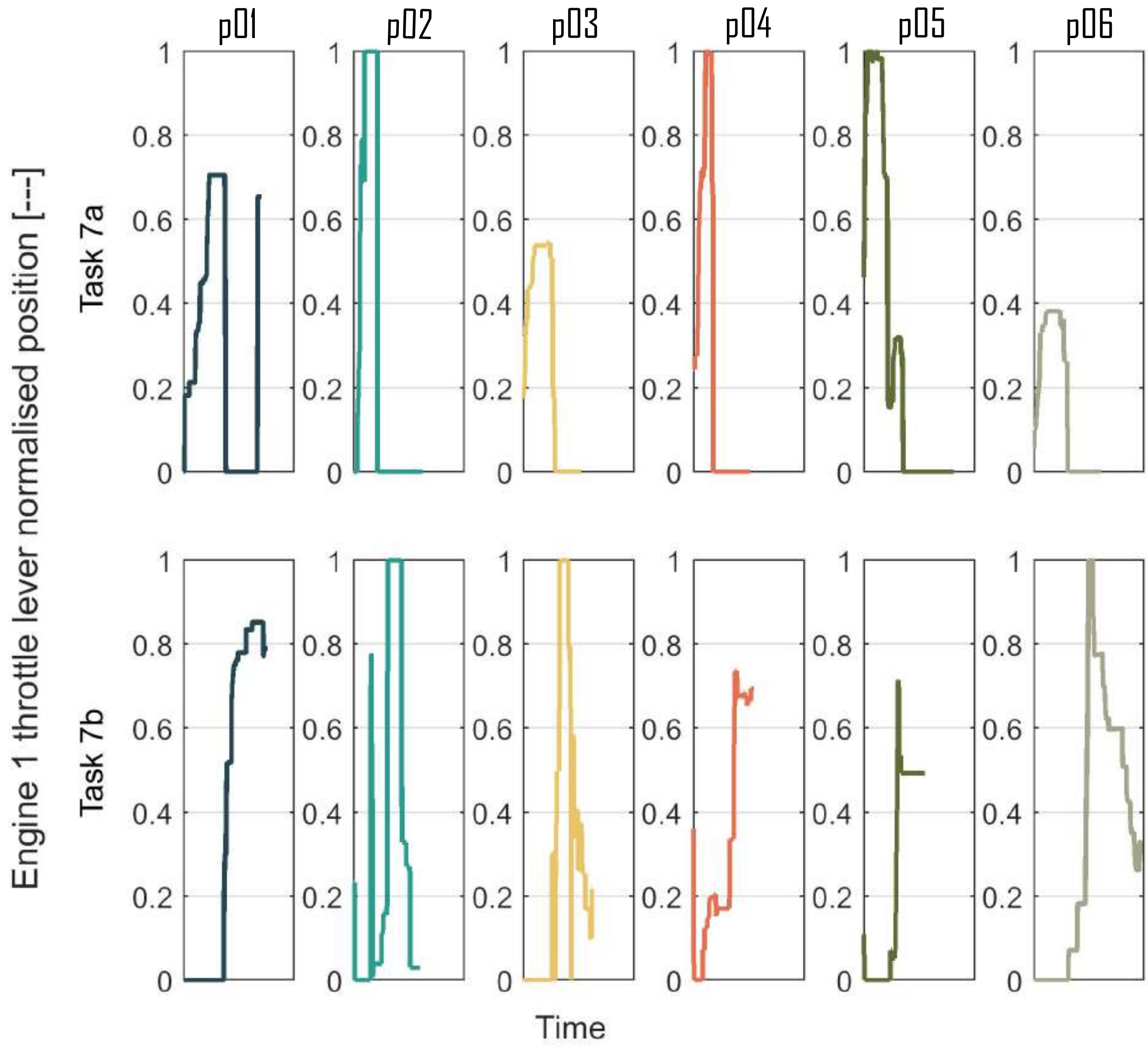

Figure 40: Scenario 03, Tasks 7a and 7b – Use of engine 1.
[Source: The author]

gain", "waiting for the aircraft to stabilise to act on the controls" and "not mixing up controls in different axes"; 'p01', on the other hand, reported "the condition did not make room for anything other than trying to stay in control of the vehicle", which is corroborated by Figures 34 and 35, since 'p01' typically used the controls at larger amplitudes and higher frequencies.

The CHRs assigned at the end of the manoeuvre seemed to reflect the pilots' opinion on a possible PIO; however, except for 'p01', the event was of "normal" controllability for both the qualitative and quantitative classification methods.

Scenario 04 | Task 1b

In comparison to Task 1a, the aircraft was at a higher energy level in Task 1b and its negative longitudinal attitude was under evaluation, and, according to 'p03', "the reduced need to work with the throttle levers reduced the provocation of asymmetries and facilitated the execution of the manoeuvre". The reading was ratified by most participants, who applied "small" and "infrequent" inputs in pitch, roll and yaw – the latter was not even used by most pilots.

Figure 35 shows 'p01' and 'p02' provided more frequent longitudinal inputs than the other pilots, and the comment cards revealed this difference, although subtle, actually constituted the adoption of a different control strategy due to the tendency for a longitudinal PIO. Figure 41 displays a comparison of stick inputs and the aircraft pitch angle for 'p01', 'p02' and 'p06', who reported no tendency for a PIO; pitch oscillations were more pronounced for 'p01' and 'p02', and a lag was observed between their inputs and the aircraft response.

Similarly to Task 1a, the CHRs in Task 1b seemed to be connected to a pilot's impression on a possible PIO, since the higher ratings were assigned by 'p01' and 'p02'. In general, for both the qualitative and quantitative classification methods, the event was "normal"; the only exception was 'p02', for whom the manoeuvre was a "borderline LOC-I condition".

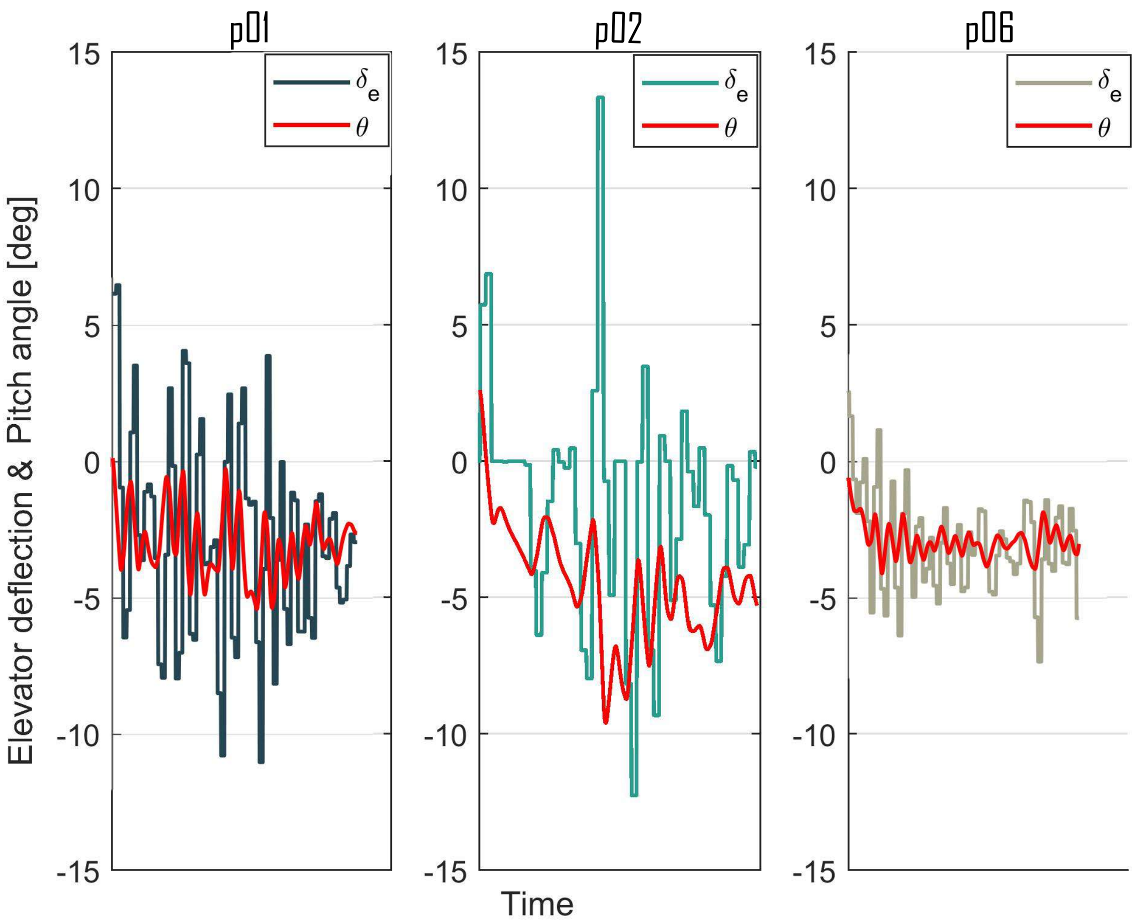

Figure 41: Scenario 04, Task 1b – Elevator deflection and pitch angle.
[Source: The author]

Scenario 04 | Task 2a

Although focused on the lateral axis, the duration of Task 2a, associated with a low aircraft energy, required pilots' actuation on the pitch control. In fact, the average RMS_{pitch}

was twice the average RMS_{roll} – Figure 34 –, and their rates of utilisation — Figure 35 – were similar. No significant use of rudder pedals was registered.

According to the pilots, the aircraft had "sluggish" responses in both pitch and roll, but there was harmony between them (although not the usual harmony of a regular aircraft), which improved its piloting characteristics to some extent. The greatest difficulty was to deal with the power asymmetry for controlling the airspeed, which required "an unusual mental anticipation of the aircraft's response to power variations", according to 'p02' and 'p05'. None of the pilots reported tendencies for a PIO during the manoeuvre, except 'p02', who described a slight tendency on the longitudinal axis.

From the Cooper-Harper scale and QLC perspectives, the event was in the "normal" controllability category for most pilots. The only outlier was 'p03', for whom the quantitative method classified the manoeuvre as a "borderline LOC-I condition".

Scenario 04 | Task 2b

The differences between Tasks 2a and 2b were the energy level of the aircraft and the side of the turn performed. As shown in Figure 34, the average $RMS_{control}$ showed a significant reduction between the tasks, especially in pitch, due to the higher airspeed in Task 2b. Concerning $RMS_{control_{rate}}$ — Figure 35 –, the new energetic condition did not yield significant changes, and pilots tended to use the controls at similar frequencies (the exceptions were 'p03' in pitch, and 'p04' in roll).

Despite the differences expected between the tasks in terms of control actuation, the pilots reported an increase in mental workload in Task 2b (tending towards "high", as opposed to "moderate" in Task 2a), and, according to a pilot, "the aircraft seemed to move in pitch without me having commanded it". It is speculated that, as the pilots displaced the stick laterally, they involuntarily also displaced it longitudinally, which is natural. In normal circumstances, such inputs are readily fed back so that pilots can correct them; however, given the delay between inputs and outputs in Scenario 04, they "lingered" to enter the dynamics of the aircraft, and when they finally did, they surprised the pilots. Consequently, such characteristics increased the pilots' workload, opened room for a longitudinal PIO, and "dismantled" the control harmony mentioned in Task 2a.

Although both CHRs and QLC captured such a control degradation for some pilots, most of them still classified the event as "normal".

Scenario 04 | Task 3a

The pilots understood that reaching and maintaining the requested pitch angle was "hard" in this manoeuvre, especially because "the aircraft took long to provide the responses, and when they came, they were "abrupt", as summarised by one of the participants. Despite the short duration of the manoeuvre, the pilots also actuated on the lateral and directional axes, since the power demand was significant and hence the asymmetry generated by the use of the throttle levers.

Regarding control strategies, **(i)** all pilots used ailerons to compensate for yaw deviations; however, ’p06’ also applied rudder in considerable amplitudes[ii] – Figure 34 –; **(ii)** all pilots accelerated the engines, but they reached no consensus on the possibility of exercising airspeed control, since, as shown in Figure 42, ‘p03’, ’p04’ and ’p06’ reached the stop of the throttle levers and were left with no control margins, whereas ’p01’, ’p02’ and ’p05’ did not reach the stops, but still classified the difficulty to control it as "fair" to "hard"; and **(iii)** pilots significantly diverged regarding $RMS_{control_{rate}}$ – Figures 34 and 42 –, but no reasons were identified for that.

Most pilots agreed on the existence of a tendency for a pitch PIO; it was light for ’p01’, however, the others claimed it was expressive and the reason for the use of special control techniques that aimed at reducing input gain. Only ’p05’ reported no tendencies for a PIO. The overall workload was classified as "moderate" to "high". The lack of roll control activity by ’p02’ stood out – Figures 34 and 35 –, demonstrating the pilot was mentally overwhelmed, and eventually abandoned the control on the lateral axis, which s/he ratified: "at a certain point, I simply stopped the manoeuvre (acting on the controls) where I was".

Such a high workload demand was captured by the CHRs, since they classified the event as a "borderline LOC-I condition" for most pilots; from the QLC perspective, however, the manoeuvre was "normal" for all pilots.

Scenario 04 | Task 3b

In Task 3b, the pilots maintained the understanding they had in Task 3a, i.e., capturing and maintaining the assigned pitch angle was "hard". On the other hand, it was easier to keep the wings levelled and the desired heading. Figure 43 shows the pilots moved the throttle levers by larger displacements in Task 3b, which, in theory, would have led to larger and more frequent stick/pedals inputs. However, it did not occur, as shown by the reduction of the average $RMS_{control}$ and $RMS_{control_{rate}}$ in comparison to Task 3a (see Figures 34 and 35).

Such a reduction in the use of the controls was a consequence of the higher aircraft energy level in Task 3b, which caused greater restoring aerodynamic moments – Weathercock effect – that ultimately facilitated the maintenance of the aircraft’s trajectory. Figure 43 clearly shows power variations produced much fewer oscillations in the yaw rate in Task 3b comparatively to Task 3a. Concerning airspeed control, ’p03’, ’p04’ and ’p06’ reported no control margins, since they brought the levers to idle; whereas the other pilots could control the parameter ("easy" to "fair" difficulty) – no conclusion on the topic could be drawn.

Although the pilots had worked less in the controls in Task 3b, they reported a "moderate" to "high" workload due to a "significant" tendency of the aircraft to divert to a longitudinal PIO. Such a stronger tendency in comparison to Task 3a was probably again associated with the energy state, since the higher airspeed increased the "aerodynamic power" of the controls,

[ii] It was probably a consequence of her/his experience in command of the EMB-120 Brasília, an aircraft whose power variations also produce yaw deviations due to the rotation of the engines in the same direction

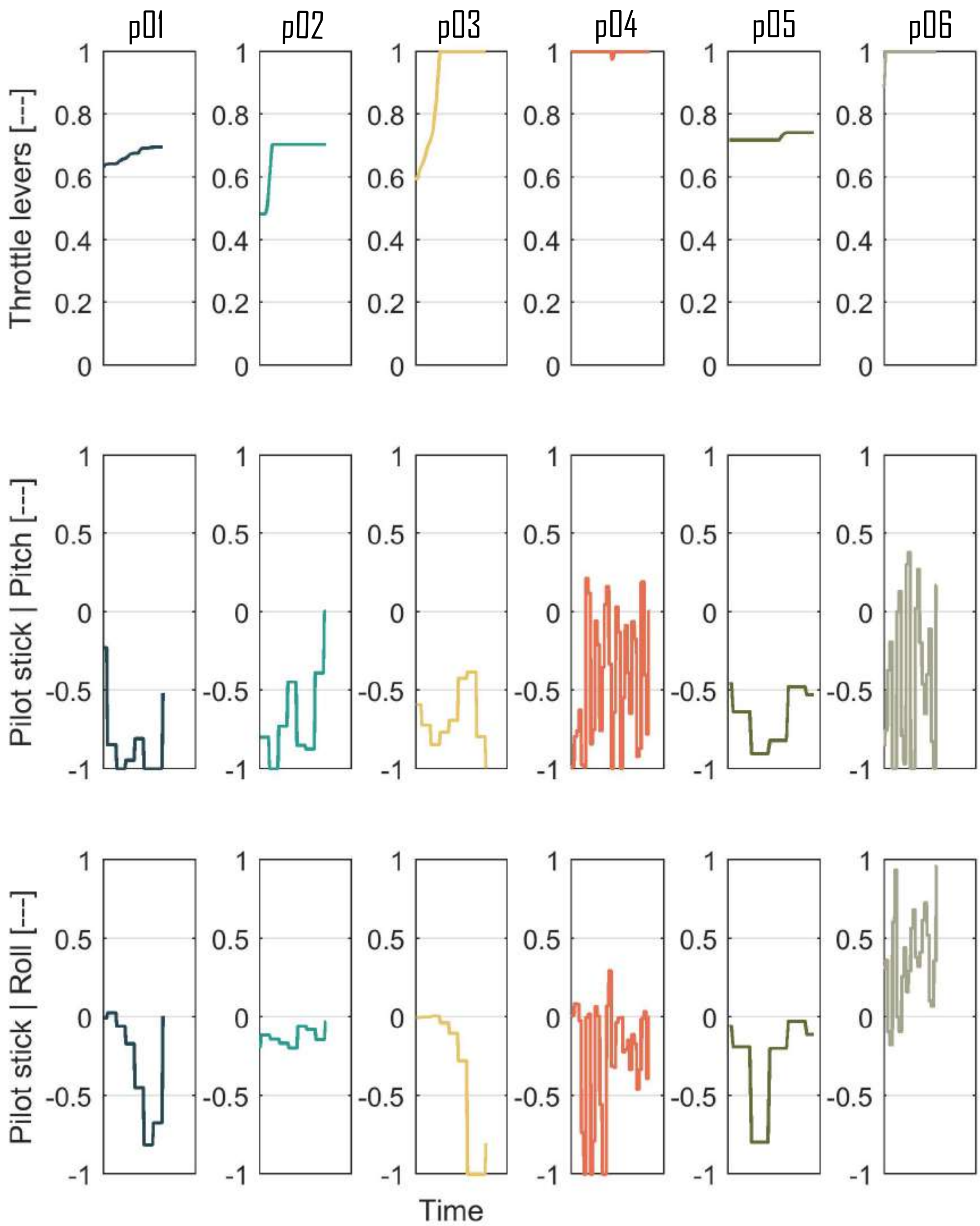

Figure 42: Scenario 04, Task 3a – Pitch, roll and throttle inputs.
[Source: The author]

making any input more significant. The tendency for a PIO was consensual, and pilots had typically provided inputs of "low" to "medium" magnitude; however, their control behaviour in the longitudinal axis was not conclusive, as evidenced by the significant standard deviations of both RMS_{pitch} and $RMS_{pitch_{rate}}$.

Finally, concerning the controllability of the event, two pilots assigned CHRs in the "borderline LOC-I condition" category, whereas the other four classified it as "normal". From the

QLC viewpoint, the manoeuvre was "normal" for three pilots and a "LOC-I" for the other three.

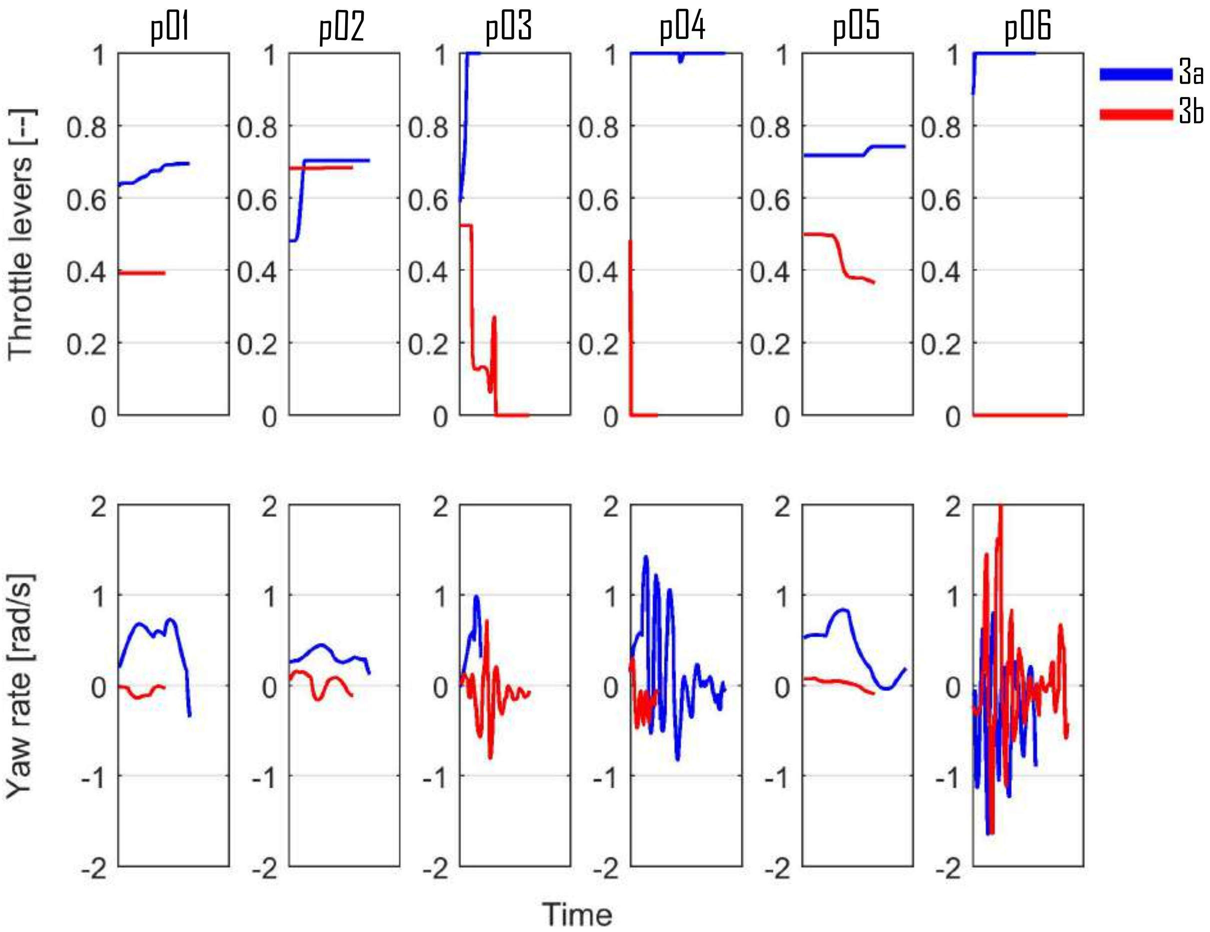

Figure 43: Scenario 04, Tasks 3a and 3b – Engine use and yaw rate.
[Source: The author]

Scenario 04 | Task 4a

Three control strategies were used in this manoeuvre; they are described in what follows, according to $RMS_{control}$, $RMS_{control_{rate}}$, pilots' comments, and Figure 44:

- 'p01' and 'p05' applied longitudinal inputs of low amplitude (usually below 20% of the total control travel) and lateral inputs far from the control stops (they reached a maximum displacement of 70% and 45% of the control travel, respectively). Although 'p01' was more oscillatory in the roll command, both pilots reported the difficulty in controlling the pitch and roll attitudes ranged between "easy" and "fair", since there were no tendencies for a PIO, and no special control techniques were required;
- 'p02' and 'p06' adopted a control behaviour marked by oscillations of the stick position in both axes, especially in the lateral one, where they even reached the control stops. Both pilots reported tendencies for a lateral PIO, and 'p02' "moved away from the controls" to mitigate the oscillations, while 'p06' tried to "constantly anticipate the aircraft". Consequently, they classified the workload level as "moderate" to "high"; and

- ’p03’ used a mixed control strategy with no remarkable characteristics and occasionally aligned with that adopted by either of the aforementioned group, and reported it was more difficult to maintain the bank angle than the altitude. However, it was a very quick task, and eventually "easy", in general.

Regarding the controllability classification of the event, it was "normal" for ’p01’, ’p03’ and ’p05’, and a "borderline LOC-I condition" for ’p02’ according to the qualitative and quantitative methods; for ’p06’, it was also a "borderline LOC-I condition" from the qualitative perspective, but a "normal" event for the quantitative method. Data are missing for ’p04’ in this manoeuvre.

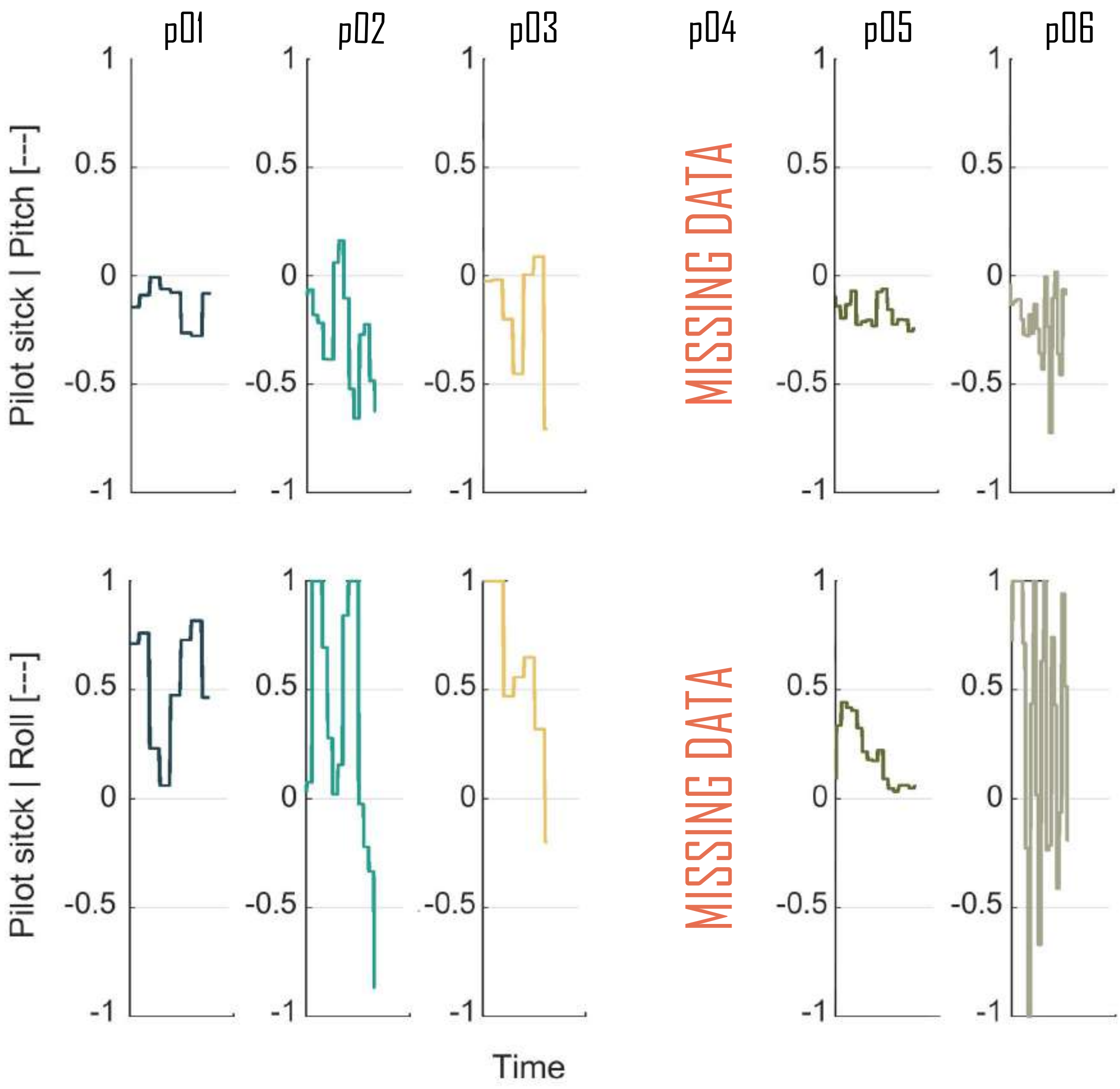

Figure 44: Scenario 04, Task 4a – Pitch and roll inputs.
[Source: The author]

Scenario 04 | Task 4b

The pilots used a control strategy that consisted of the application, at similar rates, of pitch and roll inputs, respectively, around 60% and 80% of the total control travel (the significant standard deviation of RMS_{roll} was due to the isolated actuation of 'p06', who, as mentioned in other tasks, understood "high gain" at levels typically below than those practiced by the other participants). There was no significant use of rudder pedals. Unlike Task 4a, the pilots used no special control techniques in Task 4b, and reported no tendency for a PIO. The altitude control demanded more attention than the bank angle control.

The energy management in Tasks 4a and 4b was the reason for such differences in the pilots' perceptions. In both tasks, the aircraft energy was used for the change of the lateral attitude, and the maintenance of altitude and airspeed; however, the tasks differed regarding initial airspeed and side of the turn. In Task 4a, the aircraft was faster and the turn was over engine 2, which was a more natural attitude in the conditions of Scenario 04, and meant that less energy was required for the turn. Conversely, in Task 4b, once the engines were accelerated, the faster and more powerful response of engine 1 generated a rolling moment in the opposite direction of the intended turn, thus requiring more energy for the turn and reducing the available energy share to maintaining altitude and airspeed. As a consequence of such a combination between aileron and engine inputs, the aircraft became laterally more docile, since the resulting roll rates were reduced in Task 4b in comparison to Task 4a, as shown in Figure 45. Ultimately, the characteristics present in Task 4a were eliminated in Task 4b, and the pilots focused on the longitudinal axis, since less energy was available to control it and the airspeed was close to that of stall.

The event was of "normal" controllability for all pilots, according to both the Cooper-Harper scale and QLC.

Scenario 04 | Task 5

All pilots reported this manoeuvre was "difficult" in every aspect, and demanded "high" mental workload, because **(i)** an ILS approach is a naturally demanding task, since the margins are small, **(ii)** mixed and undesirable dynamic developments were produced for every single input, and **(iii)** from the beginning to the end of the manoeuvre, the pilots attempted to understand and predict the behaviour of the aircraft.

To some extent, Figures 34 and 35 display a certain commonality in the pilots' control actuation, and Figure 46 shows they tended to provide large-amplitude inputs at high frequency in the longitudinal and lateral axes, most of the times concentrating the longitudinal inputs on the pitch up region (negative values), and frequently reaching the lateral stick stops.

However, Figure 46 also shows some special control techniques reported by the pilots, i.e., **(i)** application of asymmetric throttle levers by 'p01' and 'p03' towards eliminating the yawing and rolling moments induced by power variations, **(ii)** application of rudder inputs by 'p02' to compensate for the "sluggish" roll response, and **(iii)** application of small power variations and use of a constant rudder deflection by 'p06'. According to all pilots, the motivation for

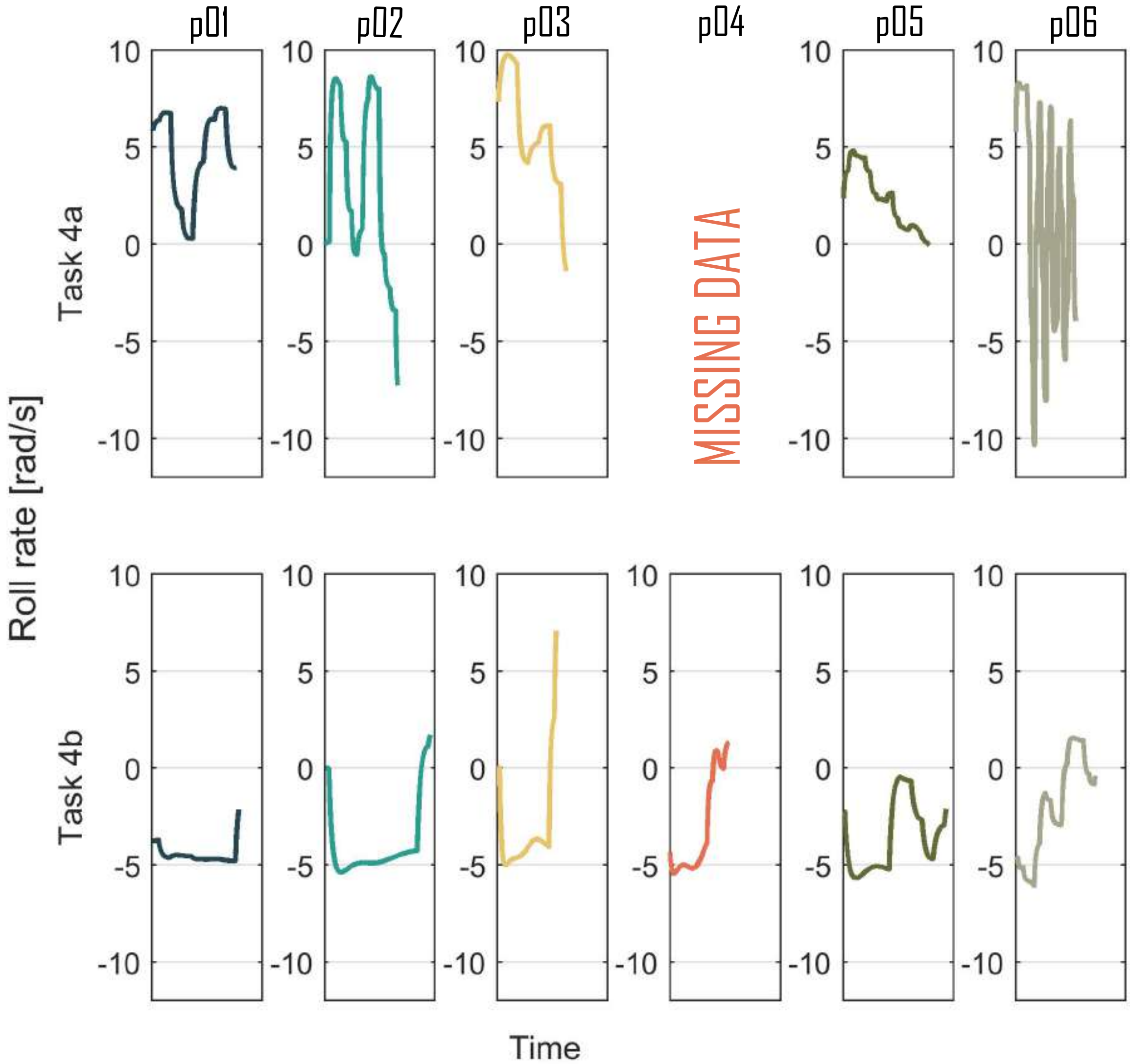

Figure 45: Scenario 04, Tasks 4a and 4b – Roll rate.
[Source: The author]

such techniques was the need for better control conditions on the lateral and directional axes. Only 'p06' reported no tendency for a PIO, since the other pilots claimed it existed on both longitudinal and lateral axes – it was stronger on the former.

Regarding the qualitative controllability classification, 'p01', 'p02' and 'p05' considered it a "LOC-I", since they could not even effectively try and interpret the aircraft behaviour; for 'p03', it was a "borderline LOC-I condition"; and 'p06' classified it as "normal". From the quantitative perspective, the manoeuvre was "normal" for 'p01' and 'p06', a "borderline LOC-I condition" for 'p03' and 'p05', and a "LOC-I" for 'p02'. Data are missing for 'p04' in this manoeuvre.

Scenario 04 | Task 6a

Within individual nuances concerning the interpretation of the “high gain” term, the average $RMS_{control}$ and $RMS_{controlrate}$ show the pilots tended to converge to the use of similar elevator, aileron and rudder inputs. However, during the comment section, 'p01', 'p04' and 'p05' reported they frequently used the throttle levers during the manoeuvre, which was not informed by the other participants. Figure 47 shows the differences in actuation between the mentioned groups of pilots.

Such a difference in the control strategies seemed to find correspondence on the CHRs, since the handling qualities were better for the pilots of the first group than for those of the second. A comment made by 'p03' corroborated the hypothesis: "there was an apparent discontinuity in the roll rate in the middle of the task (moment when the side of the turn was changed), accompanied by an adverse yaw", showing the pilots who worked on the levers reduced or even eliminated the discontinuity.

In any case, however, the event was of "normal" controllability for all pilots, according to the qualitative method; the QLC classified it as a "LOC-I" for 'p01', 'p02' and 'p04', a "borderline LOC-I condition" for 'p04', and as a "normal" one for 'p05' and 'p06'.

Scenario 04 | Task 6b

The control strategies adopted in Task 6b were very similar to those used in Task 6a. The most remarkable differences were:

- an increase in pitch input demand due to the reduced airspeed. Figure 34 shows the average RMS_{pitch} was approximately 70% in Task 6b in contrast to 30% in Task 6a;
- an increase in workload reported by 'p01', 'p04' and 'p05'. Although the pilots used power variations in Task 6b, since the initial airspeed of the manoeuvre was close to the stall speed, they managed the airspeed more closely and also used the levers to smooth the aircraft's rolling and yawing tendencies. Eventually, it represented a deterioration of the aircraft handling qualities;
- maintenance of the control strategy used in Task 6a by 'p03' and 'p06'. However, they reported the aircraft had "good" predictability of control, which is shown in Figure 47 by the lower roll rates in Task 6b in comparison to Task 6a. For both pilots, the handling qualities were better in Task 6b than in Task 6a; and
- a modification in the control strategy in Task 6b by 'p02' by the application of successive power increments during its execution – Figure 47. However, the pilot reported it deteriorated the pitch control to a condition in which "the sidestick was almost always at the pitch up stop", representing a threat to the control of the aircraft in her/his opinion.

The Cooper-Harper scale classified the event as "normal" (the exception was 'p02'); however, according to the QLC, it was "normal" for 'p05', a "borderline LOC-I condition" for 'p01', 'p03' and 'p06', and a "LOC-I" for 'p02' and 'p04'.

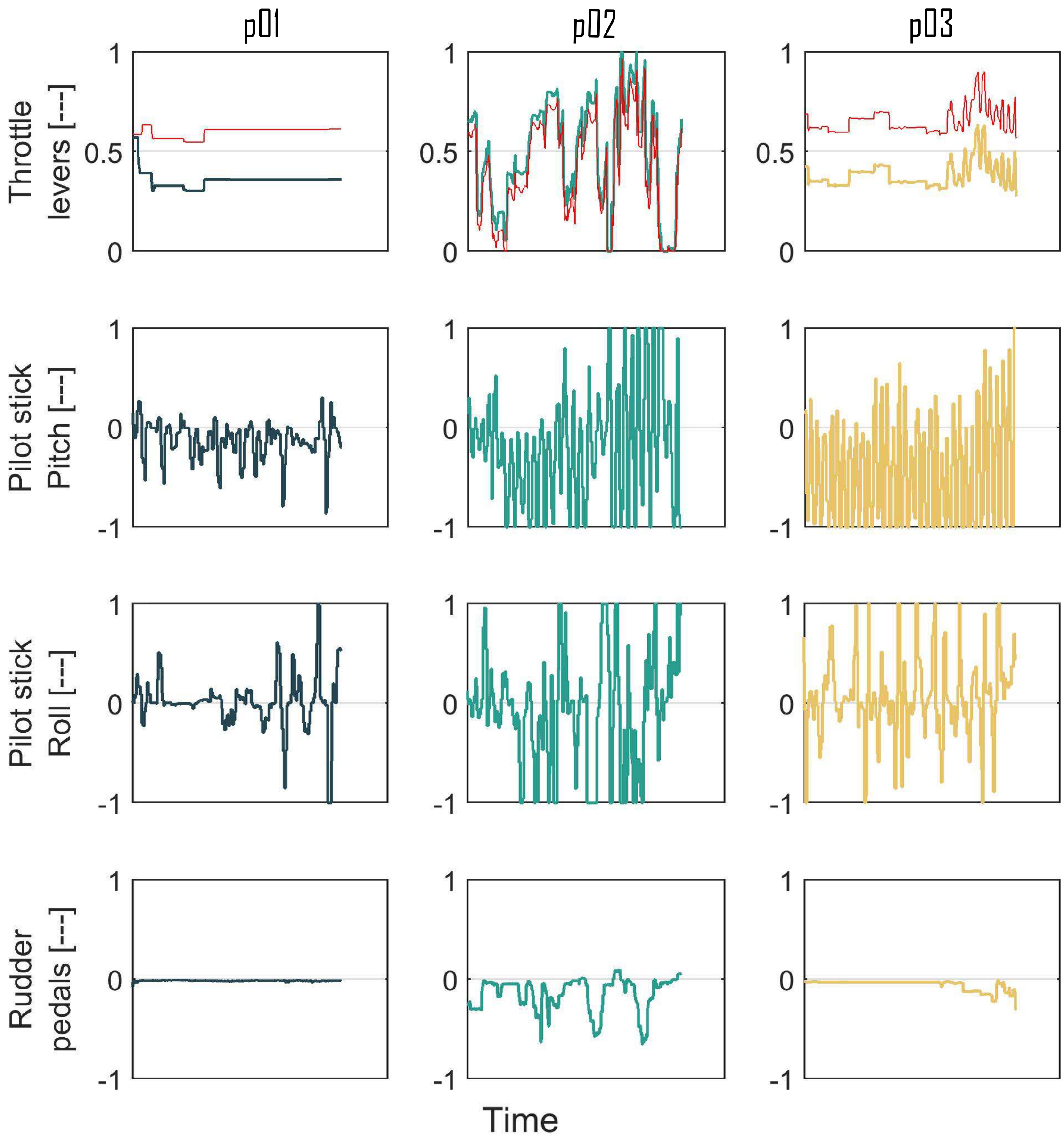

Figure 46: Scenario 04, Task 5 – Pilot control action.
[Source: The author]

Scenario 04 | Task 7a

According to the pilots' comments, the control strategy adopted in this manoeuvre consisted of **(i)** no use of rudder pedals, **(ii)** frequent small-amplitude longitudinal inputs concentrated on the pitch up region, occasionally reaching the control stop, **(iii)** frequent lateral inputs, reaching the stops to initiate the turns, and **(iv)** significant power variations for airspeed control, rather than for compensating for any motion tendency. Figures 34 and 35 corroborate the comments.

The pilots also claimed it was "hard" to change and maintain the aircraft's attitude, and, although the response of the vehicle was generally "sluggish" and they had applied low gains,

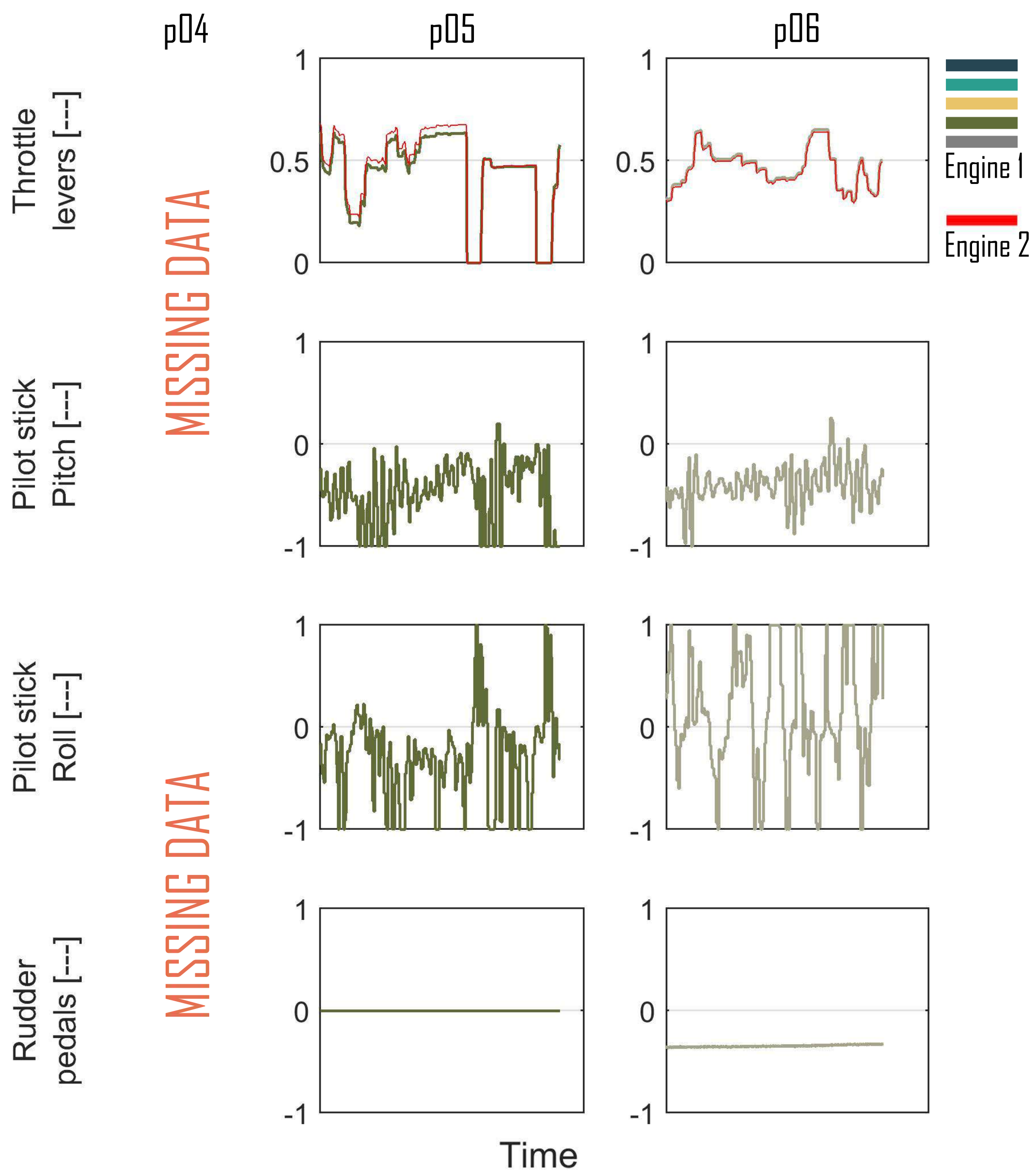

Figure 46: Scenario 04, Task 5 – Pilot control action, Continued.
[Source: The author]

the aircraft showed a tendency for a longitudinal PIO. Differently from 'p01', 'p02' and 'p04', who reported a "strong" tendency ('p02' even used special techniques to mitigate the PIO by "neutralising the roll control before the aircraft actually reached the condition of interest"), 'p03', 'p05' and 'p06' considered it "light".

For most pilots, the overall workload ranged between "moderate" and "high", and they assigned CHRs within the "normal" controllability category (the only exception was 'p01', who assigned a CHR in the "borderline LOC-I condition" category). Regarding the QLC, the event was "normal" for 'p03', a "borderline LOC-I condition" for 'p04', 'p05' and 'p06', and a "LOC-I" for 'p01' and 'p02'.

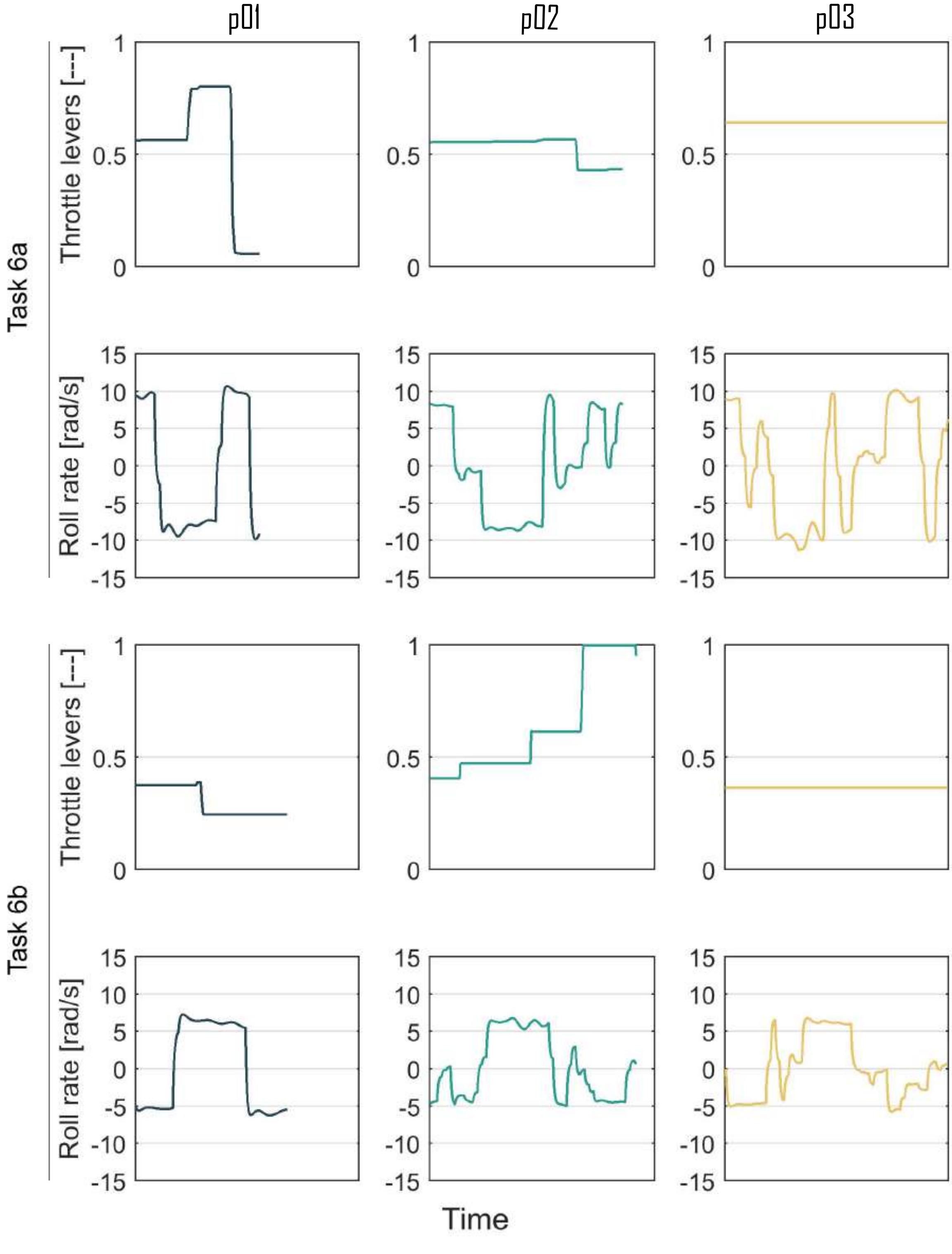

Figure 47: Scenario 04, Tasks 6a and 6b – Throttle levers and roll rate.
[Source: The author]

Scenario 04 | Task 7b

In comparison to Task 7a, the higher aircraft energy in Task 7b lowered the average $RMS_{control}$ and $RMS_{control_{rate}}$ in both longitudinal and lateral axes, as expected (Figures 34

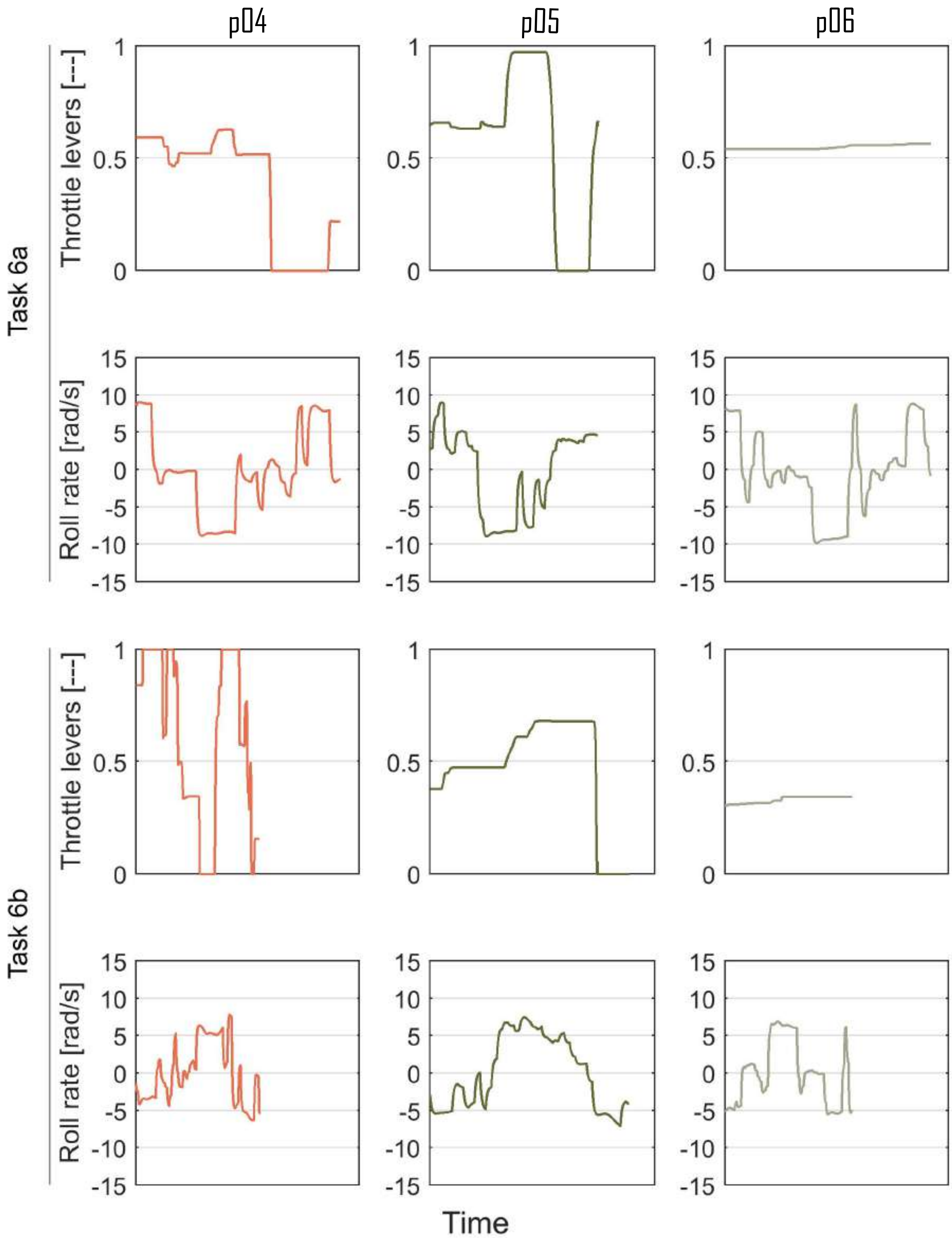

Figure 47: Scenario 04, Tasks 6a and 6b – Throttle levers and roll rate, Continued.
[Source: The author]

and 35); however, the actuation of 'p01' and 'p03' was considerably different from the strategy adopted by the other pilots, as evidenced by the significant standard deviations of the parameters.

Figure 48 shows differences in both longitudinal and lateral axes, but especially in the

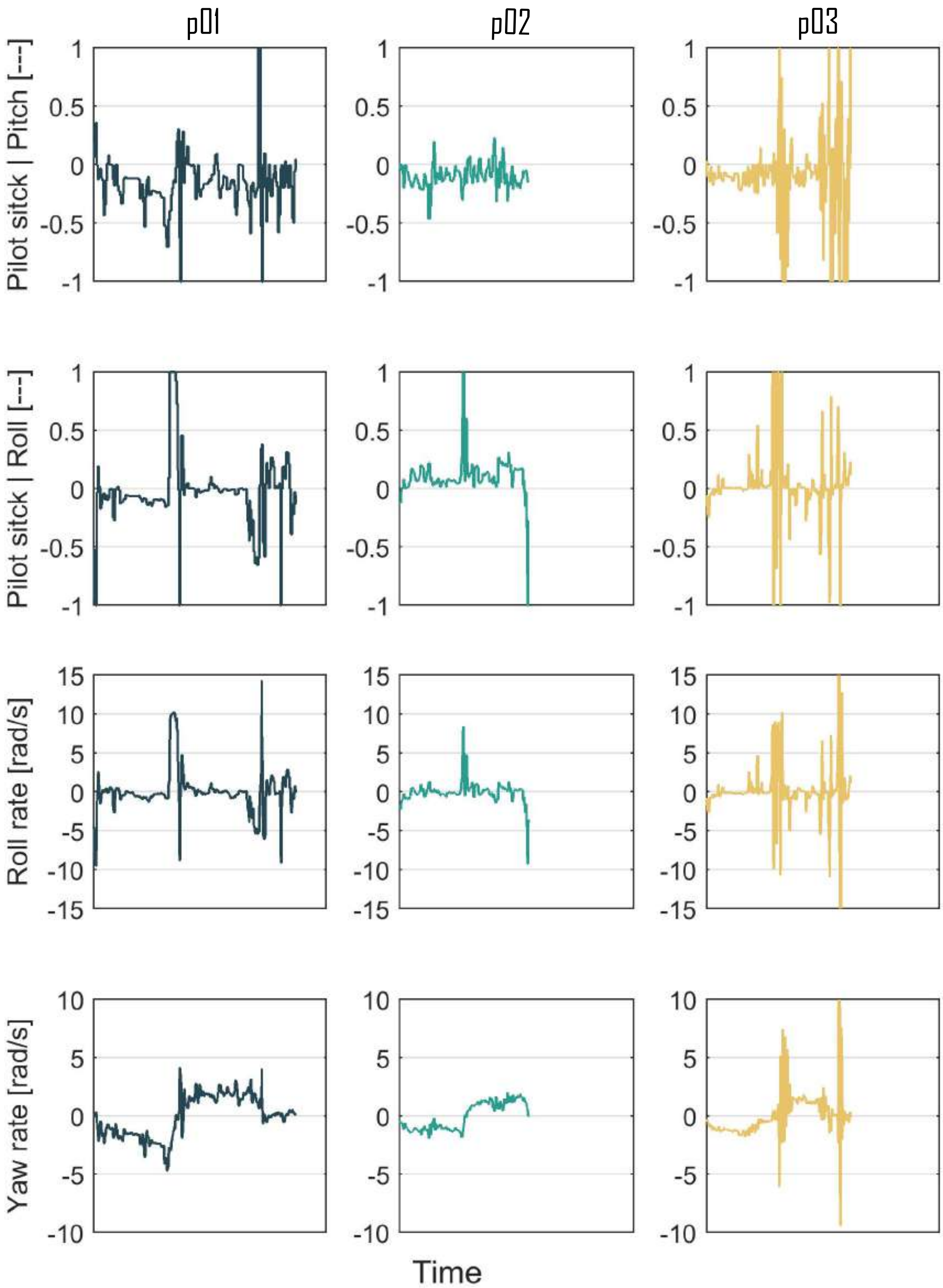

Figure 48: Scenario 04, Task 7b – Pilot control actions and roll and yaw rates.
[Source: The author]

latter. While most aviators applied "small" inputs in pitch, 'p01' and 'p03' reached the control stops and reported a "strong" tendency for a longitudinal PIO, denied by the others. Regarding the lateral axis, again, 'p01' and 'p03' frequently reached the control stops, whereas some of the

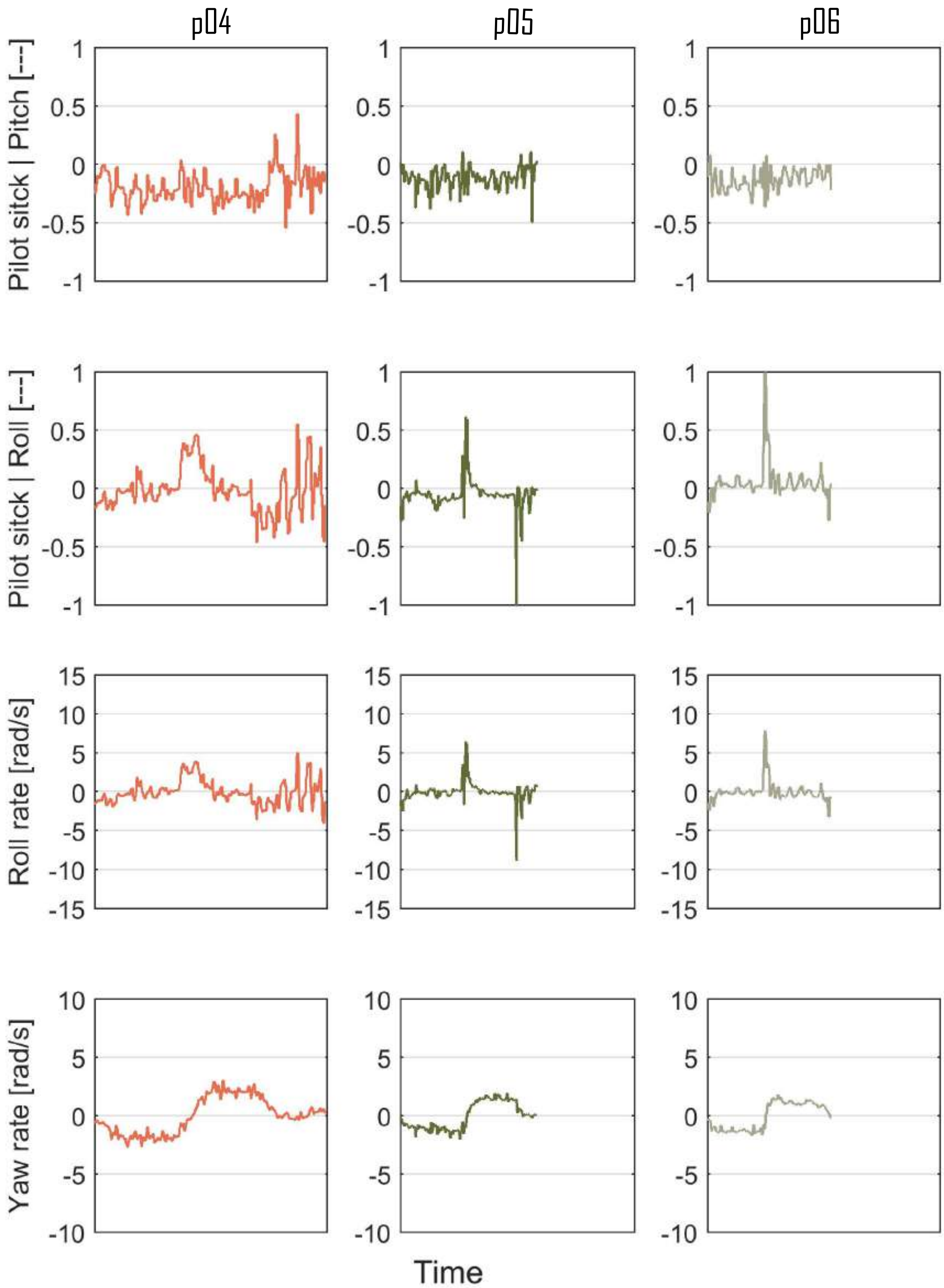

Figure 48: Scenario 04, Task 7b – Pilot control actions and roll and yaw rates, Continued.
[Source: The author]

other pilots classified the lateral response of the aircraft as "desirable". Consequently, the outlier pilots experienced higher and more oscillatory roll and yaw rates, which inevitably increased their workload (see Figure 48).

Whereas the aircraft handling qualities significantly improved from Task 7a to Task 7b for most pilots, it degraded for 'p03', who reported to have lost control at a certain point, and considered the manoeuvre a "LOC-I". However, the CHRs assigned by all other pilots were within the "normal" controllability band. From the quantitative approach, the manoeuvre was a "LOC-I" for 'p01' and 'p03', and an event of "normal" controllability for most of the other participants.

As a conclusion of the aforementioned along this section, the pilots were given the opportunity to explore and try different control strategies in the experiments. Moreover, a "solitary" pilot using a particular control strategy was rarely observed (e.g., 'p03' in Scenario 04 Task 4a); most of the times, the pilots used a same strategy in a given task. Such a "commonality" is a result of **(i)** the similar training and background of the participants, **(ii)** the use of the long-look evaluation technique, and **(iii)** the successful promotion of equal conditions for all pilots through a rigorous application of the proposed methodology.

As expected, the aircraft condition in the simulation scenarios, the tasks, and the resulting control strategies impacted the pilots' workload, hence, the assigned CHRs and the number of QLC envelopes crossed. However, the qualitative analyses did not identify the extent of such an impact on the controllability classification methods, especially because the pilots occasionally adopted the same control strategy, but the methods classified the event differently for each of them (e.g., in Scenario 03 Task 5), possibly due to the interpretative possibilities of the Cooper-Harper scale, and the fact the manoeuvres typically brought the aircraft close to the edges of some QLC envelopes (UA and SI, especially). Consequently, slight differences in control actuation potentially led to more/fewer envelopes crossed, eventually changing the controllability classification even for a same control strategy.

The next section presents and discusses the results of quantitative association tests between variables derived from the approaches towards a deeper investigation on the correlation between the classification methods.

5.2 Correlation Tests

Correlation tests were conducted between the *controllability categories resulting from the CHRs* and the variables derived from the application of the parametric methodology on which the QLC is based. Table 12 shows the tests used for each correlation analysis, and Appendix D provides details about the selection of the tests and verification of their assumptions.

Since the simulations were performed for six pilots and each of them executed 26 tasks – data were not collected for two tasks performed by 'p04' –, the variables of interest were computed for 154 events, i.e., 154 data points were available for the correlation analyses of each pair of variables. However, certain parameters were occasionally treated as missing values – e.g., neither the critical window, nor high-order crossing intervals could be defined in manoeuvres in which only two QLC envelopes had been crossed. Tests could not be run for $mag(\beta_{neg})$, $mag(\theta_{pos})$, and $time(\alpha_{pos})$, since they resulted in a constant nought value in all simulations. Figure 49 displays the resulting correlation coefficients and $p - values$ for each pair of variables analysed.

Bearing in mind that correlation coefficients typically vary from -1 to $+1$, the following scale of strength was used in the results interpretation:[81]

- $]-0.1,+0.1[$: neutral correlation;
- $]-0.3,-0.1] \cup [+0.1,+0.3[$: weak correlation;
- $]-0.7,-0.3] \cup [+0.3,+0.7[$: moderate correlation; and
- $[-1.0,-0.7] \cup [+0.7,+1.0]$: strong correlation

Therefore, we conclude from Figure 49:

- 20 out of the 29 correlations ($\approx$ 69%) were *weak*;
- seven ($\approx$ 24%) were *neutral*;
- two ($\approx$ 7%) were *moderate*; and
- none was *strong*.

Below are the analyses of the results for each correlation pair tested.

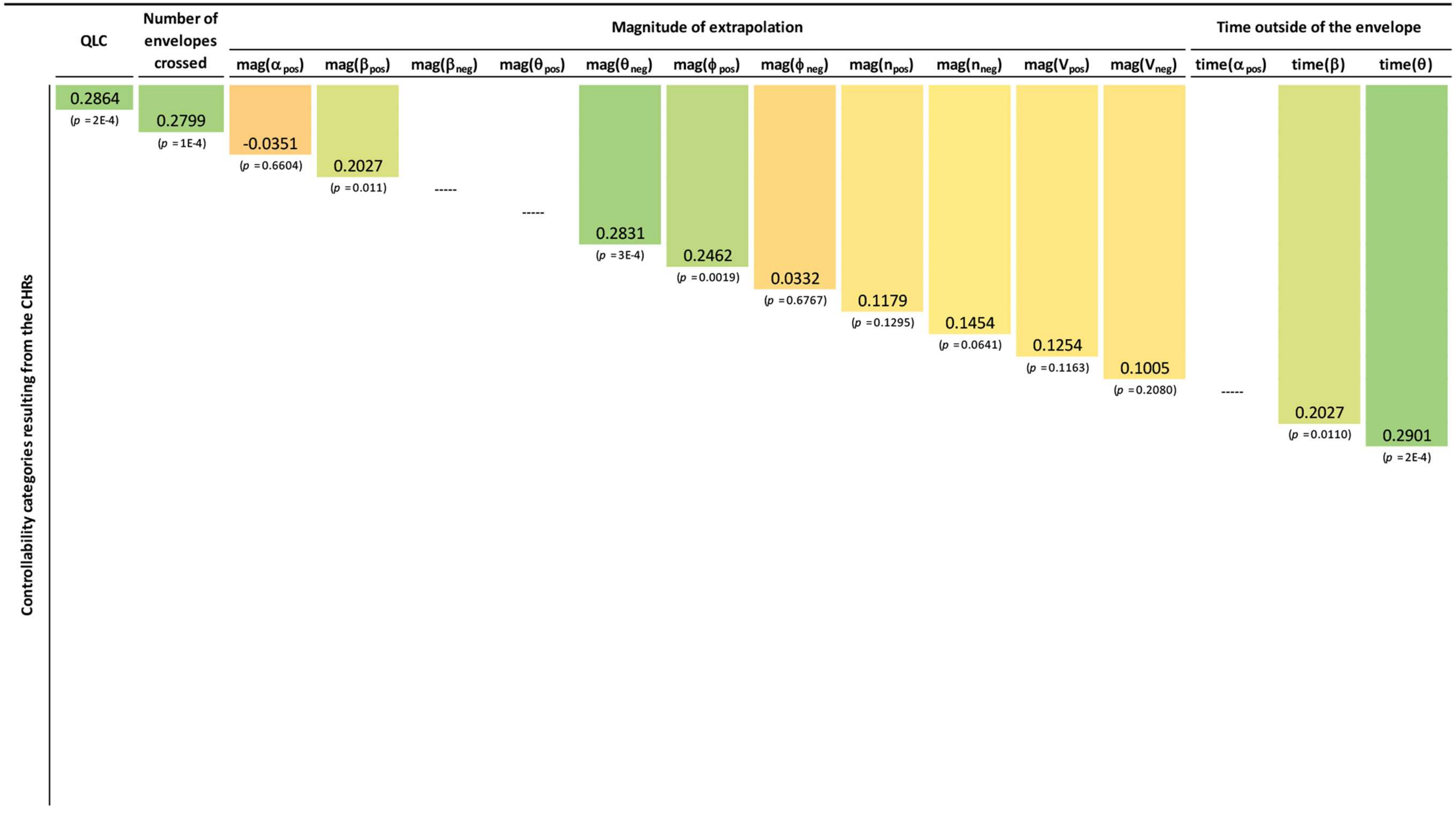

Figure 49: Correlation matrix of the results.
[Source: The author]

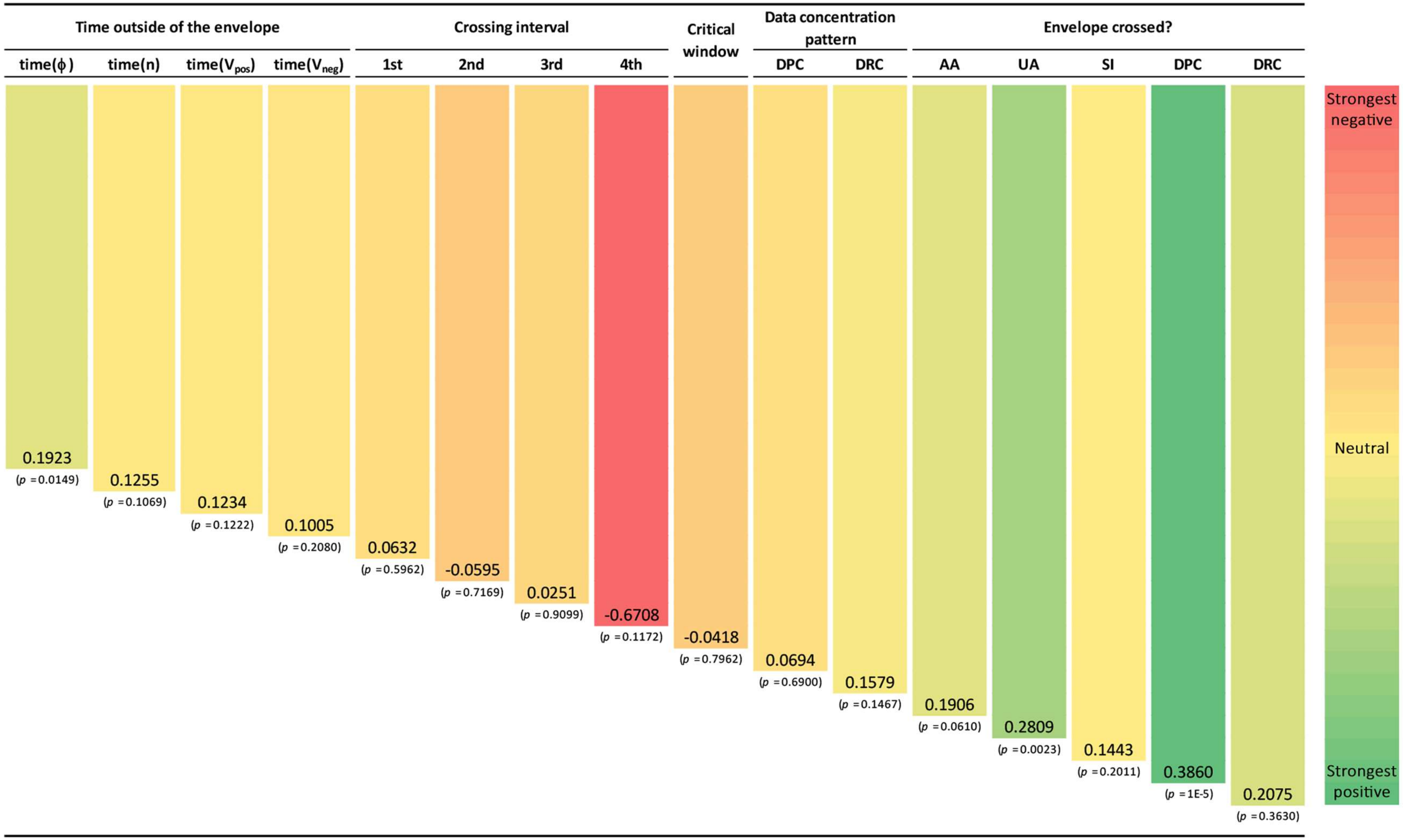

Figure 49: Correlation matrix of the results, Continued.
[Source: The author]

5.2.1 QLC

The correlation between the *controllability categories resulting from the CHRs* and the QLC (or, the *controllability categories resulting from the number of envelopes crossed*) yielded $\tau_b = 0.2864$ and $p = 2.1E - 4$, indicating a statistically significant *positive weak* association between them, i.e., statistical evidence for **accepting** our hypothesis of no clear correspondence between the way an event is classified as a LOC-I from the perspectives of pilots and the aircraft behaviour.

Table 13 shows the frequency distribution of the variables of interest (a contingency table), from which the following results are highlighted:

- events were observed in all controllability categories according to either method, and at least one was detected in all possible combinations of categories;
- most events for both the qualitative method (129 out of 154, or $\approx 84\%$) and quantitative approach (107, or $\approx 70\%$) were in the "normal" controllability category;
- both methods classified 21 events ($\approx 14\%$) as a "borderline LOC-I condition", but only four of them were simultaneously classified in such a category by both approaches;
- although "LOC-I" events were the least frequent (four occurrences, or $\approx 2.6\%$) for the qualitative scale, those in such a category were considerably more numerous (26 events, or $\approx 17\%$) for the QLC;
- the methods agreed on $97 + 4 + 2 = 103$ ($\approx 67\%$) occasions; however, such an agreement was concentrated on the "normal" category, which encompassed 97 ($\approx 94\%$) of such events; and
- the methods disagreed on $16 + 16 + 9 + 8 + 1 + 1 = 51$ ($\approx 33\%$) occasions, from which $16 + 16 + 8 = 40$ ($\approx 78\%$) events received a worse controllability classification from the quantitative method in comparison to the qualitative perspective.

Table 13: Controllability categories resulting from the classification methods.
[Source: The author]

		Controllability category according to the QLC			
		Normal condition (0 or 1 env. crossed)	**Borderline LOC-I condition** (2 env. crossed)	**LOC-I condition** (3 to 5 env. crossed)	**Total**
Controllability category resulting from the CHRs	**Normal condition** (CHR 1 to 7)	97	16	16	129
	Borderline LOC-I condition (CHR 8 to 9)	9	4	8	21
	LOC-I condition (CHR 10)	1	1	2	4
	Total	107	21	26	154

Although most of the events were similarly classified, the correlation coefficient between the controllability assessment methods was still weak, since, besides agreement, the Kendall's tau-b test also analyses the rank sequencing of the variables. When the equivalent pairs are too concentrated on a given category, the so-called "share of rank disarray" increases, thus weakening the correlation.[81] This concentration occurred in this study, since 94% of the concordant pairs were in the "normal condition" category, as shown in Table 13.

The result shows a weak association between the qualitative and the quantitative controllability assessment methods, as opposed to a result restricted to the association between them only in "LOC-I" circumstances. Although weak, an association exists; however, from the viewpoint of application of the methods aiming at a safer aviation, a stronger correlation is of greater interest.

5.2.2 Number of envelopes crossed

The correlation coefficient between the *controllability categories resulting from the CHRs* and *number of envelopes crossed* yielded $\tau_b = 0.2799$ and $p = 1.0E-4$, indicating a statistically significant *positive weak* correlation between the variables. Since its strength is very similar to that of the QLC (Section 5.2.1), although the result does not bring insights on our hypothesis, it corroborates the selection of the number of envelopes crossed made by Wilborn and Foster (2004)[37] for the definition of the controllability categories. Although the QLC classifies the controllability category of an event from the perspective of the aircraft behaviour based on a metric that has no physical meaning, the aforementioned authors properly determined the number of envelopes crossed that represents each controllability category.

5.2.3 Magnitude of excursion

Most $mag(\cdot)$ variables showed *positive weak* correlations with the *controllability categories resulting from the CHRs*; the strongest and statistically significant correlations were registered for $mag(\theta_{neg})$ – $\tau_b = 0.2831$, $p = 3.0E-4$ –, and $mag(\phi_{pos})$ – $\tau_b = 0.2462$, $p = 1.9E-3$.

The low statistical significance of $mag(\cdot)$ correlations is due to the limited number of occasions on which the variables assumed non-null values, i.e., their respective axes had been crossed (see Table 14). In fact, the constant nought value of $mag(\beta_{neg})$ and $mag(\theta_{pos})$ across the whole dataset hindered the application of tests for such variables.

It is hypothesised that $mag(\theta_{neg})$ and $mag(\phi_{pos})$ highlighted within the $mag(\cdot)$ group because they are related to the UA envelope, i.e., the QLC envelope whose parameters were directly associated with the task performance criteria and the most used by pilots to fly an aircraft.

The aircraft condition in the simulation scenarios is the reason for the discrepancy between the correlation coefficients of $mag(\phi_{pos})$ and $mag(\phi_{neg})$, i.e., in Scenarios 02, 03, and 04, engine 1 was usually more responsive than engine 2, meaning initiation of right-handed turns ($\phi > 0.0$) tended to be "more natural"; however, the aircraft also tended to go deeper into the turn. Consequently, crossing the positive bank angle limit (right-hand turn) was more frequent than exceeding the negative values (left-hand turn), although an equal number of tasks had been undertaken for either side. Possibly, β was extrapolated only for positive values due to the same reason. Still regarding the UA envelope, $mag(\theta_{pos})$ was probably never defined (i.e., in none of the events θ was greater than 25°) because pilots tended to be more cautious in pitch-up than in pitch-down manoeuvres due to stall.

Although the SI variables accounted for the greatest number of non-null values (especially the n parameters), none of their correlations was statistically significant; however, since all four correlation coefficients were in the ≈ 0.1 band, there is evidence the SI mag($\cdot$) variables indeed showed no appreciable association with the qualitative controllability assessment method.

Table 14: Magnitude of excursion – Number of non-null occurrences.
[Source: The author]

AA envelope		**UA envelope**		**SI envelope**	
Parameter	**Occurrences**	**Parameter**	**Occurrences**	**Parameter**	**Occurrences**
$mag(\alpha_{pos})$	1	$mag(\theta_{pos})$	0	$mag(n_{pos})$	18
$mag(\beta_{pos})$	3	$mag(\theta_{neg})$	11	$mag(n_{neg})$	12
$mag(\beta_{neg})$	0	$mag(\phi_{pos})$	7	$mag(V_{pos})$	2
		$mag(\phi_{neg})$	4	$mag(V_{neg})$	2

5.2.4 Time interval of excursion

The results for the $time(\cdot)$ family were very similar to those of the $mag(\cdot)$ group, since all correlations were in the *positive weak* band and UA-related variables excelled, especially in terms of statistical significance ($\tau_b = 0.2901$, $p = 2.0E-4$ for $time(\theta)$, and $\tau_b = 0.1923$, $p = 1.5E-2$ for $time(\phi)$).

Again, the relationship between the UA envelope and the PFD, as well as the number of non-null occurrences of the $time(\cdot)$ parameters – Table 15 – explain the results (e.g., $time(\alpha_{pos})$ could not be defined[iii]). Regarding the SI variables, similarly to the $mag(\cdot)$ case, the results were statistically non-significant and tended towards the neutrality band.

Table 15: Time interval of excursion – Number of non-null occurrences.
[Source: The author]

AA envelope		**UA envelope**		**SI envelope**	
Parameter	**Occurrences**	**Parameter**	**Occurrences**	**Parameter**	**Occurrences**
$time(\alpha_{pos})$	0	$time(\theta)$	11	$time(n)$	18
$time(\beta)$	3	$time(\phi)$	9	$time(V_{pos})$	2
				$time(V_{neg})$	2

5.2.5 Crossing intervals

Concerning the four crossing intervals, three correlation coefficients were in the *neutral* interval, whereas only one (to wit, the fourth interval) considerably diverged from the trend and

[iii] Despite a single occasion on which $\alpha_{norm} > +1.0$ (precisely when $mag(\alpha_{pos})$ was defined), the condition lasted less than 0.1 second, which is an interval shorter than the data collection frequency – 10 Hz –, and $time(\alpha_{pos})$ could not be computed

displayed a *negative moderate* correlation with the qualitative method. None of the results was statistically significant.

According to Table 16, as expected, the higher the order of the crossing interval, the smaller the number of valid data points (i.e., the greater the number of missing values), since "high-order" intervals depended on more envelopes to be crossed. Potentially, it is a reason for the discrepant results of the fourth interval, since it could be defined only on five occasions. Given the greater number of data points for testing the association of the other intervals and their neutral correlations, we can conclude the result for the fourth interval is an outlier, and the association between *crossing intervals* and *controllability categories resulting from the CHRs* is typically *neutral*.

Table 16: Crossing interval and Critical window – Number of valid ("non-missing") data points. [Source: The author]

Parameter		**Occurrences**
Crossing interval	**1st**	46
	2nd	25
	3rd	15
	4th	5
Critical window		26

5.2.6 Critical window

The *critical window* followed the same standard of the *crossing intervals*, since it displayed a statistically non-significant *neutral* association with the qualitative controllability assessment method[iv]. Somehow it corroborates the trend of neutrality of the time-dependent variables derived from the parametric methodology of the QLC.

Wilborn and Foster (2004, p.9)[37] defined the critical window to quantify "how long the crew had between the initial upset and the resulting loss of control to correct the situation". However, we cannot affirm the critical window indeed captured such information in this research for two main reasons: **(i)** the weak correlation between the *number of envelopes crossed* and *controllability categories resulting from the CHRs* enabled no conclusion that the *number of envelopes crossed* accounted for control degradation, and **(ii)** the experiments showed neither a clear initial upset, nor a specific moment at which the pilots reported to have lost control of the aircraft, which is partially due to the adoption of the long-look evaluation technique. Although "control degradation" is an important parameter to be tested against pilots' controllability perception, we cannot state the critical window represented it, which has led to an inconclusive result. Instead, we can only conclude the time between the crossings of the third and the first envelope neutrally correlates to the controllability categories resulting from the qualitative scale.

[iv] Table 16 shows both the critical window and the second crossing interval were defined on 26 and 25 occasions, respectively. Although an equal number of occurrences should be expected, the apparent error was caused by 'p05' crossing the AA and the DPC envelopes at the same instant of time in Task 6b from Scenario 03

5.2.7 Data concentration patterns

The data concentration patterns of both DPC and DRC showed statistically non-significant correlations with the qualitative approach – the former displayed a *neutral* association, and the latter showed a *weak* correlation.

According to Table 17, the data were typically concentrated on the squared quadrants on most occasions, from which we can infer there were no significant oppositions between pilot control inputs and the aircraft dynamic behaviour for most manoeuvres, especially regarding the pitch attitude.

The lack of statistical significance of the results is probably a consequence of such an uneven distribution of data across the types of quadrants. However, the data most frequently concentrated on tapered quadrants of the corresponding envelope when the pilots reported tendencies for a longitudinal/lateral PIO (pilots' comments and the data concentration pattern showed an agreement in $\approx 55\%$ of the longitudinal events – DPC – and $\approx 62\%$ for the lateral events – DRC). Although the *data concentration patterns* provides no relevant information for broadening our comprehension on the way quantitative metrics relate to pilots' controllability perception, it can be very useful for the study of PIO events, since a clear distinction on how data are distributed in DPC and DRC was observed when pilots have reported PIO tendencies.

Table 17: Number of occurrences in which data concentrated on squared and tapered quadrants. [Source: The author]

	QLC envelope	
Type of Quadrant	**DPC**	**DRC**
Squared	131	107
Tapered	23	47

5.2.8 Envelope crossed

The crossing of four out of five envelopes showed a *positive weak* correlation with the qualitative assessment method, and one (to wit, *crossing the DPC*) displayed a *positive moderate* correlation. The only statistically significant results in the *envelope crossed* family were achieved for the crossings of UA ($\phi_c = 0.2809$ and $p - value = 2.3E - 3$) and DPC ($\phi_c = 0.3860$ and $p - value = 1.0E - 5$), although such envelopes had been extrapolated in the experiments on relatively few occasions, as shown in Table 18.

As addressed elsewhere, the data plotted in the UA envelope are directly related to the parameters most used by the pilots to control an aircraft; therefore, a significant result was expected in that regard. Additionally, both strength (weak) and direction (positive) of the correlation of *crossing the UA* corroborate the results obtained for other UA-related parameters (e.g., $mag(\theta_{neg})$, $mag(\phi_{pos})$, $time(\theta)$, and $time(\phi)$), and provide evidence that, in general, variables linked to the UA envelope display a positive weak correlation with the way pilots perceive the controllability of an aircraft. Although variables related to the AA and SI envelopes also generally showed positive weak correlation coefficients, the same conclusion cannot be drawn for them, since the statistically significant results concentrated on parameters linked to the UA envelope.

Crossing the DPC was the only parameter with a moderate statistically significant correlation with the qualitative assessment method; therefore, we can infer pilots' controllability perception is more strongly related to the existence or not of consistency between their longitudinal inputs and the dynamic behaviour of the aircraft (as detailed in Section 3.2, crossing the boundaries of the DPC means the control inputs disagree with the aircraft's motion tendency). Moreover, in $\approx 47\%$ of the occasions on which the DPC was crossed, the extrapolation occurred while pilots were providing pitch-up inputs and the aircraft displayed a pitch-down attitude.

Crossing the DRC (another "control envelope") showed a weak non-significant correlation result, although the DRC had been crossed twice as many times than the DPC (Table 18), and a greater number of more laterally demanding tasks was performed in the research in comparison to those more longitudinally demanding (12 and seven, respectively). The result corroborates the relevance of the control condition on the longitudinal axis (rather than on the lateral one) for pilots' controllability assessment.

Table 18: Envelope crossed – Number of valid ("non-missing") data points.
[Source: The author]

Parameter		**Occurrences**
QLC Envelope	**AA**	39
	UA	18
	SI	20
	DPC	36
Critical window	**DRC**	70

5.3 Final Discussion

The proposed methodology enabled the achievement of the objectives of the research, since the control strategies adopted by the pilots in different simulation scenarios/tasks and their impact on the controllability assessment methods, as well as the quantitative variables more directly related to the way pilots perceive the controllability of an aircraft were identified. However, most tested correlations showed no statistical significance and were in the *positive weak* band. It is hypothesised that such characteristics are due to the low variability of the controllability category classification, especially from the qualitative approach, as shown in Table 13. Several factors contributed to the reduced variability, hence, to the overall results of this research, and are explored in the sequence.

Regarding the qualitative approach

I. The massive efforts devoted to a common understanding for all pilots of the wording used by the Cooper-Harper scale succeeded, since no misinterpretations were identified in the experiments. However, the subjectivity of the scale, which could (and should) not be completely eliminated, was a dominant factor on the crucial decisions that positioned the CHRs on the controllability categories, i.e., on the answers to the questions *"Is it controllable?"* and *"Is the workload tolerable?"*;

II. Although the ratings of the Cooper-Harper scale can be rearranged into controllability categories, such a rearrangement produced a massive disproportion in the number of CHRs representative of each category, i.e., seven for the "normal" condition, two for the "borderline LOC-I", and one for the "LOC-I", which also contributed to the non-normal distribution of the controllability categories, since much more "normal controllability" ratings were available;

III. Both handling qualities and control of an aircraft are known to change over time, i.e., they can improve/degrade, as opposed to simply being "good"/"bad". The original proposition of the Cooper-Harper scale provided pilots with ten ratings to translate their opinion on the handling qualities; however, its rearrangement offered only three categories to represent their understanding of the controllability of an aircraft. Consequently, the rearrangement of the CHRs enabled no capture of nuances of controllability, suggesting it is much more like a "discrete" than a "continuous" variable. Such a "rigidity" introduced a non-linearity/discontinuity to the rearranged scale, contributing to the uneven distribution of the controllability categories resulting from the experiments;

IV. Most tasks performed were more demanding either on the longitudinal, or lateral axis; however, the CHR assigned at the end of each manoeuvre assessed the "overall" controllability of the aircraft, i.e., it did not represent any axis. Hodgkinson (1999)[54] suggested separately assessing and assigning independent ratings for each axis. Adopting such a strategy could have resulted in a more detailed reading of the pilots' perception and expanded the dataset; however, it would also have required specific training for the participating pilots, since they were not used to evaluating the aircraft condition in such a way. Axis-specific CHRs may have resulted in a more even distribution of the controllability category data, probably increasing the statistical significance of the correlation tests;

V. As explained in Section 3.3, the pilots evaluated their degree of compensation during the handling qualities/controllability assessment process in function of several variables, among which sensation of motion and feedback provided by the controls. The limitations of the EB#2 research simulator possibly softened the dynamic characteristics of the aircraft, and consequently misled pilots in their evaluation, thus culminating in the assignment of CHRs that tended towards the "normal controllability category". Although the pilots did not frequently complain about the simulator during the experiments, the saturation limits that impeded the platform from moving beyond 15° in pitch and roll and the lack of control force feedback significantly reduced their sensation of control effort, contributing to the inequality of controllability data distribution. Such concerns are not unique to EB#2, but also to flight simulators used for real pilot training, and have led aviation authorities to mandate improvements in motion emulation in simulators towards making them more realistic.[24,82]

Regarding the quantitative approach

I. The definition of the borderlines of the QLC envelopes was based on a fully operational aircraft, whilst the experiments were performed for LOC-I test scenarios, i.e., conditions under which the aircraft was faulty (e.g., in Scenario 02, the effectiveness of the elevator was 25% of that of a fully operational aircraft). Consequently, the envelopes were not representative of the condition of the simulation aircraft models, and were always too permissible, reducing the chances of crossing the envelopes. Ultimately, the QLC tended to classify an event as of "normal controllability", since a few envelopes were typically crossed, which also reduced the variability of the parameters derived from the parametric methodology (e.g., $mag(\alpha_{pos})$ was different from zero on only one occasion);

II. Tasks connected to real-life were simulated for evaluations of the controllability condition of the aircraft. Real-life manoeuvres take advantage of safety margins, and, although relatively tight performance limits were used in the experiments, such margins were typically consumed in the simulated tasks (this is the reason for safety margins, i.e., they hinder the extrapolation of industry-accepted limits). Consequently, the aircraft tended to remain inside the QLC envelopes, contributing to the concentration of the quantitative controllability data around the "normal" condition;

III. Due to the lack of specific literature on a methodology that defines task performance parameters and their tolerances, the same performance criteria were used for all simulation scenarios, despite their theoretically different levels of difficulty. Although such an alternative was also used by other authors (e.g., Samili et al. (2017)[35] and Lombaerts et al. (2009)[77]), it is hypothesised that scenario-specific performance criteria would have provided a more even level of difficulty for tasks performed under different aircraft conditions and potentially resulted in more events classified in controllability categories other than "normal";

IV. Still regarding performance criteria, from a safety perspective, we could not accept the "adequate" level of performance was achieved in situations such as stall, overspeed, or entry in unusual attitudes. Moreover, it was mandatory to display the parameters that defined the criteria for the pilots, so that they could adapt their control actions. Given such restrictions, the tasks were inevitably linked to certain parameters directly observed by the QLC (e.g., pitch and roll angles, and airspeed), and the crossing of at least two envelopes (to wit, UA and SI – Table 16 shows the smallest number of crossings was registered for such envelopes) was hampered by the task design process. Ultimately, the performance criteria also contributed to reducing the number of QLC envelopes crossed, and the variability of both controllability classification and parameters derived from the envelopes.

CONCLUSIONS & FUTURE WORK

6 CONCLUDING REMARKS AND FUTURE RESEARCH

This research aimed at the obtaining of insights into the existence and extent of an association between qualitative and quantitative controllability assessment methods by answering some key research questions (RQ), addressed in the sequence. However, the conclusions are always partial, since they refer to the very specific conditions of the research (aircraft model, simulation scenarios, tasks, pilots, simulator etc.), and there is always room for further developments.

6.1 Conclusions on the Research Questions

RQ 1. ***Could we find a reliable qualitative controllability assessment method?***

Section 3.3.1 explored a new interpretation of the CHRs based on the wording of the Cooper-Harper scale, and the ratings, which originally addressed handling qualities traits, were reorganised into controllability categories. Despite the subjectivity of the scale and its limitations of use, the parameters related to the use of the controls ($RMS_{control}$ and $RMS_{control_{rate}}$) and the pilots' comments (presented and discussed in Section 5.1) confirmed the proposed re-interpretation of the CHRs can reliably address pilots' understandings of the controllability of an aircraft.

Recommendations

- If the Cooper-Harper scale is employed in other studies on controllability, statistical means must be found so that the disproportion of ratings in each controllability category resulting from the re-interpretation of the scale can be addressed and its effects can be reduced;
- Still in case the Cooper-Harper scale is used in future research, tasks should be designed in a way their performance criteria are not directly related to the airspeed and aircraft orientation parameters. A suggestion is to undertake tasks such as a landing approach, in either visual or instrument condition, and take parameters such as PAPI or ILS indicators as performance criteria. This way, pilots would have more freedom to develop their control strategies and be less limited by parameters directly affected by the use of the controls;
- Although handling qualities and controllability are related, the Cooper-Harper scale assesses the former, whereas this research was focused on the latter. Therefore, another recommendation is to design a controllability-focused scale, which should also mitigate the aforementioned disproportion of ratings; and
- The "new" scale should also provide more openings than the Cooper-Harper scale in terms of its application, especially regarding the necessity of the definition of task performance criteria.

RQ 2. ***Can we accept and use the only current quantitative controllability assessment method?***

In the study that defined the QLC, Wilborn and Foster (2004)[37] suggested a lack of evidence on the number of envelopes crossed that should define the controllability categories, e.g., a lack of consensus on whether the "LOC-I" category should be better represented by the crossing of three or four envelopes. However, the similarity and statistical significance of the resulting correlation coefficients of both *QLC* and *number of envelopes crossed* (Figure 49) led to our acceptance of the controllability classification proposal of the aforementioned authors, i.e., a "normal" controllability condition is represented by zero or one envelope crossed, a "borderline LOC-I" is characterised when two envelopes are extrapolated, and a "LOC-I" is denoted by three or more QLC envelopes crossed.

Recommendations

- More studies should be conducted for identifying whether such a finding can be extended to other conditions, especially regarding tasks, since they were very specific in this research and, in most cases, their performance criteria were directly related to some parameters of the QLC envelopes (notably, UA and SI); and
- Since the *number of envelopes crossed* is not directly related to the motion of an aircraft, its possible association with the dynamic behaviour of the vehicle, as well as the inclusion of additional envelopes to the quantitative criteria should be investigated (e.g., none of the QLC envelopes considers the use of the engines, and Section 5.1 addressed the way different uses of such controls changed the aircraft behaviour). The correlation tests conducted provided glimpses of a possible inclusion of new envelopes to the quantitative criterion; however, no conclusion could be drawn.

RQ 3. ***How are the controllability assessment methods related?***

Section 5.1 was devoted to a qualitative discussion on the impact of the control strategies on both pilots' perception of the controllability of an aircraft and number of QLC envelopes crossed; however, only by the correlation tests (Section 5.2) we could state there is a positive weak association between the controllability categories resulting from the application of the Cooper-Harper scale and the QLC.

Since both the re-interpretation of the CHRs and the controllability categories criterion suggested by Wilborn and Foster (2004)[37] have been "validated", the result of the weak correlation led to the acceptance of our hypothesis of no clear correspondence between the controllability classification of an event from the perspective of pilots and the dynamic behaviour of an aircraft (Section 1.3).

Recommendations

- Apart from the recommendations related to the qualitative scale (addressed elsewhere), regarding the quantitative method, future research should investigate the impact of the aircraft condition on the boundaries of the QLC envelopes so that they can be redesigned to more realistically representing the actual condition of the vehicle; and
- Future studies with methodologies similar to the one adopted in this project should try and find ways to "disconnect" the application of the qualitative and quantitative methods, since they could not be independently applied in this research due to reasons discussed elsewhere (e.g., the connection between performance criteria and parameters of the UA and SI envelopes).

RQ 4. ***Can other parameters provide further insights into the association between the methods?***

Similarly to the QLC, most of the parameters derived from the methodology on which it is based revealed a positive weak correlation with pilots' opinion. Despite a considerable number of parameters with similar results, the low statistical significance of most of them showed the results were largely influenced by the several occasions on which the derived parameters could not be defined.

Nonetheless, a statistically significant positive moderate correlation was identified for the *crossing the DPC* variable. Such a result showed pilots' controllability perception is more strongly associated with events on the longitudinal axis (rather than on the lateral or directional axes), and with the way their control inputs "talk" to the motion of the aircraft, since the DPC is the envelope that represents the trade-off between pilot pitch inputs and the longitudinal dynamic behaviour of the vehicle.

Recommendations

- The generally low statistical significance of the results reinforces **(i)** the need for future studies on the redefinition of the QLC envelopes, since more realistic boundaries should lead to more occasions on which the envelopes are crossed, consequently increasing the variability of the parameters derived from the QLC, and the statistical significance of their correlation tests; and **(ii)** the definition of tasks not directly related to the parameters of the QLC;
- Other researchers are also encouraged to derive additional parameters from the parametric methodology, especially related to the DPC. A possibility is to examine variables of time and magnitude of extrapolation of such an envelope, since they are physically more meaningful than the crossing of the envelope, and can potentially establish stronger associations with the qualitative assessment method; and
- Given the evident possibilities of using unmanned vehicles in the future, the determination of stronger connections between the controllability assessment methods becomes even more relevant, enabling, for example, the training of quantitative artificial neural networks based

on the qualitative assessment, so that the networks can be embedded in such vehicles, allowing them to "humanly" assessing their controllability conditions in real-time. Such possibilities should also be investigated.

6.2 Recommendations for the EB#2 Flight Simulator

Concerning EB#2, some suggestions for future studies include:

- installation of a control force feedback system for the sidestick and rudder pedals, since it can considerably increase the realism of the simulator, and also because the control feedback feeling is crucial for the piloting action;
- re-calibration of motion saturation limits so that the simulator can reach greater attitude angles and/or accelerations, and mitigate the "softened dynamics" issues faced in this research;
- increase in the trustworthiness of the aircraft simulation models available in EB#2 in high-angle attitudes, since such attitudes are remarkable in upset conditions;
- enhancement of avionics systems for simulations of "automation surprises", since such a precursor has become increasingly frequent in several aviation incidents/accidents (not only LOC-I); and
- transformation of EB#2 into a two-pilot simulator towards broadening its research uses and enhancing its realism, since every commercial flight deck has two pilots, and team decisions are made in safety-threatening events. A two-pilot simulator would also enable investigations on other Human Factor-related topics, e.g., efficiency of new procedures in dealing with startle and surprise events.

6.3 Key Points

Accidents, unfortunately, will never cease to occur. The search for increased flight safety and, especially in the context of this research, mitigation of LOC-I accidents, are daily tasks for those involved in the aerial activity and certainly do not end with this study.

Below are the key contributions of this research to society towards a better understanding of the LOC-I phenomenon:

- Validation of the use of methods, which are sufficient, although not optimised, for the observation of the LOC-I phenomenon from the perspectives of its two main participants;
- Evidences that the understanding of the LOC-I phenomenon from the perspectives of human pilots and aircraft behaviour is dissimilar; therefore, the results indicate the design and evaluation of "solutions" for LOC-I must be assessed from both perspectives, as opposed to the current standard practices; and
- A direction on the translation of pilots' perception of controllability into quantitative variables towards the optimisation of controllability assessment methods, regardless of their qualitative or quantitative focus.

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APPENDIXES

APPENDIX A – *NORMAL* AND *ICING* FLIGHTGEAR BOEING 777 MODEL CONFIGURATION FILES

Some parameters of the normal Boeing 777 .XML YASim FlightGear configuration file were modified to conceiving the "icing" aircraft dynamic model. The changes were made towards an aircraft presenting: **(i)** sooner and more abrupt stalls of the wings and horizontal stabiliser; **(ii)** less effective ailerons and elevator, i.e., less lift and more drag increments produced by deflections in comparison to the usual condition; and **(iii)** slower and less powerful engine 2 in comparison to engine 1. The modifications are detailed in what follows and more information on parameters of the .XML YASim dynamic model configuration file can be found on YASim webpage.[83]

Regarding item **(i)**, *<wing> and <hstab> <stall aoa, width and peak>* parameters were changed in a way the angle of attack of the maximum lift coefficient was reduced by approximately 25% and the aggressiveness of the stall was increased by approximately 40%.

Relatively to item **(ii)**, the lift increment produced by the deflection of the ailerons was reduced by 20% by altering the *<wing> <flap1 lift>* parameter, whereas the drag increment was augmented by 40% by the modification of the *<wing> <flap1 drag>* variable. The same idea was applied for the corresponding parameters in the *<hstab> <flap0>* section, i.e., the lift increment caused by the elevator deflection was reduced by 15%, whereas the drag increment was augmented by 40%.

Concerning item **(iii)**, the *<thrust> and <spool-time>* parameters in the *<jet>* section relative to engine 2 were altered to reducing the maximum available thrust by 43% and multiplying the spool-time by five. Since the other parameters also changed in the *<jet>* section (to wit: *<egt>*, *<n1-idle>*, *<n1-max>*, *<n2-idle>*, and *<n2-max>*) had no physical significance for FlightGear, they did not impact the aircraft dynamic model and were altered for instrument indication purposes so that pilots were displayed with a fair and consistent indication.

Below is a comparison between the "normal" and "icing" aircraft dynamic files used in the research. Changes are highlighted in grey.

NORMAL MODEL

```xml
<airplane mass="315000" version="YASIM_VERSION_32">
    <!-- NORMAL MODEL -->

  <!-- Approach configuration -->
  <approach speed="132" alt="0.0" aoa="5.0" fuel=
  "0.2" glide-angle="0.0">
      <control-setting axis=
      "/controls/engines/engine[0]/throttle-act"
      value="0.25"></control-setting>
      <control-setting axis=
      "/controls/engines/engine[1]/throttle-act"
      value="0.25"></control-setting>
      <control-setting axis=
      "/controls/flight/flaps" value="1"
      ></control-setting>
      <control-setting axis=
      "/surface-positions/slats" value="1"
      ></control-setting>
      <control-setting axis=
      "/controls/gear/gear-down" value="1"
      ></control-setting>
      <solve-weight idx="0" weight="360"
      ></solve-weight>
      <solve-weight idx="1" weight="42072"
      ></solve-weight>
  </approach>
```

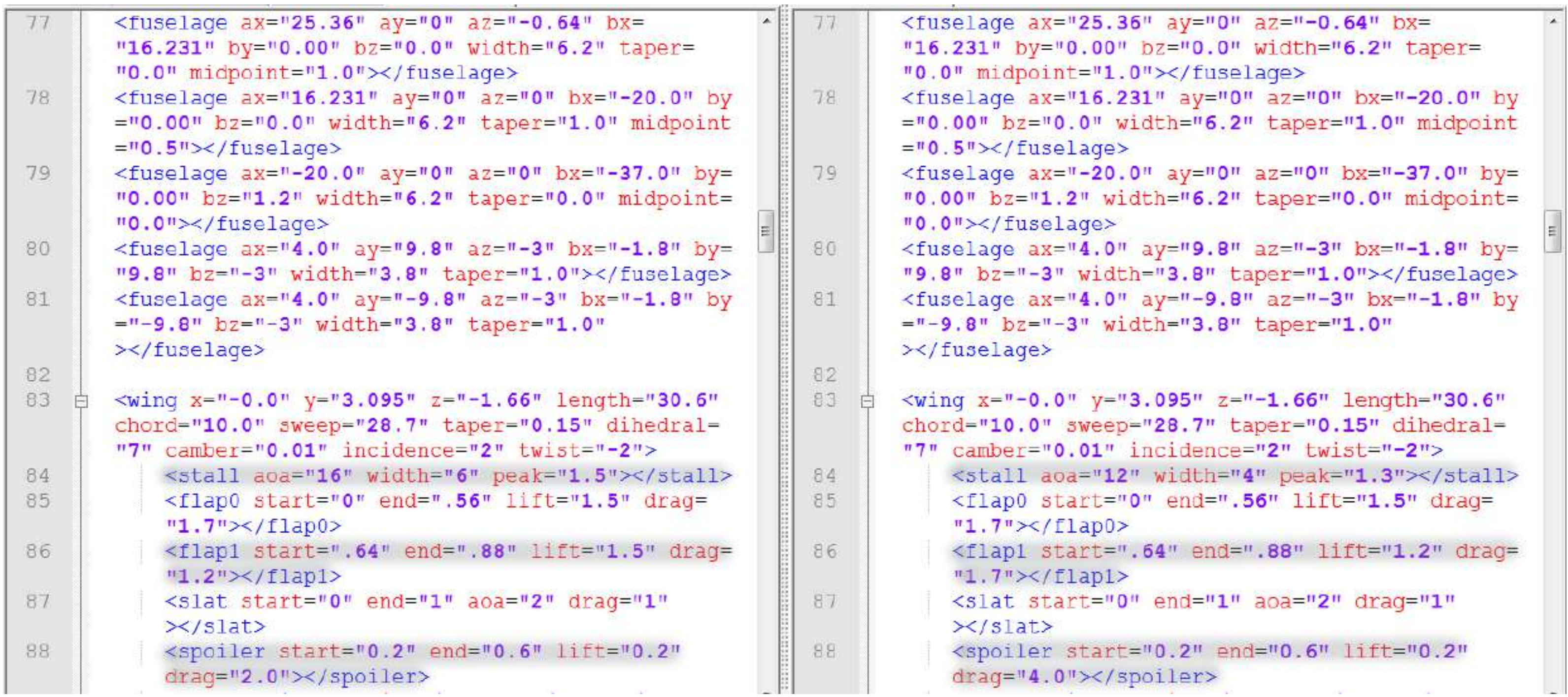
ICING MODEL

```xml
<airplane mass="315000" version="YASIM_VERSION_32">
    <!-- ICING MODEL -->

  <!-- Approach configuration -->
  <approach speed="132" alt="0.0" aoa="5.0" fuel=
  "0.2" glide-angle="0.0">
      <control-setting axis=
      "/controls/engines/engine[0]/throttle-act"
      value="0.25"></control-setting>
      <control-setting axis=
      "/controls/engines/engine[1]/throttle-act"
      value="0.25"></control-setting>
      <control-setting axis=
      "/controls/flight/flaps" value="1"
      ></control-setting>
      <control-setting axis=
      "/surface-positions/slats" value="1"
      ></control-setting>
      <control-setting axis=
      "/controls/gear/gear-down" value="1"
      ></control-setting>
      <solve-weight idx="0" weight="360"
      ></solve-weight>
      <solve-weight idx="1" weight="42072"
      ></solve-weight>
  </approach>
```

```xml
<!-- Cruise configuration -->
<cruise speed="512" alt="35000" fuel="0.8"
glide-angle="0.0">
    <control-setting axis=
    "/controls/engines/engine[0]/throttle-act"
    value="0.95"></control-setting>
    <control-setting axis=
    "/controls/engines/engine[1]/throttle-act"
    value="0.95"></control-setting>
    <control-setting axis=
    "/controls/flight/flaps" value="0.0"
    ></control-setting>
    <control-setting axis=
    "/controls/flight/elevator-trim" value="0"
    ></control-setting>
    <control-setting axis=
    "/controls/gear/gear-down" value="0"
    ></control-setting>
    <solve-weight idx="0" weight="360"
    ></solve-weight>
    <solve-weight idx="1" weight="42072"
    ></solve-weight>
</cruise>

<cockpit x="22.8" y="0.5" z="0.75"></cockpit>
```


```xml
<!-- Cruise configuration -->
<cruise speed="512" alt="35000" fuel="0.8"
glide-angle="0.0">
    <control-setting axis=
    "/controls/engines/engine[0]/throttle-act"
    value="0.95"></control-setting>
    <control-setting axis=
    "/controls/engines/engine[1]/throttle-act"
    value="0.95"></control-setting>
    <control-setting axis=
    "/controls/flight/flaps" value="0.0"
    ></control-setting>
    <control-setting axis=
    "/controls/flight/elevator-trim" value="0"
    ></control-setting>
    <control-setting axis=
    "/controls/gear/gear-down" value="0"
    ></control-setting>
    <solve-weight idx="0" weight="360"
    ></solve-weight>
    <solve-weight idx="1" weight="42072"
    ></solve-weight>
</cruise>

<cockpit x="22.8" y="0.5" z="0.75"></cockpit>
```


<fuselage ax="25.36" ay="0" az="-0.64" bx=
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"9.8" bz="-3" width="3.8" taper="1.0"></fuselage>
<fuselage ax="4.0" ay="-9.8" az="-3" bx="-1.8" by
="-9.8" bz="-3" width="3.8" taper="1.0"
></fuselage>
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chord="10.0" sweep="28.7" taper="0.15" dihedral=
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"1.7"></flap0>
<flap1 start=".64" end=".88" lift="1.5" drag=
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></slat>
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drag="2.0"></spoiler>
<fuselage ax="25.36" ay="0" az="-0.64" bx=
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="-9.8" bz="-3" width="3.8" taper="1.0"
></fuselage>
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<flap1 start=".64" end=".88" lift="1.2" drag=
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></slat>
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"1.0"></control-input>
<control-output control="SLAT" prop=
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transition-time="78"></control-speed>
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transition-time="2"></control-speed>
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split="true"></control-input>
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```


```
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control="FLAP0"></control-input>
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```

```
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></control-output>
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prop=
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></control-output>
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  "/controls/flight/elevator-trim" control=
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  "FLAP0"></control-input>
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```

```xml
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  ></flap0>
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  control="FLAP0" invert="true"></control-input>
  <control-input axis=
  "/controls/flight/rudder-trim" control="FLAP0"
  invert="true"></control-input>
  <control-output control="FLAP0" prop=
  "/surface-positions/rudder-pos-norm" min="1"
  max="-1"></control-output>
</vstab>

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thrust="93400" spool-time="3" egt="840" tsfc=
"0.34 " epr="40" n1-idle="18.5" n1-max="110.5"
n2-idle="70" n2-max="107" reverse="0.4">
  <control-input axis=
  "/controls/engines/engine[0]/throttle-act"
  control="THROTTLE"></control-input>
  <control-input axis=
  "/controls/engines/engine[0]/reverser-act"
  control="REVERSE_THRUST"></control-input>
```


```xml
<vstab x="-30.0" y="0.00" z="2.7" chord="8.0"
length="12.2" taper="0.3" sweep="33">
  <stall aoa="14" width="5" peak="1.5"></stall>
  <flap0 start="0" end="1" lift="1.4" drag="1.2"
  ></flap0>
  <control-input axis="/controls/flight/rudder"
  control="FLAP0" invert="true"></control-input>
  <control-input axis=
  "/controls/flight/rudder-trim" control="FLAP0"
  invert="true"></control-input>
  <control-output control="FLAP0" prop=
  "/surface-positions/rudder-pos-norm" min="1"
  max="-1"></control-output>
</vstab>

<jet x="1.16" y="9.89" z="-2.995" mass="17000"
thrust="93400" spool-time="3" egt="840" tsfc=
"0.34 " epr="40" n1-idle="18.5" n1-max="110.5"
n2-idle="70" n2-max="107" reverse="0.4">
  <control-input axis=
  "/controls/engines/engine[0]/throttle-act"
  control="THROTTLE"></control-input>
  <control-input axis=
  "/controls/engines/engine[0]/reverser-act"
  control="REVERSE_THRUST"></control-input>
```

```xml
    <control-output control="REVERSE_THRUST" prop=
    "/surface-positions/reverser-norm[0]"
    ></control-output>
    <control-speed control="REVERSE_THRUST"
    transition-time="3"></control-speed>
    <actionpt x="-2.7" y="9.89" z="-2.995"
    ></actionpt>
  </jet>

  <jet x="1.16" y="-9.89" z="-2.995" mass="17000"
  thrust="93400" spool-time="3" egt="840" tsfc=
  "0.34" epr="40" n1-idle="18.5" n1-max="110.5"
  n2-idle="70" n2-max="107" reverse="0.4">
    <control-input axis=
    "/controls/engines/engine[1]/throttle-act"
    control="THROTTLE"></control-input>
    <control-input axis=
    "/controls/engines/engine[1]/reverser-act"
    control="REVERSE_THRUST"></control-input>
    <control-output control="REVERSE_THRUST" prop=
    "/surface-positions/reverser-norm[1]"
    ></control-output>
    <control-speed control="REVERSE_THRUST"
    transition-time="3"></control-speed>
    <actionpt x="-2.7" y="-9.89" z="-2.995"
    ></actionpt>
  </jet>
```

```xml
    <control-output control="REVERSE_THRUST" prop=
    "/surface-positions/reverser-norm[0]"
    ></control-output>
    <control-speed control="REVERSE_THRUST"
    transition-time="3"></control-speed>
    <actionpt x="-2.7" y="9.89" z="-2.995"
    ></actionpt>
  </jet>

  <jet x="1.16" y="-9.89" z="-2.995" mass="17000"
  thrust="53400" spool-time="15" egt="570" tsfc=
  "0.34" epr="40" n1-idle="12.5" n1-max="75.0"
  n2-idle="47.5" n2-max="72.6" reverse="0.4">
    <control-input axis=
    "/controls/engines/engine[1]/throttle-act"
    control="THROTTLE"></control-input>
    <control-input axis=
    "/controls/engines/engine[1]/reverser-act"
    control="REVERSE_THRUST"></control-input>
    <control-output control="REVERSE_THRUST" prop=
    "/surface-positions/reverser-norm[1]"
    ></control-output>
    <control-speed control="REVERSE_THRUST"
    transition-time="3"></control-speed>
    <actionpt x="-2.7" y="-9.89" z="-2.995"
    ></actionpt>
  </jet>
```

```xml
<!-- nose -->
<gear x="19.28" y="0.00" z="-5.55" compression=
"0.7" spring="1.2" damp="1" sfric="1.5" dfric=
"1.0">
  <!-- up to 70 degrees max steering angle with
  tiller, input is limited to 7 degrees with
  rudder (see Nasal/ground_steering.nas) -->
  <control-input control="STEER" axis=
  "/controls/gear/nosegear-steering-cmd-norm"
  src0="-1.0" dst0="-1.2217304764" src1="1.0"
  dst1="1.2217304764"></control-input>
  <control-output control="STEER" prop=
  "/controls/gear/nosegear-steering-angle-rad"
  ></control-output>
  <control-input axis="/controls/gear/gear-down"
  control="EXTEND"></control-input>
  <control-output control="EXTEND" prop=
  "/gear/gear[0]/position-norm"></control-output>
  <control-speed control="EXTEND" transition-time
  ="19"></control-speed>
</gear>

<gear x="-6.39" y="5.6" z="-5.7" compression=
"0.8" spring="1.0" sfric="1" dfric="0.9">
  <control-input axis=
  "/autopilot/autobrake/left-brake-output"
  control="BRAKE"></control-input>
```


```xml
<!-- nose -->
<gear x="19.28" y="0.00" z="-5.55" compression=
"0.7" spring="1.2" damp="1" sfric="1.5" dfric=
"1.0">
  <!-- up to 70 degrees max steering angle with
  tiller, input is limited to 7 degrees with
  rudder (see Nasal/ground_steering.nas) -->
  <control-input control="STEER" axis=
  "/controls/gear/nosegear-steering-cmd-norm"
  src0="-1.0" dst0="-1.2217304764" src1="1.0"
  dst1="1.2217304764"></control-input>
  <control-output control="STEER" prop=
  "/controls/gear/nosegear-steering-angle-rad"
  ></control-output>
  <control-input axis="/controls/gear/gear-down"
  control="EXTEND"></control-input>
  <control-output control="EXTEND" prop=
  "/gear/gear[0]/position-norm"></control-output>
  <control-speed control="EXTEND" transition-time
  ="19"></control-speed>
</gear>

<gear x="-6.39" y="5.6" z="-5.7" compression=
"0.8" spring="1.0" sfric="1" dfric="0.9">
  <control-input axis=
  "/autopilot/autobrake/left-brake-output"
  control="BRAKE"></control-input>
```

```
    <control-input axis=
    "/controls/gear/brake-parking" control="BRAKE"
    ></control-input>
    <control-input axis="/controls/gear/gear-down"
    control="EXTEND"></control-input>
    <control-output control="EXTEND" prop=
    "/gear/gear[1]/position-norm"></control-output>
    <control-speed control="EXTEND" transition-time
    ="20"></control-speed>
  </gear>

  <gear x="-6.39" y="-5.6" z="-5.7" compression=
  "0.8" spring="1.0" sfric="1" dfric="0.9">
    <control-input axis=
    "/autopilot/autobrake/right-brake-output"
    control="BRAKE"></control-input>
    <control-input axis=
    "/controls/gear/brake-parking" control="BRAKE"
    ></control-input>
    <control-input axis="/controls/gear/gear-down"
    control="EXTEND"></control-input>
    <control-output control="EXTEND" prop=
    "/gear/gear[2]/position-norm"></control-output>
    <control-speed control="EXTEND" transition-time
    ="20"></control-speed>
  </gear>
```


```
    <control-input axis=
    "/controls/gear/brake-parking" control="BRAKE"
    ></control-input>
    <control-input axis="/controls/gear/gear-down"
    control="EXTEND"></control-input>
    <control-output control="EXTEND" prop=
    "/gear/gear[1]/position-norm"></control-output>
    <control-speed control="EXTEND" transition-time
    ="20"></control-speed>
  </gear>

  <gear x="-6.39" y="-5.6" z="-5.7" compression=
  "0.8" spring="1.0" sfric="1" dfric="0.9">
    <control-input axis=
    "/autopilot/autobrake/right-brake-output"
    control="BRAKE"></control-input>
    <control-input axis=
    "/controls/gear/brake-parking" control="BRAKE"
    ></control-input>
    <control-input axis="/controls/gear/gear-down"
    control="EXTEND"></control-input>
    <control-output control="EXTEND" prop=
    "/gear/gear[2]/position-norm"></control-output>
    <control-speed control="EXTEND" transition-time
    ="20"></control-speed>
  </gear>
```

```xml
<!-- aft axle on left main gear -->
<gear x="-7.8" y="5.6" z="-6.22" compression="3.0" spring="1.2">
  <control-input axis="/controls/gear/gear-down" control="EXTEND"></control-input>
  <control-output control="EXTEND" prop="/gear/gear[3]/position-norm"></control-output>
  <control-speed control="EXTEND" transition-time="20"></control-speed>
  <!-- 8 degrees main gear steering when nose gear steering above 13 degrees commanded (see Nasal/ground_steering.nas) -->
  <control-input control="STEER" axis="/controls/gear/maingear-steering-cmd-norm" src0="-1.0" dst0="-0.1396263402" src1="1.0" dst1="0.1396263402"></control-input>
  <control-output control="STEER" prop="/controls/gear/maingear-l-steering-angle-rad"></control-output>
</gear>

<!-- aft axle on right main gear -->
<gear x="-7.8" y="-5.6" z="-6.22" compression="3.0" spring="1.2">
  <control-input axis="/controls/gear/gear-down" control="EXTEND"></control-input>
```


```xml
<!-- aft axle on left main gear -->
<gear x="-7.8" y="5.6" z="-6.22" compression="3.0" spring="1.2">
  <control-input axis="/controls/gear/gear-down" control="EXTEND"></control-input>
  <control-output control="EXTEND" prop="/gear/gear[3]/position-norm"></control-output>
  <control-speed control="EXTEND" transition-time="20"></control-speed>
  <!-- 8 degrees main gear steering when nose gear steering above 13 degrees commanded (see Nasal/ground_steering.nas) -->
  <control-input control="STEER" axis="/controls/gear/maingear-steering-cmd-norm" src0="-1.0" dst0="-0.1396263402" src1="1.0" dst1="0.1396263402"></control-input>
  <control-output control="STEER" prop="/controls/gear/maingear-l-steering-angle-rad"></control-output>
</gear>

<!-- aft axle on right main gear -->
<gear x="-7.8" y="-5.6" z="-6.22" compression="3.0" spring="1.2">
  <control-input axis="/controls/gear/gear-down" control="EXTEND"></control-input>
```

```xml
    <control-output control="EXTEND" prop=
    "/gear/gear[4]/position-norm"></control-output>
    <control-speed control="EXTEND" transition-time
    ="20"></control-speed>
    <!-- 8 degrees main gear steering when nose
    gear steering above 13 degrees commanded (see
    Nasal/ground_steering.nas) -->
    <control-input control="STEER" axis=
    "/controls/gear/maingear-steering-cmd-norm"
    src0="-1.0" dst0="-0.1396263402" src1="1.0"
    dst1="0.1396263402"></control-input>
    <control-output control="STEER" prop=
    "/controls/gear/maingear-r-steering-angle-rad"
    ></control-output>
  </gear>

  <!--  fake gear as tail contact point for
  tailstrikes -->
  <gear x="-19.84" y="0.00" z="-3.38" compression=
  "0.1" spring="1" damp="1" sfric="0.5" dfric="0.5">
  </gear>

    <!-- apu -->
  <vstab x="0" y="0" z="0" length="0" chord="0">
      <flap0 start="0" end="1" lift="0" drag="0"
      ></flap0>
```


```xml
    <control-output control="EXTEND" prop=
    "/gear/gear[4]/position-norm"></control-output>
    <control-speed control="EXTEND" transition-time
    ="20"></control-speed>
    <!-- 8 degrees main gear steering when nose
    gear steering above 13 degrees commanded (see
    Nasal/ground_steering.nas) -->
    <control-input control="STEER" axis=
    "/controls/gear/maingear-steering-cmd-norm"
    src0="-1.0" dst0="-0.1396263402" src1="1.0"
    dst1="0.1396263402"></control-input>
    <control-output control="STEER" prop=
    "/controls/gear/maingear-r-steering-angle-rad"
    ></control-output>
  </gear>

  <!--  fake gear as tail contact point for
  tailstrikes -->
  <gear x="-19.84" y="0.00" z="-3.38" compression=
  "0.1" spring="1" damp="1" sfric="0.5" dfric="0.5">
  </gear>

    <!-- apu -->
  <vstab x="0" y="0" z="0" length="0" chord="0">
      <flap0 start="0" end="1" lift="0" drag="0"
      ></flap0>
```

```xml
    <control-input axis="/controls/APU/running"
    control="FLAP0"></control-input>
    <control-output control="FLAP0" prop=
    "controls/APU/rpm"></control-output>
    <control-speed control="FLAP0" transition-time=
    "30"></control-speed>
  </vstab>

  <tank x="-4.3" y="5" z="-1.5" jet="true" capacity
  ="9500"></tank>
  <tank x="-4.3" y="0" z="-2.5" jet="true" capacity
  ="0"></tank>
  <tank x="-4.3" y="-5" z="-1.5" jet="true"
  capacity="9500"></tank>

  <weight x="22.0" y="0" z="0" mass-prop=
  "/sim/weight[0]/weight-lb"></weight>
  <weight x="-4.3" y="0" z="0" mass-prop=
  "/sim/weight[1]/weight-lb"></weight>

  <ballast x="22" y="0" z="4" mass="5000"></ballast>

 <thruster x="-19.284" y="0" z="-5.4" vx="1" vy="0"
  vz="0" thrust="100000.0">
  <control-input axis=
  "/sim/model/pushback/force-x-yasim" control=
  "THROTTLE" src0="-1" src1="1" dst0="-1" dst1="1"
  ></control-input>
 </thruster>
 <thruster x="-19.284" y="0" z="-5.4" vx="0" vy="1"
  vz="0" thrust="100000.0">
  <control-input axis=
  "/sim/model/pushback/force-y-yasim" control=
  "THROTTLE" src0="-1" src1="1" dst0="-1" dst1="1"
  ></control-input>
 </thruster>

</airplane>
```

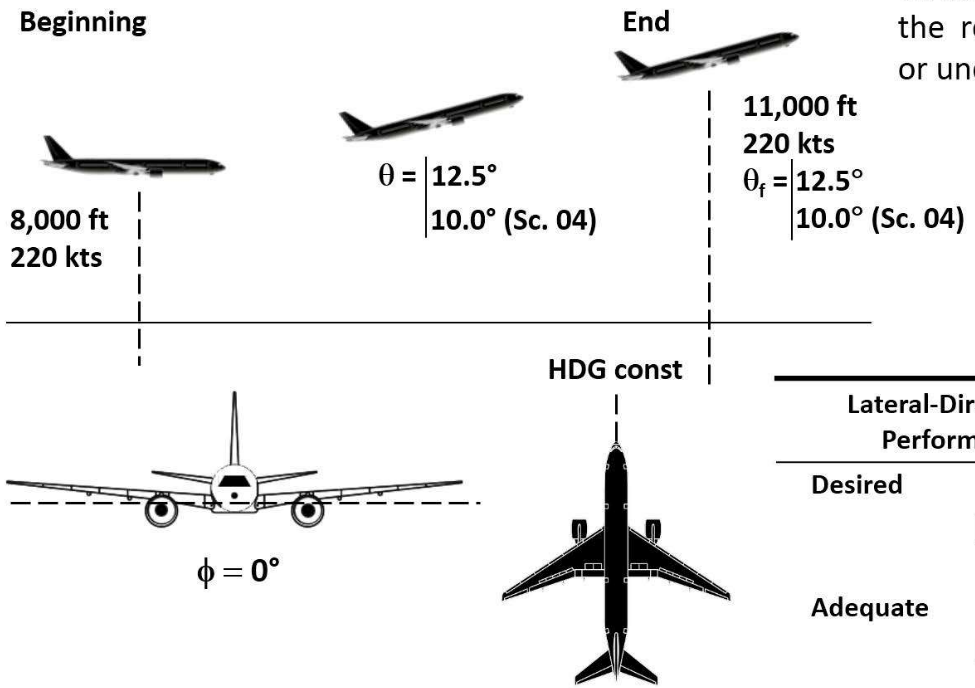

```xml
    <control-input axis="/controls/APU/running"
    control="FLAP0"></control-input>
    <control-output control="FLAP0" prop=
    "controls/APU/rpm"></control-output>
    <control-speed control="FLAP0" transition-time=
    "30"></control-speed>
  </vstab>

  <tank x="-4.3" y="5" z="-1.5" jet="true" capacity
  ="9500"></tank>
  <tank x="-4.3" y="0" z="-2.5" jet="true" capacity
  ="0"></tank>
  <tank x="-4.3" y="-5" z="-1.5" jet="true"
  capacity="9500"></tank>

  <weight x="22.0" y="0" z="0" mass-prop=
  "/sim/weight[0]/weight-lb"></weight>
  <weight x="-4.3" y="0" z="0" mass-prop=
  "/sim/weight[1]/weight-lb"></weight>

  <ballast x="22" y="0" z="4" mass="5000"></ballast>

 <thruster x="-19.284" y="0" z="-5.4" vx="1" vy="0"
  vz="0" thrust="100000.0">
  <control-input axis=
  "/sim/model/pushback/force-x-yasim" control=
  "THROTTLE" src0="-1" src1="1" dst0="-1" dst1="1"
  ></control-input>
 </thruster>
 <thruster x="-19.284" y="0" z="-5.4" vx="0" vy="1"
  vz="0" thrust="100000.0">
  <control-input axis=
  "/sim/model/pushback/force-y-yasim" control=
  "THROTTLE" src0="-1" src1="1" dst0="-1" dst1="1"
  ></control-input>
 </thruster>

</airplane>
```

APPENDIX B – SET OF TASKS

This is a compendium of the set of manoeuvres performed in the research. A schematic view of the tasks is presented together with their initial conditions, objectives, descriptions, and associated levels of performance.

Task 1a

Objective: maintain longitudinal attitude (climb)



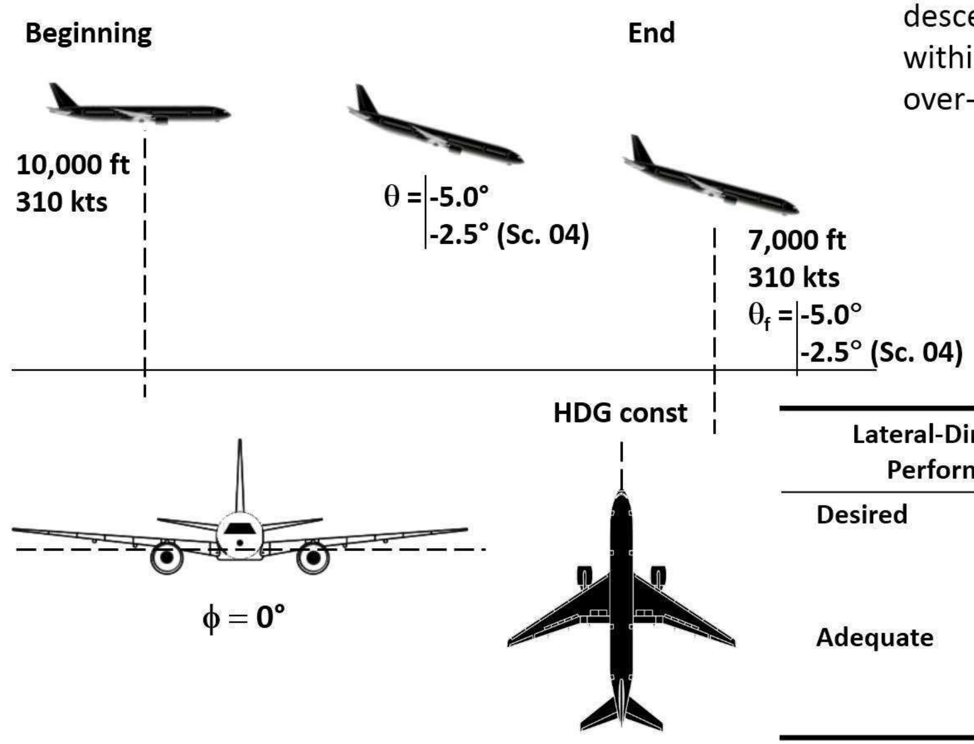
Description: Reach θ = 12.5° (10.0° in Sc. 04) and attain it until completing a 3,000 ft climb. Maintain heading and airspeed within the required performance bands. No over- or undershoots.

Aircraft Configuration
- Flaps: retracted
- LDG: up

Lateral-Directional Performance	Longitudinal Performance
Desired	**Desired**
Heading ± 4°	θ ± 2°
	Speed ± 5 kts
Adequate	**Adequate**
Heading ± 8°	θ ± 4°
	Speed ± 10 kts

Task 1b

Objective: maintain longitudinal attitude (descent)



Description: Reach θ = -5.0° (-2.5° in Sc. 04) and attain it until completing a 3,000 ft descent. Maintain heading and airspeed within the required performance bands. No over- or undershoots.

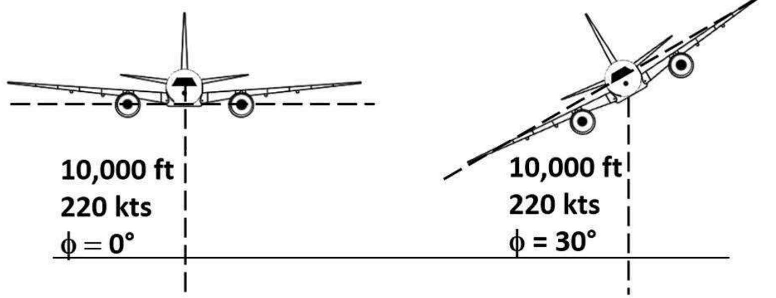
Aircraft Configuration
Flaps: retracted
LDG: up

Lateral-Directional Performance	Longitudinal Performance
Desired	**Desired**
Heading ± 4°	θ ± 2°
	Speed ± 5 kts
Adequate	**Adequate**
Heading ± 8°	θ ± 4°
	Speed ± 10 kts

Task 2a

Objective: maintain lateral attitude (right turn)

Beginning **End**

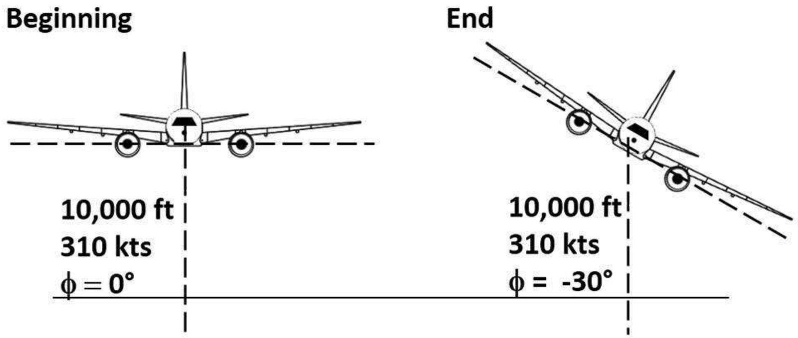


Description: Reach $\phi = 30°$ and attain it until completing a 90° turn (cross it with 30° bank). Maintain altitude and airspeed within the required performance bands. No over- or undershoots.

Lateral-Directional Performance		**Longitudinal Performance**	
Desired		**Desired**	
	$\mid \phi \pm 3°$		$\mid$ Altitude ± 100 ft
			$\mid$ Speed ± 5 kts
Adequate		**Adequate**	
	$\mid \phi \pm 6°$		$\mid$ Altitude ± 200 ft
			$\mid$ Speed ± 10 kts

Aircraft Configuration
Flaps: retracted
LDG: up

Task 2b
Objective: maintain lateral attitude (left turn)



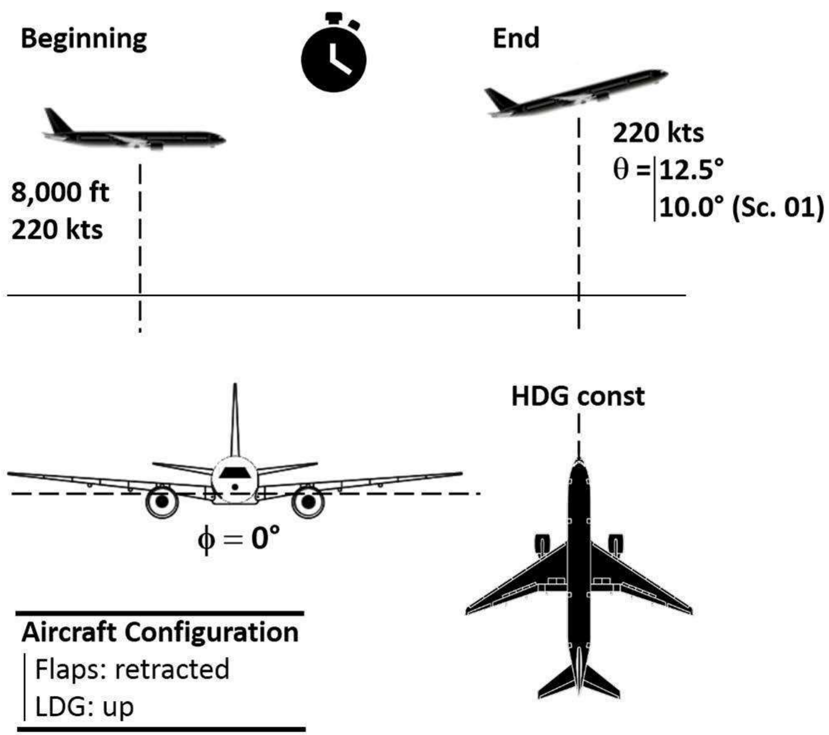
Lateral-Directional Performance	Longitudinal Performance
Desired	**Desired**
| $\phi \pm 3°$	| Altitude ± 100 ft | Speed ± 5 kts
Adequate	**Adequate**
| $\phi \pm 6°$	| Altitude ± 200 ft | Speed ± 10 kts

Description: Reach $\phi = -30°$ and attain it until completing a 90° turn (cross it with -30° bank). Maintain altitude and airspeed within the required performance bands. No over- or undershoots.

Aircraft Configuration
| Flaps: retracted
| LDG: up

Task 3a

Objective: change longitudinal attitude (climb)

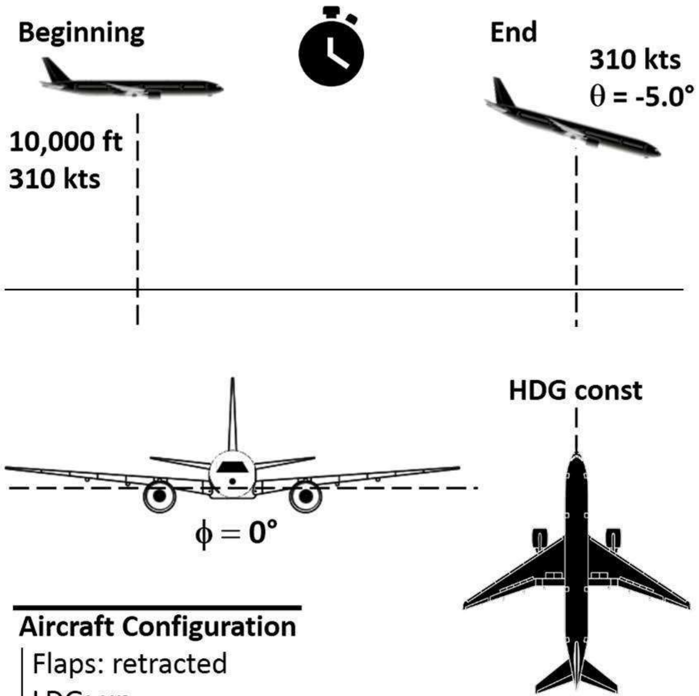


Description: Reach $\theta = 12.5°$ (10.0° in Sc. 01) as quickly and precisely as possible. Maintain heading and airspeed within the required performance bands. No over- or undershoots.

Lateral-Directional Performance	Longitudinal Performance
Desired	**Desired**
| Heading ± 4°	| θ ± 2°
	| Speed ± 5 kts
Adequate	**Adequate**
| Heading ± 8°	| θ ± 4°
	| Speed ± 10 kts

Timing Performance
Desired
| Complete within 3 sec
Adequate
| Complete within 6 sec

Task 3b
Objective: change longitudinal attitude (descent)



Aircraft Configuration
| Flaps: retracted
| LDG: up

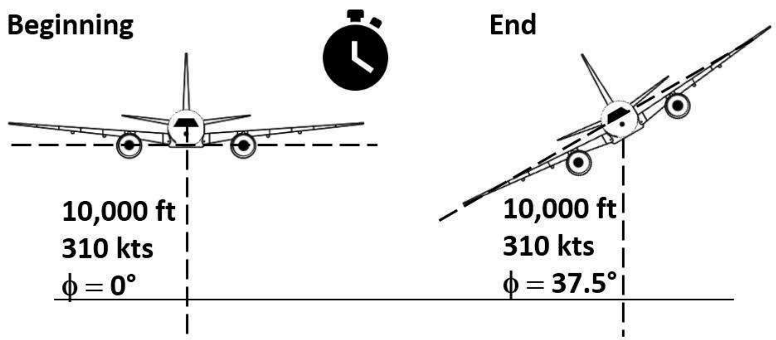
Description: Reach θ = -5.0° as quickly and precisely as possible. Maintain heading and airspeed within the required performance bands. No over- or undershoots.

Lateral-Directional Performance	Longitudinal Performance
Desired	**Desired**
| Heading ± 4°	| θ ± 1.5° | Speed ± 8 kts
Adequate	**Adequate**
| Heading ± 8°	| θ ± 3° | Speed ± 15 kts

Timing Performance
Desired
| Complete within 3 sec
Adequate
| Complete within 6 sec

Task 4a

Objective: change lateral attitude (right turn)

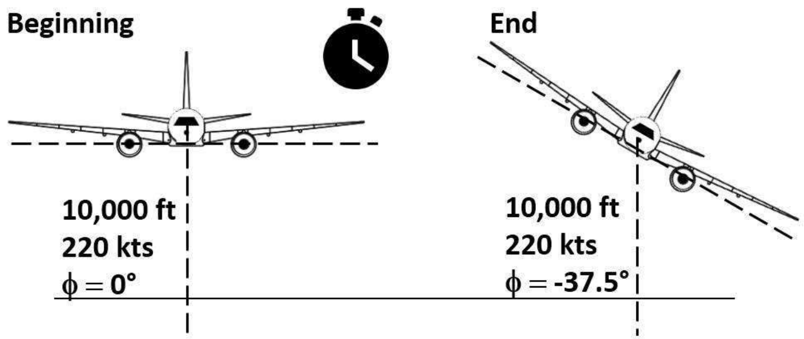


Description: Reach ϕ = 37.5° as quickly and precisely as possible. Maintain altitude and airspeed within the required performance bands. No over- or undershoots.

Aircraft Configuration
| Flaps: retracted
| LDG: up

Lateral-Directional Performance		Longitudinal Performance		Timing Performance	
Desired		**Desired**		**Desired**	
	ϕ ± 3°		Altitude ± 100 ft		Complete within 5 sec
			Speed ± 5 kts		
Adequate		**Adequate**		**Adequate**	
	ϕ ± 6°		Altitude ± 200 ft		Complete within 8 sec
			Speed ± 10 kts		

Task 4b
Objective: change lateral attitude (left turn)



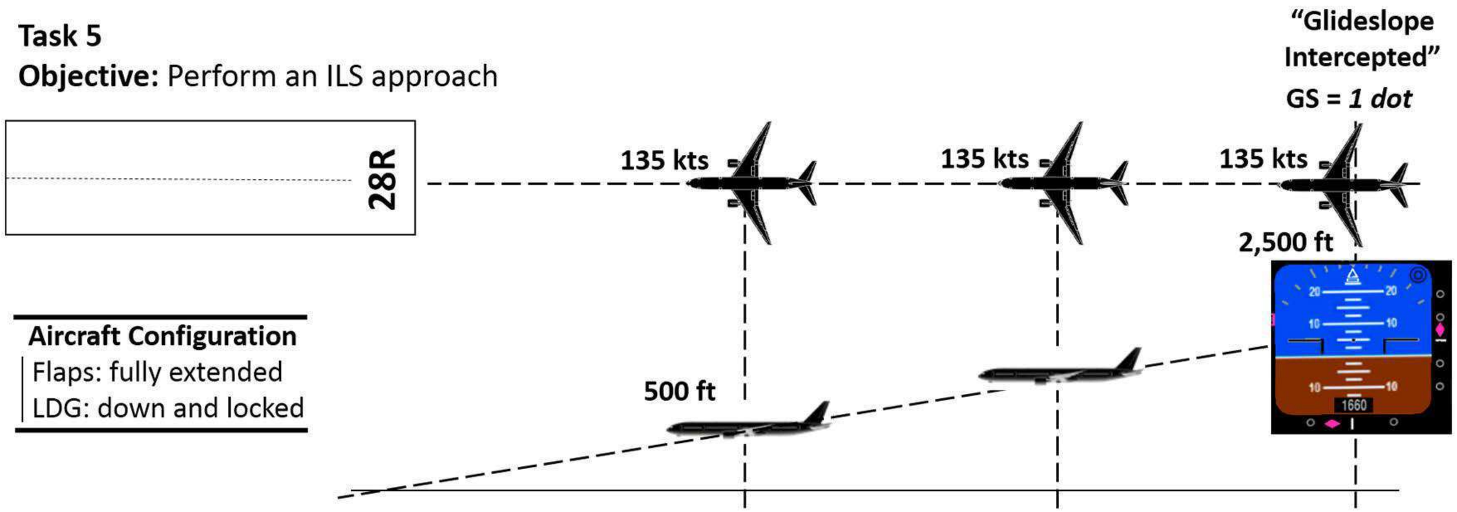
Description: Reach ϕ = -37.5° as quickly and precisely as possible. Maintain altitude and airspeed within the required performance bands. No over- or undershoots.

Aircraft Configuration
Flaps: retracted
LDG: up

Lateral-Directional Performance	Longitudinal Performance	Timing Performance
Desired	**Desired**	**Desired**
| ϕ ± 3°	| Altitude ± 100 ft | Speed ± 5 kts	| Complete within 5 sec
Adequate	**Adequate**	**Adequate**
| ϕ ± 6°	| Altitude ± 200 ft | Speed ± 10 kts	| Complete within 8 sec

Task 5

Objective: Perform an ILS approach



Aircraft Configuration

| Flaps: fully extended

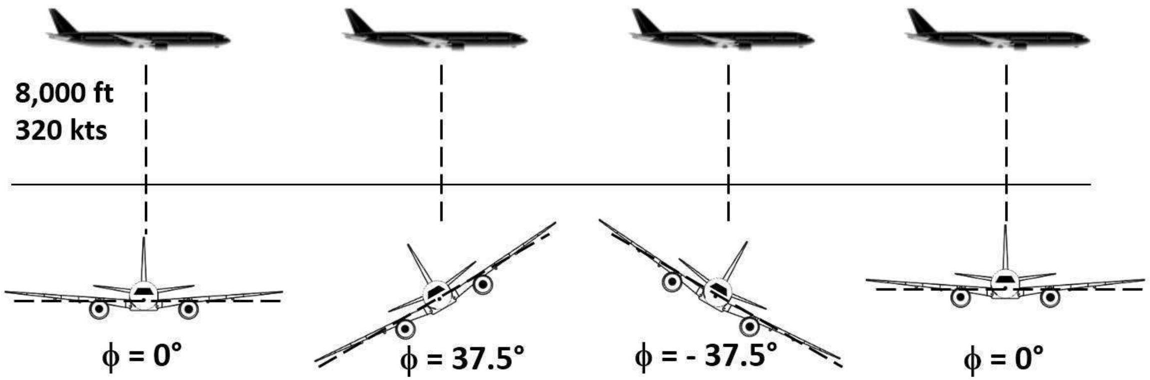
| LDG: down and locked

Description: Intercept and follow glideslope and localizer from 2,500 ft altitude up to 500 ft AGL. Maintain altitude and airspeed within the required performance bands.

Lateral-Directional Performance	Longitudinal Performance
Desired	**Desired**
| LOC offset ± 1 dot	| GS offset ± 1 dot
| No-PIO	| Speed ± 8 kts
Adequate	**Adequate**
| LOC offset ± 2 dots	| GS offset ± 2 dots
| No-PIO	| Speed ± 15 kts

Task 6a

Objective: High gain simultaneous actuation on all three axes (high airspeed)



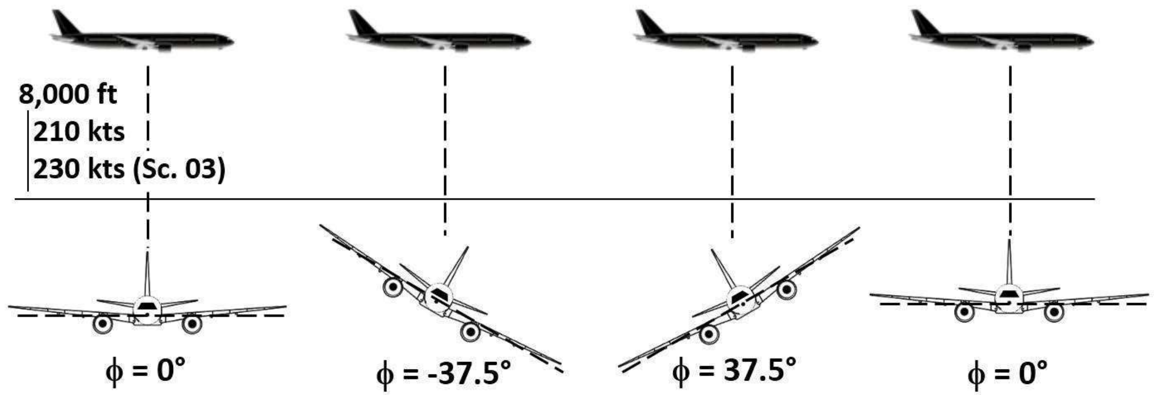
Aircraft Configuration
Flaps: retracted
LDG: up

Description: From level flight, turn right and reach $\phi = 37.5°$. Turn left up to $\phi = -37.5°$ and then go back to level flight. No over- or undershoots. Be as quick and precise as possible.

Lateral-Directional Performance		Longitudinal Performance	
Desired	$\phi \pm 3°$	**Desired**	Speed $\leq$ 330 kts
Adequate	$\phi \pm 6°$	**Adequate**	Speed $\leq$ 330 kts

Task 6b

Objective: High gain simultaneous actuation on all three axes (low airspeed)



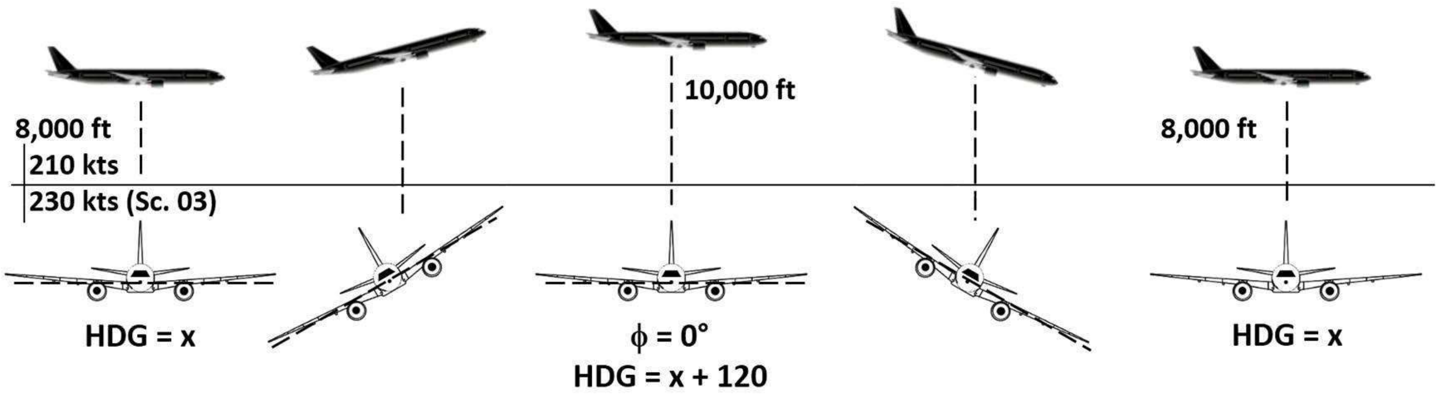
Aircraft Configuration
Flaps: retracted
LDG: up

Description: From level flight, turn left and reach $\phi = -37.5°$. Turn right up to $\phi = 37.5°$ and then go back to level flight. No over- or undershoots. Be as quick and precise as possible.

Lateral-Directional Performance		Longitudinal Performance	
Desired		**Desired**	
	$\phi \pm 3°$		Speed $\geq$ 200 kts
Adequate		**Adequate**	
	$\phi \pm 6°$		Speed $\geq$ 200 kts

Task 7a

Objective: Low gain simultaneous actuation on all three axes (low airspeed)



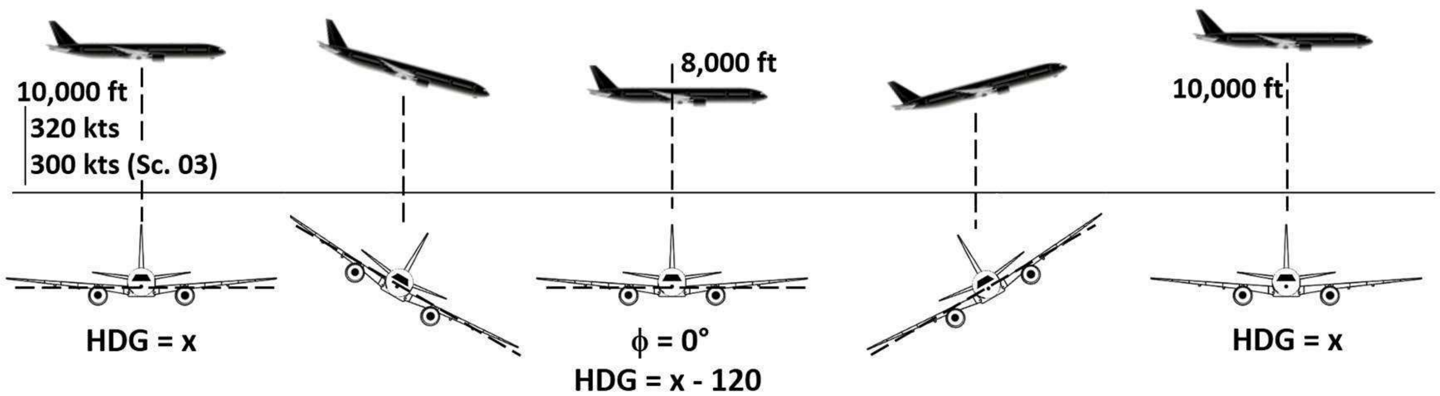
Description: Climb 2,000 ft and turn right for a 120° heading change. Return to a level flight and start a 2,000 ft descent and left turn to return to the beginning point. No over- or undershoots in altitude and heading.

Aircraft Configuration
Flaps: retracted
LDG: up

Lateral-Directional Performance		**Longitudinal Performance**	
Desired		**Desired**	
	Heading ± 3°		Altitude ± 200 ft
			Speed $\geq$ 200 kts
Adequate		**Adequate**	
	Heading ± 6°		Altitude ± 400 ft
			Speed $\geq$ 200 kts

Task 7b

Objective: Low gain simultaneous actuation on all three axes (high airspeed)



Description: Descend 2,000 ft and turn left for a 120° heading change. Return to a level flight and start a 2,000 ft climb and right turn to return to the beginning point. No over- or undershoots in altitude and heading.

Aircraft Configuration
Flaps: retracted
LDG: up

Lateral-Directional Performance		Longitudinal Performance	
Desired		**Desired**	
	Heading ± 3°		Altitude ± 200 ft
			Speed $\leq$ 330 kts
Adequate		**Adequate**	
	Heading ± 6°		Altitude ± 400 ft
			Speed $\leq$ 330 kts

APPENDIX C – TESTS FOR THE α_{SW} DETERMINATION

This annexe provides the data assessed for the determination of the angle of attack for stall warning activation – α_{SW}. Tests were conducted for a Boeing 777-200ER at 460,000 lb @ 44% MAC.

Both for the *clean* (no flaps, landing gear up) and *dirty* (full flaps, landing gear down) aircraft configurations, data were collected by the following procedure: trimming the vehicle, and then gently increasing the angle of attack at a rate equivalent to the reduction of *1 knot per second* in airspeed. Three trials were performed for each configuration, and resulted in the following curves:

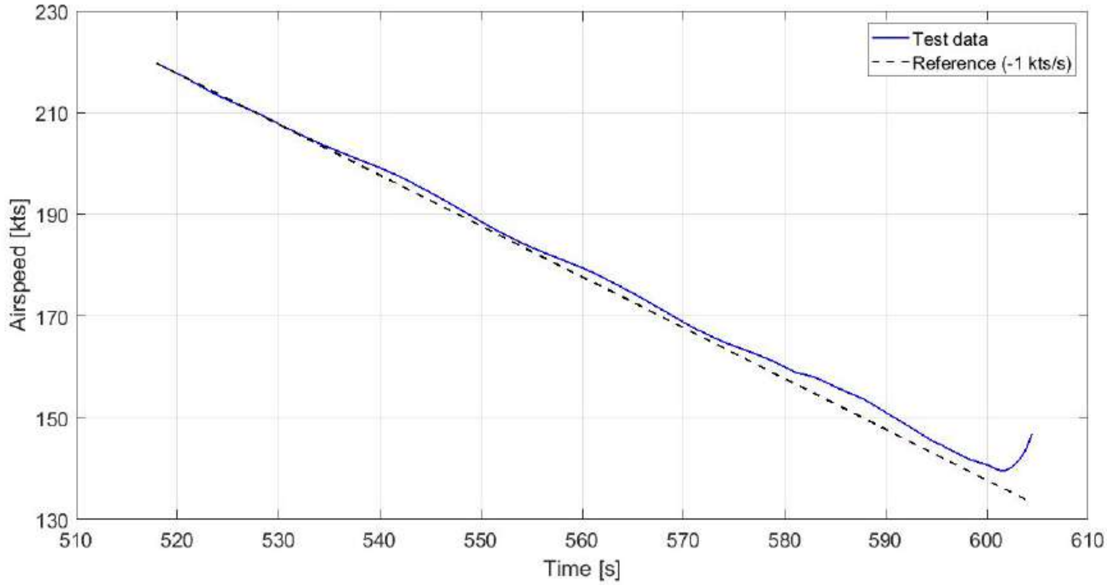
- airspeed *vs* time: for the test validation;
- c_L *vs* α: for the visualisation of the angle of attack behaviour; and
- p *vs* α: for showing the moment at which a rolling tendency became evident.

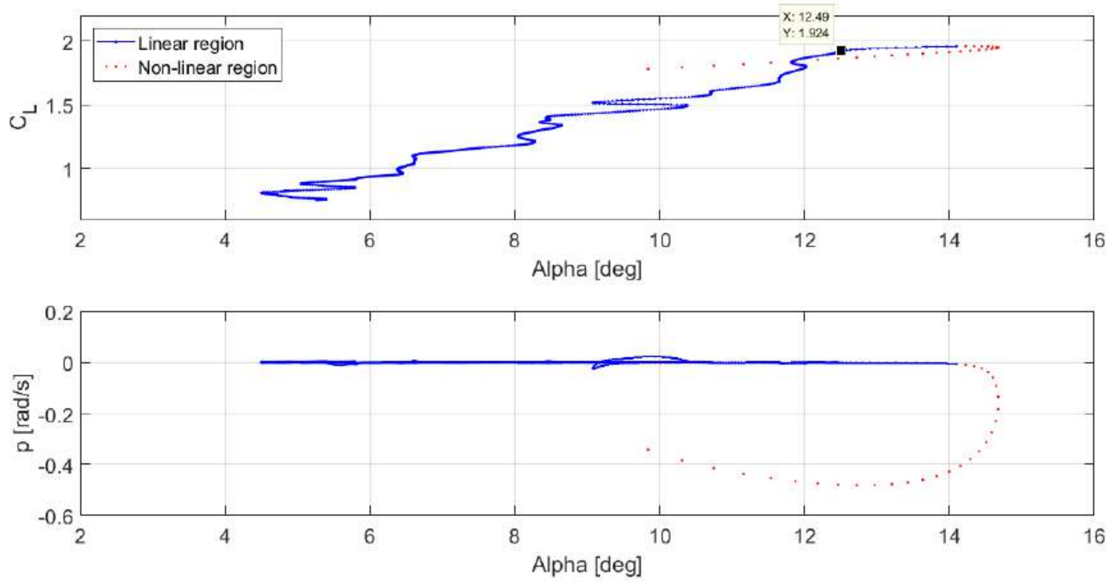
α_{SW} was determined as the angle of attack corresponding to the moment at which either c_L *vs* α became nonlinear, i.e., the derivative of the rolling angular velocity with respect to α became significantly different from zero. However, a careful observation of c_L *vs* α curves in the *clean* condition showed a typical "plateau" in the region of maximum c_L, i.e., a significant variation in the angle of attack was *not* accompanied by a distinguished increment in the lift coefficient. Therefore, α_{SW} was approximated as the first angle in the plateau region. Such a phenomenon was not observed in the *dirty* condition. The normalisation parameter was calculated as the mean value between trials:

Test Flight	α_{SW}	
	Clean	***Dirty***
	No flaps LDG up	Full flaps LDG down
A	12.49°	13.73°
B	12.15°	14.20°
C	12.42°	13.60°
Mean-value	**12.35°**	**13.84°**

C.1 Clean configuration

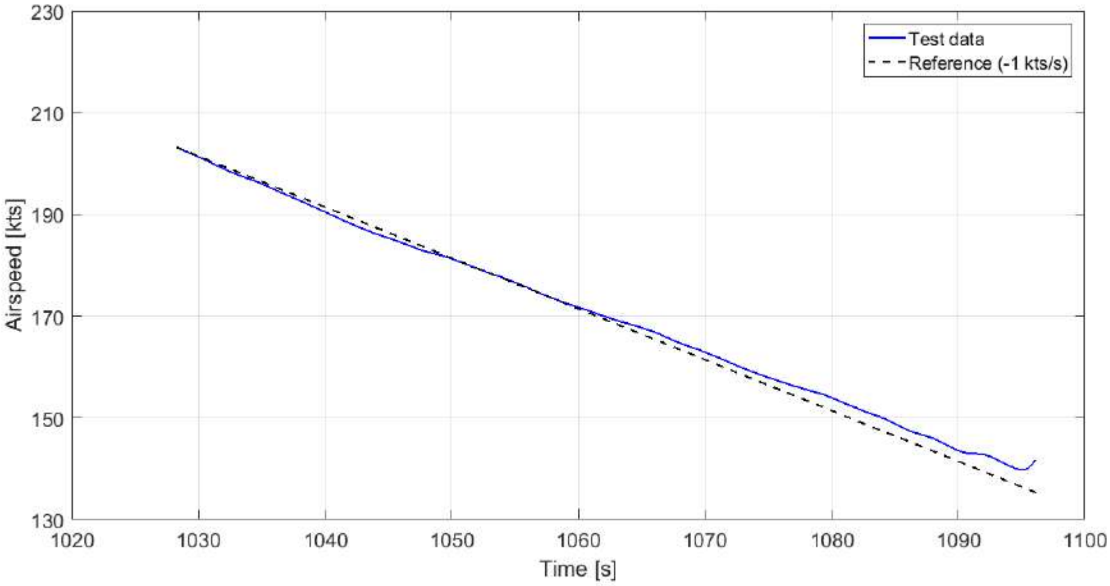
- Flight A

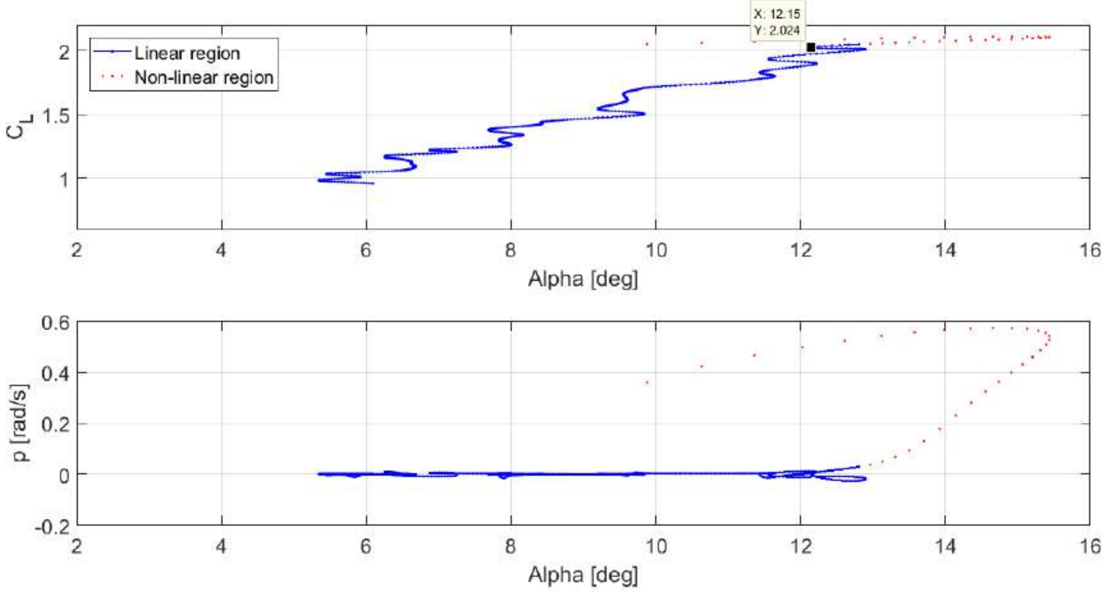




Resulting α_{SW}: 12.49°

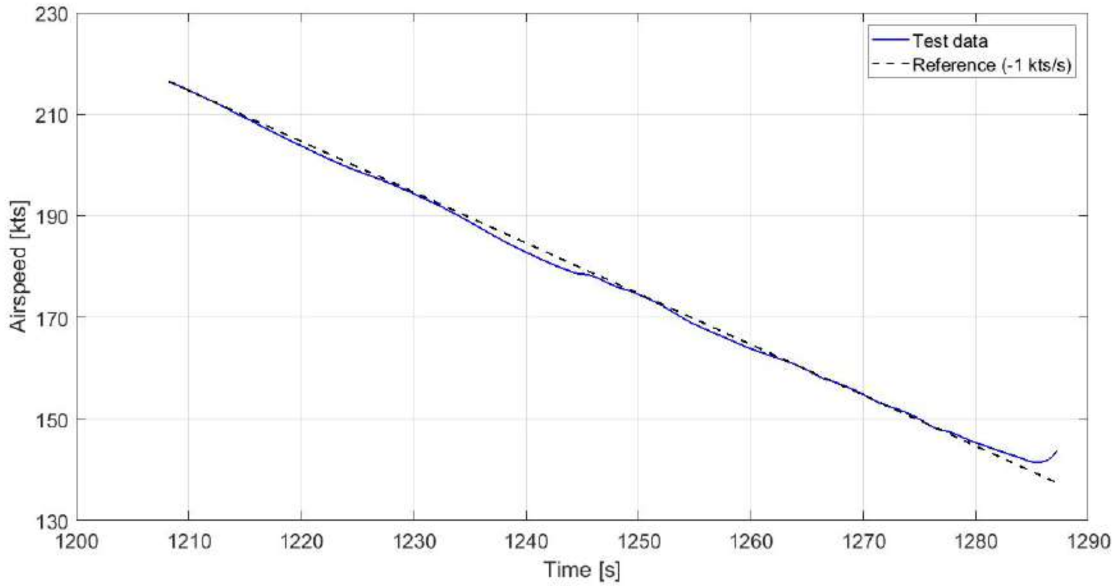
- Flight B

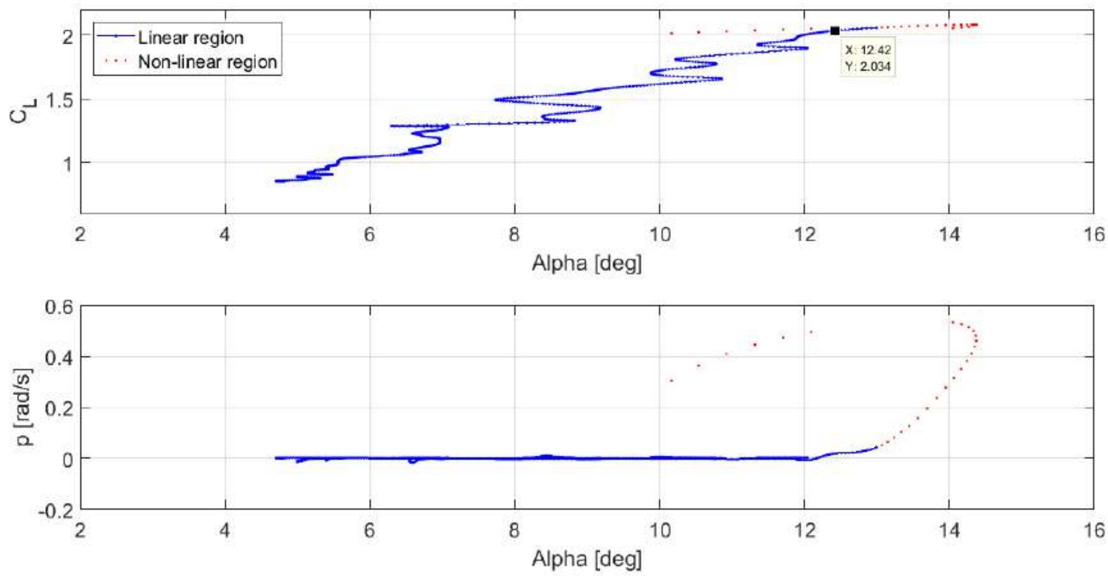




Resulting α_{SW}: 12.15°

- Flight C

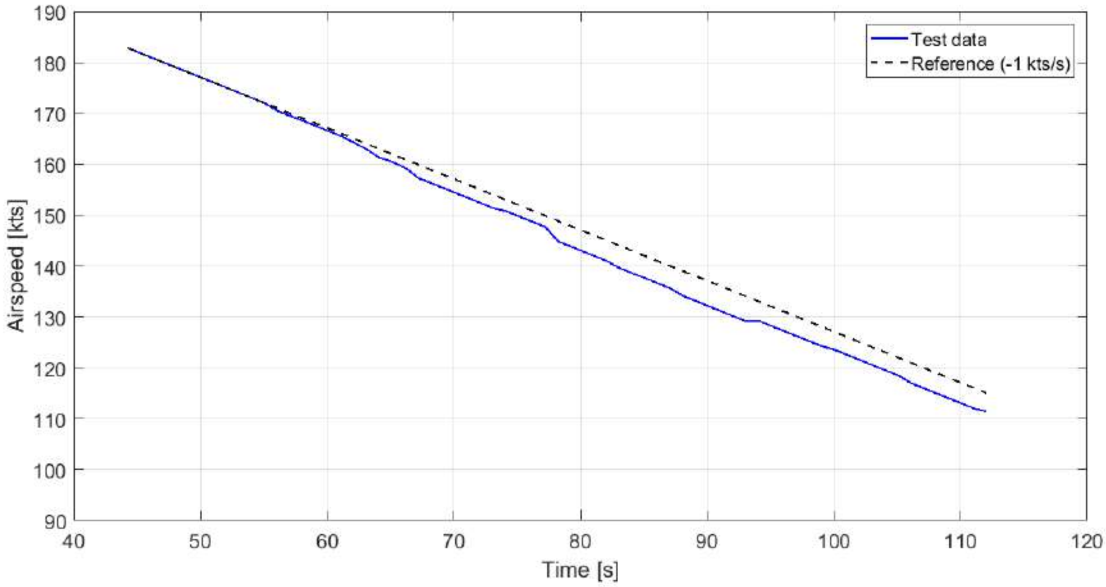


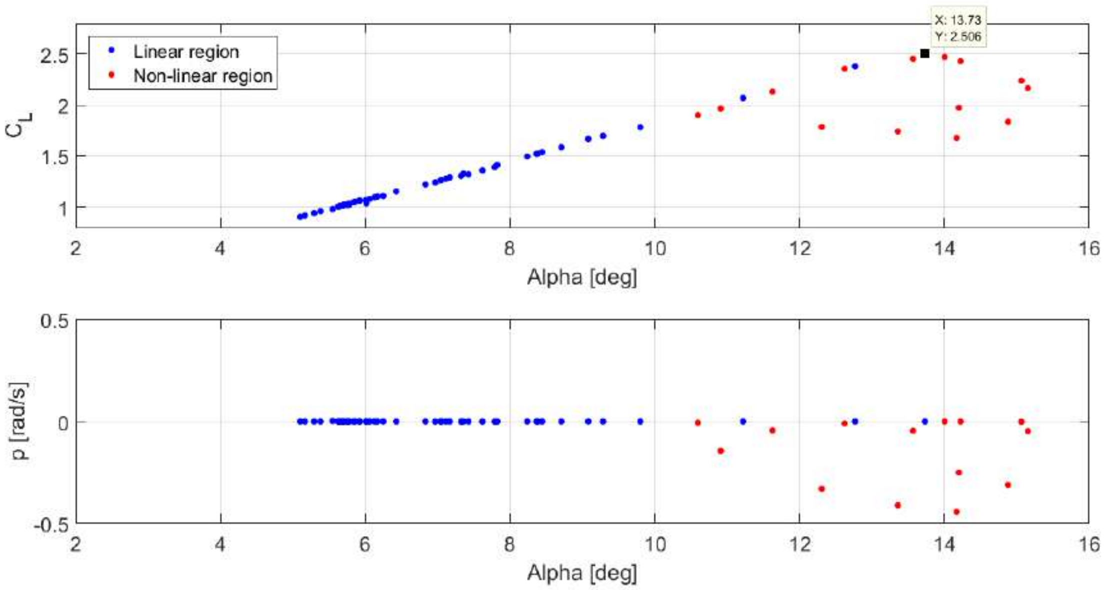


Resulting α_{SW}: 12.42°

C.2 Dirty configuration

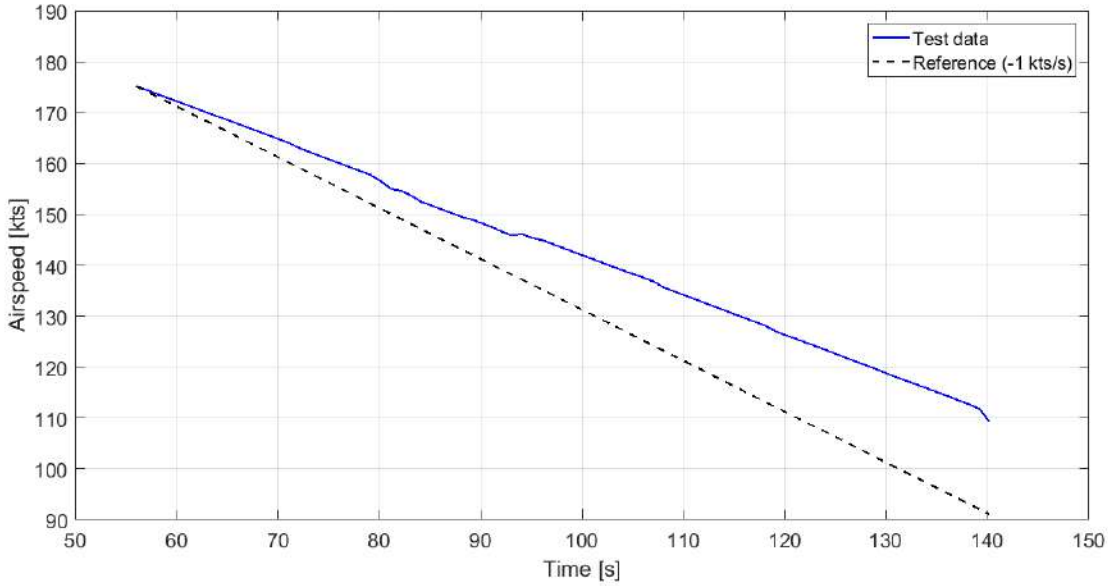
- Flight A

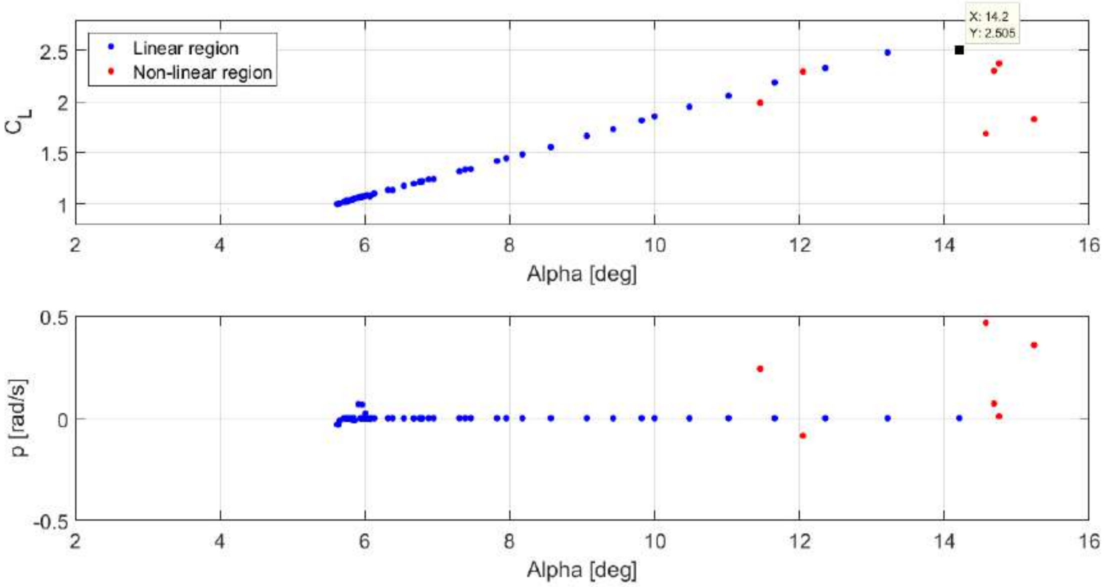




Resulting α_{SW}: 13.73°

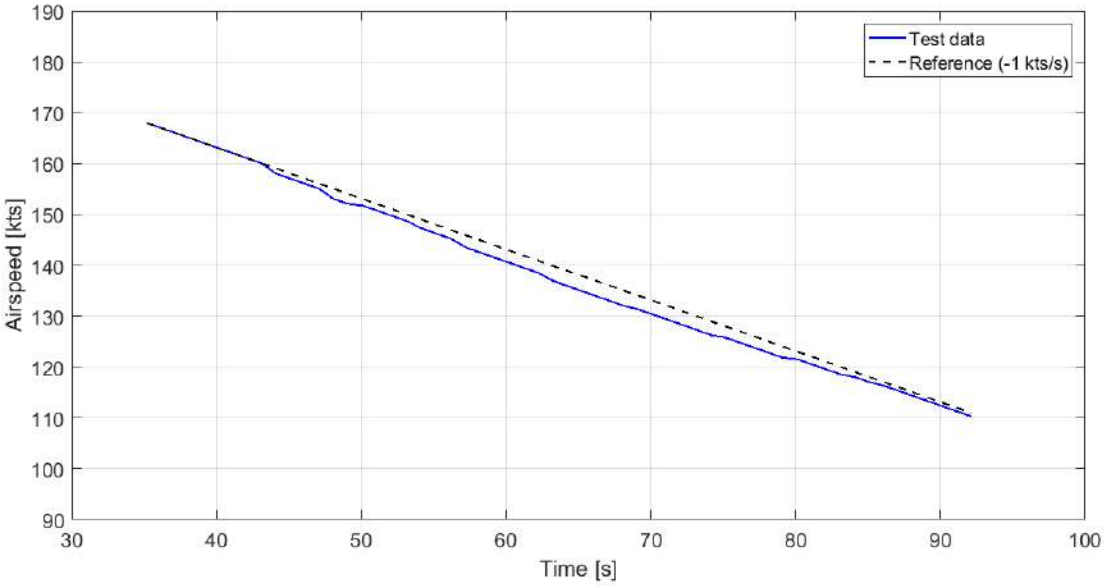
- Flight B

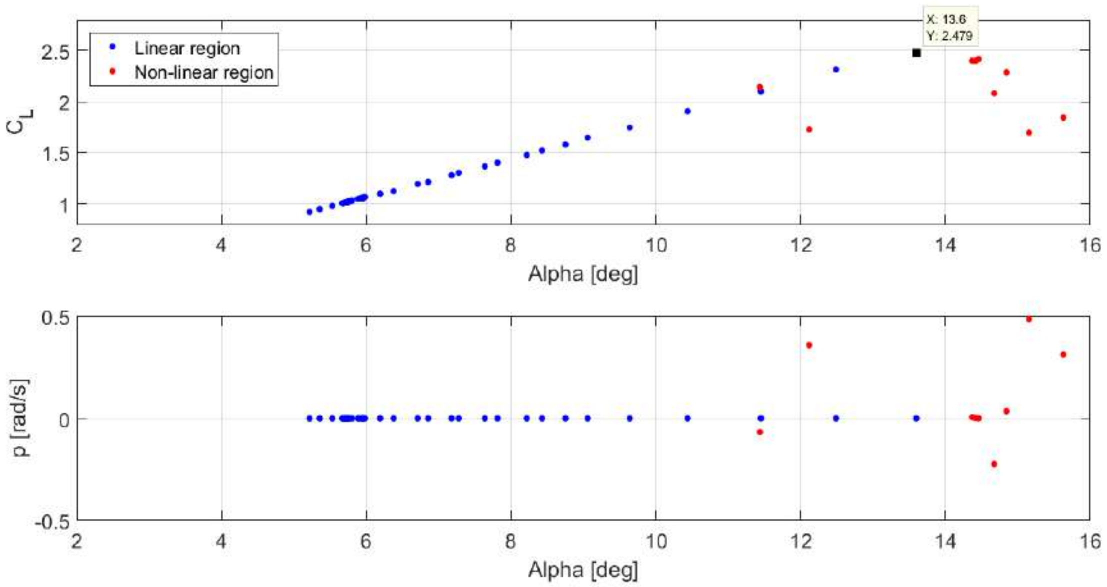




Resulting α_{SW}: 14.20°

- Flight C





Resulting α_{SW}: 13.60°

APPENDIX D – STATISTICAL CONSIDERATIONS

Certain statistical concepts explored throughout the thesis are summarised in this annexe, which includes types of statistical classification for variables, correlation tests, and significance of results. It also details the application of the concepts in the research, covering classification of the parameters explored and verification of assumptions for the correlation tests.

D.1 Types of Variable

Statistically speaking, variables can be generally classified into *discrete* and *continuous*, as detailed in the sequence.[81] A researcher must understand their classification, since it directly impacts on data processing and analysis.

Discrete variables

Discrete (or qualitative, or categorical) variables represent qualities or attributes. Although they can (and normally are) be denoted by numerical values (typically integers), such numbers are only "labels". Below are some of the frequent subgroups:

- **(Multi)Nominal variables:** the most basic level of categorical variables, whose values are mutually exclusive and indicate groups.[81] Regarding major racing car teams in Formula 1, for example, a car can be manufactured only by Ferrari, Mercedes, RedBull, and Renault; therefore, variable *manufacturer* can be statistically treated as a multi-nominal one. An identification number can be attributed to each manufacturer (e.g., *"1"* for Ferrari, *"2"* for Mercedes, and so on), however, such numbers are only labels for the names of the manufacturers;
- **Dichotomous variables:** particular nominal variables that accept only two categories. Ayrton Senna, for example, either drove, or not, for Ferrari (only "Yes" or "No" are possible answers); and
- **Ordinal variables:** categorical variables that can be ordered (or ranked), i.e., relative intensities can be established between variables of a given group (larger/smaller, better/worse etc.); however, the "distance" between them cannot be measured.[81] For example, the first driver in a race finished 30 seconds ahead of the second, who finished a tenth of a second before the third place; in relation to the podium, the time interval between the drivers does not matter, and their positions (first, second, and third, i.e., the ordinal variables) do not represent differences in performance; instead, the positions only establish an order of arrival.

Continuous variables

The capture of the time interval between the drivers in the above example requires continuous (or quantitative, or metric) variables, which are the ones that can be measured on a continuum numerical scale of equally spaced gradations (equidistant).[81,84] Continuous variables are subdivided into:

- **Interval variables**, which can be measured along a continuum and associated with a numerical value; however, they do not have a natural zero. An example is temperature in degrees Celsius, since 0°C does not represent absence of temperature; instead, it is only a number with "no special meaning";[81,84] and
- **Ratio variables**, which are interval variables with a natural zero. An example is temperature in Kelvin, since 0 K represents the theoretical "absence" of temperature (or molecular agitation);[81,84]

D.2 Classification of the variables explored in the research

The classification of variables is a choice[84] that depends on both research and researcher. This section details the classification of those explored in this research and provides reasons for the choices made.

Controllability categories resulting from the CHRs

This variable was treated as a *categorical ordinal variable*, since the categories could be ordered (they represent the degradation of control of an aircraft), but the distance between them could not be measured.

Number of envelopes crossed

The number of envelopes crossed aimed at representing controllability, and, although the distance between them could be ordered and measured (e.g., four envelopes crossed is twice as much as two envelopes crossed), our hypothesis was such a variable did not measure the distance between controllability categories. Consequently, and benefiting from possible statistical choices, the parameter was treated as a *categorical ordinal variable.*

QLC

Similarly to the controllability categories resulting from the CHRs, since QLC is the criterion that establishes the categories based on the number of QLC envelopes crossed, it was treated as a *categorical ordinal variable.*

Magnitude of excursion

The magnitude of excursion was defined as a multiplicative factor representing how far an aircraft was from a determined nominal flight condition, i.e., it was measured along a continuum in which number zero physically represented "no excursion". Therefore, it was classified as a *continuous ratio variable.*

Time interval of excursion

Since it is a time interval, it was treated as a *continuous ratio variable*.

Data concentration patterns

Since the parameter represented a mutually exclusive condition (i.e., data concentrated on either the "squared", or "tapered" quadrant), it was classified as a *categorical dichotomous variable*.

Crossing intervals

The variable was treated as a *continuous ratio variable* because it measured a time period. Moreover, it was important to distinguish between the following two conditions: **(i)** a zero crossing interval denoted two envelopes had been crossed at the same instant, therefore, it was indeed a zero in data post-processing, and **(ii)** if, for example, only four envelopes had been extrapolated, the fourth crossing interval did not exist and was treated as a missing value in data processing.

Critical window

Since the critical window is a time interval between two specific instants of time, it was also treated as a *continuous ratio variable*. Similarly to the previous case, zero critical windows (i.e., the hypothetical condition in which the first and the third QLC envelopes were crossed at the same instant) were differentiated from missing values (i.e., when less than three QLC envelopes had been crossed) in data post-processing.

Envelope crossed

An envelope could be either crossed or not; therefore, it was treated as a *categorical dichotomous variable*.

D.3 Bivariate analyses

The association between the qualitative and quantitative controllability assessment methods was evaluated by bivariate analyses; more specifically, by association tests that yielded correlation coefficients.

Association tests are calculation methods that evaluate the strength and the direction of a relationship between variables, and typically result in a non-dimensional number (called correlation coefficient) in the [-1, +1] interval[i]. The choice for an association test depends on the

[i] The closer the coefficient to the unit, the stronger the relationship between the variables, whereas a null value means the variables are completely independent. A negative coefficient shows certain variable(s) increase(s) and the other(s) decrease(s), and vice-versa

statistical type of the variables considered. Nevertheless, correlation coefficients can be compared, regardless of the association tests that calculated them.[81]

Essential information on the association tests used in this research is provided in what follows, and details can be found in Cleff (2014).[81]

Spearman's rank correlation

Spearman's rank correlation coefficient – ρ – describes the relationship between two *ranked* variables (e.g. ordinal variables). To use such a test, the variables of interest must firstly be ranked; then, the method of calculation of Spearman's rho measures the distance between their ranks.[81]

Taking, for example, the 154 *controllability categories resulting from the CHRs* data points collected, the "ranking" process consisted in sorting them and assigning "grades" (the so-called ranks) to each data point. Data points sharing a same value received the same "grade" (in an analogy with a podium, all manoeuvres whose controllability was classified as "normal" would share the same place in the podium). The same process was applied for all variables of interest.

The correlation coefficient between two variables (x and y) was calculated by Spearman's rho as

$$\rho = \frac{\frac{1}{n}\sum_{i=1}^{n}\left(\left(R(x_i) - \overline{R(x)}\right)\left(R(y_i) - \overline{R(y)}\right)\right)}{\sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}\left(R(x_i) - \overline{R(x)}\right)^2\right)\left(\frac{1}{n}\sum_{i=1}^{n}\left(R(y_i) - \overline{R(y)}\right)^2\right)}} \tag{D.1}$$

where $R(x)$ and $R(y)$ represent the ranks of variables x and y, respectively, and $\overline{R(x)}$ and $\overline{R(y)}$ are the corresponding mean ranks.

Spearman's rho can be used if the following two assumptions are satisfied:

I. The two variables are measured on an ordinal scale or, if they are continuous variables, they have been ranked; and
II. The two variables are paired observations. An example is the "*controllability categories resulting from the CHRs* and *QLC*" pair for each pilot.

Moreover, although not an assumption, but a recommendation, data should be checked for monotonicity[ii], since Spearman's rho assesses the strength of a monotonic relationship between the parameters. Therefore, if it is known beforehand that data are far from a monotonic relationship, another method should be selected.[85]

A great advantage of Spearman's rho is it imposes no restrictions on the individual statistical distribution of the variables evaluated (e.g., data can be non-normally distributed), which is positive, especially when working with ordinal variables.[80] Regarding its disadvantages, the most relevant are: **(i)** it faces difficulty in dealing with tied ranks ("grades" assigned to data

[ii] Monotonic relationships between two variables are those in which **(i)** an increase in a variable leads to an increase in the other, or *(ii)* an increase in a variable leads to a decrease in the other. Monotonicity can be checked by a scatterplot

points sharing a same value), affecting the results in case of numerous tied ranks, and **(ii)** in the process of ranking a variable, a cardinal scale is used, thus imposing a constant distance between consecutive ranks, which is a problem especially when the variable to be ranked is an ordinal one (it can be very difficult to prove the categories of an ordinal variable are all equidistant).[81]

Kendall's tau-b correlation

Kendall's tau-b correlation coefficient – τ_b – is one of the members of the so-called *Kendall's tau* group of coefficients. The main advantage of the group is it works well with tied ranks and imposes no rank equidistance, which are some of the drawbacks of Spearman's correlation coefficient.[81]

The requirements for using Kendall's tau-b are the same as those for Spearman's ρ, i.e.:

I. The two variables are measured on an ordinal scale or, if they are continuous variables, they have been ranked; and
II. The two variables are paired observations.

Additionally, data should show monotonicity.[86]

Kendall's tau-b evaluates the association between variables based on concordant and discordant pairs. Below is the procedure for calculating the correlation between two variables (x and y):[81]

1 ranks are assigned to x and y in a process similar to that for Spearman's;
2 the ranks are sorted in an ascending order for either x, or y. For example, let us say we have chosen to order $R(x)$; therefore, $R(x)$ becomes the so-called *anchor column*, and $R(y)$ is the *reference column*;
3 the rank combinations in the reference column are compared in a complex process that assesses all possible combinations;
4 the resulting number of concordant and discordant pairs is counted. Concordant pairs occur when $R(y_i) < R(y_j)$ for $i < j$ and discordant ones occur when $R(y_i) > R(y_j)$ for $i < j$;
5 the length of tied ranks for x and y are computed; and
6 Equation D.2 computes Kendall's tau-b.

$$\tau_b = \frac{P - I}{\sqrt{\left(\frac{n(n-1)}{2} - T\right)\left(\frac{n(n-1)}{2} - U\right)}} \tag{D.2}$$

where

- P is the number of concordant pairs;
- I is the number of discordant pairs;
- T is the number of cases with ties only on variable x;
- U is the number of cases with ties only on variable y.

Goodman and Kruskal's gamma correlation

Goodman and Kruskal's gamma – γ – assesses the correlation between two ordinal variables; its use is indicated when many ties are present in a dataset. It is similar to Kendall's tau-b, since it measures similarity between data in terms of concordant and discordant pairs. The following two assumptions must be checked so that Goodman and Kruskal's gamma can be used:[87]

I Both variables are measured on an ordinal scale; and
II The variables establish a monotonic relationship.

The main difference between such a test and the others presented elsewhere is the variables tested must establish a monotonic relationship, which limits the use of Goodman and Kruskal's γ, especially when one of the variables has a small number of possible categories.

Cramer's V correlation

Cramer's V – ϕ_c – is one of the few correlation methods that assesses the relationship between two ordinal or nominal (including dichotomous) variables; it can assume values in the [0, +1] interval, in which the extremes respectively represent "absence" and "perfect" correlation.[81]

The formulation of Cramer's V is based on the chi-square calculation, i.e., it compares the frequency of the variables observed in the experiment to the frequencies corresponding to the condition of no association.[88] The usual procedure to compute Cramer's V is to plot the data collected in a contingency table and apply Equation D.3.

$$\phi_c = \sqrt{\frac{\mathcal{X}^2}{n\Big(min(k,m) - 1\Big)}} \tag{D.3}$$

where $\mathcal{X}$ is the chi-square value[iii], n is the number of observations, and k and m represent, respectively, the total number of columns and rows in the contingency table.

The literature is not very precise on the assumptions of Cramer's V; however, since it is a type of chi-square calculation, it may inherit the assumptions of chi-square, i.e.:[88]

I one of the variables is ordinal and the other is nominal (including the dichotomous case);
II the number of possible categories for the ordinal variable is not too large;[81]
III there is independence of observations, e.g., in the present research, each pilot is independent of the other, i.e., none of them performed the experiments together; and
IV all observations should (<u>must</u>, according to some authors[88]) display expected counts (the frequencies corresponding to the condition of no association) greater than five.

Biserial rank correlation

The biserial rank correlation – r_{bisR} – assesses the correlation between dichotomous and ordinal variables. For example, let us say x is a dichotomous variable and y is an ordinal one.

[iii] Details on the calculation of the chi-square value are provided in Cleff (2014)[81]

The biserial rank coefficient is calculated by

$$r_{bisR} = \frac{2}{n}\left(\overline{R(y_1)} - \overline{R(y_0)}\right) \tag{D.4}$$

where n is the total sample size, and $\overline{R(y_0)}$ and $\overline{R(y_1)}$ are, respectively, the mean ranks for nominal values $x = 0$ and $x = 1$ of the ordinal variable.[81] Equation D.4 is valid only when the dataset has no tied ranks.

Since r_{bisR} is a relatively unusual correlation coefficient, some computational software (e.g., IBM SPSS®) does not even bring it in the libraries. Therefore, the biserial rank correlation has been removed from the list of possible tests in this research.

Finally, Table 19 shows a summary of possible association tests according to combinations of the types of variable used in this research.[81]

Table 19: Bivariate association tests according to the types of variable.
[Source: Adapted from Cleff (2014) [81]]

Type of variable		**Categorical variables**		**Continuous variables**	
		Dichotomous	**Ordinal**		
Categorical variables	**Dichotomous**	—	Cramer's V (ϕ_c)	—	
	Ordinal		Spearman's rho (ρ)	Ranking of the continuous variable and application of	Spearman's rho (ρ)
			Kendall's tau-b (τ_b)		Kendall's tau-b (τ_b)
			Goodman's gamma (γ)		
Continuous variables				—	

D.4 Deciding on a test

This section discusses the selection of the correlation test that assessed the association of each pair of variables analysed in the research; the decision process was based on **(i)** types of variable and **(ii)** verification of the necessary assumptions for the test.

I. *Controllability categories resulting from the CHRs* vs *QLC*

- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *QLC*: categorical, ordinal.
- **Possible association tests**
  - Spearman's rho;
  - Kendall's tau-b (selected); or
  - Goodman and Kruskal's gamma.

The difference among the correlation tests is the existence or not of a monotonic relationship between the variables. Figure 50 is a scatterplot that relates the variables of interest and shows the relationship is *not* monotonic. A considerable number of tied ranks was observed for both variables. Due to such characteristics, **Kendall's tau-b** correlation test was selected to assess the association between the variables.

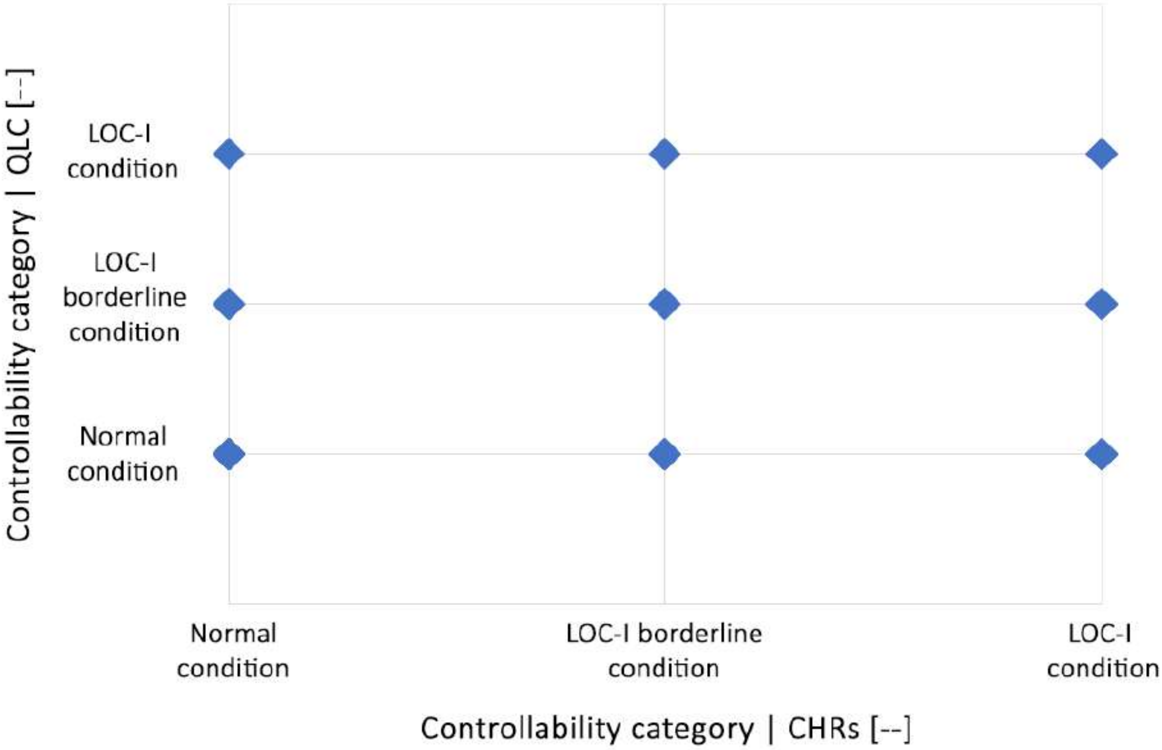


Figure 50: Relationship between the *controllability categories resulting from the CHRs* and *QLC*. [Source: The author]

II. *Controllability categories resulting from the CHRs* vs *Number of envelopes crossed*

- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *Number of envelopes crossed*: categorical, ordinal.
- **Possible association tests**
  - Spearman's rho;
  - Kendall's tau-b (selected); or
  - Goodman and Kruskal's gamma.

Similarly to the previous case, Figure 51 shows a *non*-monotonic relationship between the variables of interest. Again, a considerable number of tied ranks was observed, and **Kendall's tau-b** was selected.

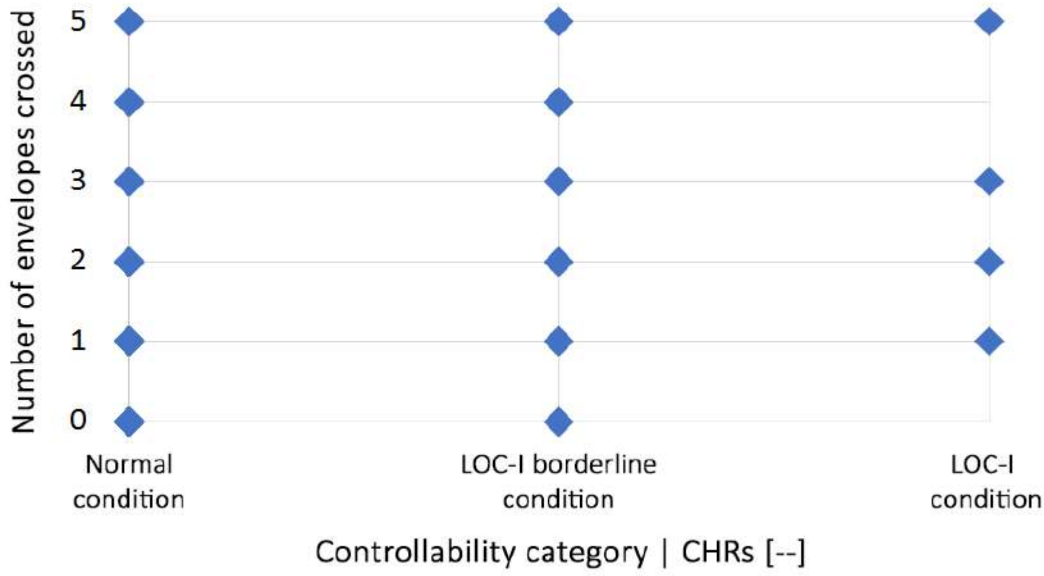


Figure 51: Relationship between the *controllability categories resulting from the CHRs* and *number of envelopes crossed.*
[Source: The author]

III. *Controllability categories resulting from the CHRs* vs *Magnitude of excursion*

- **Valid for**

  - $mag(\alpha_{pos})$;
  - $mag(\beta_{pos})$;
  - $mag(\beta_{neg})$;
  - $mag(\theta_{pos})$;
  - $mag(\theta_{neg})$;
  - $mag(\phi_{pos})$;
  - $mag(\phi_{neg})$;
  - $mag(n_{pos})$;
  - $mag(n_{neg})$;
  - $mag(V_{pos})$;
  - $mag(V_{neg})$.

- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *Magnitudes*: continuous, ratio.
- **Possible association tests:** no correlation test assesses the relationship between ordinal and continuous variables.[89] An alternative, however, is to consider the continuous variable an ordinal one for enabling the application of
  - Spearman's rho; or
  - Kendall's tau-b (selected).

Figure 52 shows the scatterplots of the variables in the *magnitude of excursion* family and the reference parameter – in all cases, the curve is *not* monotonic. A considerable number of tied ranks was observed; therefore, **Kendall's tau-b** was selected as the assessment method for all variables in the magnitude of excursion group.

IV. *Controllability categories resulting from the CHRs* vs *Time interval of excursion*

- **Valid for**

  - $time(\alpha_{pos})$;
  - $time(\beta)$;
  - $time(\theta)$;
  - $time(\phi)$;
  - $time(n)$;
  - $time(V_{pos})$;
  - $time(V_{neg})$.

- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *Time*: continuous, ratio.
- **Possible association tests:** similarly to the previous case, the continuous variable was ranked prior to the application of either
  - Spearman's rho; or
  - Kendall's tau-b (selected).

Figure 53 shows the relationship between the variables of interest. Due to the considerable number of tied ranks and the *non*-monotonic relationships, **Kendall's tau-b** was selected.

V. *Controllability categories resulting from the CHRs* vs *Crossing intervals*

- **Valid for**
  - First crossing interval;
  - Second crossing interval;
  - Third crossing interval; and
  - Fourth crossing interval.
- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *Crossing intervals*: continuous, ratio.
- **Possible association tests:** due to the lack of correlation methods, the continuous variable was ranked prior to the application of either
  - Spearman's rho; or
  - Kendall's tau-b (selected).

Figure 54 is a scatterplot of the relationship between the *controllability categories resulting from the CHRs* and the rankings of each *crossing interval* (ordinal variable). Except for the *first crossing interval*, tied ranks are rare; however, a significant number of missing data was observed, especially for high-order crossing intervals. Although in some cases the relationship tended to be monotonic, **Kendall's tau-b** was selected to assess the correlations in the *crossing intervals* family.

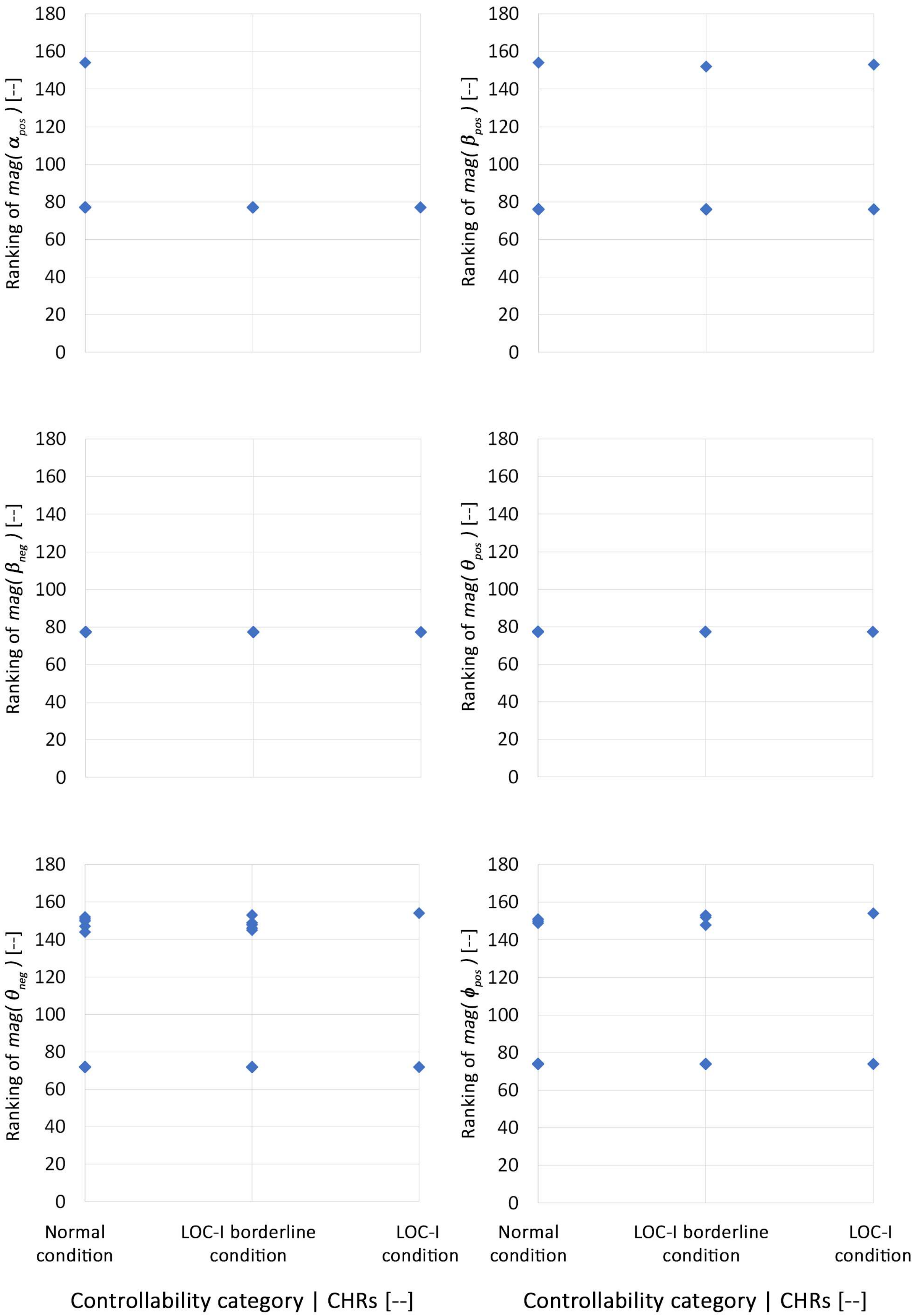


Figure 52: Relationship between the *controllability categories resulting from the CHRs* and the rankings of the *magnitude of excursion* family (ordinal variable).
[Source: The author]

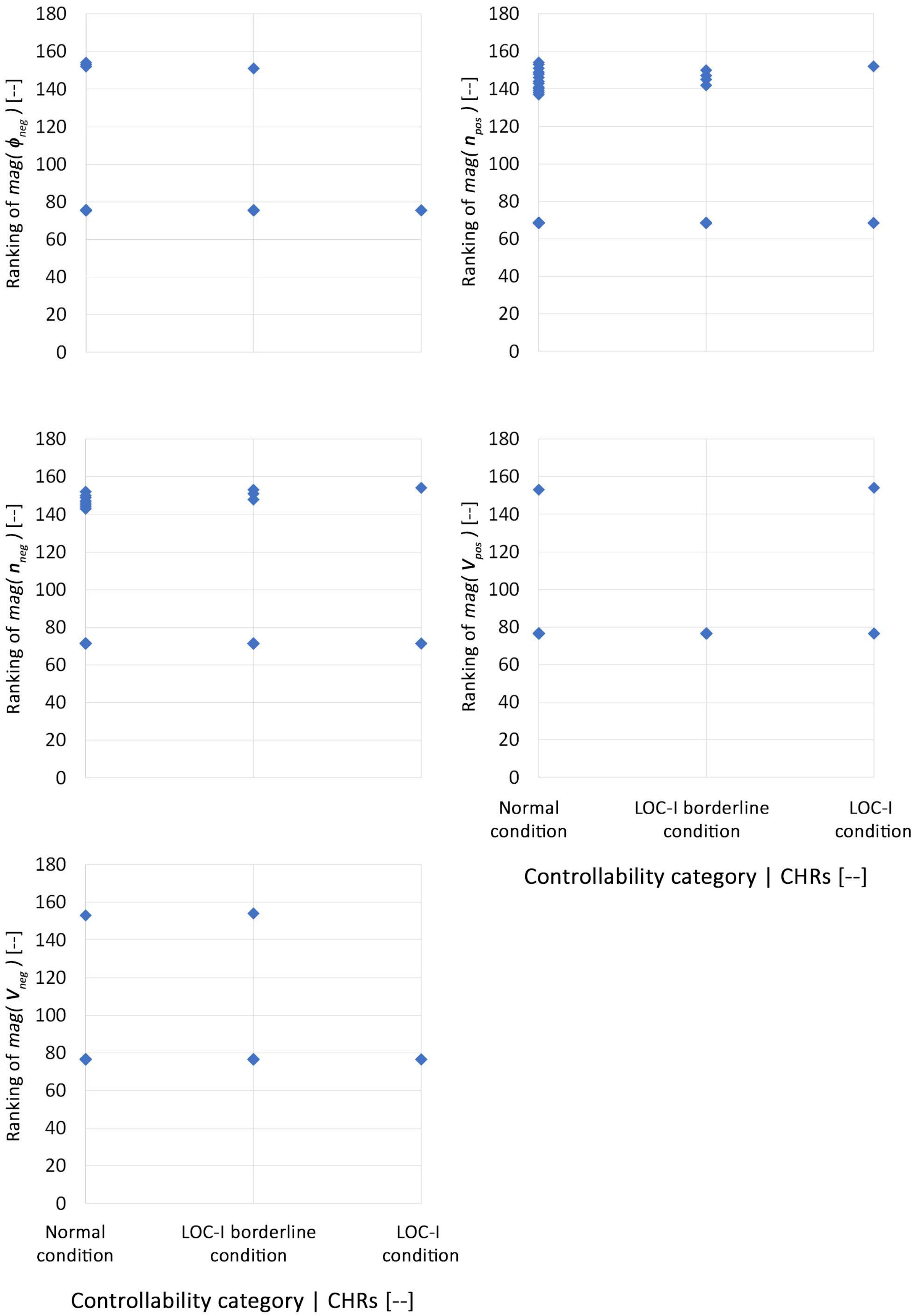


Figure 52: Relationship between the *controllability categories resulting from the CHRs* and the rankings of the *magnitude of excursion* family (ordinal variable), Continued.
[Source: The author]

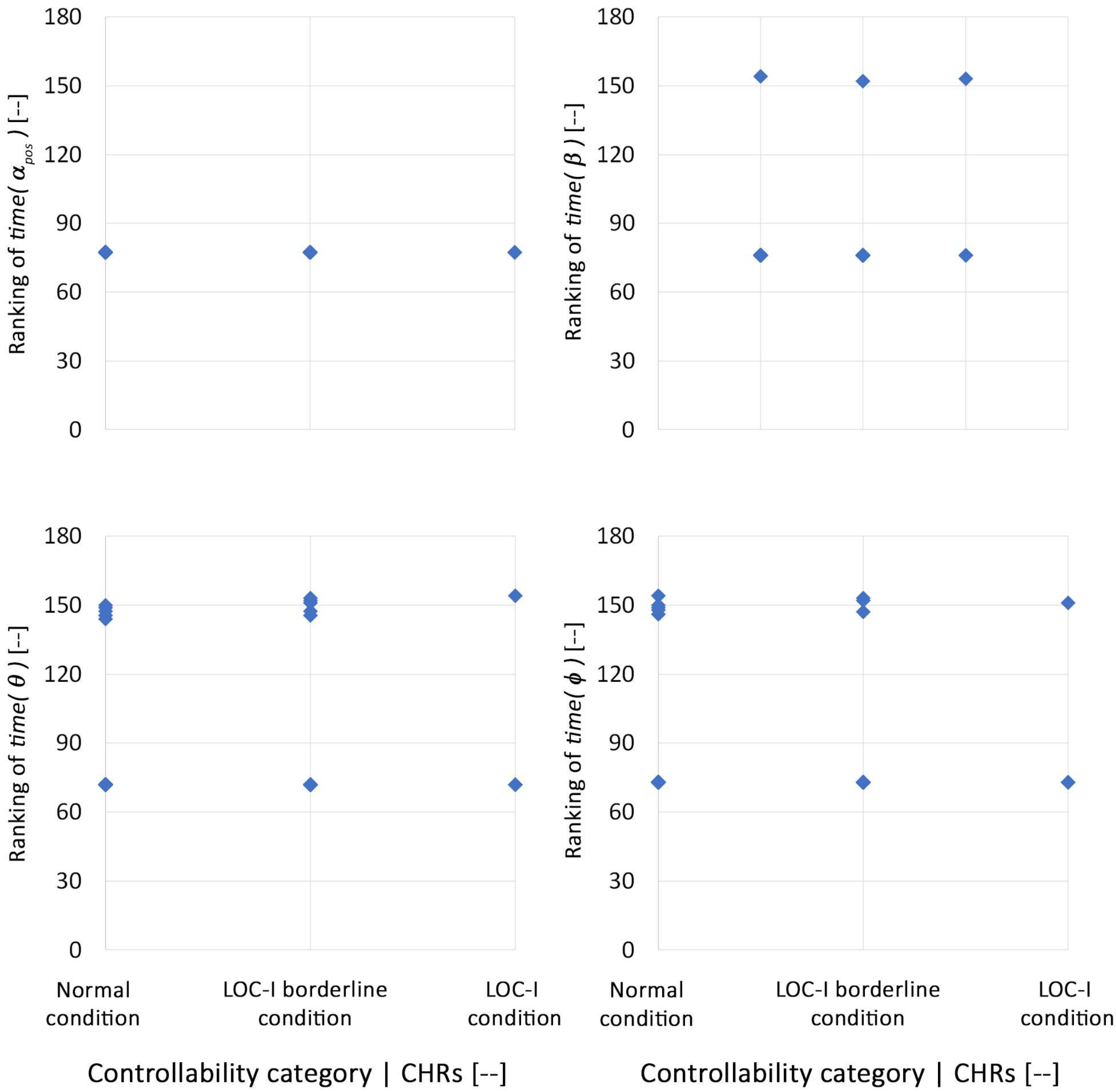


Figure 53: Relationship between the *controllability categories resulting from the CHRs* and the rankings of the *time interval of excursion* family (ordinal variable).
[Source: The author]

VI. *Controllability categories resulting from the CHRs* vs *Critical window*

- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *Critical window*: continuous, ratio.
- **Possible association tests:** again, after the ranking of the continuous variable, it was possible to apply
  - Spearman's rho; or
  - Kendall's tau-b (selected).

Figure 55 shows the relationship between the variables, which, although very close, was *not* monotonic. A considerable number of missing data was observed, and, again, **Kendall's tau-b** was chosen.

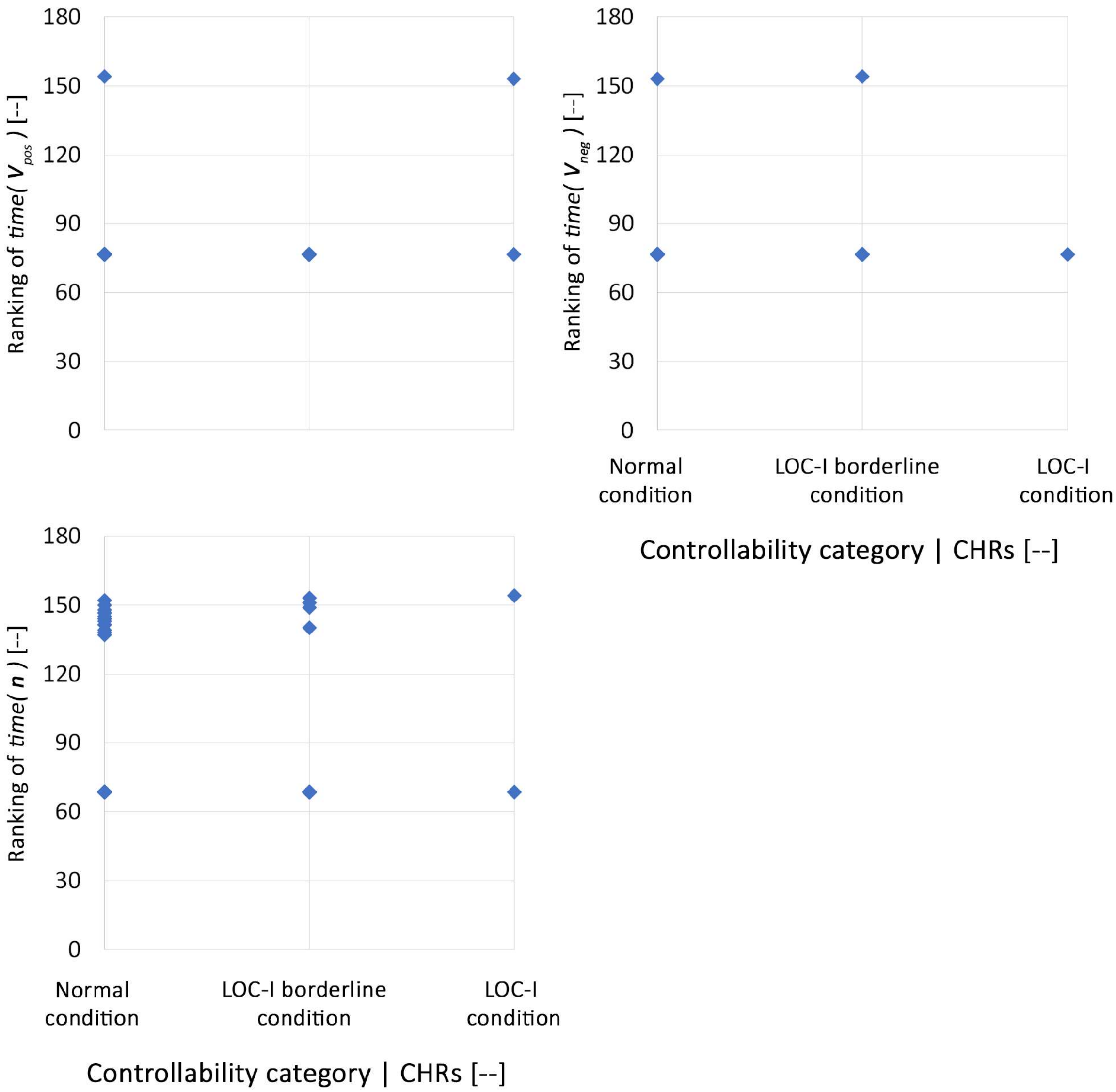


Figure 53: Relationship between the *controllability categories resulting from the CHRs* and the rankings of the *time interval of excursion* family (ordinal variable), Continued.
[Source: The author]

VII. *Controllability categories resulting from the CHRs* vs *Data concentration patterns*

- **Valid for**
  - Dynamic Pitch Control envelope (DPC);
  - Dynamic Roll Control envelope (DRC).
- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *Data concentration patterns*: categorical, dichotomous.
- **Possible association tests**
  - Cramer's V.

Table 20 shows the frequency distribution of the variables of interest and the occurrence of the undesirable condition of some cells with less than *five* expected counts (on three occasions

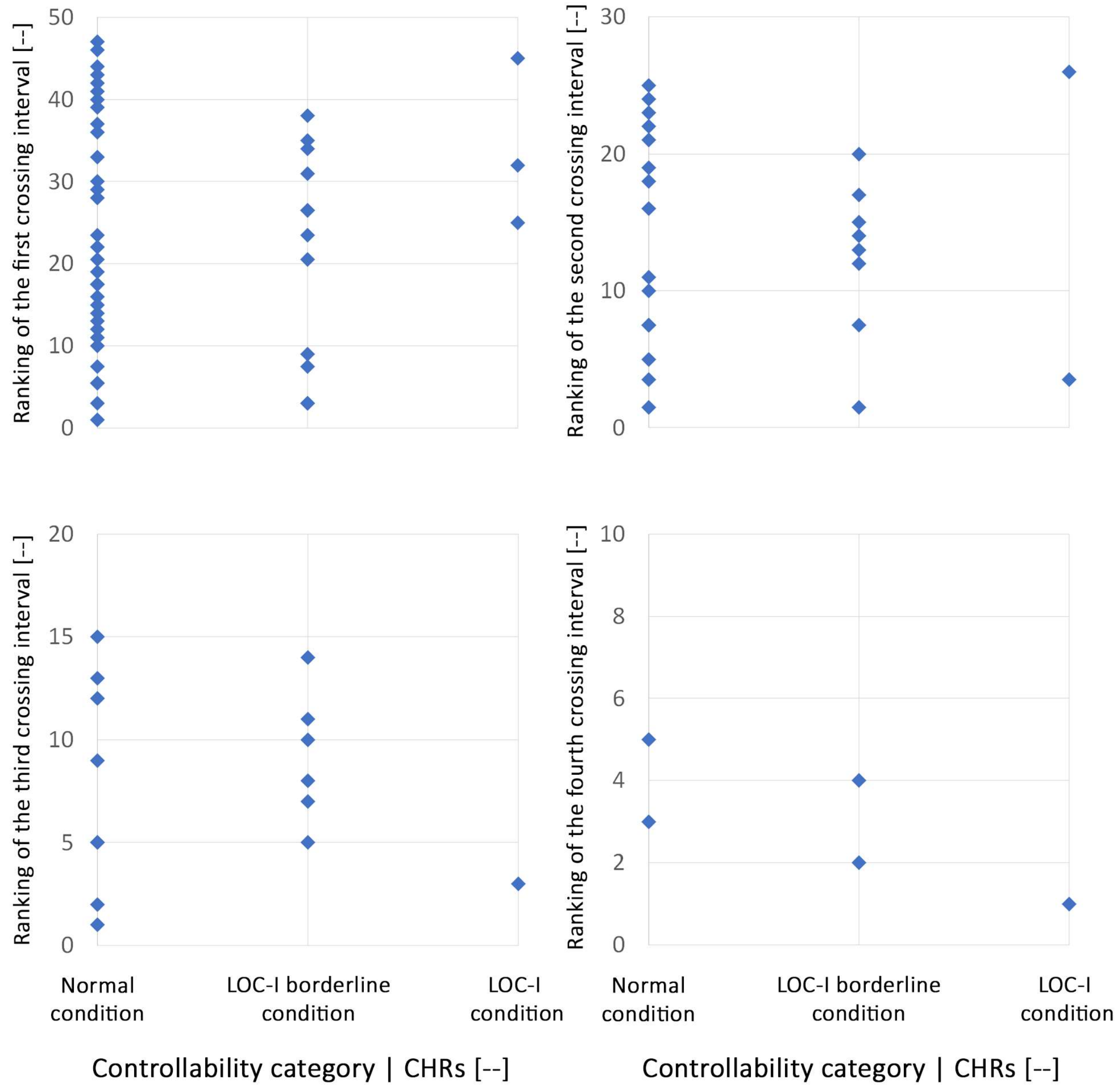


Figure 54: Relationship between the *controllability categories resulting from the CHRs* and the rankings of the *crossing intervals* (ordinal variable).
[Source: The author]

for DPC, and on two for DRC). Due to the uncertainty on the necessity of accomplishing such an assumption and the lack of another possible correlation test, Cramer's V was applied.

Table 20: Contingency table of the *Controllability categories resulting from the CHRs* and *Data concentration patterns*. The resulting chi-square values are also shown.
[Source: The author]

			Controllability category resulting from the CHRs						
			Normal condition		Borderline LOC-I condition		LOC-I condition		Chi-square value
			Count	Expected count	Count	Expected count	Count	Expected count	
Data concentration patterns	DPC quadrants	Squared	109	109.7	18	17.9	4	3.4	0.742
		Tapered	20	19.3	3	3.1	0	0.6	
	DRC quadrants	Squared	91	89.6	15	14.6	1	2.8	3.838
		Tapered	38	39.4	6	6.4	3	1.2	

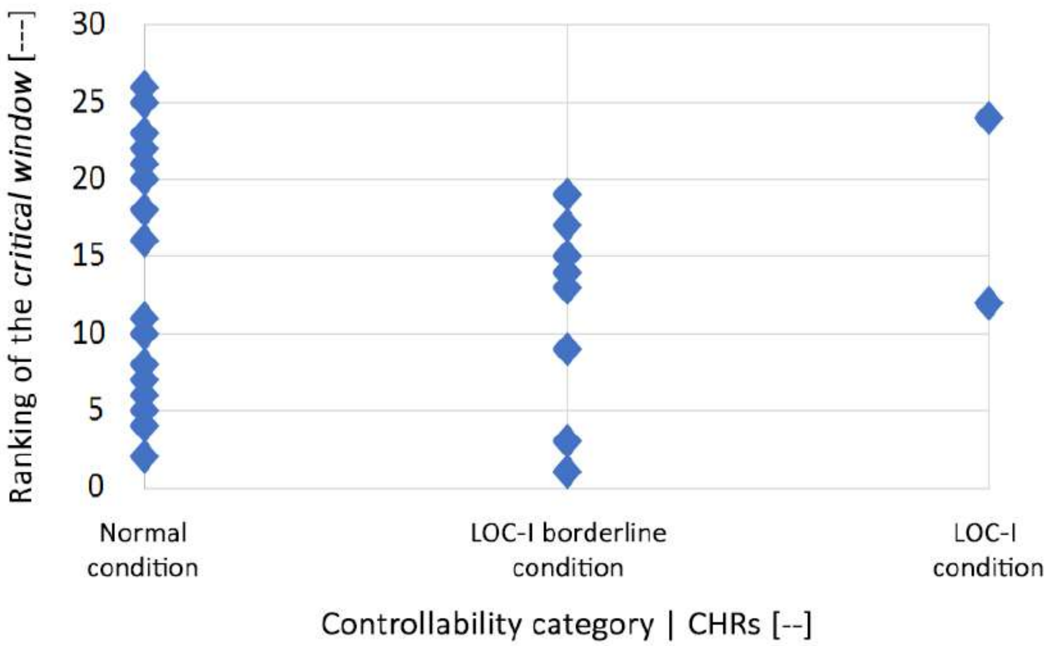


Figure 55: Relationship between the *controllability categories resulting from the CHRs* and the ranking of the *critical window* (ordinal variable).
[Source: The author]

VIII. *Controllability categories resulting from the CHRs* vs *Envelope crossed*

- **Types of variables**
  - *Controllability categories resulting from the CHRs*: categorical, ordinal;
  - *Envelope crossed*: categorical, dichotomous.
- **Possible association tests**
  - Cramer's V.

Table 21 is a cross-tabulation of the variables of interest. Similarly to the previous case, less than *five* expected counts were registered on some occasions (two for AA and DRC, and three for UA, SI and DPC). Given the lack of another possible correlation test, Cramer's V was applied.

Table 21: Contingency table of the *Controllability categories resulting from the CHRs* and *Envelope crossed*. The resulting chi-square values are also shown.
[Source: The author]

			Controllability category resulting from the CHRs						Chi-square value
			Normal condition		Borderline LOC-I condition		LOC-I condition		
			Count	Expected count	Count	Expected count	Count	Expected count	
Specific envelope crossed	**AA**	**Envelope not crossed**	101	96.3	12	15.7	2	3	5.595
		Envelope crossed	28	32.7	9	5.3	2	1	
	UA	**Envelope not crossed**	119	113.9	14	18.5	3	3.5	12.15
		Envelope crossed	10	15.1	7	2.5	1	0.5	
	SI	**Envelope not crossed**	115	112.2	16	18.3	3	3.5	3.207
		Envelope crossed	14	16.8	5	2.7	1	0.5	
	DPC	**Envelope not crossed**	108	98.8	9	16.1	1	3.1	22.94
		Envelope crossed	21	30.2	12	4.9	3	0.9	
	DRC	**Envelope not crossed**	75	70.4	9	11.5	0	2.2	6.629
		Envelope crossed	54	58.6	12	9.5	4	1.8	

D.5 Statistical significance

Since samples were used in this study (i.e., only six out of millions of pilots worldwide), the significance of the results was interpreted against a larger population for extrapolating the conclusions. Briefly speaking, a result is statistically significant when evidence show it was not obtained from a sampling error or by chance. In practical terms, a statistical significance level (α) is set ($\alpha = 0.05$ or 0.01, typically) and the so-called $p - value$ is calculated; if $p - value \leq \alpha$, the characteristics observed in a test can be extended to a whole population. Detailed explanations can be found in Walpole (2011).[80]

APPENDIX E – DATA OF EACH PILOT

This annexe provides individual pilot data collected in the experiments, including **(i)** CHRs assigned in each task, **(ii)** RMS of pilot control deflections (for all three axes), **(iii)** RMS of pilot control deflection rates (for all three axes), and **(iv)** number of QLC envelopes crossed.

Such data are plotted in four graphs divided over two pages. Since the scale of the vertical axis varies from graph to graph (even for the same pilot), the reader is advised to read the plots carefully.

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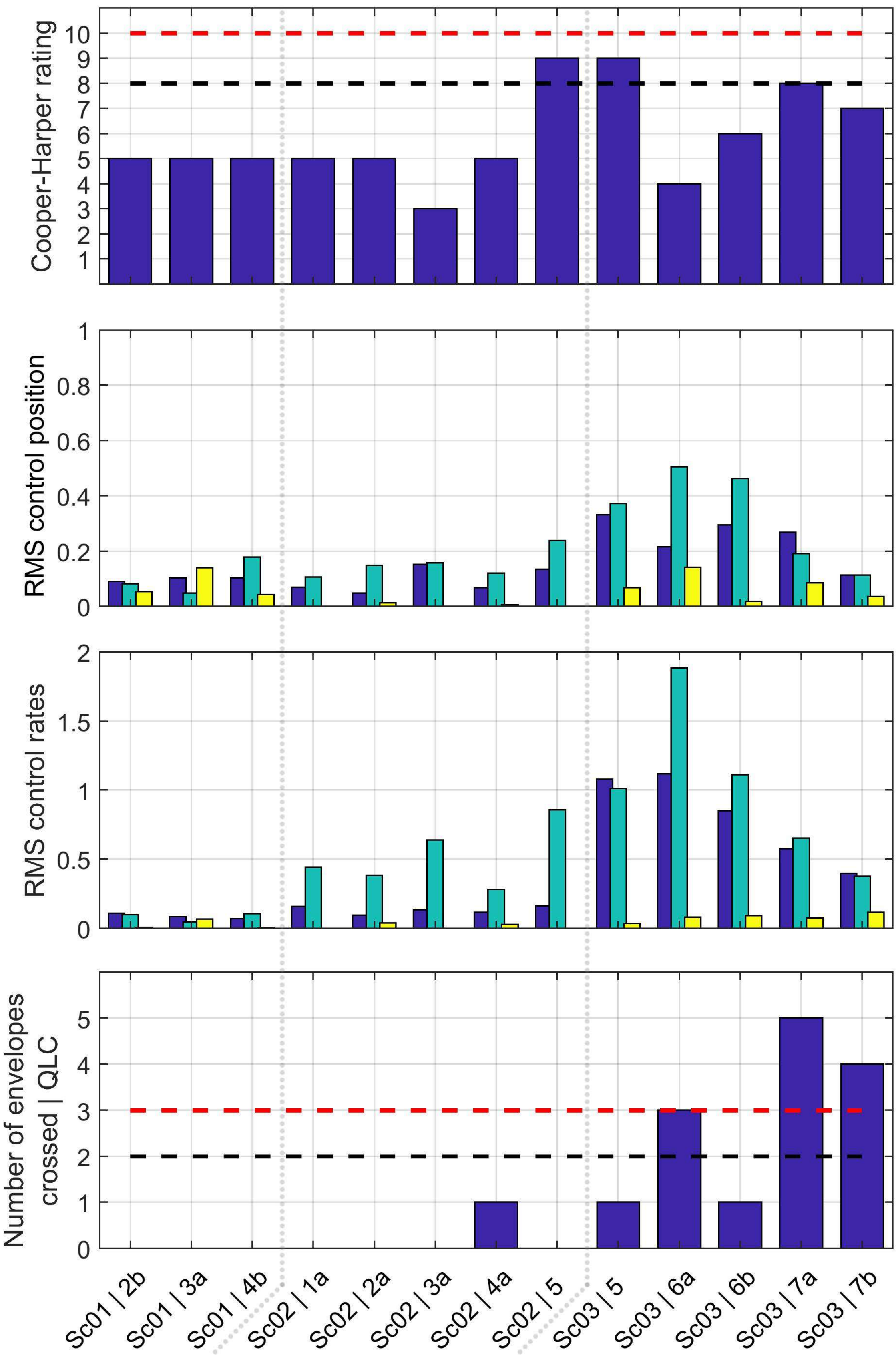
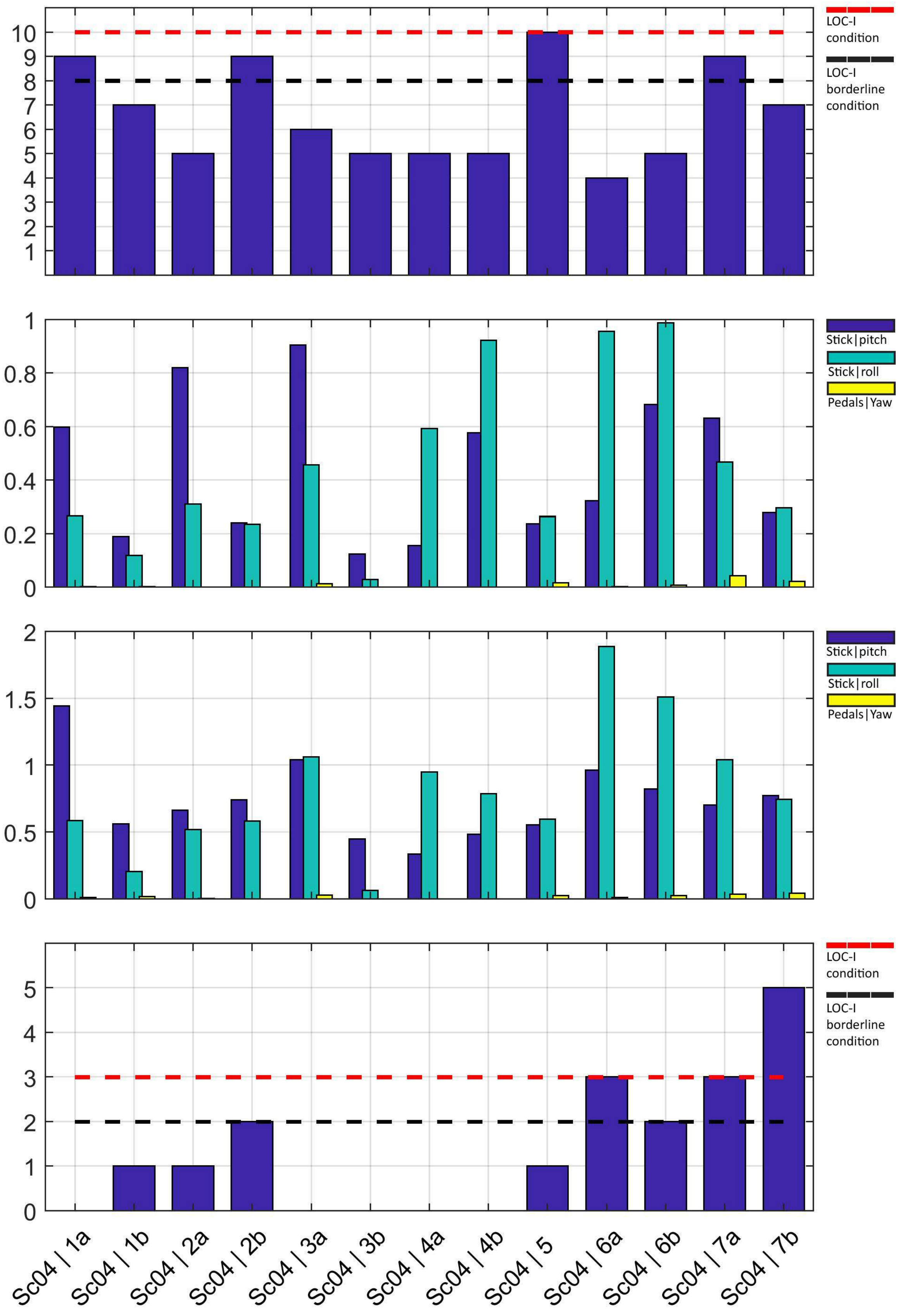
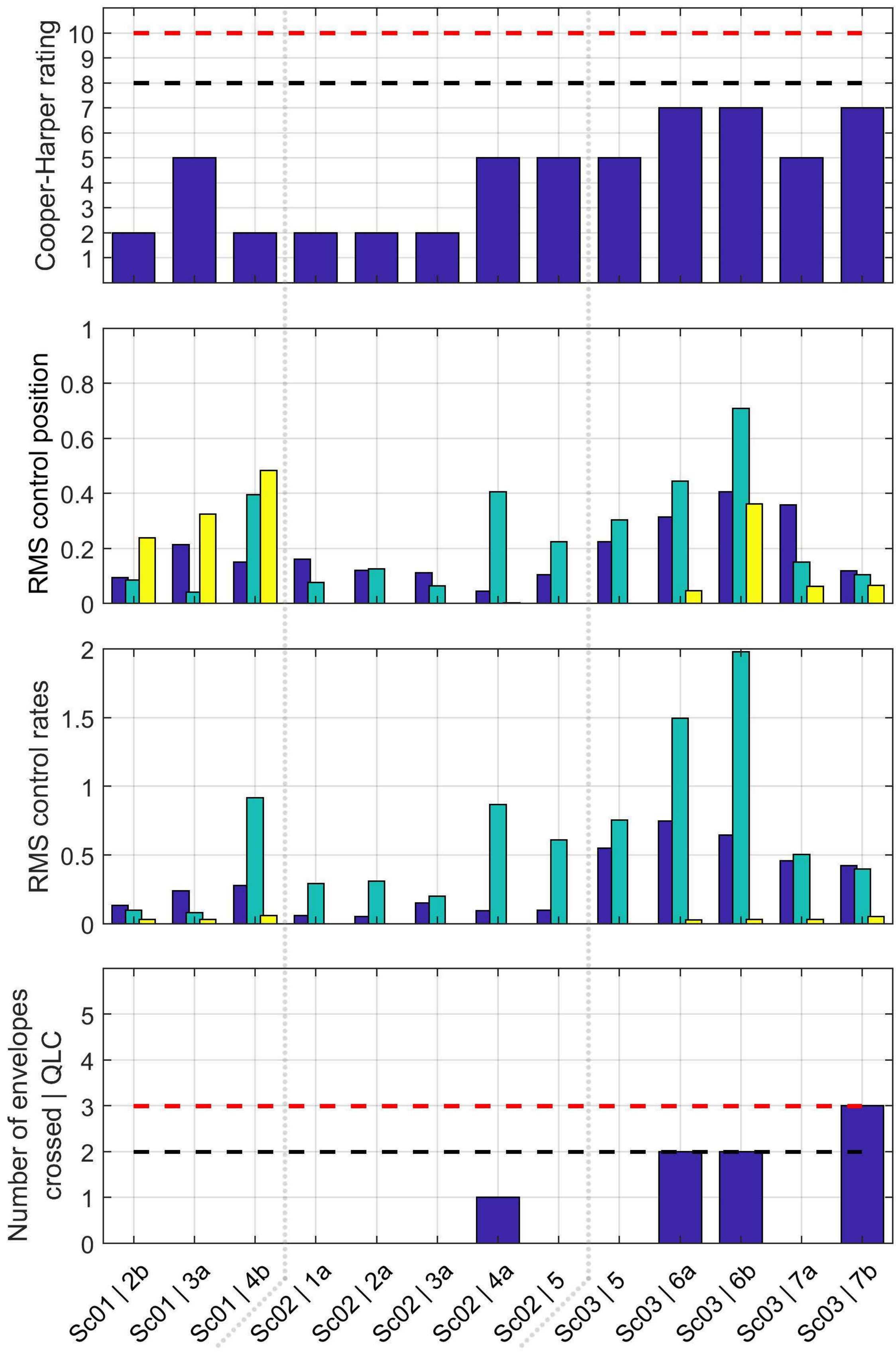
Pilot | 'p01'

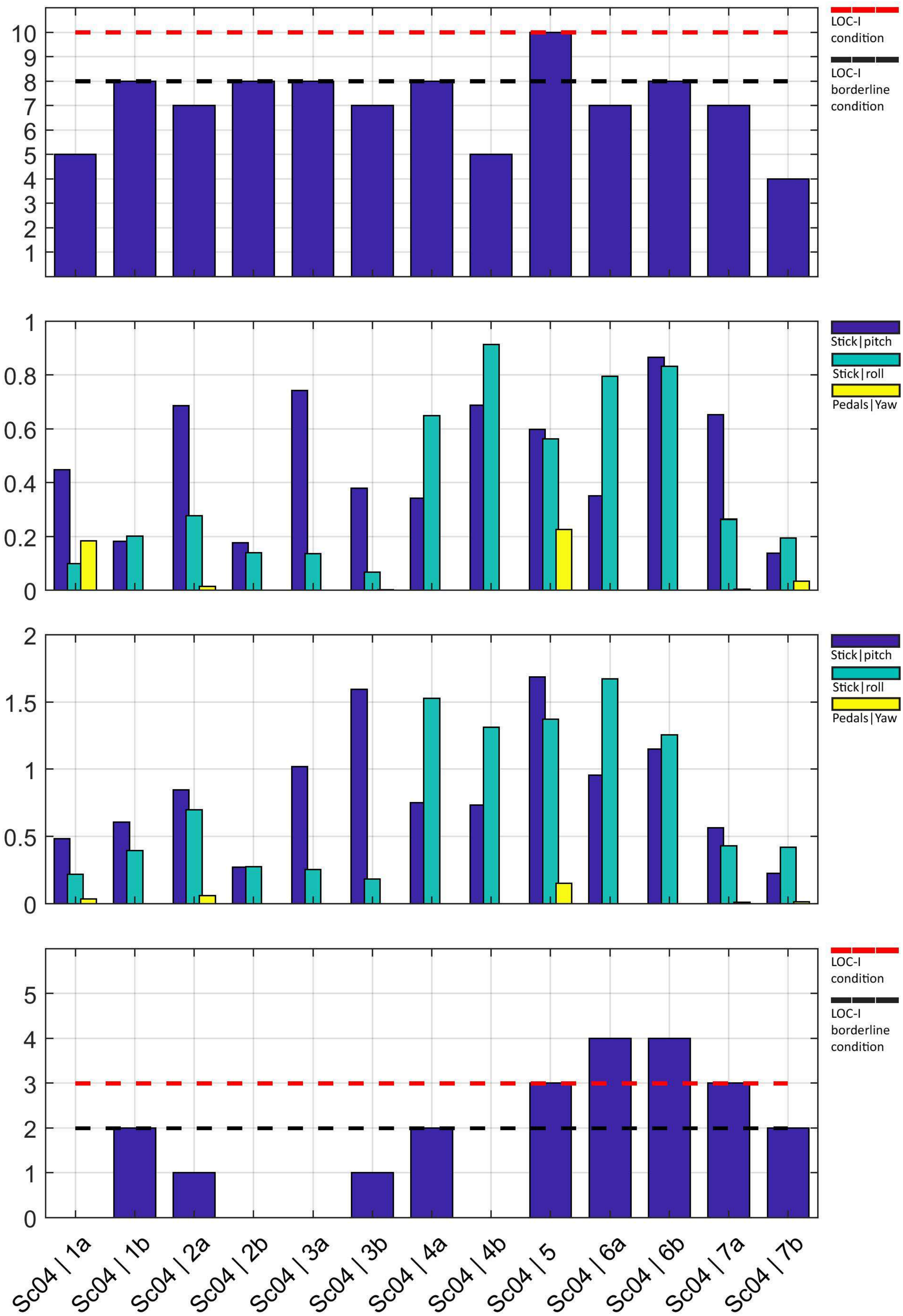

Cooper-Harper rating
1
2
3
4
5
6
7
8
9
10
RMS control position
0
0.2
0.4
0.6
0.8
1
RMS control rates
0
0.5
1
1.5
2
Number of envelopes crossed | QLC
0
1
2
3
4
5
Sc01 | 2b
Sc01 | 3a
Sc01 | 4b
Sc02 | 1a
Sc02 | 2a
Sc02 | 3a
Sc02 | 4a
Sc02 | 5
Sc03 | 5
Sc03 | 6a
Sc03 | 6b
Sc03 | 7a
Sc03 | 7b



LOC-I condition
LOC-I borderline condition
Stick|pitch
Stick|roll
Pedals|Yaw
Stick|pitch
Stick|roll
Pedals|Yaw
LOC-I condition
LOC-I borderline condition
Sc04 | 1a
Sc04 | 1b
Sc04 | 2a
Sc04 | 2b
Sc04 | 3a
Sc04 | 3b
Sc04 | 4a
Sc04 | 4b
Sc04 | 5
Sc04 | 6a
Sc04 | 6b
Sc04 | 7a
Sc04 | 7b

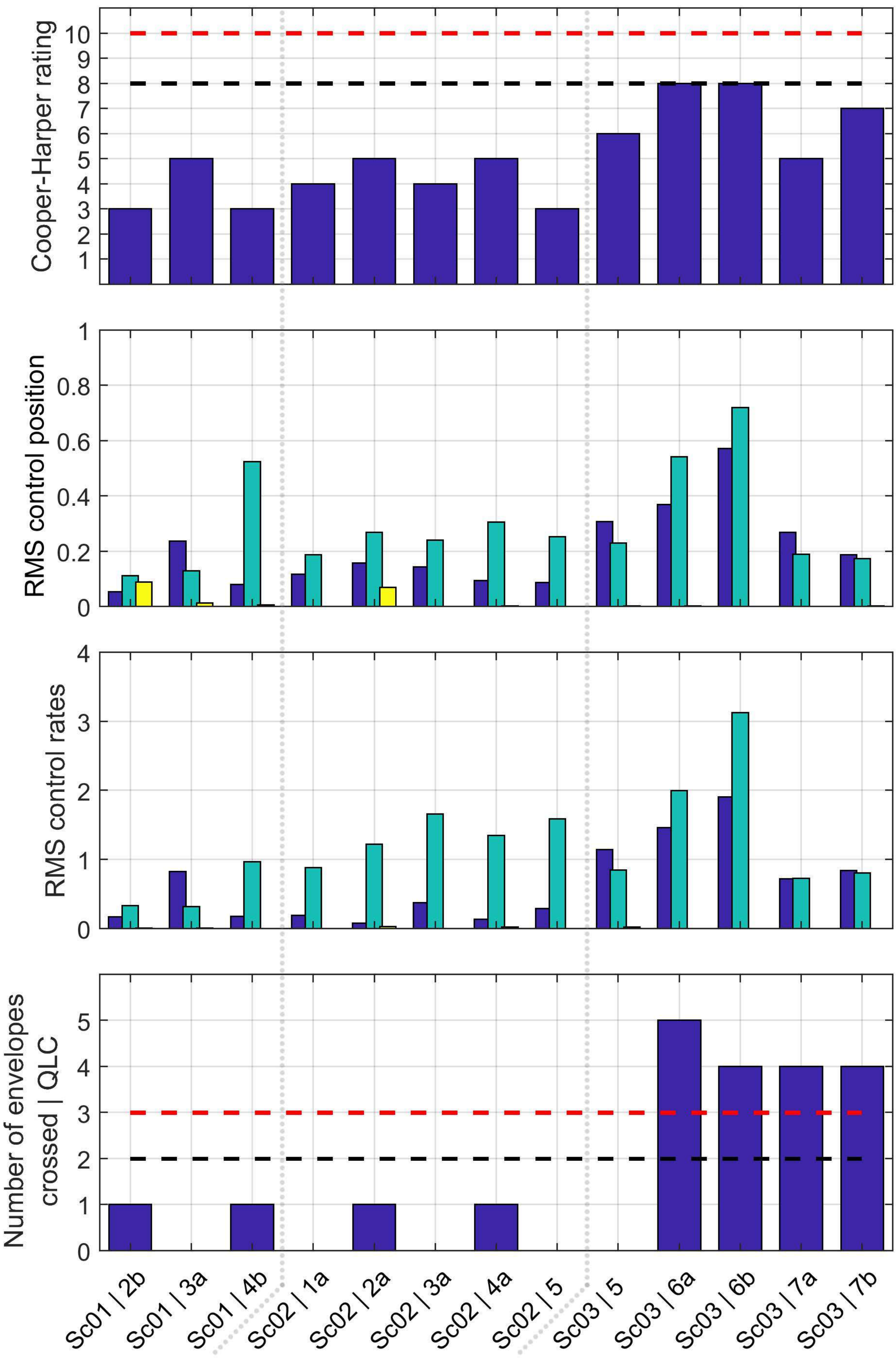
Pilot | 'p02'

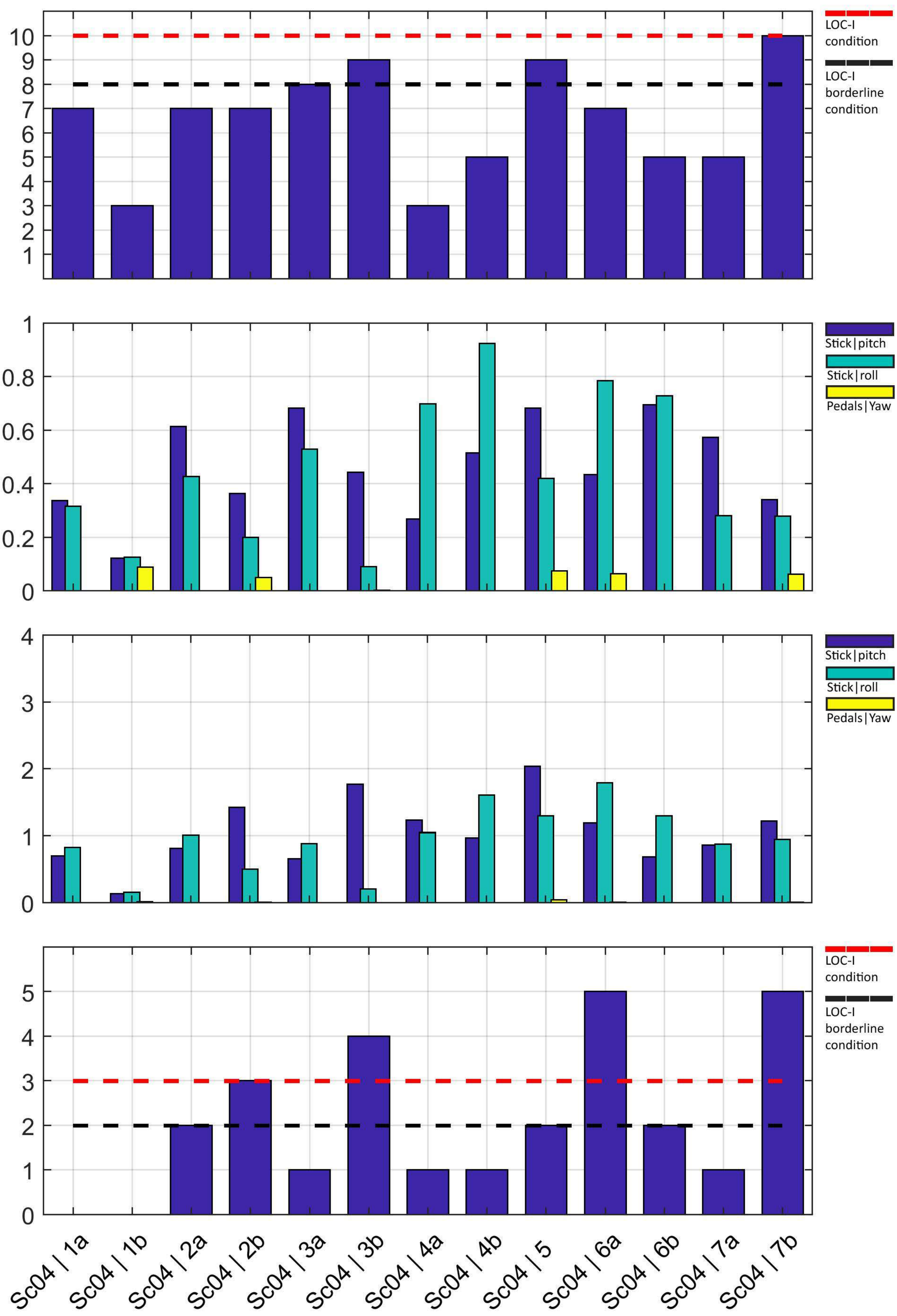

Cooper-Harper rating
RMS control position
RMS control rates
Number of envelopes crossed | QLC
Sc01 | 2b
Sc01 | 3a
Sc01 | 4b
Sc02 | 1a
Sc02 | 2a
Sc02 | 3a
Sc02 | 4a
Sc02 | 5
Sc03 | 5
Sc03 | 6a
Sc03 | 6b
Sc03 | 7a
Sc03 | 7b



LOC-I condition
LOC-I borderline condition
Stick|pitch
Stick|roll
Pedals|Yaw
Sc04 | 1a
Sc04 | 1b
Sc04 | 2a
Sc04 | 2b
Sc04 | 3a
Sc04 | 3b
Sc04 | 4a
Sc04 | 4b
Sc04 | 5
Sc04 | 6a
Sc04 | 6b
Sc04 | 7a
Sc04 | 7b

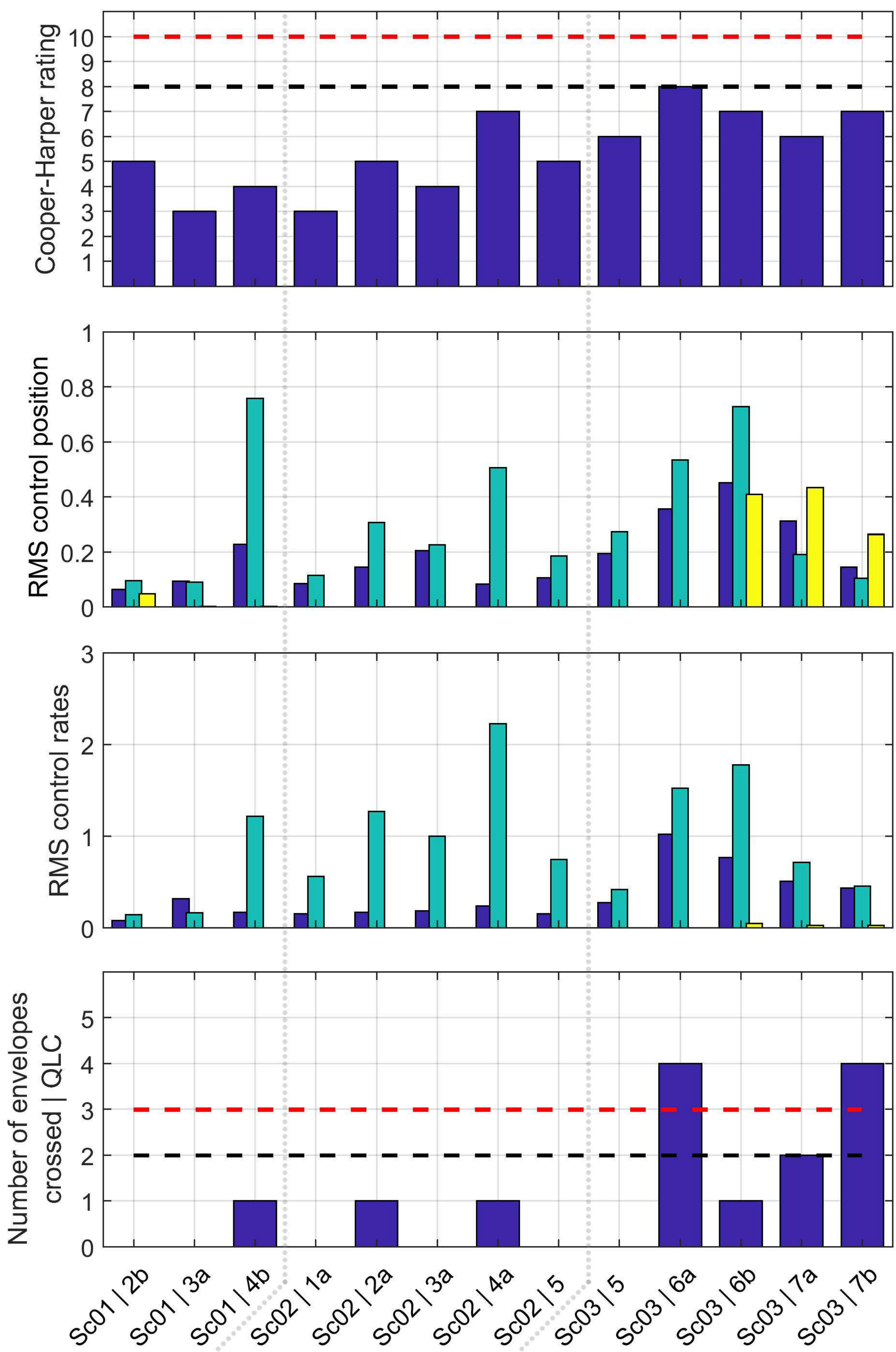
Pilot | ’p03’

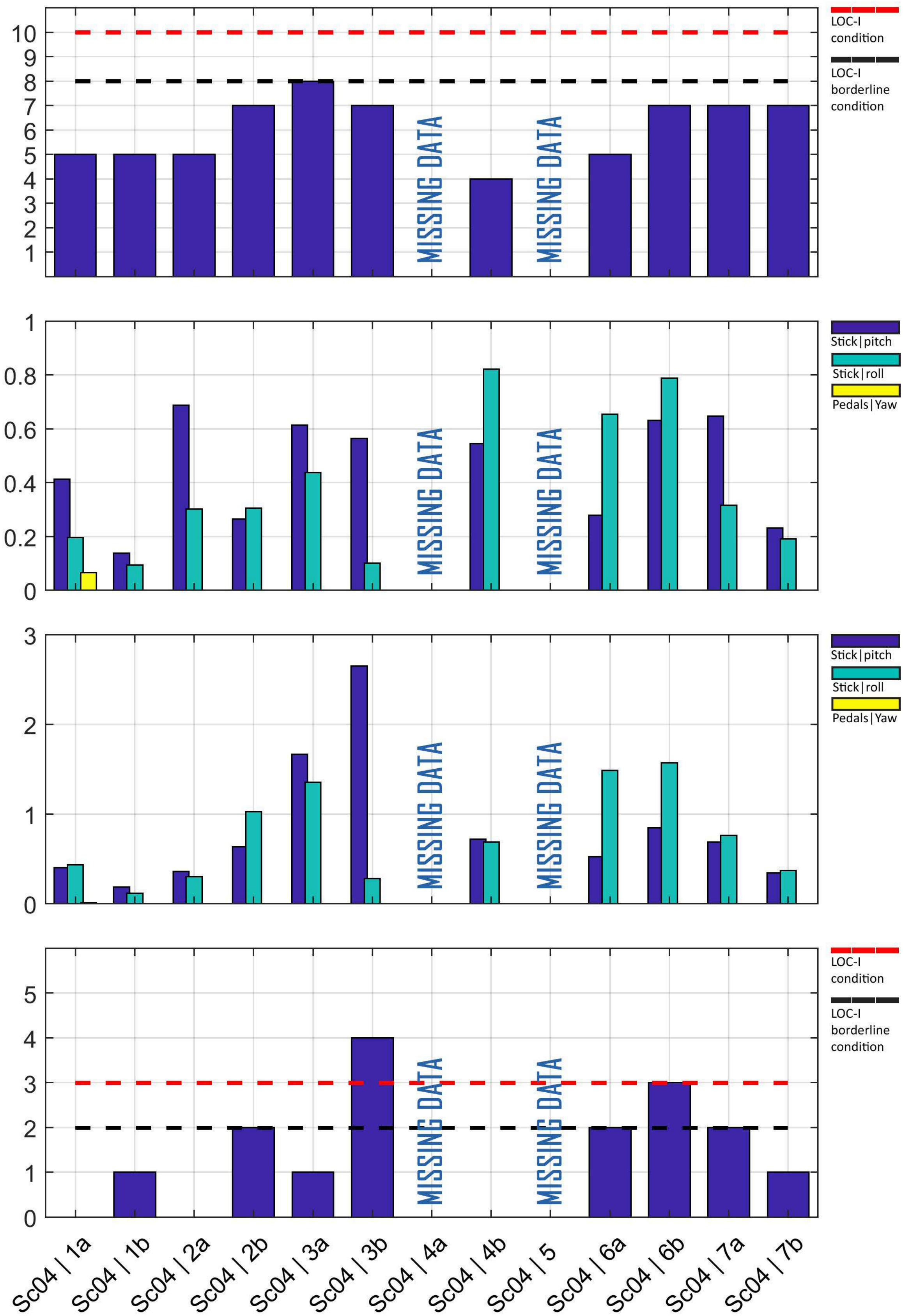

Cooper-Harper rating
RMS control position
RMS control rates
Number of envelopes crossed | QLC
Sc01 | 2b
Sc01 | 3a
Sc01 | 4b
Sc02 | 1a
Sc02 | 2a
Sc02 | 3a
Sc02 | 4a
Sc02 | 5
Sc03 | 5
Sc03 | 6a
Sc03 | 6b
Sc03 | 7a
Sc03 | 7b



LOC-I condition
LOC-I borderline condition
Stick|pitch
Stick|roll
Pedals|Yaw
Stick|pitch
Stick|roll
Pedals|Yaw
LOC-I condition
LOC-I borderline condition
Sc04 | 1a
Sc04 | 1b
Sc04 | 2a
Sc04 | 2b
Sc04 | 3a
Sc04 | 3b
Sc04 | 4a
Sc04 | 4b
Sc04 | 5
Sc04 | 6a
Sc04 | 6b
Sc04 | 7a
Sc04 | 7b

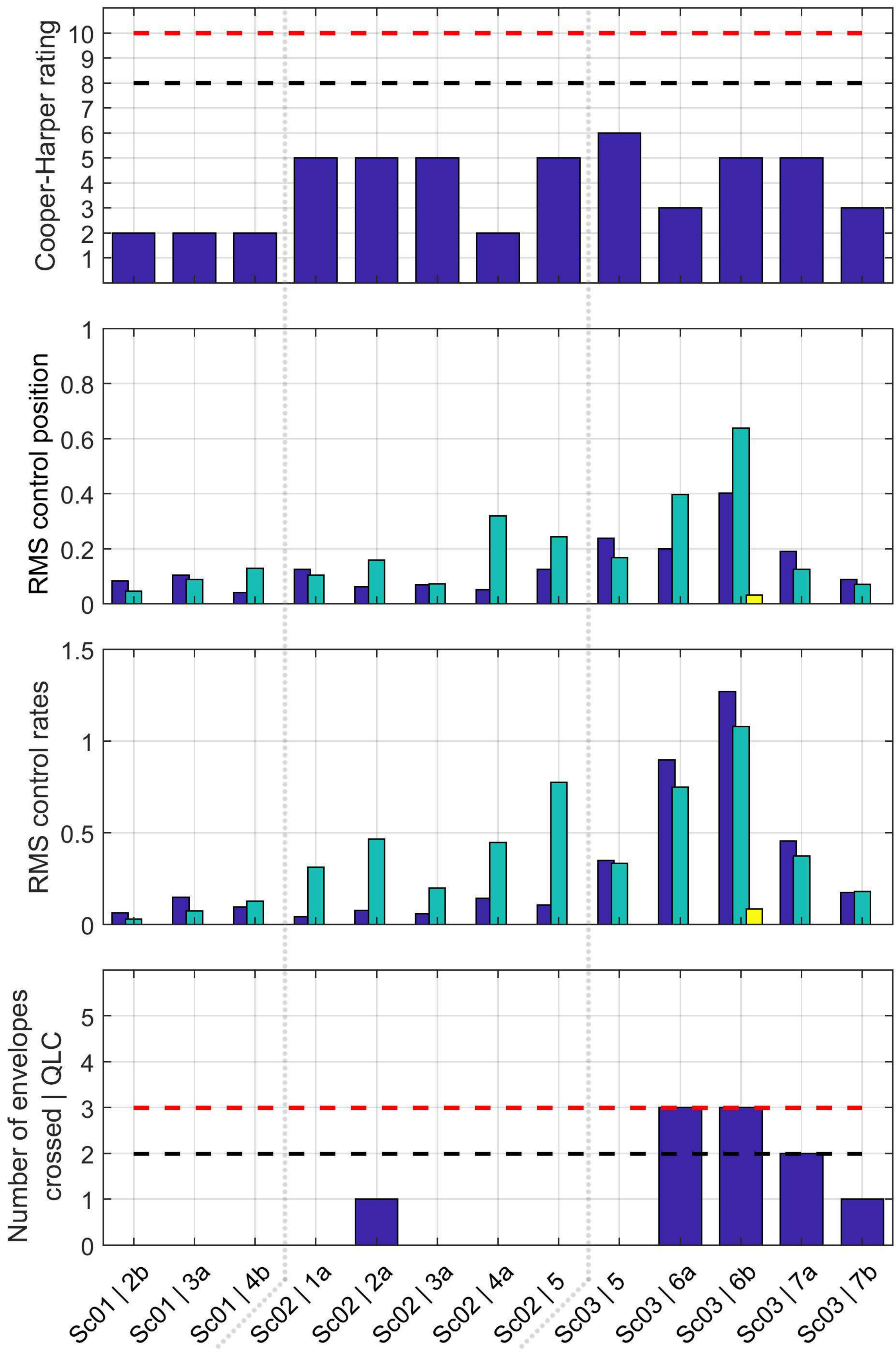
Pilot | 'p04'

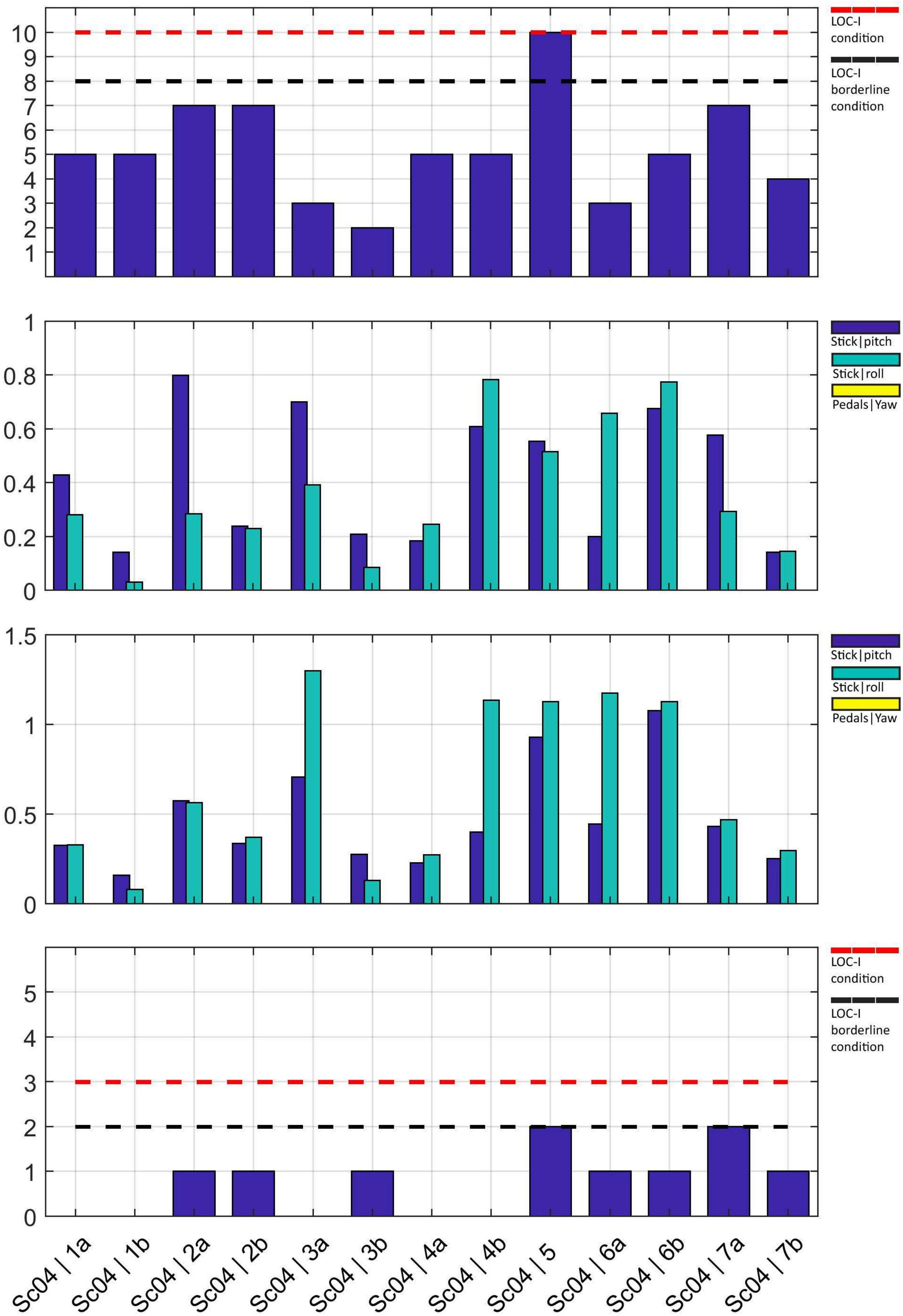

Cooper-Harper rating
10
9
8
7
6
5
4
3
2
1
RMS control position
1
0.8
0.6
0.4
0.2
0
RMS control rates
3
2
1
0
Number of envelopes crossed | QLC
5
4
3
2
1
0
Sc01 | 2b
Sc01 | 3a
Sc01 | 4b
Sc02 | 1a
Sc02 | 2a
Sc02 | 3a
Sc02 | 4a
Sc02 | 5
Sc03 | 5
Sc03 | 6a
Sc03 | 6b
Sc03 | 7a
Sc03 | 7b



LOC-I condition
LOC-I borderline condition
Stick|pitch
Stick|roll
Pedals|Yaw
MISSING DATA
MISSING DATA
Sc04 | 1a
Sc04 | 1b
Sc04 | 2a
Sc04 | 2b
Sc04 | 3a
Sc04 | 3b
Sc04 | 4a
Sc04 | 4b
Sc04 | 5
Sc04 | 6a
Sc04 | 6b
Sc04 | 7a
Sc04 | 7b

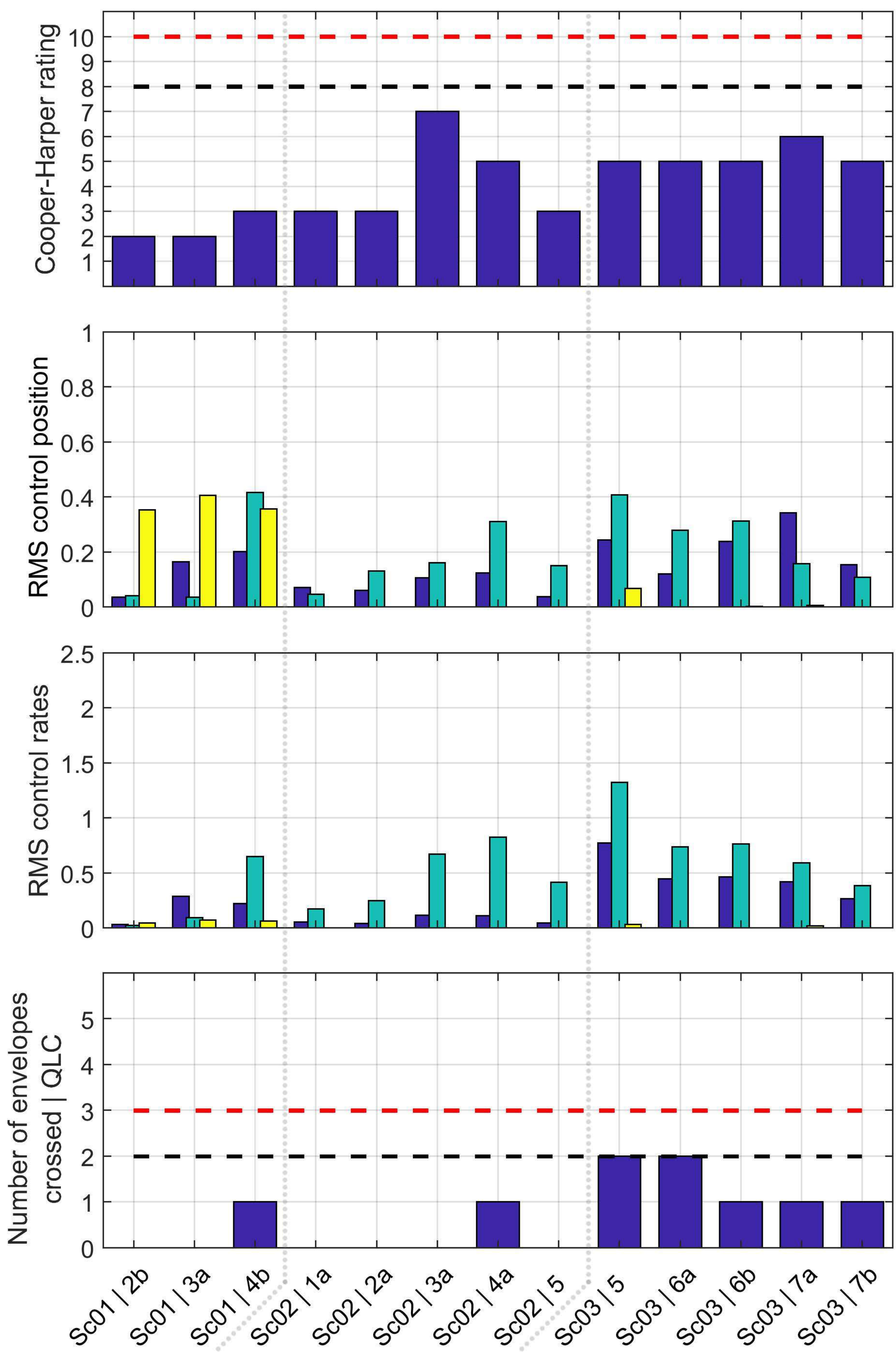
Pilot | 'p05'


Cooper-Harper rating
10
9
8
7
6
5
4
3
2
1
RMS control position
1
0.8
0.6
0.4
0.2
0
RMS control rates
1.5
1
0.5
0
Number of envelopes crossed | QLC
5
4
3
2
1
0
Sc01 | 2b
Sc01 | 3a
Sc01 | 4b
Sc02 | 1a
Sc02 | 2a
Sc02 | 3a
Sc02 | 4a
Sc02 | 5
Sc03 | 5
Sc03 | 6a
Sc03 | 6b
Sc03 | 7a
Sc03 | 7b

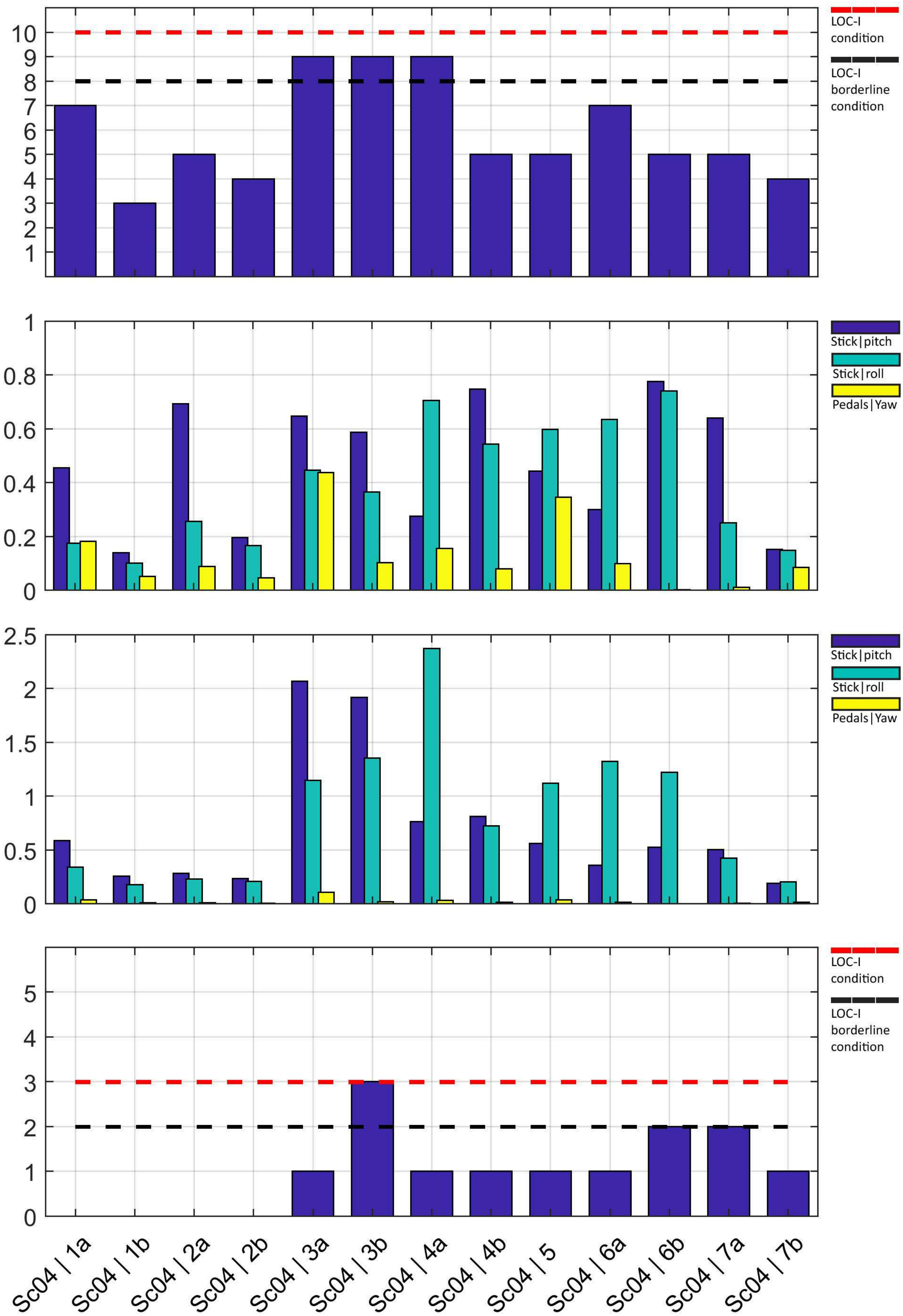


10
9
8
7
6
5
4
3
2
1
LOC-I condition
LOC-I borderline condition
1
0.8
0.6
0.4
0.2
0
Stick|pitch
Stick|roll
Pedals|Yaw
1.5
1
0.5
0
Stick|pitch
Stick|roll
Pedals|Yaw
5
4
3
2
1
0
LOC-I condition
LOC-I borderline condition
Sc04 | 1a
Sc04 | 1b
Sc04 | 2a
Sc04 | 2b
Sc04 | 3a
Sc04 | 3b
Sc04 | 4a
Sc04 | 4b
Sc04 | 5
Sc04 | 6a
Sc04 | 6b
Sc04 | 7a
Sc04 | 7b

Pilot | 'p06'

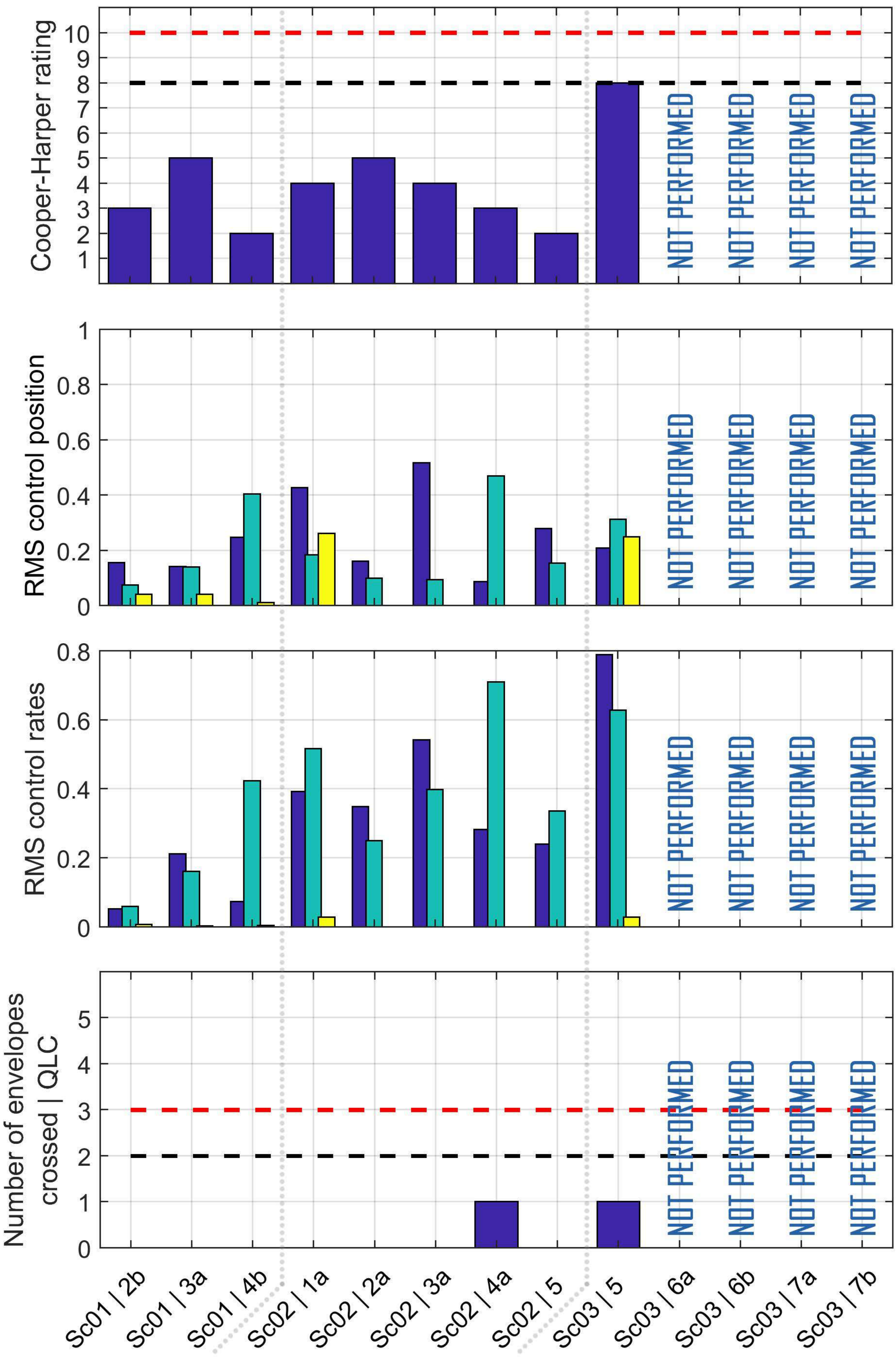


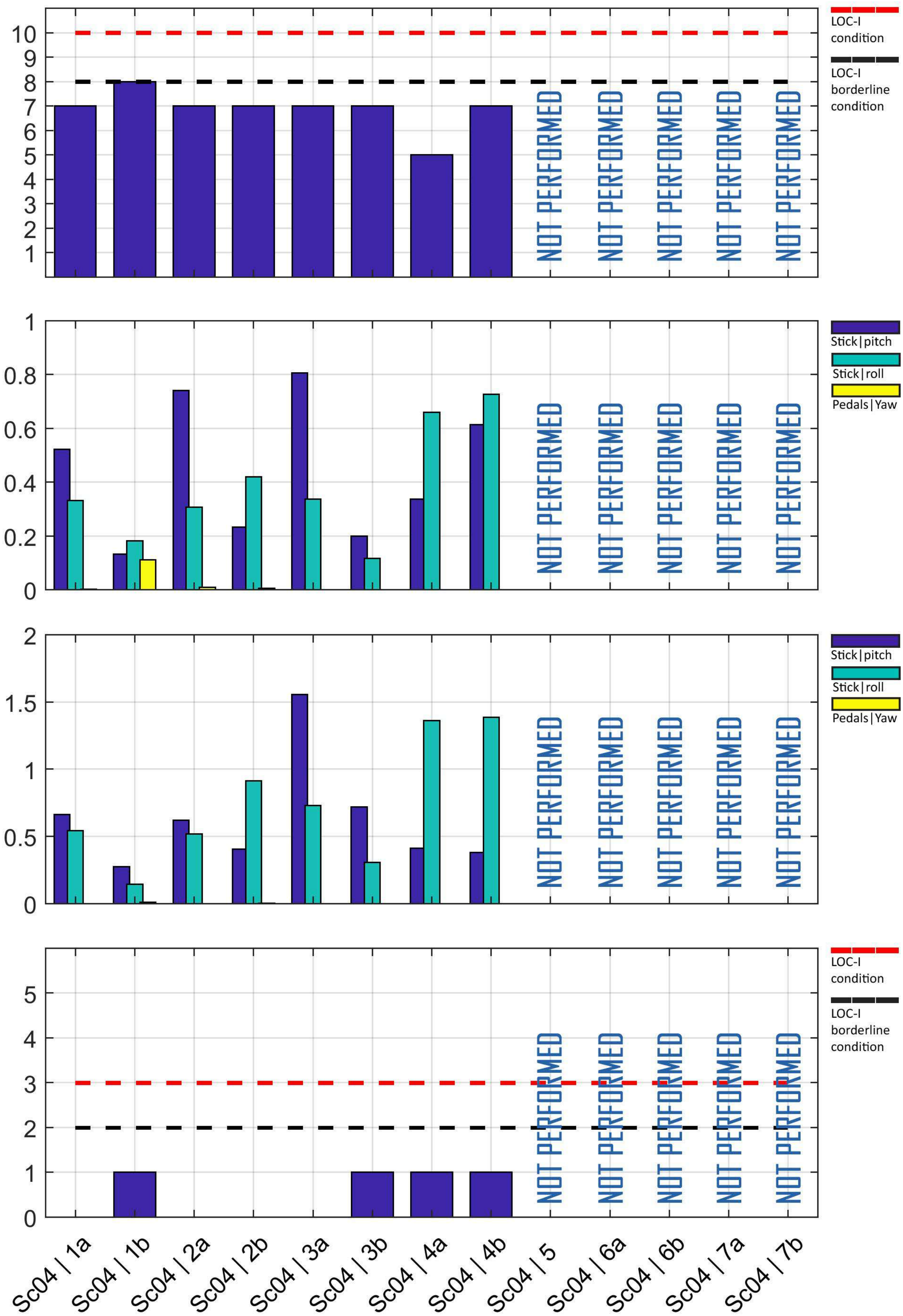
Cooper-Harper rating
10
9
8
7
6
5
4
3
2
1
RMS control position
1
0.8
0.6
0.4
0.2
0
RMS control rates
2.5
2
1.5
1
0.5
0
Number of envelopes crossed | QLC
5
4
3
2
1
0
Sc01 | 2b
Sc01 | 3a
Sc01 | 4b
Sc02 | 1a
Sc02 | 2a
Sc02 | 3a
Sc02 | 4a
Sc02 | 5
Sc03 | 5
Sc03 | 6a
Sc03 | 6b
Sc03 | 7a
Sc03 | 7b



LOC-I condition
LOC-I borderline condition
Stick|pitch
Stick|roll
Pedals|Yaw
Sc04 | 1a
Sc04 | 1b
Sc04 | 2a
Sc04 | 2b
Sc04 | 3a
Sc04 | 3b
Sc04 | 4a
Sc04 | 4b
Sc04 | 5
Sc04 | 6a
Sc04 | 6b
Sc04 | 7a
Sc04 | 7b

Pilot | 'p07'


Cooper-Harper rating
RMS control position
RMS control rates
Number of envelopes crossed | QLC
NOT PERFORMED
Sc01 | 2b
Sc01 | 3a
Sc01 | 4b
Sc02 | 1a
Sc02 | 2a
Sc02 | 3a
Sc02 | 4a
Sc02 | 5
Sc03 | 5
Sc03 | 6a
Sc03 | 6b
Sc03 | 7a
Sc03 | 7b


LOC-I condition
LOC-I borderline condition
Stick|pitch
Stick|roll
Pedals|Yaw
NOT PERFORMED
Sc04 | 1a
Sc04 | 1b
Sc04 | 2a
Sc04 | 2b
Sc04 | 3a
Sc04 | 3b
Sc04 | 4a
Sc04 | 4b
Sc04 | 5
Sc04 | 6a
Sc04 | 6b
Sc04 | 7a
Sc04 | 7b

ANNEXES

ANNEXE A – LOC-I TEST SCENARIOS

This annexe presents the set of 60 LOC-I test scenarios conceived by C. Belcastro in "Validation of Safety-Critical Systems for Aircraft Loss-of-Control Prevention and Recovery".[41]

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
				Single Precursor LOC Scenarios: Vehicle Failure, Damage			
1	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Flight Control Component Failure (Control Surface Actuator)	Takeoff (Repeat for Approach, Cruise)	Jammed Surface Actuator (Varying Positions from Neutral to Hard-over)			
2	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Flight Control Component Failure (Control Surface Actuator)	Takeoff (Repeat for Approach, Cruise)	Loss of Control Effectiveness (25%, 50%, 75%, 100%)			
3	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Flight Control Component Failure (Engine)	Takeoff (Repeat for Approach, Cruise)	Single Engine Failure (25%, 50%, 75%, 100% Thrust Reduction)			
4	Analysis, Batch Simulation, Piloted Simulation	Flight Control Component Failure (Engine)	Takeoff (Repeat for Approach, Cruise)	Double Engine Failure (25%, 50%, 75%, 100% Thrust Reduction)			
5	Analysis, Batch Simulation, Piloted Simulation	Flight Control Component Failure (Actuator)	Landing (Repeat for Takeoff, Cruise)	Control Effector Reversal			
6	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Vehicle Impairment Resulting from Overweight / Improper Loading	Cruise (Repeat for Takeoff, Approach)	Variations in Weight & C.G. location			
7	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Vehicle Dynamics Changes Resulting from Damage Conditions	Cruise (Repeat for Takeoff, Approach)	Fuselage Damage			

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
8	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Uncontained Engine Failure Resulting in Vehicle Damage	Cruise (Repeat for Takeoff, Approach)	Structural Damage (Lifting Surface, Control Surface, Fuselage); Single Engine Thrust Set to 0			
9	Analysis, Batch Simulation, Piloted Simulation	Uncontained Engine Failure Resulting in Vehicle Damage	Cruise (Repeat for Takeoff, Approach)	Structural Damage (Lifting Surface, Control Surface, Fuselage); Single Engine Thrust Set to 0, Loss of Control Effectors due to Cut Hydraulics Lines (Varying Levels of Loss from 1 to All), Collateral Damage to Underlying Systems			
10	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Vehicle Dynamics Changes Resulting from Icing Conditions	Approach, Cruise, Takeoff	Varying Levels of Vehicle Dynamics Changes under Ice Accretion (from Mild Through Destabilizing), Varying Degrees of Control Effectiveness Loss (Control Surfaces, Engines, Both)			
Single Precursor LOC Scenarios: External Hazard							
11	Analysis, Batch Simulation, Piloted Simulation	Wind Shear / Turbulence	Approach (Repeat for Takeoff)			Various Wind Shear Profiles (from Mild to Severe), Varying Levels of Turbulence (Light, Medium, Heavy)	
12	Analysis, Batch Simulation, Piloted Simulation	Wake Vortex Encounter	Approach (Repeat for Takeoff)			Varying Wake Profiles, Intensities, and Incidence Angles	
Two Precursor LOC Scenarios: Crew Error –> Upset							
13	Analysis, Batch Simulation, Piloted Simulation	Inadvertent Control Input by Crew followed by Abnormal Attitude Upset	Cruise (Repeat for Takeoff, Approach)		1. Inadvertent Pitch Down Command (Repeat for Roll, Yaw)		2. Undesired Change in Pitch (Roll, Yaw)
14	Piloted Simulation	Inadvertent Autopilot Disengage by Crew Leading to Stall/Spin	Cruise (Repeat for Takeoff, Approach)		1. Inadvertent Disengage Control of Ailerons (Repeat for Elevator, Rudder, Throttle)		2. Stall / Spin

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	**Adverse Onboard Conditions** Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	**Inappropriate Crew Response** PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	**External Hazards & Disturbances** Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	**Vehicle Upset Conditions** Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
15	Piloted Simulation	Inappropriate Control inputs on Go-around Leading to Stall	Approach		1. Poor Energy Management on Go-around (Continued Aft Column with Reducing Airspeed)		2. Pitch Up, Decreased Airspeed
16	Piloted Simulation	Failure to Recover from Stall due to Distraction	Approach, Takeoff		1. Distraction (Traffic Pattern, Fatigue) Resulting in No Response or Delayed / Ineffective Response		2. Stall
17	Piloted Simulation	Upset Resulting from Inappropriate Piloting Technique on Final Approach	Approach (Repeat for Takeoff)		1. Inappropriate Piloting Technique on Approach / Takeoff, Ineffective Recovery		2. Various Upset Conditions
Two Precursor LOC Scenarios: Vehicle Problem –> Upset							
18	Analysis, Batch Simulation, Piloted Simulation	Failure in Inertial Reference Unit Leading to Vehicle Upset (Abnormal Attitude / Stall / Uncontrolled Descent)	Cruise (Repeat for Approach, Takeoff)	1. Error in Attitude (Pitch, Roll, Yaw) Measurement			2. Undesired Pitch, Roll, Yaw from Autopilot (or Commanded by Crew)
19	Analysis, Batch Simulation, Piloted Simulation	Incorrect Flap Setting on Takeoff Leading to Stall	Takeoff (Repeat for Approach)	1. Various Flap Settings (from 0 to less than full)			2. Stall
20	Analysis, Batch Simulation, Piloted Simulation	Unresponsive Engines Leading to Lowspeed Stall / Uncontrolled Descent	Approach (Repeat for Cruise, Takeoff)	1. Engines Unresponsive to Throttle Commands by Crew / System			2. Low Speed Stall, Uncontrolled Descent
21	Analysis, Batch Simulation, Piloted Simulation	Uncommanded Bank (Repeat for Pitch, Yaw) Leading to Extreme Attitude Upset	Cruise (Repeat on Approach Using Autoland)	1. Autopilot / Autoland Failure: Erroneous Roll Command Varying for 10, 20, 40, 60 Degrees (Repeat for Pitch, Yaw)			2. Abnormal Roll, Pitch, Yaw
22	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Control Surface Failure Leading to Uncommanded Attitude / Stall–Spin Upset	Approach (Repeat for Cruise, Takeoff)	1. Horizontal Stabilizer / Elevator Failure (Loss, Reversal) (Repeat for Ailerons, Vertical Stabilizer / Rudder); Control Surface Asymmetry (Inability to Retract Flaps/Slats on One Side) and Surface Loss			2. Uncommanded Attitude, Asymmetric forces, Stall / Spin, Varying Degrees of Instability in Longitudinal / Lateral-directional axes

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
23	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Engine Failure Leading to Asymmetric Force/Acceleration Upsets	Approach (Repeat for Cruise, Takeoff)	1. Single Engine Failures Leading to Asymmetry			2. Asymmetric Force Upset
24	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Uncommanded Airspeed Reduction Leading to Stall	Takeoff (Repeat for Cruise, Approach)	1. Uncommanded Reduction in Engine Power			2. Stall
25	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Icing Impairment Leading to Abnormal Attitudes & Stall	Takeoff, Approach, Cruise	1. Varying Degrees of Vehicle Dynamics Changes (Lifting & Control Surface Impairments–Including Loss of Controllability & Hinge Moment Reversal), Varying Degrees of Engine Icing Effects from None to Thrust Roll-back			2. Abnormal Roll, Pitch, Yaw; Stall
Two Precursor LOC Scenarios: External Hazard –> Upset							
26	Analysis, Batch Simulation, Piloted Simulation	Wake Encounter Leading to Abnormal Attitude Upset	Approach, Takeoff			1. Varying Wake Profiles, Intensities, and Incidence Angles	2. Abnormal Roll, Pitch, Yaw; Abnormal Angular Rates
27	Analysis, Batch Simulation, Piloted Simulation	Wind Shear / Turbulence Leading to Abnormal Trajectory / Stall	Approach, Takeoff			1. Various Wind Shear Profiles (from Mild to Severe), Varying Levels of Turbulence (Light, Medium, Heavy)	2. Abnormal Trajectory, Stall
Two Precursor LOC Scenarios: External Hazard –> Vehicle Hazard							
28	Analysis, Batch Simulation, Piloted Simulation	Mid-Air Encounter with Another Aircraft Resulting in Vehicle Damage	Cruise, Approach, Takeoff	2. Various Levels of Structural Damage (Lifting Surface, Control Surface, Fuselage) from Moderate to Destabilizing		1. Another Vehicle Suddenly Appears within Range of Aircraft Requiring a Sudden Avoidance Maneuver	
Two Precursor LOC Scenarios: Vehicle Hazard –> External Hazard							
29	Analysis, Batch Simulation, Piloted Simulation	Sensor Failure Followed by Various External Hazards (Poor Visibility, Wake, Wind Shear, Turbulence)	Cruise, Approach, Takeoff	1. Single / Multiple Failure(s) in Measurement System (Altitude, Airspeed, Attitude)		2. Various Wake Levels and Impingement Angles; Various Wind Shear Profiles; Varying Levels of Turbulence (Light, Medium, Heavy); Day and Night Conditions	

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
30	Analysis, Batch Simulation, Piloted Simulation	Engine Failure Followed by Various External Hazards (Poor Visibility, Wake, Wind Shear, Turbulence)	Cruise, Approach, Takeoff	1. Single/Double Engine Failure (25%, 50%, 75%, 100% Thrust Reduction)		2. Various Wake Levels and Impingement Angles; Various Wind Shear Profiles; Varying Levels of Turbulence (Light, Medium, Heavy); Day and Night Conditions	
31	Analysis, Batch Simulation, Piloted Simulation	Control Surface Failure Followed by External Hazard (Poor Visibility, Wake, Wind Shear, Turbulence)	Cruise, Approach, Takeoff	1. Varying Control Surface Failures involving Single / Multiple Surfaces (Jammed, Loss of Effectiveness, Reversal)		2. Various Wake Levels and Impingement Angles; Various Wind Shear Profiles; Varying Levels of Turbulence (Light, Medium, Heavy); Day and Night Conditions	
32	Analysis, Batch Simulation, Piloted Simulation	Single Engine & Control Surface Failures Followed by External Hazard	Cruise, Approach, Takeoff	1. Single Engine Failure (100% Thrust Reduction), Varying Control Surface Failure (Jammed, Loss of Effectiveness, Reversal) Consistent with Uncontained Engine Failure, Underlying Instrumentation Failure Consistent with Uncontained Engine Failure, Various levels of Structural Damage (Lifting Surface, Control Surface, Fuselage) from None to Destabilizing		2. Various Wake Levels and Impingement Angles; Various Wind Shear Profiles; Varying Levels of Turbulence (Light, Medium, Heavy); Day and Night Conditions	
Three Precursor LOC Scenarios: Vehicle Problem –> Inappropriate Crew Response –> Vehicle Upset							
33	Analysis, Batch Simulation, Piloted Simulation	Failure in Measurement System Followed by Failure by Control System and Crew to Maintain Velocity Resulting in Vehicle Stall	Approach, Cruise (e.g., During Climb / Descent), Takeoff	1. Failure in Measurement System (Altitude, Airspeed, Attitude) while Autothrottle and/or Autopilot are Engaged	2. Crew is Distracted with a Faulty Flight Deck System (Cruise) or an Intense Nextgen Operational Task (Approach, Takeoff), and Assumes Autoflight Systems are Working Properly; Pilot Fails to Recover (Pilot Provides: a. Ineffective b. Delayed c. Exacerbating Recovery Commands)		3. Aircraft Enters a Low Speed Stall

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
34	Analysis, Batch Simulation, Piloted Simulation	Single Engine Failure / Malfunction Followed by Failure of Crew to Respond Leading to Vehicle Upset (Asymmetry, Abnormal Angular Rates, Stall)	Takeoff, Approach, Cruise	1. Single Engine Failure (Unresponsive to Throttle Commands)	2. Crew is Incapacitated (Cruise) or Distracted with High-intensity NextGen Workload (Takeoff / Approach); Pilot Fails to Recover (Pilot Provides: a. Ineffective b. Delayed c. Exacerbating Recovery Commands)		3. Abnormal Angular Rates, Thrust Asymmetry, Stall
35	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Control Surface Failure / Malfunction Followed by Failure of Crew to Respond Leading to Vehicle Upset (Asymmetry, Abnormal Angular Rates, Instability, Stall/Departure)	Takeoff, Approach, Cruise	1. Varying Control Surface Failure Involving Single Surface (Jammed, Loss of Effectiveness, Reversal)	2. Pilot Fails to Respond Appropriately (Pilot Provides Control Commands in Varying Degrees of Responsiveness: a. None b. Delayed c. Ineffective d. Exacerbating)		3. Abnormal Angular Rates, Force Asymmetries, Instabilities, Departure from Controlled Flight
36	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Vehicle Suffers Airframe Structural Damage, Pilot Doesn't Respond Properly to Change in Dynamics, Vehicle Enters Upset	Takeoff, Approach, Cruise	1. Airframe Damage at Varying Levels of Severity Resulting in Changes to Vehicle Dynamics (Includes Stable, Neutrally Stable, Unstable Dynamics); Scenarios with and without Single Engine Failures; Scenarios with and without Control Surface Loss of Effectiveness	2. Pilot Fails to Respond Appropriately (Pilot Provides Control Commands in Varying Degrees of Responsiveness: a. None, b. Delayed, c. Ineffective, **d.** Exacerbating)		3. Abnormal Angular Rates, Force Asymmetries, Instabilities, Departure from Controlled Flight
37	Analysis, Batch Simulation, Piloted Simulation	Icing with Vehicle Impairment Followed by Loss of Energy State Awareness and Inappropriate Crew Response Leading to Vehicle Stall	Takeoff, Approach, Cruise	1. Vehicle Dynamics Changes under Airframe Ice Accretion, Varying Degrees of Engine Icing Effects from None to Thrust Roll-back	2. Crew is Unaware of Low Energy State, and Fails to Recover from Stall (Pilot Provides Control Commands in Varying Degrees of Responsiveness: a. None b. Delayed c. Ineffective d. Exacerbating)		3. Slow Degradation in Airspeed, Slow Loss of Altitude, Stall (Low Energy)

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
38	Analysis, Batch Simulation, Piloted Simulation	Icing with Vehicle Impairment Followed by Inappropriate Crew Response (Incapacitation) Leading to Stall	Takeoff, Approach, Cruise	1. Vehicle Dynamics Changes under Airframe Ice Accretion, Varying Degrees of Engine Icing Effects from None to Thrust Roll-back	2. Crew Fatigue / Impairment Resulting in: a. No Response b. Delayed Response c. Exacerbating Response		3. Stall / Departure
39	Analysis, Batch Simulation, Piloted Simulation	Icing with Vehicle Impairment Followed by Inappropriate Crew Control Input Leading to Oscillatory Vehicle Response	Takeoff, Approach, Cruise	1. Vehicle Dynamics Changes under Airframe Ice Accretion with Varying Degrees of Destabilized Vehicle Response in Roll, Pitch, Yaw, Varying Degrees of Engine Icing Effects from None to Thrust Roll-back	2. Crew Provides Ineffective Recovery, PIO Induced in a. Roll b. Pitch c. Yaw		3. Oscillatory Response in Roll, Pitch, Yaw
Three Precursor LOC Scenarios: External Hazard –> Inappropriate Crew Response –> Vehicle Upset							
40	Analysis, Batch Simulation, Piloted Simulation	Poor Visibility Leading to Pilot Spatial Disorientation and Stall / Spiral Dive	Takeoff, Approach (with and without Go-Around), Cruise		2. Spatial Disorientation: Pilot is Inactive (Repeat with Exacerbating Control Inputs)	1. Piloted Simulation: Night (Repeat with Fog/Clouds)	3. Right/Left Roll to Spiral Dive (Varying Pitch Angles and Vehicle Velocities); Stall / Departure
41	Analysis, Batch Simulation, Piloted Simulation	Poor Visibility Leading to Pilot Spatial Disorientation and Stall / Spiral Dive	Takeoff, Approach, Cruise		2. Spatial Disorientation: Pilot is Inactive (Repeat with Exacerbating Control Inputs)	1. Piloted Simulation: Night (Repeat with Fog/Clouds), Turbulence, Thunderstorms	3. Right/Left Roll to Spiral Dive (Varying Pitch Angles and Vehicle Velocities); Stall / Departure
42	Analysis, Batch Simulation, Piloted Simulation	Wind Shear Followed by Inappropriate Crew Response and Vehicle Upset (Sudden Drop in Ground Speed and Rapid Descent)	Takeoff, Approach		2. Crew Responds Inappropriately: a. Delayed Reaction b. Incorrect Recovery c. Exacerbating Inputs	1. Various Wind Shear Profiles; Varying Levels of Turbulence (Light, Medium, Heavy)	3. Airspeed / Ground Speed Excursions, Sudden Drop in Ground Speed, Stall, Rapid Descent
43	Analysis, Batch Simulation, Piloted Simulation	Wind Shear Encounter Followed by PIO Leading to Vehicle Upset	Approach (with and without Go-Around), Takeoff		2. PIO Induced a. Roll b. Pitch c. Yaw	1. Various Wind Shear Profiles (from None to Severe), Severe Wind Gusts (Longitudinal, Lateral, Angled)	3. Oscillations in Roll, Pitch, Yaw
Three Precursor LOC Scenarios: External Hazard –> Vehicle Problem –> Upset							

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
Three Precursor LOC Scenarios: External Hazard –> Vehicle Problem –> Upset							
44	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Icing with Vehicle Impairment Followed by Failure of Airspeed Sensor (Blocked Pilot Tube) Leading to Vehicle Stall	Approach, Takeoff, Cruise	1. Vehicle Dynamics Changes under Airframe Ice Accretion, Varying Degrees of Engine Icing Effects from None to Thrust Roll-back; 2. Erratic Airspeed Measurements		1. Simulator: Day and Night, with and without Fog / Clouds, Icing Conditions with and without Snow	3. Stall, Various Levels of Destabilizing Effects from None to Unstable in a. One b. Two c. Three Axes
45	Analysis, Batch Simulation, Piloted Simulation, Subscale Flight Testing	Icing with Vehicle Impairment Followed by Control Surface Failure Leading to Vehicle Stall	Approach, Takeoff, Cruise	1. Vehicle Dynamics Changes under Airframe Ice Accretion, Varying Degrees of Engine Icing Effects from None to Thrust Roll-back; 2. Horizontal Stabilizer / Elevator Failure (Loss, Reversal) (Repeat for Ailerons, Vertical Stabilizer / Rudder); Control Surface Asymmetry (Inability to Retract Flaps/Slats on One Side) and Surface Loss		1. Simulator: Day and Night, With and Without Fog / Clouds, Icing Conditions with and without Snow	3. Asymmetric Forces, Stall, Various Levels of Destabilizing Effects from None to Unstable in a. One b. Two c. Three Axes
46	Analysis, Batch Simulation, Piloted Simulation	Icing with Vehicle Impairment Followed by All Engine Flame-Out Leading to Vehicle Stall	Cruise	1. Various Degrees of Vehicle Dynamics Changes under Airframe Ice Accretion (from None to Destabilizing); 2. Engine Flame-out Effects on All Engines (Thrust Set to Zero)		1. Simulator: Day and Night, With and Without Fog / Clouds, Icing Conditions with and without Snow	3. Decreasing Airspeed, Stall, Various Levels of Destabilizing Effects from None to Unstable in a. One b. Two c. Three Axes
47	Analysis, Batch Simulation, Piloted Simulation	Wind Shear Encounter Followed by Control System Failure Leading to Stall	Approach (with and without Go-Around), Takeoff	2. Failure in a. Autopilot b. Autothrottle c. Control Surface Actuators (Jammed, Reversal); Scenarios with and without Single Engine Failures		1. Simulator: Day and Night, With and Without Fog / Clouds, Various Wind Shear Profiles (with and without Rain / Thunderstorm Activity), Varying Levels of Turbulence (Light, Medium, Heavy)	3. Attitude Excursions a. Roll b. Pitch c. Yaw; Airspeed Variations: a. Decreasing b. Increasing; Asymmetric Forces under Jammed Surface Failures; Stall

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
48	Analysis, Batch Simulation, Piloted Simulation	Extreme Turbulence Followed by Temporary Onboard Power Outage Resulting in Vehicle Upset	Cruise	2. Temporary Power Outage with Loss of Power to a. Flight b. Navigation c. Engine d. All Instruments		1. Simulator: Day and Night, With and Without Fog / Clouds, Varying Levels of Turbulence (Light, Medium, Heavy)	3. Abnormal Attitudes, Abnormal Airspeed / Angular Rates, Stall
Three Precursor LOC Scenarios: Crew Error –> Vehicle Problem –> Upset							
49	Analysis, Batch Simulation, Piloted Simulation	Failure to Correctly Configure Aircraft Resulting in Impaired Vehicle Response and Abnormal Flight Trajectory	Approach (with and without Go-Around) / Takeoff	2. Vehicle Cannot Generate Enough Lift	1. Failure by Crew to Extend a. Flaps b. Slats c. Flaps & Slats		3. Abnormal Trajectory Resulting from Inability to Achieve Proper Lift
50	Analysis, Batch Simulation, Piloted Simulation	Inadvertent Deployment / Disengagement of Auto-flight System Resulting in Impaired Vehicle Response and Stall	Approach / Takeoff	2. For a. Vehicle Cannot Generate Enough Airspeed b. Aircraft Cannot Maintain Trim Condition	1. Inadvertent Deployment / Disengagement of a. Thrust Reverser (Single Engine) b. Takeoff-Go Around Mode		3. Abnormal Attitude (Pitch, Roll), Airspeed Decrease, Stall
51	Analysis, Batch Simulation, Piloted Simulation	Failure to Trim Control Surface Resulting in Impaired Vehicle Response and Asymmetric Forces / Abnormal Attitudes	Approach / Takeoff	2. Control Surface Cannot Generate Proper Forces / Moments to Maintain Desired Flight Path	1. Failure by Crew to Properly Trim a. Rudder b. Elevator c. Ailerons		3. Abnormal Attitude (Yaw, Pitch, Roll), Abnormal Forces / Moments, Abnormal Trajectory
52	Analysis, Batch Simulation, Piloted Simulation	Inadvertent Deployment of Control Surface Resulting in Vehicle Damage and Vehicle Upset	Cruise	2. Various Levels of Structural Damage with and without Loss of Control Effector	1. Inadvertent Symmetric / Asymmetric Deployment of: a. Flaps b. Slats c. Flaps & Slats		3. Abnormal / Asymmetric Forces / Moments, Uncontrolled Descent
Three Precursor LOC Scenarios: Inappropriate Crew Response –> Upset –> Vehicle Impairment / Damage							
53	Analysis, Batch Simulation, Piloted Simulation	Poor Visibility Resulting in Crew Spatial Disorientation Leading to Vehicle Upset and Resulting in Damage	Cruise	3. Various Levels of Structural Damage with and without Loss of Control Effector	1. Crew Spatial Disorientation Resulting in a. Nonresponsive, Followed by b. Exacerbating Control Inputs	1. Night with Poor Visibility	2. Spiral Dive

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
Three Precursor LOC Scenarios: Vehicle Impairment –> Vehicle Upset –> Inappropriate Crew Response							
54	Analysis, Batch Simulation, Piloted Simulation	Icing with Vehicle Impairment Followed by Vehicle Stall and Inappropriate Crew Response	Approach, Takeoff, Cruise	1. Various Degrees of Vehicle Dynamics Changes under Airframe Ice Accretion (from Mild to Destabilizing), Varying Degrees of Engine Icing Effects from None to Thrust Roll-back	3. Crew Responds Inappropriately: a. Delayed Reaction b. Incorrect Recovery	1. Simulator: Icing Conditions with and without Snow	2. Stall, Various Levels of De-Stabilizing Effects from None to Unstable in a. One b. Two c. Three Axes
Four Precursor LOC Scenarios: Vehicle Failure –> Inappropriate Crew Response –> Upset –> Vehicle Damage							
55	Analysis, Batch Simulation, Piloted Simulation	Engine Failure Followed by Crew Distraction Leading to Upset and Vehicle Damage	Cruise	1. Single Engine Failure (100% Thrust Loss); 4. Various Levels of Structural Damage with and without Loss of Control Effector	2. Crew Distraction Resulting in Delayed Response Followed by Excessive Response		3. Decreased Airspeed, Asymmetric Forces / Moments, Stall / Departure
Four Precursor LOC Scenarios: Vehicle Failure / Malfunction –> External Hazard –> Inappropriate Crew Response –> Upset							
56	Analysis, Batch Simulation, Piloted Simulation	System Failure / Malfunction Followed by Severe Winds / Turbulence Followed by Inappropriate Crew Response and Vehicle Upset	Cruise	1. Failure of Inertial Reference System	3. Crew Distracted with Failure Provides: a. No Response b. Delayed Response c. Delayed Plus Exacerbating Response	2. Severe Sustained Winds (Crosswinds, or Other) or Turbulence	4. Abnormal Attitudes
57	Analysis, Batch Simulation, Piloted Simulation	Vehicle Impairment (Incorrect Configuration) Followed by Wind Gusts Followed by Inappropriate Crew Response (PIO) and Vehicle Upset	Takeoff, Approach (Including Go-Around)	1. Incorrect Flap Settings (None, Intermediate Settings)	3. Pilot Induced Oscillations (PIO) in Response to Wind Gusts	2. Various Gust / Turbulence Levels (Low, Moderate, Severe) and Incidence (Lateral, Longitudinal, Vertical)	4. Abnormal Attitudes and Angular Rates Commensurate with Wind Gusts
Four Precursor LOC Scenarios: External Hazard –> Vehicle Failure / Malfunction –> Inappropriate Crew Response –> Upset							
58	Analysis, Batch Simulation, Piloted Simulation	Turbulence Followed by Advanced System Failure / Malfunction Followed by Inappropriate Crew Response and Vehicle Upset	Cruise	2. Advanced Flight Control System Malfunction Resulting in Mode Change (e.g., Envelope Protection Mode Engaged)	3. Pilot Unaware of Mode Change in Flight Control System Resulting in a. No Response b. Delayed Response c. Exacerbating Response	1. Severe Turbulence	4. Abnormal Attitudes, Airspeed Excursions

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions Vehicle Impairment; System Faults, Failures, & Errors; Vehicle Damage	Inappropriate Crew Response PIO, SD, Poor Energy Management, Mode Confusion, Ineffective Recovery, Crew Fatigue, Impairment, Failure to Take Appropriate Action, Inappropriate Piloting Technique	External Hazards & Disturbances Poor Visibility, Inclement Weather, Atmospheric Disturbance, Abrupt Maneuver (for Aircraft or Obstacle Avoidance)	Vehicle Upset Conditions Abnormal Attitude, Abnormal Airspeed / Angular Rates, Asymmetric Force, Abnormal Flight Trajectory, Uncontrolled Descent / Spiral Dive, Stall / Departure
Four Precursor LOC Scenarios: External Hazard –> Upset –> Inappropriate Crew Response –> Vehicle Impairment / Damage							
59	Analysis, Batch Simulation, Piloted Simulation	Turbulence Resulting in Vehicle Upset Followed by Excessive Crew Response Leading to Vehicle Damage	Cruise	4. Control Surface Loss (Elevator, Rudder, Ailerons) Consistent with Turbulence & Crew Response	3. Excessive Control Inputs by Crew	1. Various Turbulence Levels (Low, Moderate, Severe) and Incidence (Lateral, Longitudinal, Vertical)	2. High-altitude High-speed Upsets Commensurate with Turbulence Applied
60	Analysis, Batch Simulation, Piloted Simulation	Wake Vortex Resulting in Vehicle Upset Followed by Excessive Crew Response Leading to Vehicle Damage	Takeoff / Landing	4. Control Surface Loss (Elevator, Rudder, Ailerons) with and without Various Levels of Vertical / Horizontal Stabilizer Loss (25%, 50%, 75%, 100%)	3. Excessive Control Inputs by Crew	1. Various Wake Levels and Impingement Angles	2. Abnormal Angular Rates Commensurate with Wake