Robustness of Idle-throttle Continuous Descent Approach Trajectories against Modified Timing Requirements

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This paper reports on a study of the robustness of Continuous Descent Approach (CDA) trajectories in the face of late changes to the Required Time of Arrival (RTA). We demonstrate a method for determining limits on how much the RTA can be modified, as a function of notification lead-time, without significantly impacting on optimality of the CDA. Our focus is on the period between Top Of Descent (TOD) from cruise level and arrival at a metering fix. The aim is to help determine how flexible airspace constraints would need to be in order to accommodate robust CDA. The Aircraft Intent Description Language (AIDL) is used as the modelling language.

I. Introduction

In this paper we report the results of a study of the robustness of Continuous Descent Approach (CDA) trajectories in the face of late changes to the Required Time of Arrival (RTA). We demonstrate a method for determining limits on how much the RTA can be changed, as a function of notification lead-time, without significantly impacting on the main goal of 'ideal' CDA. We define an ideal CDA as an idle-throttle descent along a fixed lateral approach path with a planned speed schedule. (The reasoning behind our definition is explained below; other definitions are possible.[1]) Such trajectories are desirable for many different economic and environmental reasons, including fuel use, emissions and noise abatement.

Underlying the motivation for this study is the assumption that, as a result of improved trajectory prediction and trajectory conformance, in the ideal future trajectory-based ATM (Air Traffic Management) System, most of the current tactical ATC approach-sequencing practices will have been replaced by a mechanism for adjusting RTAs, with supporting processes for recalculating the affected trajectories from knowledge of user preferences.[1–4] It is thus vital to understand the key parameters of such a mechanism when designing supporting tools and procedures for CDA: namely, according to how soon one realises that a change to an RTA may be required, how much change is feasible without significant loss of the benefits of CDA, and what variation is associated with the revised trajectory.

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I.A. Background

A number of studies[1,5,6] have considered the final approach segment and Terminal Manoeuvring Area (TMA) aspects of CDA, but we focus on the approach phase here, between Top of Descent (TOD) and arrival at a metering fix. Our ultimate aim is to inform the redesign of airspace to enable CDA to be flown with as little intervention as possible (in this case, just one single speed adjustment), by understanding what air-side flexibility is possible.

Other studies[4] have considered the issue of modifying RTA while in the flight is in cruise phase, which is clearly the preferred option if possible since adjustment can be made relatively easily and cheaply. However, for the foreseeable future it is inevitable that adjustments will sometimes need to be made to the aircraft's RTA once a descent from cruise level has been initiated. This would typically be due to 'last minute' events that could not always be predicted accurately, such as runway activity, spacing adjustments, and deconfliction with departing aircraft. This prompts the question of how much flexibility exists after descent has begun.

Current tactical ATCo (Air Traffic Controller) approaches to modifying approach trajectories to insert delay into a trajectory include vectoring and holding, both of which are undesirable because they involve extra fuel burn, noise and workload for flight crew and controllers. Our approach is instead to check to what degree the aircraft's FMS (Flight Management System) can use elevator control to accommodate the change, keeping a fixed lateral path and modifying the speed schedule. A steeper (hence faster) descent will result in the aircraft passing the fix earlier; a shallower descent will make it pass later. Of course this will result in a change to the altitude profile, and a change to the height at which the fix is passed, but (within limits) we expect this to be an acceptable compromise. Where path lengthening is feasible, this could be incorporated into a shallower descent, in order to insert a delay without needing to change the height target – but that will be left to a later study. For now we are interested in the extent to which it is feasible to achieve the new RTA while following a fixed lateral path, and the consequent effect on the speed and height at which the fix is passed.

Put in a different way, the objective is to determine what values of ΔRTA and lead-time will require path lengthening and/or holding in addition to speed control.

Note that we are considering ideal idle-throttle CDAs as a way of minimising fuel use/emissions and addressing noise abatement. This is by contrast with CDAs that follow a fixed pre-determined three-dimensional geometrical profile (VNAV-Path descent). Although the latter are certainly an improvement on stepped approaches, they become suboptimal if the RTA changes, since engine control is required in order to maintain the vertical profile. In our approach the throttle remains at idle throughout descent, until the metering fix is passed; what happens after that is outside the scope of our immediate study (but see Section III.A below for more discussion).

I.B. The Modelling Approach

Our study was performed using a prototype trajectory modelling tool developed by BRTE. The tool uses the *Aircraft Intent Description Language (AIDL)*[7] as the input format.

AIDL is a formal language developed by BRTE to describe and exchange *aircraft intent* information. In the context of trajectory prediction, aircraft intent means an unambiguous description of how the aircraft is intended to be operated within a certain time interval. AIDL is characterized by an alphabet and a grammar. The alphabet is formed by a set of instructions, which are conceptual elements used to model the basic commands, guidance modes and control strategies at the disposal of the pilot/FMS, to direct the operation of the aircraft. The AIDL grammar is defined in such a way that a valid AIDL sentence is guaranteed to unambiguously define the aircraft's trajectory, given a suitable set of initial conditions, aircraft performance model and model of the environment. This makes AIDL ideally suited for use as the input language for a wide range of real-time/fast-time simulators and trajectory prediction tools.

Previously AIDL has been considered as a potential tool for transfer of aircraft intent information between air- and ground-based systems, for example to examine the conditions under which conflicts can arise.[8] Our application demonstrates its use for modelling and testing new concepts of operation such as CDA.

For our study, AIDL sentences were developed to describe the baseline CDA scenarios and their variants, including different intervention lead-times and revised speed schedules. Then BRTE's prototype trajectory-computation tool was used in a series of experiments to calculate the effect on the time, height and speed at which the metering fix gets passed. The effects of a number of different environmental, aircraft and flight-deck factors on the results were also modelled, using variants of the baseline AIDL sentences.

I.C. Structure of this Paper

The remainder of this paper is organised as follows. Section II describes AIDL in more detail. Section III describes the CDA scenario on which the approach is illustrated: namely, a Boeing 737-800 (B738) series aircraft performing an idle-throttle Mach/CAS descent from cruise level to pass over a metering fix at a given time. Some time after TOD the flight crew modify the aircraft's Mach/CAS speed schedule values, and the aircraft's trajectory gets modified accordingly: the aircraft continues to fly at idle throttle and elevator controls are used to achieve the new speed schedule. Section IV presents the main results of the B738 study, in terms of the effect that different speed schedule values have on the time, height and speed at which the aircraft passes the fix.

Section V investigates the sensitivity of the results to various different flight factors, including environmental factors (barometric pressure and wind), aircraft factors (weight), and flight deck factors (cruise height and initial speed schedule). We assume that these variations are known prior to descent and incorporated into the calculation of the TOD point and original RTA. It would be a straightforward matter to modify our models to treat them instead as uncertainty factors if desired (individually or collectively), but we have not done so here.

Section VI summarises the results of a second study, involving a Boeing 777-300 (B773) series aircraft on a longer descent, by way of comparison.

I.D. Acronyms

AIDL	Aircraft Intent Description Language	CDA	Continuous Descent Approach
APM	Aircraft Performance Model	EM	Environmental Model
ATCo	Air Traffic Controller	FMS	Flight Management System
ATM	Air Traffic Management	RTA	Required Time of Arrival
B738	Boeing 737-800	ΔRTA	net change in RTA
B773	Boeing 777-300	TAS	True Air Speed
BRTE	Boeing Research & Technology Europe	TCI	Trajectory Computation Infrastructure
CAS	Calibrated Air Speed	TOD	Top Of Descent

II. The Aircraft Intent Description Language (AIDL)

This section describes the modelling language used in the study. As noted above, AIDL is characterized by an alphabet and a grammar. The alphabet is formed by a set of *instructions*, which are conceptual elements used to model the basic commands, guidance modes and control strategies at the disposal of the flight crew and/or FMS, to direct operation of the aircraft. The grammar describes rules for assembling instructions into sets and sequences, in order to describe aircraft intent. A valid AIDL sentence describes a unique 4D aircraft trajectory when interpreted in an appropriate *Trajectory Computation Infrastructure (TCI)* environment.[9] Each of these aspects is described in more detail below.

II.A. AIDL instructions

Table 1 lists the 34 instruction types currently supported by AIDL. There are AIDL instructions for all different aspects of aircraft motion: lateral and vertical motion, speed, energy, engine and configuration settings. They are grouped into the following classes:

- *Set instructions* model control and configuration transients. Typically, a set instruction captures the evolution of a state or configuration variable from an initial to a target value according to an externally defined function (e.g., the APM may define the transients of flap deployment).
- *Law instructions* model closed-loop control and guidance laws. Typically, these instructions capture the evolution of a control or state variable as a function of one or more state variables (e.g., a law describing the evolution of the Mach number as a function of the altitude).

Table 1. AIDL instruction types

AIDL Alphabet - Σ_{AIDL}					
#	**Keyword**	**Instruction**	**#**	**Keyword**	**Instruction**
1	SL	Speed Law	18	HT	Hold Throttle
2	HS	Hold Speed	19	OLT	Open Loop Throttle
3	HSL	Horizontal Speed Law	20	SBA	Set Bank Angle
4	HHS	Hold Horizontal Speed	21	BAL	Bank Angle Law
5	EL	Energy Law	22	HBA	Hold Bank Angle
6	HE	Hold Energy	23	OLBA	Open Loop Bank Angle
7	VSL	Vertical Speed Law	24	CL	Course Law
8	HVS	Hold Vertical Speed	25	HC	Hold Course
9	SPA	Set Path Angle	26	TLP	Track Lateral Path
10	PAL	Path Angle Law	27	SHL	Set High Lift devices
11	HPA	Hold Path Angle	28	HHL	Hold High Lift devices
12	OLPA	Open Loop Path Angle	29	SSB	Set Speed Brakes
13	AL	Altitude Law	30	SBL	Speed Brakes Law
14	HA	Hold Altitude	31	HSB	Hold Speed Brakes
15	TVP	Track Vertical Path	32	OLSB	Open Loop Speed Brakes
16	ST	Set Throttle	33	SLG	Set Landing Gear
17	TL	Throttle Law	34	HLG	Hold Landing Gear

- *Hold instructions* are simplified Law instructions. They describe situations where a desired motion or configuration variable is to be maintained constant (e.g., hold altitude constant).
- *Open Loop instructions* model direct commands of the pilot over the controls at his/her disposal.
- *Track instructions* model guidance along a predefined geometry.

An AIDL instruction is characterized by a mathematical equation called the *effect* of the instruction, which is to be satisfied simultaneously with the equations of motion during a certain time interval, called the *execution interval* of the instruction. Basically, the execution interval of an instruction indicates for the period over which this instruction affects the aircraft's motion. The execution interval is defined by means of a *begin* and an *end trigger*, which respectively specify the conditions that define the starting and ending times of the execution interval.

For instance, an HA instruction can finish when certain capture condition (e.g., Mach number or path distance) is reached. Triggers can be made up of AND and OR logical operators for more complicated conditions, such as: climb at constant vertical speed (using HVS) ends when either the aircraft reaches certain altitude OR has covered certain path distance.

AIDL instructions sometimes include additional *specifiers* to indicate which type of speed, path angle, altitude, etc., is explicitly controlled by the instruction. For example, an SL instruction needs a specifier to say whether Mach, true airspeed (TAS) or calibrated airspeed (CAS) is being kept constant. Table 2 shows just some of the specifiers available. A complete list of specifiers can be found in Ref. 9

II.B. AIDL grammar

AIDL's grammar contains both lexical and syntactical rules. Lexical rules govern the combination of instructions into words of the language, which are called *operations* and correspond to elemental behaviours elicited by the aircraft in response to the combination of instructions. Syntactical rules govern the concatenation of words into valid sequences of operations joined by triggers, called *sentences*. The AIDL grammar is defined in such a way that a valid AIDL sentence is guaranteed to define the aircraft's trajectory completely and

Table 2. Some AIDL instruction specifiers

Instructions	Parameter	Keyword	Units
SL, HS	Mach number	MACH	–
	calibrated airspeed	CAS	kt
	true airspeed	TAS	kt
	indicated airspeed	IAS	kt
HA	geopotential pressure altitude	PRE	ft
	geometric altitude	GEO	ft
TL	max climb regime	MCMB	–
	low idle throttle regime	LIDL	–
	go around regime	GA	–
	throttle control parameter	THRO	–
	thrust coefficient	CT	–

unambiguously over the corresponding execution interval, given a suitable set of initial conditions, aircraft performance model and model of the environment.

AIDL is based on the principle that, during any given time interval, the trajectory of an aircraft (considered as a mass-point) is determined by closing the three degrees of freedom (3-DOF) of the aircraft motion.[9] Under certain assumptions about the underlying aircraft performance model, this is done mathematically by adding three constraints (which can be expressed as algebraic equations) to the three ordinary differential equations (ODEs) that govern the aircraft's motion. Certain AIDL instructions (called *motion instructions*) each close a single DOF of aircraft motion. The time interval during which each instruction is active is controlled through the trigger conditions.

Not any combination of three instructions results physically compatible according to the laws that govern the flight dynamics of an aircraft. However, it has been found that the rules governing valid combinations admit the structure of a formal regular language (in the sense of the Mathematical Theory of Formal Languages). The AIDL grammatical rules ensure that grammatically valid combinations of motion instructions, together with suitable initial conditions and trigger conditions, possess a unique 4D trajectory-segment solution when combined with suitable models of aircraft performance and environmental conditions (see next section).[9] The AIDL alphabet of instructions covers a very wide range of aircraft motion elements under a wide range of different possible aerodynamic configurations, including activation of high-lift devices and/or speed brakes, and landing gear status. AIDL also provides features to help trajectory modelling tasks by delegating to the TCI the location of auto and default parameter values. Moreover, the AIDL also captures current and advanced optimal flight modes. These features make AIDL ideal for platform-independent specification of aircraft intent.

See Fig. 2 below for an example of aircraft intent expressed graphically using AIDL, together with vertical and horizontal views of the corresponding trajectory.

II.C. Trajectory computation for AIDL

As noted above, a grammatically correct AIDL sentence defines a unique 4D aircraft trajectory segment for a given set of initial conditions when interpreted in a suitable model of aircraft performance and model of environmental conditions. Boeing RTE have developed a prototype tool-set for calculating this trajectory, based on the architecture in Figure 1. The general characteristics required of the different components of the Trajectory Computation Infrastructure (TCI) are described briefly below.

The *Aircraft Performance Model (APM)* is based on BADA models,[11] which provide data for prediction of the aircraft performance. The prototype tool-set used in our experiments included means for calculating forces associated with aerodynamic drag, lift, engine thrust and weight, parametrically modelled as functions of the atmosphere conditions (pressure, temperature and wind), aircraft position, aircraft true airspeed and aircraft type. (The prototype tool supports Boeing 737-800 and 777-300 series aircraft types.) It also included a series of parametric models which capture the primitive ways in which an aircraft can be operated (e.g.

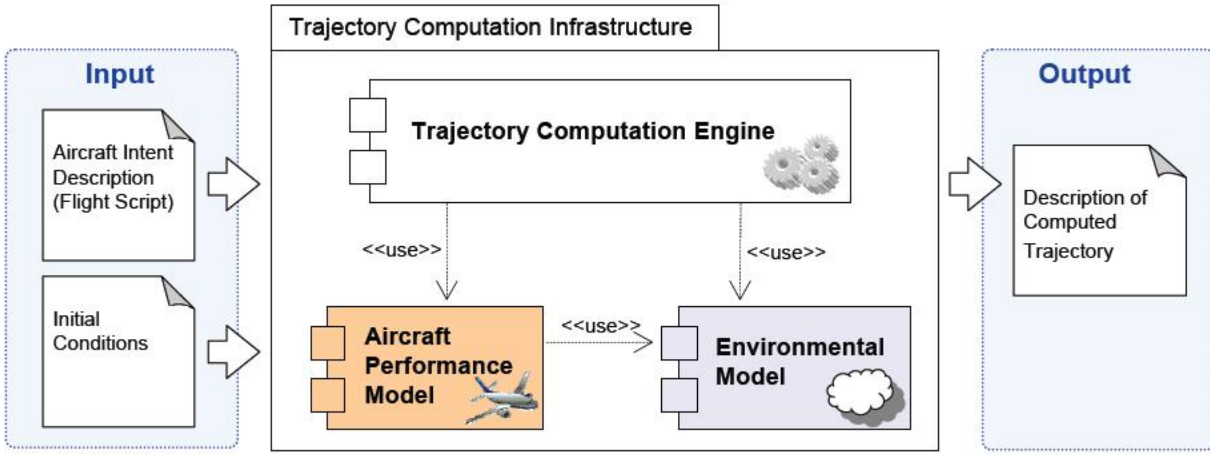

Figure 1. Trajectory Computation Infrastructure (TCI) for AIDL

the way it: deploys and retracts high-lift devices, spoilers or landing gear; holds altitude, speed, path angle and bank angle; rolls and pitches; etc) and parametric models which restrict aircraft behavior to stay within appropriate limits for safeguarding operation of the aircraft and limiting equipment degradation (e.g. speed limitations, weight limitations, load factor limitations, etc), as functions of a set of aircraft-specific parameters.

The *Environmental Model (EM)* provides means for predicting the environmental conditions (temperature, atmospheric pressure and wind) that the airplane would encounter as it flew its trajectory, as a function of spatial position and time.

The TCI used in our experiments was able to interpret AIDL expressions as sets of algebraic differential equations and numerically integrate them for given initial conditions using the APM and EM. The output was a sequence of state vector values sampled at a discrete set of time instants. It also included support for certain forms of implicit parameters in AIDL trigger conditions, such as being able to determine the appropriate point for Top Of Descent (TOD) in order to satisfy a given Required Time of Arrival (RTA) at an approach fix, or to calculate the point at which to transition smoothly from constant Mach to constant CAS during descent. It does this by iterating calculations and backtracking. We made good use of these features in our experiments, as discussed further in Section III below.

III. Case Study I: Boeing 737-800

This section describes the scenario on which the approach is illustrated: a Boeing 737-800 aircraft performing an idle-throttle Mach/CAS Continuous Descent Approach (CDA) from cruise level to pass over a metering fix at a given Required Time of Arrival (RTA) and given height and speed. Sometime after descent has commenced, ATC notifies the aircraft that the RTA needs to be changed. The question is, by how much can the RTA feasibly be modified, while still maintaining idle throttle, a constant Mach/CAS regime and clean configuration, and just using elevator controls to achieve the new speed schedule? (That is, using a steeper – thus faster – descent to achieve an earlier RTA, or a shallower – thus slower – descent to achieve a later RTA.) Of course, the answer will depend in part on how much lead-time is given. Since the revised descent trajectory will also result in the fix being passed at a new height and speed, the answer will also depend on whether these new values are tolerable, as well of course as whether the remainder of the trajectory is acceptable. As noted above, we restrict ourselves to calculating the affect that modifying the speed schedule has on the time, height and speed at which the fix is passed.

Table 3. Baseline scenario for B738 study

Initial conditions					Final conditions		
weight (tonne)	height (FL)	Mach	CAS (kt)	TAS (kt)	height (FL)	CAS (kt)	TAS (kt)
58	350	0.763	258	440	100	280	323

Section III.A explains the context of the study and the reasons behind some of the assumptions used. Section III.B describes the baseline (uninterrupted) scenario and how it was modelled in AIDL. Section III.C describes how interrupted descents (i.e., CDAs where the speed schedule was modified at a given time) were modelled in AIDL, and how the resulting effects on time, height and speed at the metering fix were calculated; the results are presented in Section IV below. Section V describes how the methodology was modified to investigate sensitivity of the results to a range of different flight factors. Section VI gives summary results for a second scenario, involving a Boeing 777-300 aircraft descending from a higher cruise level.

III.A. Context

In order to keep the study manageable, and to report the results in a systematic manner, we made some simplifying assumptions which will be explained here briefly.

The reason for considering idle throttle CDA was explained above: we wish to minimize fuel burn, emissions and (perhaps) noise. As noted above, using elevator controls to achieve a new RTA is however going to result in a change to the height and speed at which the metering fix is passed. This will mean that an aircraft operating procedure would need to be put in place to handle the rest of the descent trajectory, from the metering fix through to landing on the runway, to complement our proposed strategy. One such procedure is described in Ref. 3, for example. But these matters are outside the scope of our current study, and we focus simply on elucidating the size of the height and speed 'errors' that might result under our approach. (Note also that we are not assuming the use of any particular Flight Management System (FMS) mode on the aircraft: the purpose of the study is simply to investigate the implications of using speed control to meet revised RTAs after TOD.)

Another simplifying assumption is that we consider just a single modification to the descent trajectory, and assume that speed schedules are kept constant before and after the trajectory change. The reason for considering just a single change was to keep the experiments manageable; however, the methodology could easily be adapted to more complex situations, such as where further constraints are imposed (additional to, or in place of, the revised RTA requirement), such as speed or height limits (upper and/or lower). The motivation for keeping speed schedules constant is that this is a typical ATC-related operating principle in many existing ATM systems, intended to facilitate maintenance of ATCo situation awareness, and we anticipate that this principle is likely to remain important – if not become even more important – in future. (The new speed schedule would need to be conveyed to the ATM System of course, and checked for conflicts before a revised clearance would be granted, but such matters are outside the scope of our study.)

Finally, we have described our study in terms of modifying the trajectory to achieve a revised RTA. There is an underlying assumption that time-based management of air traffic at key points ("metering" at fixes) is, and will remain, important in high traffic-density ATM. But in lower density ATM it may be preferable to allow the on-board FMS to calculate a revised speed schedule which is optimal for that flight overall (through to landing), and to inform ATC of the desired revision to RTA. But that is outside the current study; the modelling methodology could be modified to cater for such a situation if desired.

III.B. Baseline Scenario

This section describes the baseline (uninterrupted) CDA scenario and how it was modelled in AIDL. The aircraft descends from cruise level FL350 and cruise speed Mach.763 to pass over a metering fix at height FL100 (see Table 3). The aircraft's initial weight is 58 tonnes and the aircraft is in a clean configuration throughout descent (i.e., no speed brakes or high-lift devices deployed, and landing gear retracted). The fix's coordinates are 25° N and 15° W, and the aircraft's lateral path is a great circle, at a constant bearing of 180° (i.e., due South). The CAS value of the speed schedule is 280 kt. The standard atmospheric model was used,[10] with a temperature of 15 °C at sea level and no wind.

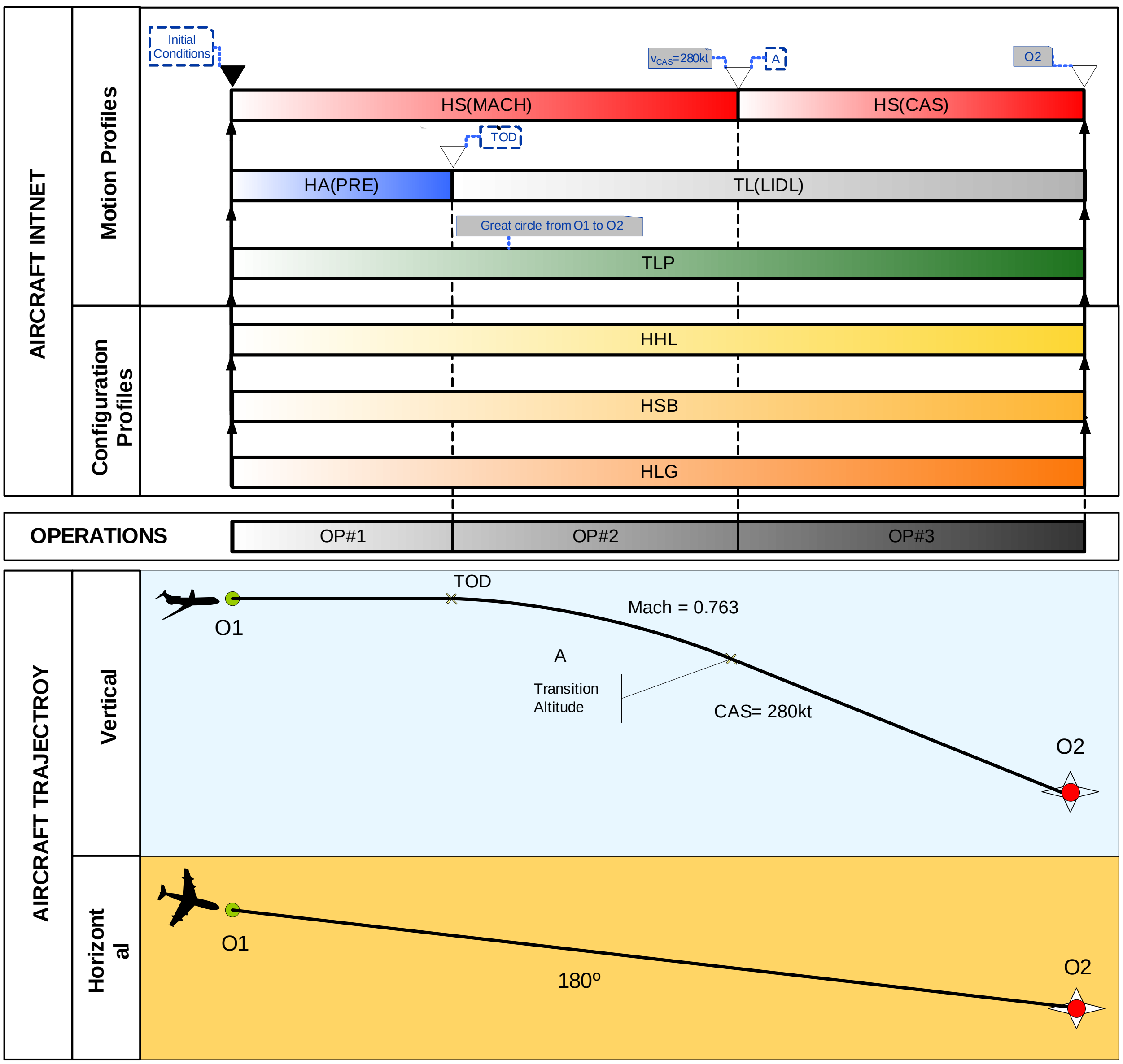

Figure 2. The baseline (uninterrupted) B738 CDA trajectory in AIDL

The AIDL representation of this baseline case is given in the top part of Fig. 2. The initial conditions can be summarized as clean aerodynamic configuration at a geopotential pressure altitude of 35,000 ft with Mach number M of 0.763. The initial HS (Hold Speed) and HA (Hold Altitude) instructions have their specifier shown within the instruction box. The HA operation concludes at point TOD, which is modelled by a floating trigger. At this point the power plant transitions to second operation OP#2 and then maintains the LIDL (Low Idle) regime, which is shown within the TL (Throttle Law) instruction. This causes the aircraft to start descent. The aircraft maintains its speed at Mach 0.763, represented by means of an HS instruction with Mach as specifier. This instruction is active until the calibrated airspeed (CAS) is 280kt; at this moment – called the transition altitude (TA) – the condition defining the floating trigger is satisfied and OP#2 ends. Thereafter the aircraft stops flying at constant Mach to continue at constant CAS of 280 kt (OP#3).

On the lateral path, the sequence consists of a single instruction, corresponding to following a great circle path defined by the O1 and O2 way points, corresponding to the starting point and the meter fix lat/long coordinates, respectively. This is specified using the TLP (Track Lateral Path) instruction with an intrinsic constraint, defined in the box above the instruction. Finally, on the configuration threads the sequence represents the clean configuration state with the landing gear, high lift devices and speed brakes in retracted positions (configuration instructions HLG, HHL and HSB respectively).

BRTE's prototype AIDL-based trajectory computation tool was used to calculate where and when TOD would occur, using the standard BADA B738 performance characteristics.[11] The tool calculated that TOD would occur 70 NM and 651 secs away from the fix. Likewise, the tool calculated that the Mach/CAS transition would take place 69 secs after TOD. The initial speed (Mach.763) equates to 440 kt True Air Speed (TAS) and 258 kt CAS. The aircraft overflies the fix at 323 kt TAS. The trajectory computed by the tool for this case is called the *reference run* (or sometimes, the *nominal case*) in what follows.

III.C. Interventions to Modify RTA

For the purposes of analysis, we consider two types of modification to the trajectory during a Mach/CAS descent.

The first type, which we call a *rescheduled CAS intervention*, is where the CAS value of the speed schedule is revised during the Mach phase of descent before the new CAS is reached. (The aircraft's calibrated airspeed steadily increases during a typical constant Mach descent.) The AIDL sentence representing this situation is almost exactly the same as before, except that the CAS value in the floating trigger (between operations OP#2 and OP#3) is changed from 280 kt to the appropriate new value, and the floating trigger for TOD is replaced by a value trigger, using the value of TOD computed from the reference run.

The second type of trajectory modification, which we call an *altered CAS intervention*, is where the CAS value of the speed schedule is revised during the CAS phase of descent. Fig. 3 illustrates how this is modelled in AIDL. This involves adding a fourth operation (OP#4), in which a speed law is used with the new value of CAS (250 kt in the example illustrated) triggered at time t_c (B) and then held constant until the fix is overflown (O2). Note that this results in an instantaneous change in the value of CAS in the corresponding equations of motion, which is clearly unrealistic in practice. We could remedy this by making some assumptions about how the flight crew would achieve the change in practice, and then model it in AIDL and extract the results. If the speed change is done quickly enough though, we expect that the results will not be very different from the ones obtained using our simplified approach.

A third possible scenario, where both the Mach and the CAS values are changed after descent has commenced, was not considered in this study; nor was the case where the CAS value is revised during the Mach phase but after the new CAS value has already been exceeded. The technique used for the altered CAS interventions could easily be adapted for these cases. However the time frames within which the interventions would need to take place is quite short in both cases, so the results will not differ much from the other cases, while complicating the analysis somewhat.

Figure 4 shows the true airspeed (TAS) values calculated by the tool for three cases: the baseline reference run ("nominal case"); a rescheduled CAS run where the CAS value has been changed to 300 kt during the Mach phase ("300(R)"); and an altered CAS run where the CAS value has been altered to 260 kt with a lead-time of 395 secs ("260(A)"). Figure 5 shows the pitch values for the same runs: this illustrates what the elevator controls actually do during the runs. Figure 6 shows the average ground speed for the same runs. Finally, Figure 7 shows the descent profile for the 3 comparison trajectories. In short, the 260(A) descent

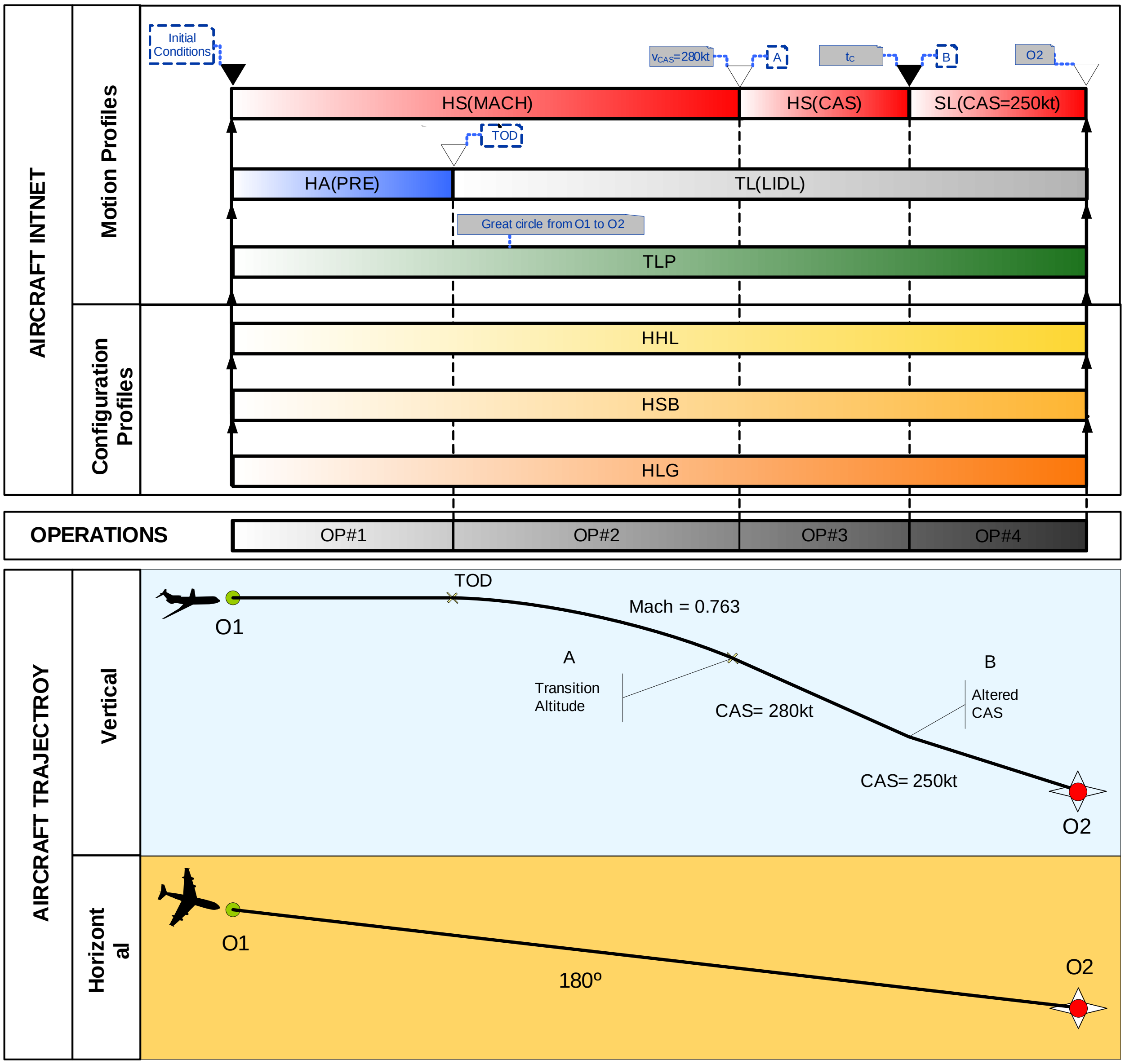

Figure 3. An example 'altered CAS' trajectory represented in AIDL

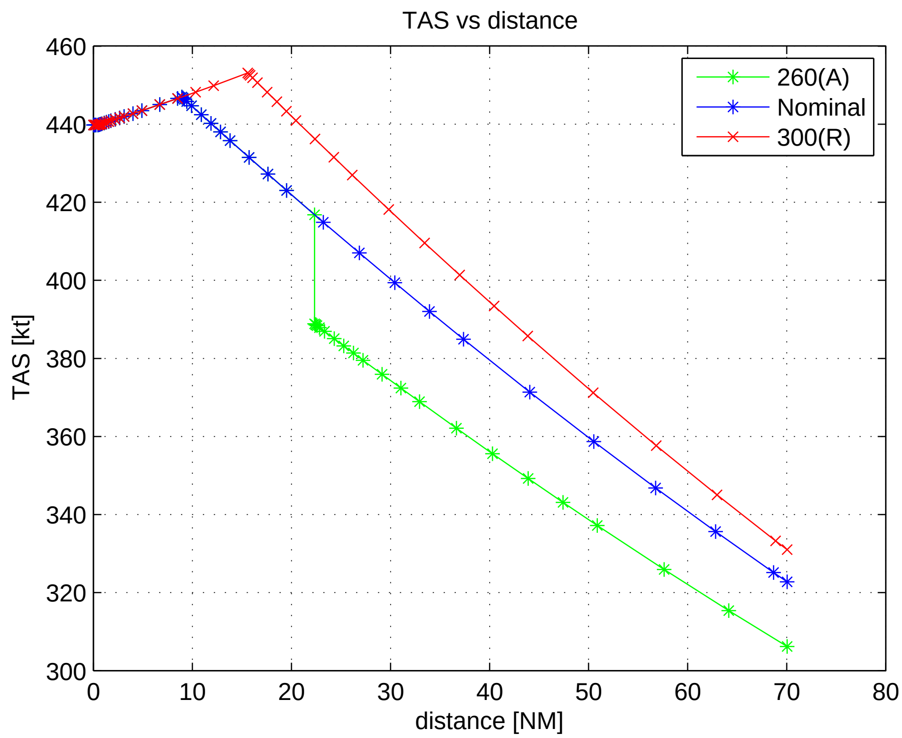

Figure 4. TAS vs distance from TOD for 3 example B738 runs

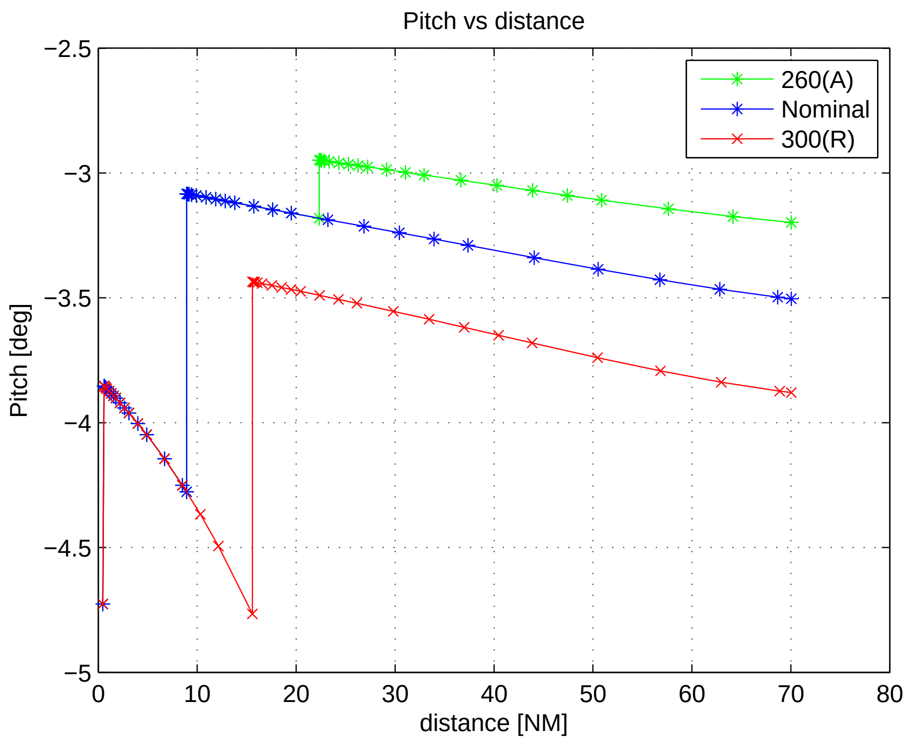

Figure 5. Pitch values for the 3 example B738 runs

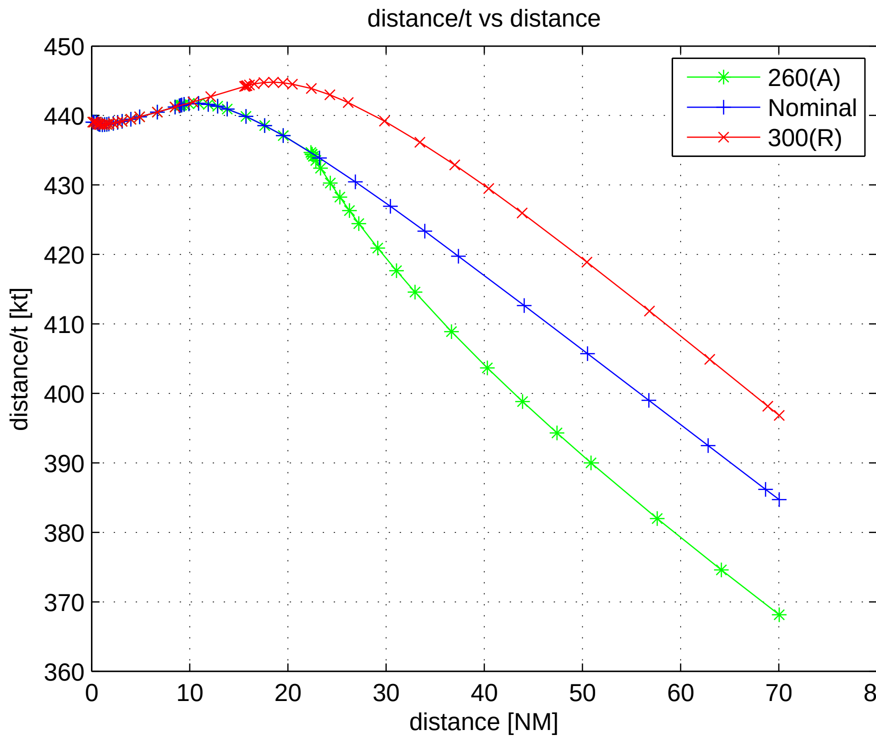

Figure 6. Average ground speed values for the 3 example B738 runs

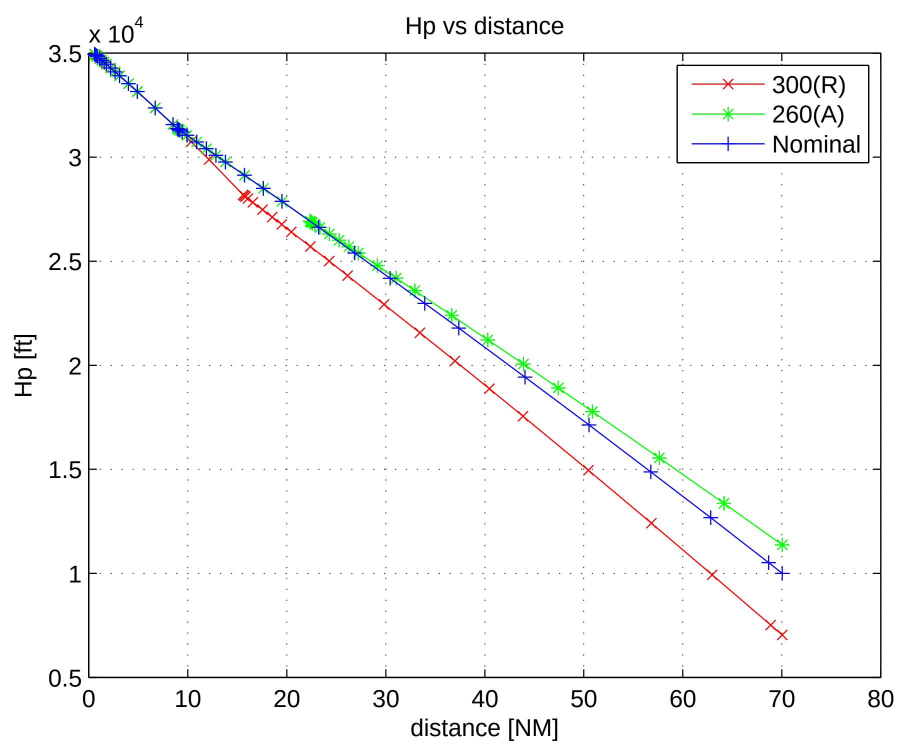

Figure 7. Descent profile for the 3 example B738 runs

is shallower and slower than the baseline (uninterrupted) CDA, whereas the 300(R) descent is steeper and faster.

In Section IV below we vary the value of CAS used in the two different types of intervention and report the effect on the time as which the fix is overflown (ΔRTA) and the associated changes in height and speed at which the fix is passed. In Section V we modify parameters in the initial conditions, Aircraft Performance Model and Environment Model to simulate variations in different flight factors, and rerun the experiments in order to investigate the sensitivity of the results to those factors.

IV. Results

This section reports the results of the experiments to determine the effect that different speed schedule values have on the time, height and speed at which the aircraft passes the fix, according to the amount of lead-time given (see Section III for details). Here the Mach value is kept constant and a CAS value of 280 kt is used as the reference case. We report the results obtained by varying the CAS value of the modified speed schedule between 250 kt and 310 kt in steps of 10 kt in two cases, according to whether the CAS value is changed during the Mach or CAS phase of Mach/CAS descent.

In what follows the "height error" (Δheight) is reported as the difference between the height at which the fix is passed and the nominal height (10,000 ft) in pressure altitude, and "speed error" (Δspeed) is the difference in true airspeed from the nominal speed at which the fix is passed (323 kt). Figures reported are rounded as follows: time to the nearest whole second, speed to the nearest knot, and (pressure) height to the nearest 10 ft.

IV.A. Rescheduled CAS Interventions

For the rescheduled CAS interventions, where the CAS value of the Mach/CAS descent is changed before the transition from the Mach regime, we varied the CAS value is varied from 260 kt to 310 kt. (The CAS value at cruise is 258 kt, so values lower than this cannot be used, for the reasons given in Section III.C.)

Table 4. Effect of Rescheduled CAS interventions

Revised CAS value	transition time (sec after TOD)	lead-time (sec)	ΔRTA (sec)	height error (ft)	speed error (kt)
260	7	>644	26	2850	-10
270	39	>612	12	1450	-5
280	69	-	0	0	0
290	97	>582	-11	-1480	4
300	122	>582	-20	-2960	8
310	146	>582	-28	-4460	12

Table 4 summarizes the results for the different CAS values. It shows the net amount by which the time-at-fix would be altered (ΔRTA) if the CAS value was revised after TOD, together with the corresponding net change in the height and speed at which the fix would be passed. The 'transition time' column indicates how long after TOD the Mach/CAS transition would occur. The 'lead-time' column indicates the minimum lead time required to allow a rescheduled CAS intervention to occur (i.e., net amount of time before the flight was originally scheduled to fly over the fix). Note that for CAS values lower than the nominal value (280kt), the lead-time is longer (i.e., the intervention needs to occur earlier in the Mach phase) since the CAS value is reached earlier. For CAS values higher than 280kt, on the other hand, the lead-time is 582 (= 651-69) secs, since after this point the flight will have transitioned into the CAS phase of descent, and a "rescheduled CAS intervention" is no longer possible. Note that the actual time at which a rescheduled CAS intervention takes place does not affect the ΔRTA (etc) results, provided of course that the CAS value is revised before the minimum lead-time is reached. Revising the CAS value after this time corresponds to the altered CAS intervention, which is treated separately below.

Discussion

As can be seen, the window of opportunity for taking this kind of intervention is relatively small. We shall see below that the altered CAS intervention can have a larger affect on the time-at-fix than this case, as well as having a substantially longer window of opportunity and wider range of CAS values. For this reason we focus analysis on the altered CAS intervention in most of the rest of the paper.

IV.B. Altered CAS Interventions

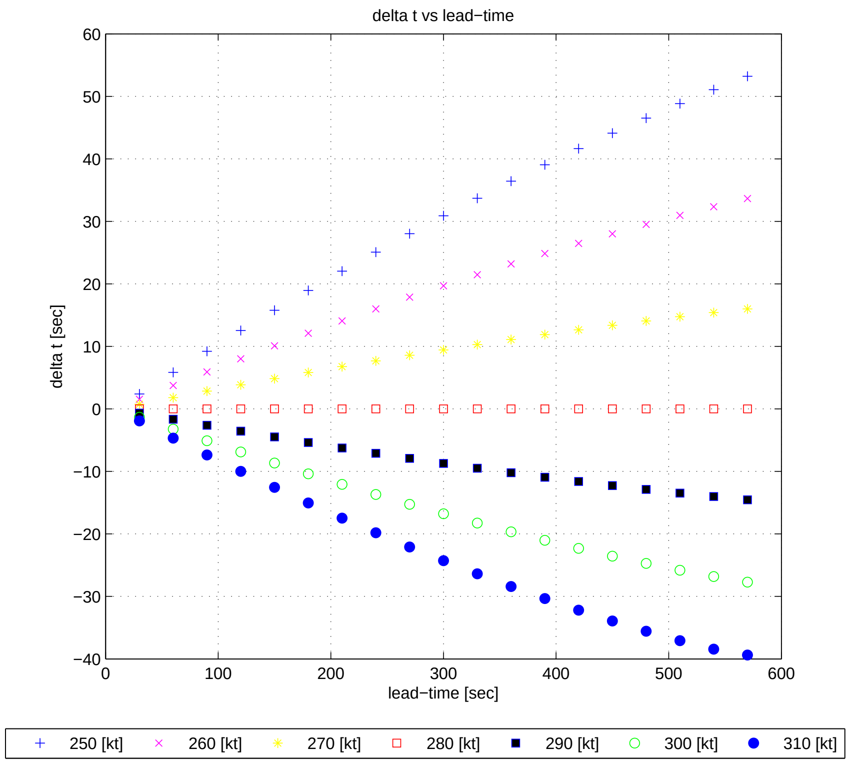

Figure 8. Effect on time-at-fix (ΔRTA) of altered CAS interventions, by lead-time

For the altered CAS interventions, we varied the CAS value of the intervention from its nominal value of 280 kt by ±30 kt, in steps of 10 kt. We varied the *lead-time* at which the intervention was applied (measured relative to the time when the flight was originally scheduled to overfly the fix) in steps of 30 sec from 30 sec up to 570 sec (which is the maximum possible, since the Mach/CAS transition takes place 582 sec before the original RTA in the baseline case). Figure 8 shows the effect on time-at-fix for the different CAS values against the lead-time. Figures 9 and 10 show the corresponding effect on height and speed error, respectively.

Table 5 extracts values for three representative cases of CAS values (the maximum and minimum values considered, plus the 260 kt case for comparison with the rescheduled CAS intervention results above) for a range of different lead-times.

Discussion

The first thing to notice is that the effect of lead-time on ΔRTA is almost linear in all cases, and almost linear with respect to the new CAS value. This means that choosing a CAS value to achieve a desired ΔRTA for a given lead-time will be relatively straightforward: it should be possible to develop simple rules of thumb for controller to apply. The effect on height error is perhaps more of a concern however, since the values are very high relative to the nominal passing height of 10,000 ft. The feasibility of such interventions will depend on other traffic and the structure of the airspace along the descent path, as well of course as the "recovery procedures" discussed in section III.A.

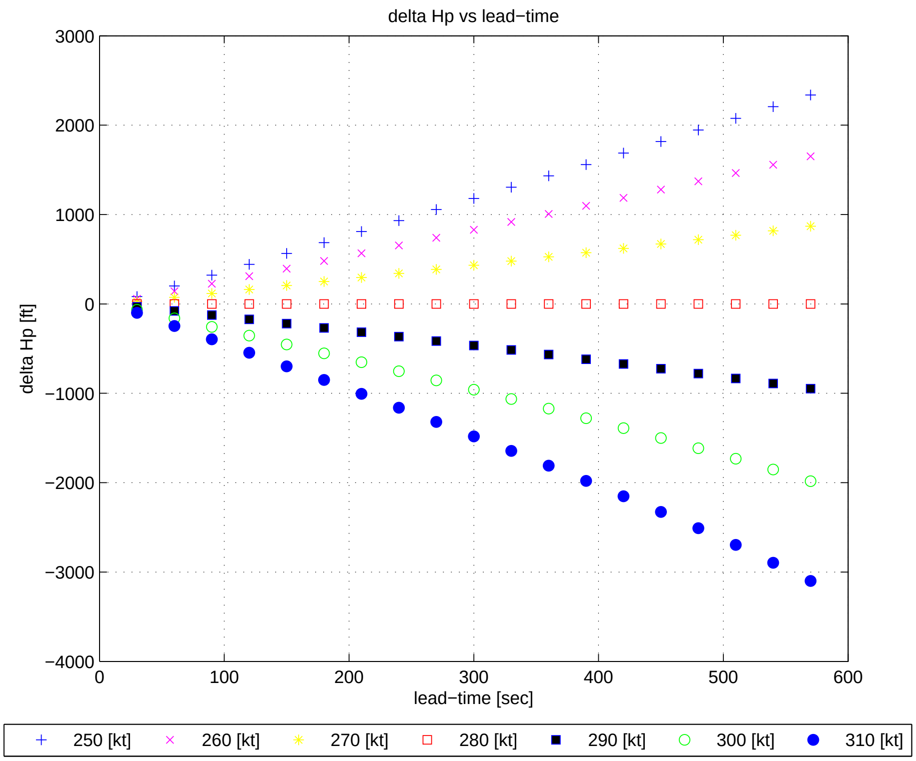

Figure 9. Effect on height-at-fix of altered CAS interventions, by lead-time

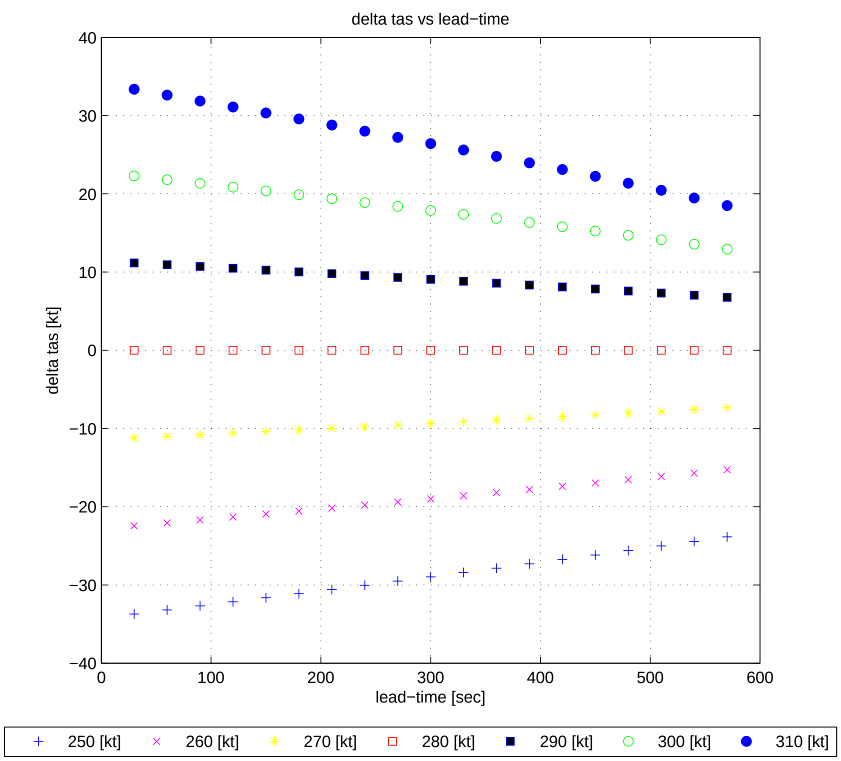

Figure 10. Effect on speed-at-fix of altered CAS interventions, by lead-time

Table 5. Effect of altered CAS intervention, by lead-time

Lead-time (sec)	CAS = 250 kt			CAS = 260 kt			CAS = 310 kt		
	ΔRTA (sec)	Δheight (ft)	Δspeed (kt)	ΔRTA (sec)	Δheight (ft)	Δspeed (kt)	ΔRTA (sec)	Δheight (ft)	Δspeed (kt)
540	52	2240	-24	33	1580	-16	-39	-2950	19
450	45	1850	-26	29	1310	-17	-34	-2380	22
300	32	1220	-29	20	850	-19	-25	-1530	26
150	17	600	-31	11	422	-21	-13	1440	30

The next thing to notice is that the effect on ΔRTA is more pronounced in the altered CAS case than for the rescheduled CAS interventions, even when the lead-time is as short as 450 secs: +29 sec for the 260 kt altered CAS case vs +26 sec for the corresponding rescheduled CAS case; and −34 sec for the 310 kt case vs −28 sec. The difference is even more extreme for longer lead-times, and/or when the lower CAS value (250 kt) is considered. Moreover, the height errors are typically less in the altered CAS cases: +1310 ft for the 260 kt case vs +2850 ft; and −2380 ft for the 310 kt CAS case vs −4460 ft. These perhaps surprising results are due in part to some of the "quirks" of the values selected for our case study, and in part due to the nature of the interventions. For example, where the new CAS value is greater than the nominal value, the rescheduled CAS intervention essentially "wastes time" waiting until the Mach/CAS transition takes place: you're better off transitioning to the CAS regime earlier (with CAS = 280) and then changing CAS to the new higher value. The explanation for the case where the new CAS value is lower than the nominal value is more subtle and needs detailed consideration of the mathematics involved.

It is a quirk of the way we have defined speed errors that they are inversely related to height errors: the greater the height error, the lower the speed error. (In short, the further the overfly altitude is from the nominal level (FL100), the closer the TAS equivalent of the new CAS is to the nominal overfly speed (323 kt).) As a result, the speed errors are greater in the altered CAS cases than for the corresponding rescheduled CAS interventions.

V. Sensitivity of the Results to Key Flight Factors

This section investigates the effect on the results of variations in the following key flight parameters:

- environmental factors: temperature and wind
- aircraft factors: weight
- flight deck factors: cruise height and cruise speed

We assume that these variations are known prior to descent and incorporated into the calculation of the TOD point and original RTA. It would be a relatively straightforward matter to modify our models to treat them instead as uncertainty factors if desired (individually or collectively), but we have not done so here. Likewise it would be straightforward to rerun the experiments with a different initial speed schedule.

For each set of parameters selected for study, a new reference run was calculated by rerunning the tool, with appropriate modifications to the AIDL expression, initial conditions and/or environmental factors used. For example, to test the effect of changing the cruise speed it is simply a matter of changing the initial conditions used in the AIDL expression (Fig.2). Running the tool gave us a new value for when TOD would occur in order to overfly the fix at the target height (FL100) under the nominal Mach/CAS speed schedule, and the resulting trajectory was then used as the new reference run.

Section V.A below describes how, and by how much, the different parameters were changed. Section V.B summarizes the effects of altered CAS interventions in the extreme cases for a representative lead-time.

V.A. Details of the Revised Reference Runs

Table 6 identifies the revised reference runs that were used for the sensitivity analysis. The "baseline" case here refers to the altered CAS run for a given CAS and lead-time: for space reasons we report only the results

Table 6. Characteristics of the various reference runs in the sensitivity analysis

Parameter	run ID	amount of change	distance	time	Mach	trans time
baseline	4	nominal run	70	651	0.763	68.9
temperature	42	+15 °C	75	677	0.763	71.6
	43	−15 °C	66	633	0.763	66.2
weight	44	−5000 kg	66	618	0.763	65.5
	45	+5000 kg	74	689	0.763	71.7
wind	46	20 kt head wind	66	656	0.763	68.9
	47	20 kt tail wind	74	656	0.763	68.9
cruise level	400	+1000 ft	72	673	0.763	90.3
	401	−1000 ft	67	632	0.763	49.6
cruise speed	402	+20 kt	71	662	0.798	24.6
	403	−20 kt	69	647	0.728	121.5
max distance	404	42, 45, 47, 400, 402	85	732	0.775	77.2
min distance	405	43, 44, 46, 401, 403	56	572	0.751	59.4

for CAS = 250 and 310 kt and lead-time = 450 sec below. Columns 1-3 note the parameter of concern, an identifier ('run ID') for the experimental condition applied, and a brief description of the amount by which the parameter was changed: see below for details of how the changes were simulated in the TCI. The other four columns give the values computed by the tool for key aspects of the resulting trajectories: 'distance' and 'time' are the horizontal distance and time between TOD and the fix, respectively; 'Mach' is the Mach value at cruise; and 'trans time' is the time between TOD and the Mach/CAS transition (which determines the maximum lead-time possible for an altered CAS intervention).

The first parameter varied was the temperature. Standard environmental conditions equate to a temperature of 15 °C (or 288.15 °K). For reference runs 42 and 43, we vary the temperature by ±15 °C from its nominal value. This represents ±5.2% with respect to the absolute temperature. Note that altering the temperature means that the pressure and geometric heights, and their rates of change, are no longer identical. Further, the relationship between the TAS, CAS and Mach values changes. We opted to keep the Mach value of cruise speed fixed in this experiment, which meant that the initial TAS values changed to 455 and 425 kt for runs 42 and 43, respectively. (For reference, the TAS and geometric heights corresponding to 280 kt CAS and pressure altitude 10,000 ft are 332 kt and 10,540 ft respectively for run 42, and 314 kt and 9,460 ft respectively for run 43.)

For reference runs 44 and 45, we varied the weight of the aircraft by ±5000 kg from its baseline initial value (58 tonnes at TOD), which is a change of ±8.6%.

For reference runs 46 and 47, we applied head and tail winds of 20 kt by modifying the values in the wind field in the Environmental Model. We kept the initial Mach speed unchanged. 73.69 and 66.41 NM.

For reference runs 400 and 401, we varied the cruise height by ±1,000 ft from its baseline initial value (35,000 ft). This variation represents ±4% with respect to the TOD-to-fix height difference of 25,000 ft. In this case we kept the initial Mach value unchanged and let the TAS value vary accordingly.

For reference runs 402 and 403, we varied the TAS value of cruise speed by ±20 kt from its baseline initial value (440 kt). This variation represents ±4.5%. Note that this TAS variation changes the scheduled Mach value in the Mach/CAS descent.

For runs 404 and 405, in order to check to what degree parameter variations reinforced or cancelled out each other, we chose a combination of the above parameter variations that would yield the maximum and minimum TOD-to-fix distances, respectively. Thus run 404 combines the parameter value modifications used in runs 42, 45, 47, 400 and 402, while run 405 combines those of runs 43, 44, 46, 401 and 403. Note that the distance and time offsets, from the baseline case, for these runs is approximately equal to the sum of the offsets of the five individual runs combined. (This is not necessarily true for the other data in Table 6.)

V.B. Results

Table 7. Effect on B738 of altered CAS intervention under different flight conditions, with lead-time 450 sec

			CAS = 250 kt			CAS = 310 kt		
Parameter	ID	change	ΔRTA	Δheight	Δspeed	ΔRTA	Δheight	Δspeed
baseline	4		+45	1840	−26	−34	−2370	+22
temperature	42	+	+45	1780	−27	−35	−2290	+23
	43	-	+45	1900	−25	−34	−2460	+21
weight	44	-	+43	2220	−24	−33	−2740	+20
	45	+	+47	1490	−28	−36	−2050	+24
wind	46	head	+48	1750	−26	−37	−2280	+23
	47	tail	+42	1920	−26	−33	−2450	+22
cruise	400	+	+45	1840	−26	−34	−2370	+22
level	401	-	+45	1840	−26	−34	−2370	+22
cruise	402	+	+45	1840	−26	−34	−2370	+22
speed	403	-	+45	1840	−26	−35	−2370	+22
max distance	404	max	+44	1520	−28	−34	−2060	+24
min distance	405	min	+46	2200	−24	−35	−2750	+20

Table 7 shows the effects of altered CAS interventions for CAS values 250 and 310 kt, when applied with a lead-time of 450 sec. The other cases of lead-time exhibited broadly similar trends to the cases reported here.

Discussion

The first thing to note is that most of the flight factors have little or no effect on the results. The two main exceptions are aircraft weight and wind. A heavier aircraft (run 45) results in slightly more extreme ΔRTA values, as does the presence of a head wind (run 46); the other factors have little affect on RTA. The effects virtually cancel out in the max/min distance cases (runs 404 and 405).

On the other hand, a lighter aircraft (run 44) results in more extreme height errors. A lower air temperature or a tail wind also exacerbate height error, but not as pronouncedly. This effect remains in the min distance case (run 405).

VI. Case Study II: Boeing 777-300

Although we did not study it in detail, we did briefly investigate an idle-throttle CDA scenario involving another aircraft type: namely, a Boeing 777-300, with an initial weight of 200 tonnes, performing a Mach/CAS descent from FL390 (39,000 ft) to pass over the metering fix at FL100. Its initial TAS was 450 kt (a Mach of 0.785 and a CAS of 243 kt), and the CAS part of the speed schedule was 280 kt as before (Table 8). For the reference run, the BRTE prototype tool calculated the following values: TOD occurred 94 NM from the fix, and the fix was overflown 862 sec later. The tropopause was encountered at 72 sec after TOD and the Mach-to-CAS transition occurred at 142 sec after TOD. At the fix, the aircraft's TAS was 323 kt.

As before, we investigated two different kinds of intervention: the "rescheduled CAS" case, where the CAS value of the speed schedule is changed before the Mach/CAS transition; and the "altered CAS" case, where it is changed during the CAS phase of descent. Figs. 11-14 give illustrative results for the 300 kt rescheduled CAS intervention and the 260 kt altered CAS intervention, with the latter taken with a lead-time of 570 sec.

Table 9 gives the results for the rescheduled CAS interventions. Figure 15 shows the effect on time-at-fix for the different CAS values against the lead-time at which the CAS value is altered. Figures 16 and 17 show the corresponding effect on height and speed error, respectively. Table 10 extracts values for three representative cases of CAS values (the maximum and minimum values considered, plus the 260 kt case for

Table 8. Baseline scenario for B773 study

Initial conditions					Final conditions		
weight (tonne)	height (FL)	Mach	CAS (kt)	TAS (kt)	height (FL)	CAS (kt)	TAS (kt)
200	390	0.785	243	450	100	280	323

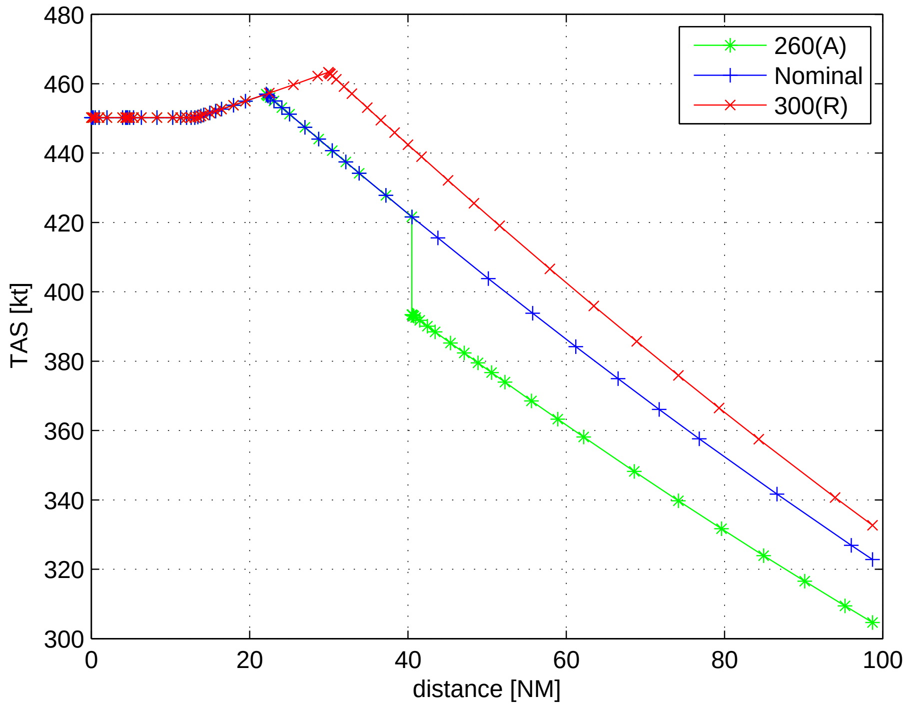

Figure 11. TAS vs distance from TOD for 3 example B773 runs

Table 9. Effect of Rescheduled CAS interventions on B773 trajectory

Revised CAS value	transition time (sec after TOD)	lead-time (sec)	ΔRTA (sec)	Δheight (ft)	Δspeed (kt)
250	31	>831	57	3490	-19
260	73	>789	35	2420	-12
270	108	>754	16	1250	-6
280	142	-	0	0	0
290	174	>720	-14	-1300	5
300	204	>720	-27	-2630	10
310	233	>720	-38	-3990	14

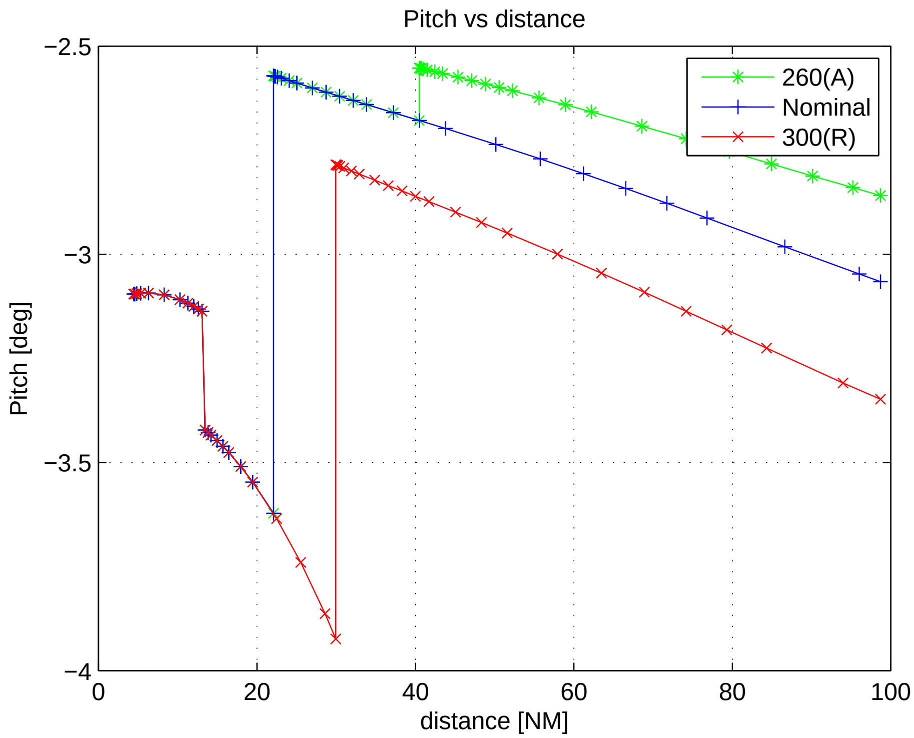

Figure 12. Pitch values for the 3 example B773 runs

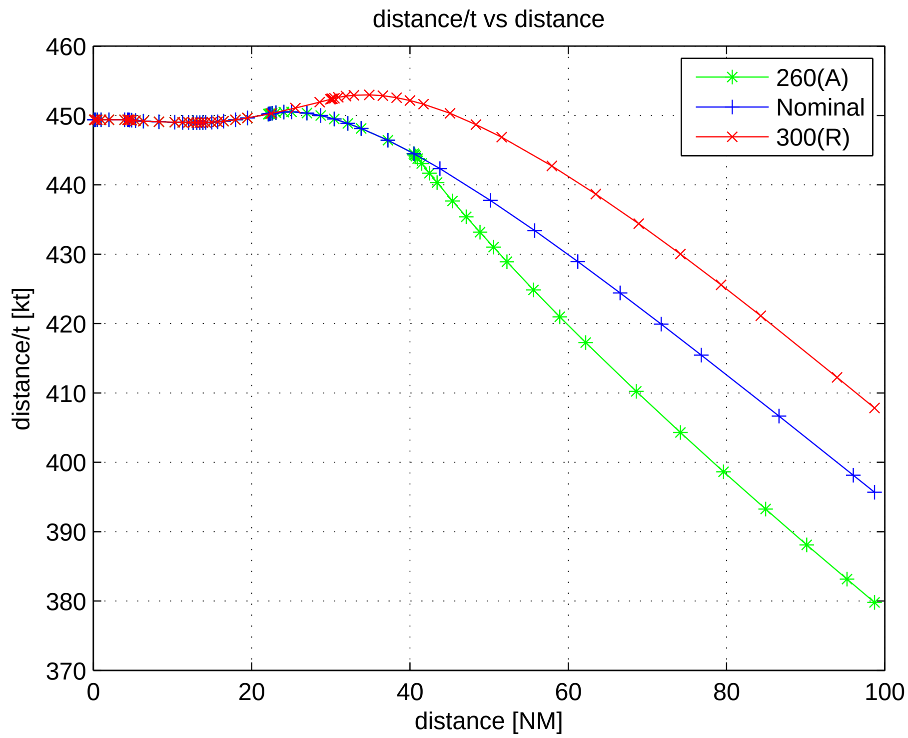

Figure 13. Average ground speed values for the 3 example B773 runs

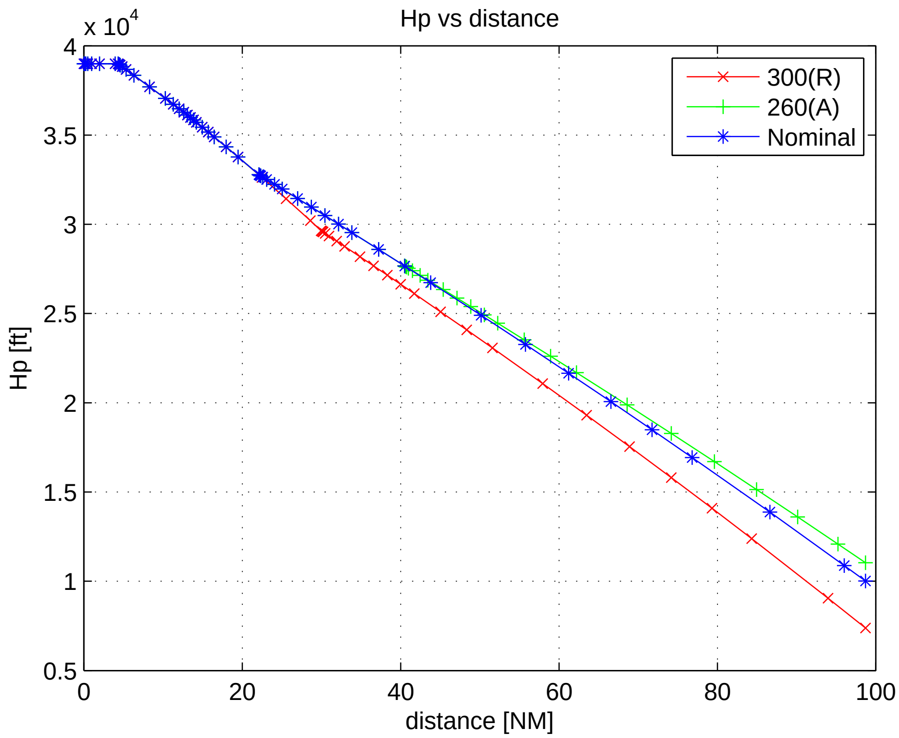

Figure 14. Descent profile for the 3 example B773 runs

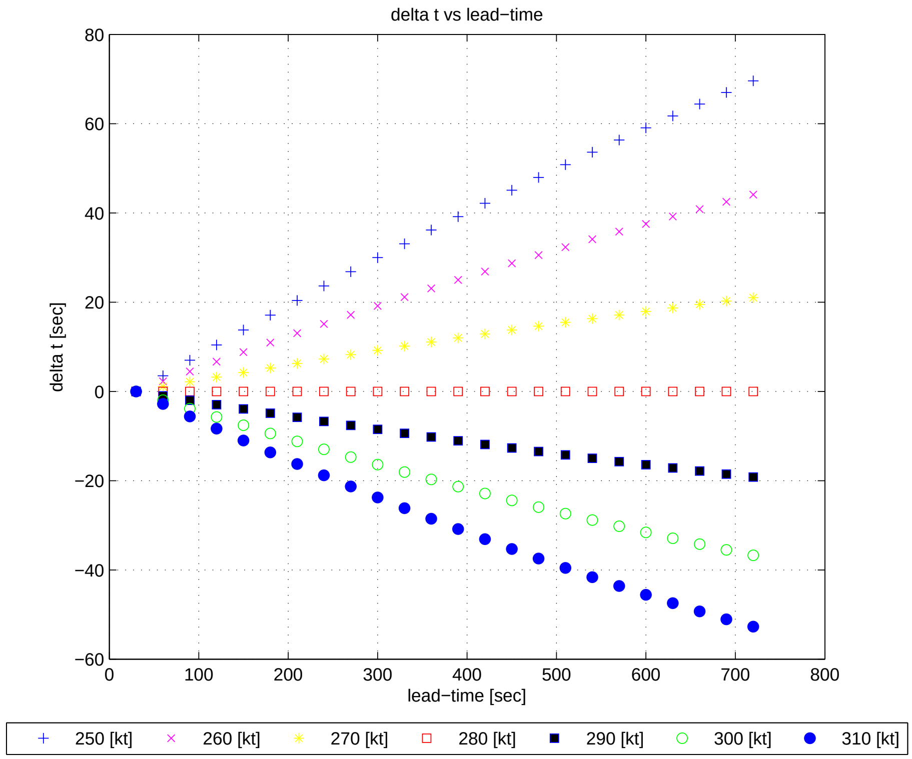

Figure 15. Effect on time-at-fix (ΔRTA) of altered CAS interventions for B773, by lead-time

comparison with the rescheduled CAS intervention results above) for a range of different lead-times. The results are broadly similar in nature to those for the B738 case, but the ΔRTA values are even larger – which is not surprising considering the aircraft has a longer descent in this case.

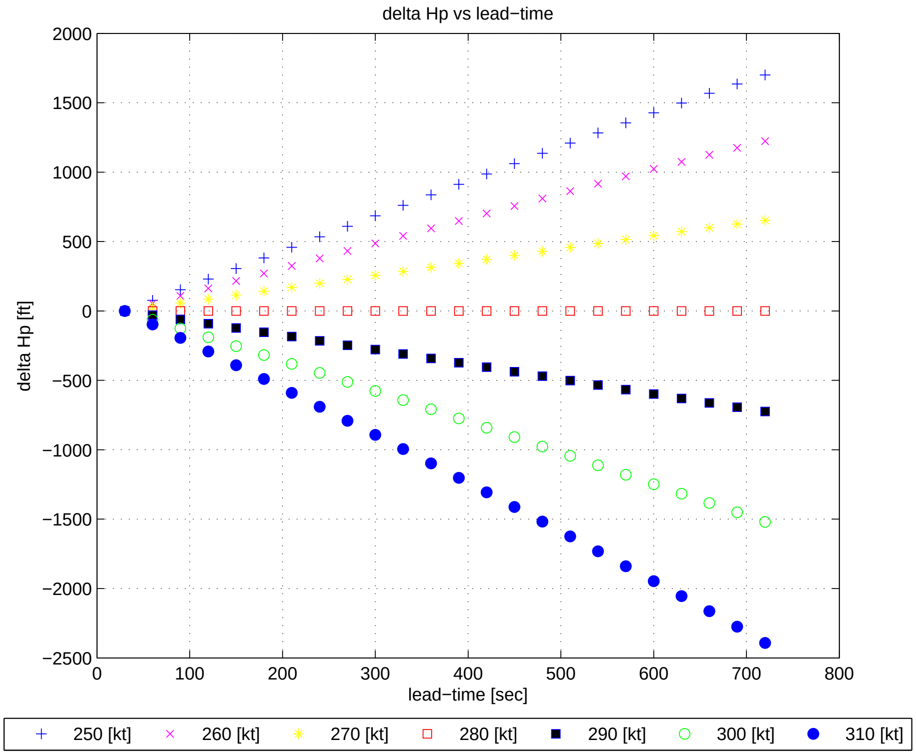

Figure 16. Effect on height-at-fix of altered CAS interventions for B773, by lead-time

Table 10. Effect on B773 of altered CAS intervention, by lead-time

Lead-time (sec)	CAS = 250 kt			CAS = 310 kt		
	ΔRTA (sec)	Δheight (ft)	Δspeed (kt)	ΔRTA (sec)	Δheight (ft)	Δspeed (kt)
720	72	1760	-26	-54	-2540	21
540	56	1350	-28	-44	-1840	25
360	39	911	-30	-31	-1200	28
180	20	458	-32	-16	-590	31

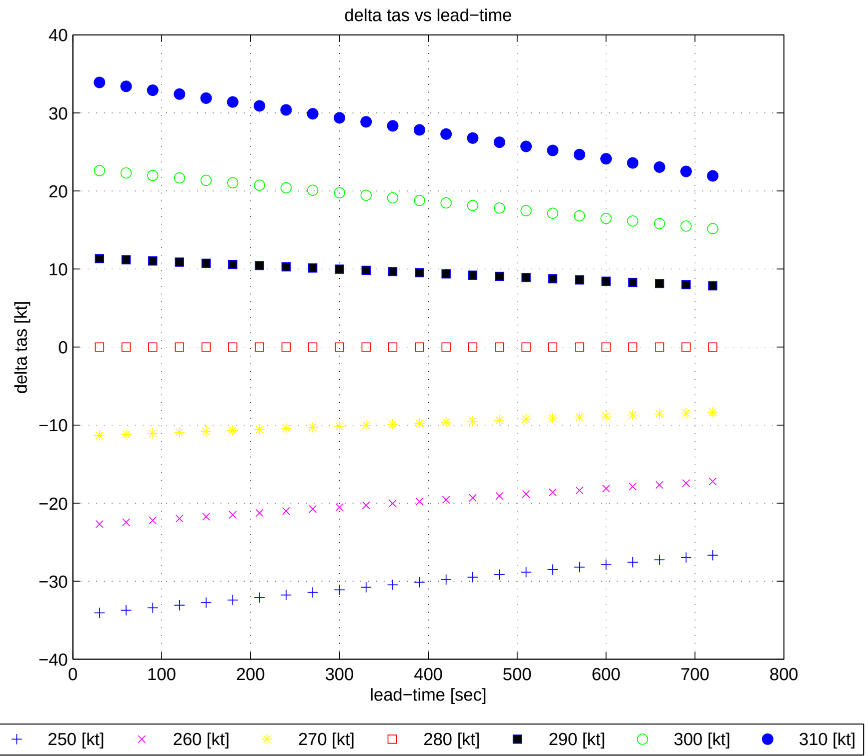

Figure 17. Effect on speed-at-fix of altered CAS interventions for B773, by lead-time

VII. Summary and Conclusions

The paper reports the results of a study into the degree to which elevator control can be used to adjust the time at which a metering fix is passed, under an idle-throttle Mach/CAS descent with a single intervention to modify the CAS value of the speed schedule used, once descent has begun. Of course, if a changed time-at-fix is required it would be much better to modify the planned trajectory prior to starting descent, but we are concerned with what flexibility is possible once descent has begun for last-minute "minor" adjustments to RTA, without impacting on the optimality of the descent.

The approach demonstrated the utility of the Aircraft Intent Description Language (AIDL) trajectory modelling language and prototype tool-set in studying such questions. We illustrated the approach in detail on a particular scenario involving a particular aircraft type, but the approach is quite general. Once the initial baseline scenario was scripted, it was straightforward to develop parameterized variants of the AIDL script representing the different experimental conditions. We were also able to check sensitivity of the results to different flight factors (including temperature, wind, aircraft initial weight, cruise height and cruise speed) simply by varying initial conditions and rerunning the experiments.

The scenario concerned a 58 tonne B737-800 aircraft descending from FL350 to FL100, with Mach 0.763 and CAS 280 kt, over 651 sec. It was found that the time-at-fix could be delayed by as much as 53 sec by changing the CAS value of the speed schedule to 250 kt, or brought forward by as much as 40 sec (with CAS = 310 kt), but at the cost of height errors of +2,300 ft and -3,000 ft respectively. (Broadly similar results were obtained for a second scenario, involving a Boeing B777-300 aircraft descending from FL390 to FL100. In this case the time-at-fix could be varied by more than +72 and -54 sec, with associated height errors of +1760 and -2540, respectively.)

It was found that, for the scenario studied, interventions taken during the CAS phase of the Mach/CAS descent generally had more effect than those taken during the Mach phase (in the sense that the magnitude of ΔRTA was greater), if taken early enough; moreover, the height error was less. This somewhat surprising result was in part due to particular values chosen in the scenario and is not a general phenomenon; never-the-less, it does illustrate the value of detailed mathematical modelling. A sensitivity analysis of the B738 scenario showed that the time change was exacerbated slightly for heavier aircraft and when flying into a headwind; however the other flight factors investigated had little affect on the results.

Anecdotal evidence suggests that this order of magnitude of ΔRTA may be at least as good as what can currently be achieved using path lengthening on approach, but that pilots would probably prefer this method (elevator control) for workload and fuel burn reasons.

One practical limitation of the approach is that current airspace design includes many constraints, such as height and/or speed limits, which preclude optimal CDA. In future work we would like to apply a similar approach to Continuous Climb Departures (CCD), and to investigate the degree to which crossing paths in Standard Terminal Arrival Route (STAR) and Standard Instrument Departure (SID) configurations can be designed to facilitate use of optimal user preferred trajectories. (See for example Ref. 1 for a proposal for an Extended Terminal Manoeuvring Area arrivals-route structure that would be suitable for optimal CDA.) Further work is also required to investigate what issues might arise when RTA is being used for spacing, such as what further constraints need to be added to which interventions are taken and when, so as to avoid spacing issues during descent.

Acknowledgments

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