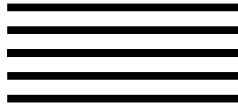
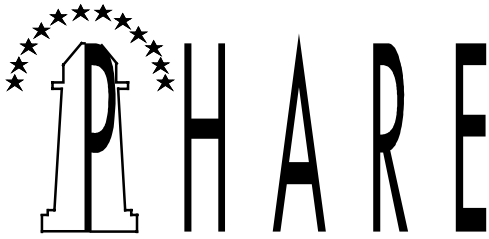


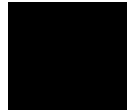
PROGRAMME FOR  
HARMONISED AIR TRAFFIC  
MANAGEMENT RESEARCH  
IN EUROCONTROL



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EUROPEAN ORGANISATION FOR THE SAFETY OF AIR NAVIGATION, EUROCONTROL



## **EXPERIMENTAL FLIGHT MANAGEMENT SYSTEM**

### **Prediction of Optimal 4D Trajectories in the Presence of Time and Altitude Constraints**



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# An Approach to the Prediction of Optimal Trajectories in the Presence of Time and Altitude Constraints.

## 1. Summary

Several current experiments in Air Traffic Management involve the use of long term prediction of aircraft trajectories as a way of ensuring efficient and conflict free flights from gate to gate. The Experimental Flight Management System was developed as part of the Eurocontrol PHARE program to provide an airborne element for such experiments. The potential efficiency of such approaches requires that it be possible to check trajectories against each other to identify any conflicts between them. An aircraft following an agreed trajectory can then be assured a trouble free and unperturbed flight. Preferred trajectories from several aircraft will inevitably lead to conflicts which must be resolved by constraining one or more aircraft to fly a non-optimum trajectory. Such traffic avoidance constraints may occur at any point in a trajectory and may involve changes to the lateral track, to altitudes or to timing. This paper is concerned with the techniques used in EFMS to modify an optimum trajectory as little as possible in order for it to be able to meet constraints.

## 2. Introduction

The Experimental Flight Management System, (EFMS), was developed as part of the Programme for Harmonisation of Air Traffic Management, (ATM), in Eurocontrol, (PHARE). It enables a range of real and simulated aircraft to take part in ATM experiments involving the exchange by datalink of detailed constraints from Air Traffic Control, (ATC), and predicted trajectories from the aircraft. This paper is concerned with the mechanisms used by EFMS to allow the prediction of nearly optimum trajectories in the presence of traffic avoidance constraints.

The basis for the EFMS modification process is the definition of an optimum flight in a suitable way for controlled modification. This is done by means of a Phase Table which describes the typical flight in terms of a series of subphases from takeoff to a level approach to ILS intercept.

The route which the aircraft is to fly is described by a Constraint List based on a series of waypoints. This structure is also used in uplinks from ATC to specify constraints on the flight.

Meteorological forecasts are used to build in the effects of wind and temperature.

The performance of the aircraft is simulated by a specific model which provides information about thrust and drag with the aircraft flown as described in the phase table.

The modification process works with the above inputs to arrive at a trajectory prediction which is as close as possible to the original phase table but meets the constraints. .

## 3. The Phase Table

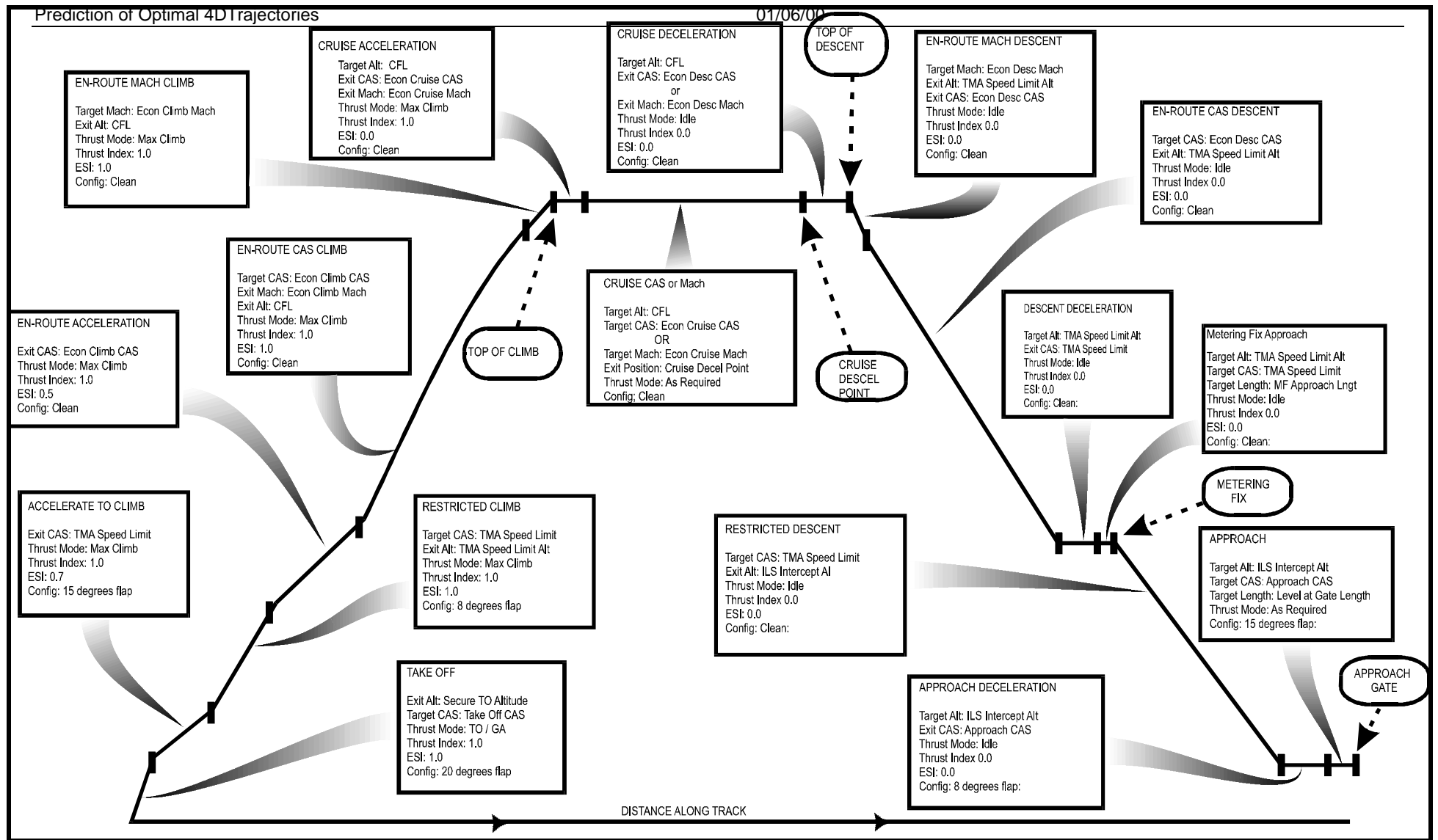
The Phase Table performs two rather separate functions within the EFMS prediction area:

- The initial content of the phase table is defined by the user and constitutes a statement of what is the most preferred flight profile for the aircraft in the absence of any constraints other than the performance envelope. This definition may be changed as required and can be specific to the aircraft, to the flight envisaged and to the particular conditions on the day.
- The process of modification is based on changing subphases in the phase table, adding or deleting subphases, sufficiently to meet any constraints which the preferred profile does not meet. The parameters of any added subphases are derived from those which pre-exist at the same point in the phase table. The limits by which the operating parameters of any subphase may be changed are user defined.

The initial phase table describes a potential complete flight from takeoff, (TO), to a level flight before the approach gate, equivalent to the point of ILS interception. Figure 1 presents an overview of how subphase definitions combine to describe a flight profile.

- The first subphase starts from the TO point and assumes the aircraft is at TO CAS and in TO configuration. Subsequent subphases always start from the exit conditions of the preceding subphase.
- Each subphase describes the operating regime to be obeyed. This includes:
  - the aircraft configuration, essentially flaps and gear settings
  - the engine thrust mode, such as 'maximum climb thrust' or 'idle'
  - the thrust index defining the proportion of the available thrust range to be used, '1.0' means maximum available thrust, '0.0' means minimum available thrust.
- Many subphases have target parameters which remain constant: these may include CAS, Mach and Altitude,
- All subphases have exit conditions which define when the flight passes to the next subphase. Only relevant exit conditions need to be defined in a subphase:
  - Acceleration / deceleration subphases exit when the specified CAS / Mach is reached.
  - Climb / descent subphases exit when the specified altitude is reached.
  - Constant speed level phases end at specific route positions, either explicit geographic locations as at the metering fix, or implicit as at the end of cruise.
  - A subphase ends whenever any exit condition is reached.
- The use of both CAS and Mach target and exit conditions on higher level subphases is a way of building into the phase table flexibility to handle changes in cruise flight level:
  - Thus the En-Route CAS Climb will continue either to CFL if this is relatively low, or will exit when the rising Mach value reaches its exit value. The En-Route mach climb would then take over.
  - A subphase for which the exit conditions are already met is not entered, so in the case of a lower CFL, where the En-Route Mach Climb CFL exit condition has already been reached, the Mach subphase is never entered.
  - In level subphases with both CAS and Mach target values the one which gives the lower true airspeed is used.
- Some level subphases have a target length. This reflects an operational requirement that the aircraft be established in level flight for at least the length specified. Such phases occur particularly around such areas as the metering fix and approach gate.

Modification limits may be set by the user for each of the performance parameters which are used in the phase table. Thus upper and lower limits may be set for 'Economic Cruise CAS or Mach', 'Economic Descent CAS', etc..



**Figure 1 - Typical Initial Phase Table**

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### 3.1 Constraint Lists

A particular route is defined by a structure called a Constraint List. This combines the definition of the lateral track over the surface of the Earth and the definition of altitude or time windows through which the flight is required to pass. A constraint list may be based on a predefined company route from the navigation database or may be built up dynamically from individual point definitions.

The lateral route definition is based on a sequence of points which may be named waypoints or navigation aids from a navigation database. The track between the points is formed by approximations to great circles on the surface of a WGS84 geoid. There may be a turn at any point, as illustrated in figure 2.. The turns are circular arcs on the geoid which are tangential to inbound and outbound tracks and of defined radius. This route geometry is encapsulated within a software element which allows the main part of the prediction to be carried out simply in terms of positions on the route. This lateral route element, while itself of interest, is not discussed further here.

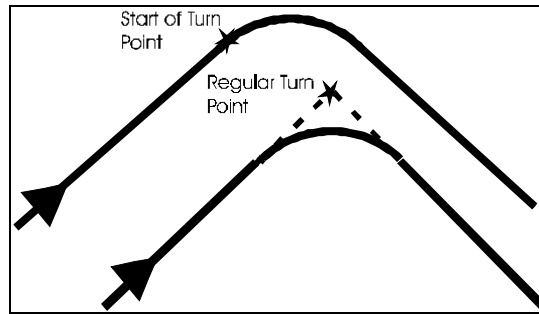


Figure 2 Turn Geometry

The flight may be constrained in time and altitude at every point on the lateral route.

- Time constraints are in terms of a time window with earliest and latest times at the point specified. There is no interpolation of time constraints between points, they are treated as applying only locally.

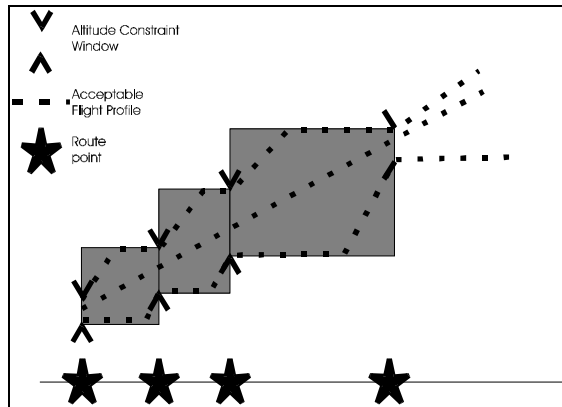


Figure 3 Altitude Constraints

- Altitude constraints are in terms of an altitude window which specifies highest and lowest acceptable altitudes at the point. The treatment of altitude constraints on successive points is illustrated by Figure 3. This shows a typical arrangement of windows for a SID, left to right, or a STAR, right to left.
- Within the SID or STAR the definition of the area in which the profile may be predicted is continuous, outside it is unconstrained.
- A prediction is considered to be compliant with the constraints if it remains anywhere within the shaded areas. The predictor is free therefore to

either climb as steeply as efficiency allows and then level out or to climb continuously at a shallower angle. The third variant illustrated, to stay low until forced to climb would be compliant but in fact is never selected by the EFMS predictor.

There is no specific limit on the number or locations of time or altitude constraints.

There are two other parameters which are associated with the constraint list:

- the proposed takeoff time
- the preferred cruise flight level (CFL)

### 3.2 Meteorology

The EFMS uses meteo forecast data in order to refine the prediction. Meteo data at several altitudes may be defined at any point along the track. The data at each level specifies wind



- This opening subphase will have an exit duration set to an experimental parameter .
  - After the opening subphase an acceleration/deceleration subphase is added to match the current aircraft speed to the target speed of the first subphase left in the phase table.
- The constraint list may indicate that the prediction is to end either in cruise or at the metering fix. Those subphases at the end of the initial phase table, after cruise or the metering fix are removed.
  - The exit positions of the level flight subphases are calculated and inserted into the phase Table. These might include :-
    - Approach (if the generation is to the gate) - the exit position of this subphase is the last waypoint in the constraint list.
    - The metering fix (if the generation is to the gate or fix) - the exit position of this level flight subphase is set as the position of the first waypoint of the STAR.
    - The end of cruise point. The exit position of the cruise subphase is set as the position of the last waypoint if the route is to end at cruise altitude. If not it is estimated from the position of the metering fix and the difference in altitude between cruise and the level flight at the metering fix.
  - These exit positions are only approximations at this stage. They will be corrected iteratively as the prediction proceeds.

## 5. Motion Simulation and Aircraft Models

The EFMS predictor is concerned with an overall prediction which fits in with the available flight envelope of the relevant aircraft. It is concerned with the attainment of relatively long term performance goals such as altitude profiles or arrival times.

The predictor does not attempt to model transient conditions such as flaring onto or off level flight subphases, takeoff or landing where the flight path angle varies significantly from the aircraft pitch angle. It is thus adequate for the modelling to be performed purely in terms of overall energy using a point mass model.

The performance of a specific aircraft type is represented by a model which provides predicted thrust and drag values for particular conditions.

Modelling is an iterative process. Each subphase in the phase table is executed in turn. A subphase exits normally when one or more of its exit conditions is met.

- Subphases are executed in time steps for which durations are set by parameter depending upon the phase of flight.
- The conditions at the start of a step are set up and the aircraft model is used to evaluate the energy excess or deficit available during the step. The operational settings defined for the subphase are used as input to the aircraft model.
  - The thrust and drag values used for a step are those estimated for the middle of the time step from current performance rather than those estimated at the start of the step.
  - This allows larger time steps to be used without introducing significant systematic errors due to changes in thrust and drag during the step. Time steps of tens of seconds can be used even in climb without significant problems.
- The energy change is applied to produce changes in CAS and / or altitude as defined by the ESI for the subphase. This sets up the conditions for the start of the next step.
- When the exit conditions are being approached the final time step duration is reduced so that the exit condition is met with reasonable accuracy.
- When a subphase exit is reached execution passes to the next subphase.

A subphase execution may exit abnormally when its continued execution will lead to the breaking of a constraint. This indicates that the phase table is incorrect and must be modified. The abnormally exited subphase is modified and extra subphases may be added to produce a new phase table which is likely to meet the constraint.

Modelling is then restarted from the first changed subphase and continues as described above.

A successful prediction corresponds to the case where all of the subphases in the phase table have been executed and the final position corresponds to the end of the route.

The strategies used for phase table modification are described below.

## **6. Modification of Phase Table to Meet Constraints**

### **6.1 Introduction**

Prediction proceeds by enactment of subphases as described above in 'Motion Simulation and Aircraft Models'. It is possible that a subphase enactment may violate constraint boundaries as described above in 'Constraint Lists'. In this case the phase table may be modified and the prediction re-enacted from the first modified subphase. The result of this will hopefully be that the constrain boundaries will not be violated by this modified prediction.

The phase table (and resulting time and latitude profile) will be modified for the following reasons:-

- to meet specific target positions in descent such as the metering fix or approach gate in the required manner.
- to avoid altitude constraint violations.
- to avoid time constraint violations.

The modified phase table will be used to simulate a new profile starting at the first modified subphase.

The specific strategy for dealing with these situations is given in the following sections of this document. Briefly the strategy is:-

- Specific target positions in descent -the exit position of the most recent level flight subphase will be adjusted.
- Be above altitude constraints in climb - climb at reduced CAS
- Stay below altitude constraints in climb - either a reduced thrust climb or the insertion of a level flight at the constrained altitude.
- Be below altitude constraints in cruise - a constant CAS/Mach descent followed by a level flight at the constrained altitude.
- Be above altitude constraints in cruise - a constant CAS/Mach climb followed by a level flight at the constrained altitude.
- Be below altitude constraints in descent - begin the current descent earlier by the adjustment of the exit position of the most recent level flight subphase.
- Stay above altitude constraints in descent - begin the current descent later by the adjustment of the exit position of the most recent level flight subphase.
- Time constraint - speed or route modification (hold or path stretch).

All constraints (altitude, time, and target point positions) are handled as they appear along the route (i.e. with no predefined order or priority).

It is necessary to remember that the overall strategy is one of iteration. A proposed phase table is tried, and if it violates a constraint a correction is applied to it and the process of modelling is repeated.

- It is not necessary in this sort of situation to worry too much that the corrections being applied are exactly what is needed.
- They only need to be approximations and to be applied in such a way as to cause a convergence onto the required solution.
- In practice the algorithms used have proved to converge rather quickly and accurately.

The iterative approach has no natural exit unless a total solution is found. Modification counts are built into the phase table to prevent any phase being modified more than a parameterised, typically 10, number of times for either altitude or time constraints. This ensures that the predictor never loops ceaselessly.

## 6.2 Strategy for Altitude Constraints

### 6.2.1 Strategy To Meet Specific Target Positions In Descent

- For the level flight subphases at the metering fix and approach gate a target length is specified together with an exit position. When one of these subphases is reached then the target length and actual length of the subphase is considered and an adjustment will be made if these lengths do not match to within a tolerance of 100 metres.
- The exit position of the previous level subphase is moved and the subphases from that point are re-enacted.
- For example consider a simple constant CAS descent without altitude constraints from cruise altitude to the level flight at the metering fix.
  - Assume that the first approximation causes the level flight to begin 3000 metres before the metering fix.
  - Assume the target length of this level flight was 1000 metres
  - The cruise will be extended by 2000 metres by moving the exit position of the cruise subphase.
  - In this way the subphase list is modified such that the predicted motion of an aircraft flying the subphases will fit the required altitude profile.
- Several possible problems can appear in performing this sort of optimisation :-
  - The end of cruise point is moved back along the route such that the cruise is removed totally. This is treated as a fatal error and no trajectory is generated.
  - In order to position the level flight at the approach gate at the correct place, the level flight to the metering fix needs to end before the metering fix. This is treated as a fatal error and no trajectory is generated.

### 6.2.2 Strategy To Meet 'Be-Above' Altitude Constraints In Climb

This requires that the climb should be carried out at a steeper angle than is used currently. The approach taken is sketched in Figure 4.

- If the current subphase is at less than max thrust then the thrust index should be increased to a possible maximum of 1.0.
- If not then the CAS of the current flight subphase should be reduced and with it the CAS values of previous subphases back to the last CAS change subphase.

The new CAS value for the climb is approximated from the formula

$$\text{New\_CAS} := \text{Current\_CAS} * \frac{\text{Elapsed\_Time}}{\text{Elapsed\_Time} + \text{Extra\_Time}}$$

where

Extra\_Time = altitude shortfall / current Altitude rate.

Altitude Shortfall = constrained lower altitude - predicted altitude.

Elapsed\_Time = the time since the end of the previous acceleration subphase.

- The reduced CAS may be no lower than the minimum CAS for the flight phase defined in the phase table.
  - EFMS implements a further restriction and does not support deceleration in the climb. Thus the reduced CAS is restricted to be no lower than the CAS prior to the last CAS change subphase.
- If the current subphases is a CAS subphase (not a constant Mach subphase) then the climb must be continued at the nominal CAS. To do this the following operations are performed :-
  - Modify the current subphase to exit at the constrained lower altitude.
  - Add an ESI acceleration subphase after the current truncated subphase to return to the nominal climb CAS.
  - Add a continuation CAS climb subphase after this ESI acceleration with the same exit conditions as the original climb.

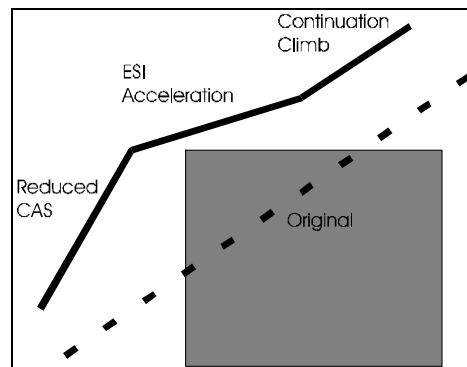


Figure 4 Be Above Constraint in Climb

### 6.2.3 Strategy To Meet Stay Below Altitude Constraints In Climb

Two possibilities exist for modification to meet upper altitude constraints in climb. If possible a decrease in thrust is used. These alternatives are sketched in Figure 5. If this method is found not to be viable then an inserted level flight is used.

- Decrease Thrust
  - The thrust of the current subphase is decreased to give a reduced rate of climb.
  - A proposed thrust index is approximated from the formula :-

$$TI_{NEW} = TI_{OLD} \frac{Drag + \frac{(Thrust - Drag) * D_1}{D_2}}{Thrust}$$

where

- $TI_{NEW}$  = proposed thrust index
- $TI_{OLD}$  = current thrust index of subphase
- Drag = predicted drag
- Thrust = predicted thrust
- $D_1$  = distance from start of subphase to current position.
- $D_2$  = distance from start of subphase to end of constrained altitude ceiling.

- If the formula returns a value of Thrust\_Index which is greater than the experimental parameter defining the lowest acceptable climb thrust index then this modification method is viable and will give a climb with a reduced altitude rate.
- An exit position is included in the modified subphase so that the reduced thrust climb ends at the constraint waypoint.
- A continuation climb subphase with the original thrust index is then inserted.
- If the formula returns a value of Thrust\_Index which is less than the experimental parameter defining the lowest acceptable climb thrust index then this modification method should not be used.

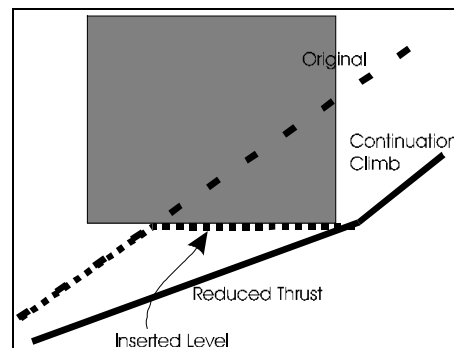


Figure 5 Stay Below Constraint in Climb

- Insert Level Flight
  - The climb subphase is truncated at the constrained maximum altitude
  - A level flight section and a continuation of the climb is added.

#### 6.2.4 Strategy To Meet Be Below Altitude Constraints In Level Flight

This is the case where in level flight a constraint is met which forces the aircraft to descend. The approach is sketched in Figure 6.

- A new level flight subphase will be inserted before the current level flight.
  - It will have the same target CAS/Mach and altitude characteristics as the original but with an exit position calculated to allow a descent to the 'stay below' altitude.
- A constant CAS/MACH descent subphase will also be inserted.
  - It will have the same target CAS/Mach as the level flight but an exit altitude of the 'stay below' altitude.
- The original level flight subphase will be modified to have a target altitude equal to the 'stay below' altitude.

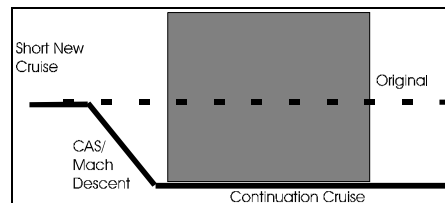


Figure 6 Be Below Constraint in Cruise

#### 6.2.5 Strategy To Meet Be Above Altitude Constraints In Level Flight

This is the case where in level flight a constraint is met which forces the aircraft to climb. The approach is sketched in Figure 7.

- A new level flight subphase is inserted before the current level flight.
  - It will have the same target CAS/Mach and altitude characteristics as the original but with an exit position calculated to allow a climb to the 'stay above' altitude.
- A constant CAS/MACH climb subphase is inserted before the current level flight.
  - It will have the same target CAS/Mach as the level flight but an exit altitude of the 'stay above' altitude.
- The original level flight subphase will be modified to have a target altitude equal to the 'stay above' altitude.
- note: the 'stay below' altitude is used as the new level since the strategy is to be as high as possible.

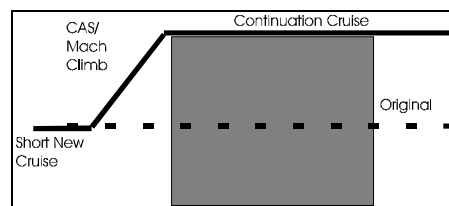


Figure 7 Be Above Constraint in Cruise

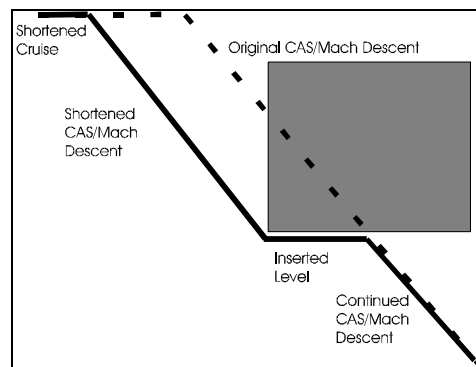
#### 6.2.6 Strategy To Meet Stay Above Altitude Constraints In Descent

- The previous level flight subphase will be lengthened to allow a later start of descent.

### 6.2.7 Strategy To Meet Be Below Altitude Constraints In Descent

A constraint of this type means that the descent preceding it must start earlier. The EFMS uses as nominal an idle descent so there is no scope for a steeper descent angle to be achieved. The approach is sketched in Figure 8.

- The previous level flight subphase will be shortened to allow an earlier start of descent.
- A level flight at the 'stay below' altitude followed by a continuation of the descent are added if necessary.
- note: EFMS presently uses idle or near idle descent subphases. Non-idle descents would introduce a possibility to optimise the descent profile to remove short level flight sections using increased thrust..



**Figure 8 Be Below Constraint in Descent**

## 7 Strategy To Meet Time Constraints.

### 7.1 Overview.

If a time control constraint point is reached and the predicted time at that point is not within the time window specified then an attempt is made to modify the previous subphases within the previously defined subphase list such that the prediction will be within the time window.

Subphases modified in this way are recorded as having been modified and a time modification count held as part of each individual subphase record is incremented.

Should the requested speed of a subphase be modified such that it reaches the defined minimum or maximum limit for that subphase or should the time modification count of any individual subphase reach a parameterised value then the subphase is marked as modified to limit.

Route modification may be attempted (by hold or path stretch) if this speed modification results in all modifiable subphases being modified to their limits and a time error still exists.

If speed modification is not possible, and path stretch is either not available or already modified to limit, and modification using hold is not viable then the prediction will be allowed to continue from the current position with a time constraint violation.

Time constraints are handled one at a time as they are met. There is no attempt to revisit a time constraint if subsequent ones prove to be difficult to meet. Thus if the first time constraint is met by passing the point at the extreme end of the time window it will not be changed if a subsequent window is earlier than the aircraft can meet.

Note that EFMS does not attempt modification for time constraints in the climb phase. This is for operational reasons rather than design or implementational ones. The techniques used could be extended to cover cases of time constraints in the climb.

### 7.2 Modification Start Point

The first step in modification for time is to find the earliest subphase in the phase table after which the modification may be performed.

This will be the one of the following which starts nearest (but before) the current position on the route :-

- The start of an acceleration/deceleration subphase at the top of climb (note : this acceleration/deceleration at TOC will be created if it does not already exist).
- The start of the acceleration/deceleration subphase after an opening subphase before the start of a cruise or descent subphase (for the case of a generation from flight at or above

cruise altitude).

- The start of the acceleration/deceleration subphase after a previous time control point.
- At the start of the prediction. In this case if the first subphase is not already an acceleration/deceleration then a new acceleration/deceleration subphase will be inserted at the start of the list.

The acceleration/deceleration subphase referred to above is modified to exit at the newly required CAS/Mach and subsequent subphases are modified to be consistent with this.

### 7.3 Viability Of Proposed Modification

Time modification by speed control is only viable if the subphases between the Modification Start Point subphase and the current subphase can be modified by changing speed.

Viability is established if for any subphase between the Modification Start Point subphase and the current subphase:-

- the time modification count is not set to the maximum allowed.
- an acceleration is required and the subphase speed is not set to maximum.
- a deceleration is required and the subphase speed is not set to minimum.

### 7.4 Calculation Of Speed Modification Factor

If speed modification is possible the factor by which speed is to be adjusted to meet the time control is calculated according to the formula :-

$$S_{FAC} = (\text{Elapsed\_Time} + \text{Time\_Error}) / \text{Elapsed\_Time}$$

where

$S_{FAC}$  = Factor by which speed is to be modified.

note:  $S_{FAC}$  is limited between 0.95 and 1.05 to smooth correction

Elapsed\_Time = time elapsed from the prediction at the modification start point  
to the predicted time at the time control point.

Time\_Error = amount by which we are early or late.

No corrections are made for the unusual case where some of the affected subphases are no longer modifiable.

### 7.4 Modification Of Subphase Speed Parameters

The target and/or exit CAS/Mach values for each subphase between the Modification Start Point subphase and the current subphase is then modified.

For each of the subphases to be modified :-

- Apply the Speed\_Modification\_Factor to target and/or exit CAS/Mach attributes.
- If the new CAS or Mach value violates the subphase min/max limits then set the value to the appropriate min or max value.
- Increment the subphase time modification count.

Modify the target CAS/Mach of the current subphase. (but not the exit CAS/Mach if it is an acceleration/deceleration).

### 7.5 Return To Nominal Speed After Modified Section

A return to the nominal speed profile after the current subphase is required if its target CAS/Mach has been modified.

The following modifications to the subphase list are required in this case:-

- The current subphase is truncated at the time constraint position (i.e. an exit position attribute will be added to the subphase.)
- An acceleration/deceleration subphase will be added to return the CAS/Mach to the previous nominal.
- A continuation subphase will be added after the acceleration/deceleration subphase. This will have the exit conditions of the original subphase.

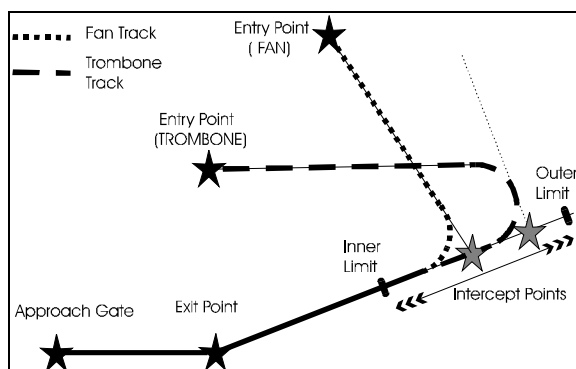
Several special case conditions must be considered :-

- The required extra subphases may exist if this is not the first time modification. They should not be duplicated.
- If the current subphase has an exit position coincident with the time control point then the continuation following the inserted acceleration/deceleration subphase is not needed.
- If the current subphase is the last subphase and also has an exit position coincident with the time control point then any return to nominal conditions is redundant.

## 7.6 Route Modification To Meet Time Constraints

### 7.6.1 Path Stretch

Speed modification may not be possible as subphase speed/modification limits have been reached. EFMS provides the possibility that the constraint list may define a path stretch area within the TMA to be used for time control.



**Figure 9 Path Stretch Geometry**

An overview of a path stretch area is shown in Figure 9. Essentially the mechanism is that the predictor is free to move the position of the intercept point towards or away from the exit point within defined limits.

Two geometrical arrangements are possible.

- The fan path stretch caters for approaches which are approximately perpendicular to the runway centreline.
- The trombone provides a conventional downwind leg approach.

Path stretching may be used if the modification start point is within the destination TMA and a path stretch is available.

The approximate path stretch route length increase/decrease can be calculated from the current length modified by Time error \* approximate ground speed.

The actual modification is carried out within the lateral route encapsulation referred to above. The subphases from the Modification Start Point, usually within the TMA are then executed again.

### 7.6.2 Hold

Route points may be nominated as being potential holding points. The most usual case of this is the metering fix point at the entry to the TMA although other points outside the TMA may also be nominated.

EFMS uses a conventional hold racetrack pattern with specified maximum CAS, which also determines the radius of turn from a parameterised maximum bank angle, and length of straight. The hold is aligned with the inbound track to the holding point.

A hold is activated when a late time constraint at or after the hold point cannot be met by (further) speed modification.

The extra distance which is required in the hold is calculated from:-

Time error \* TAS.

Note that TAS rather than ground speed is possible here because the closed nature of the hold means that wind effects are likely to cancel out.

The actual modification is carried out within the lateral route encapsulation referred to above. The subphases from the Modification Start Point are then executed again.

## **7.7 Termination**

The process described above is inherently iterative. The modelling may return repeatedly to earlier subphases as further constraints are encountered. Interactions between altitude and time constraint solutions are possible. There are cases where incompatible sets of constraints are imposed and there is no natural termination.

The process is forced to terminate in all cases by the presence of the modification counts. This is not a particularly tidy solution, but it does work in those few cases where the solution fails to converge. It is activated only where the set of constraints is internally inconsistent given the performance envelope of the aircraft.

The predictor is capable of handling constraint lists with unlimited numbers of compatible altitude and time constraints although it is normally used with relatively few of the latter. Something like three time constraints is usually the maximum used.

## **7.8 Conclusions**

The strategies described above have been implemented in EFMS and have been proved to work in a wide range of situations. The system is capable of handling realistically unlimited altitude and time constraints. Constraints which are within the flight envelope can be met with considerable accuracy. Altitude windows of zero size and time windows of less than 5 seconds can usually be met.

The Appendix presents some examples of the addition of constraints to a proposed flight.

There has been no specific effort to optimise the processing short of the use of sound design and programming principles. The system is object oriented and is written in Ada 83. The example predictions shown in the appendix take approximately 10 seconds in total run on a Sparc 20 system under Solaris. Additional constraints, particularly time constraints, adds to the processing time of course. The basic prediction and that with altitude constraints added take less than 1 second each.

## APPENDIX A- Example Prediction Modification

The following predictions were performed on a Sun Sparc 20 system running Solaris.

Each prediction is represented by two tables of data. The first describes the aircraft state at the start of each subphase used. The second describes the aircraft state at the waypoints along the route. Altitudes are shown in feet for convenience, everything else is in SI units, weights are in Newtons. The subphase table includes several entries for some subphases. These are the cases where the subphases are long and there may be significant changes in parameters, for instance groundspeed or height rate, during what is nominally a constant CAS climb.

The meteo forecast data used was provided by Meteo France and represents an actual forecast for the French airspace for a day during 1996. The effects of this can sometimes be seen from constant altitude and CAS subphases which have slightly varying ground-speeds.

The following prediction was performed with the minimum of constraints on the flight.

- There is a level acceleration to en-route climb speed at 9000
- followed by an unconstrained climb.
- The descent to the metering fix altitude is broken by a level deceleration to TMA speed at 10000.

Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Dot	Weight	Thrust	Drag	Lmts
	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
	2	92	0.29	3340	00:00:49	88	13	2544367	570149	209030	Yes
	3	92	0.29	3999	00:01:04	90	7	2543207	507171	224784	Yes
	4	126	0.41	5315	00:02:02	136	16	2539103	482211	173655	Yes
	5	126	0.44	8999	00:03:13	150	0	2534293	461114	134681	Yes
	6	139	0.48	8999	00:03:24	164	17	2533569	436011	133937	Yes
	6	139	0.54	15381	00:05:17	178	16	2526683	409117	133862	Yes
	6	139	0.6	20666	00:07:03	192	14	2520914	349761	133723	Yes
	7	139	0.65	25000	00:08:41	208	0	2515998	314743	146633	Yes
	8	165	0.76	25000	00:09:30	243	0	2513694	148182	148182	Yes
	9	165	0.76	25000	00:43:50	244	0	2451787	-5034	138319	Yes
	10	154	0.72	25000	00:44:14	230	-10	2451722	-5820	137962	Yes
	10	154	0.68	22188	00:45:38	220	-10	2451470	-5820	137962	Yes
	10	154	0.64	19268	00:47:07	209	-10	2451178	-6580	138282	Yes
	10	154	0.61	16257	00:48:40	198	-10	2450837	-7400	138712	Yes
	10	154	0.57	13159	00:50:18	189	-9	2450439	-8147	139158	Yes
	11	154	0.54	10000	00:52:01	181	0	2449982	-4089	129319	Yes
	12	129	0.45	10000	00:52:53	152	-9	2449731	-3418	173842	Yes
	13	129	0.42	6099	00:54:59	155	0	2449070	174013	174013	Yes
	14	129	0.42	6099	00:55:05	156	0	2448896	173975	173975	Yes
	15	129	0.42	6099	00:56:24	156	-9	2446662	-2242	174138	Yes
	16	129	0.39	2300	00:58:33	140	0	2445890	3611	167132	Yes
	17	98	0.3	2300	00:59:21	101	0	2445576	171173	171173	Yes

Print Aircraft State at waypoints											
MR32L	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
MRS03	3	99	0.31	4252	00:01:15	97	7	2542425	507171	224784	Yes
MAR06	4	126	0.43	8327	00:03:00	147	16	2535170	482211	173655	Yes
LOGIS	6	139	0.51	12497	00:04:25	172	16	2529793	409117	133862	Yes
SAURG	6	139	0.57	18698	00:06:22	185	15	2523088	380583	133801	Yes
MTL	8	165	0.76	25000	00:12:15	242	0	2508711	148031	148031	Yes
CMF	8	165	0.76	25000	00:25:04	246	0	2485595	147354	147354	Yes
CHW	10	154	0.61	16923	00:48:19	201	-10	2450913	-7400	138712	Yes
RBT07	14	129	0.42	6099	00:55:05	156	0	2448896	173975	173975	Yes
RBT	14	129	0.42	6099	00:56:13	156	0	2446989	173975	173975	Yes
OL220	15	129	0.4	2927	00:58:12	147	-9	2446018	-2242	174138	Yes
OL07L	17	98	0.3	2300	00:59:39	101	0	2445116	171173	171173	Yes

The following prediction was done after the following altitude constraints had been added.

Modify\_WP\_Alt at MRS03 above 500.0 below 6000.0 feet

Modify\_WP\_Alt at MAR06 above 5000.0 below 6000 0 feet

Modify\_WP\_Alt at CHW above 14000.0 below 16000 0 feet

Modify\_WP\_Alt at SAURG above 14000.0 below 16000 0 feet

Modify\_WP\_Alt at LOGIS above 1000.0 below 12000 0 feet

- The climb is interrupted by an inserted level to meet the constraint at MAR06.
- A slightly reduced thrust and thus climb rate then allows the constraints at LOGIS and SAURG to be met.
- The descent starts some 25 seconds early wrt CMF to be low enough to meet the constraint at CHW

Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Dot	Weight	Thrust	Drag	Lmts
1		92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
2		92	0.29	3340	00:00:49	88	13	2544367	570149	209030	Yes
3		92	0.29	3999	00:01:04	90	7	2543207	507171	224784	Yes
4		126	0.41	5315	00:02:02	136	16	2539103	499176	173924	Yes
5		126	0.41	6001	00:02:15	139	0	2538210	174567	174567	Yes
6		126	0.41	6001	00:03:01	139	15	2536886	476612	173509	Yes
7		126	0.44	8999	00:04:00	149	0	2532976	461108	134621	Yes
8		139	0.48	8999	00:04:11	162	15	2532253	398597	134033	Yes
9		139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
10		139	0.65	25000	00:09:46	208	0	2514279	314729	146593	Yes
11		165	0.76	25000	00:10:35	243	0	2511977	148131	148131	Yes
12		165	0.76	25000	00:43:52	244	0	2451979	-5034	138327	Yes
13		154	0.72	25000	00:44:15	231	-10	2451914	-5820	137969	Yes
13		154	0.68	22116	00:45:42	220	-10	2451656	-5820	137969	Yes
13		154	0.64	19111	00:47:13	207	-10	2451355	-6580	138289	Yes
14		154	0.6	16001	00:48:50	197	0	2451002	138788	138788	Yes
15		154	0.6	16001	00:49:20	197	-9	2450150	-8098	139106	Yes
16		154	0.54	10000	00:52:33	181	0	2449322	-4089	129284	Yes
17		129	0.45	10000	00:53:25	152	-9	2449072	-3418	173816	Yes
18		129	0.42	6099	00:55:31	155	0	2448411	173987	173987	Yes
19		129	0.42	6099	00:55:37	156	0	2448239	173949	173949	Yes
20		129	0.42	6099	00:56:56	156	-9	2446004	-2242	174111	Yes
21		129	0.39	2300	00:59:05	140	0	2445232	3611	167080	Yes
22		98	0.3	2300	00:59:53	101	0	2444918	171082	171082	Yes

Print Aircraft State at waypoints						0					
MR32L	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
MRS03	3	99	0.31	4252	00:01:15	97	7	2542425	507171	224784	Yes
MAR06	5	126	0.41	6001	00:03:01	139	0	2536905	174567	174567	Yes
LOGIS	8	139	0.49	10131	00:04:33	167	15	2530969	398597	134033	Yes
SAURG	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
MTL	11	165	0.76	25000	00:12:41	242	0	2508182	148016	148016	Yes
CMF	11	165	0.76	25000	00:25:29	246	0	2485066	147334	147334	Yes
CHW	14	154	0.6	16001	00:48:50	197	0	2450979	138788	138788	Yes
RBT07	19	129	0.42	6099	00:55:37	156	0	2448239	173949	173949	Yes
RBT	19	129	0.42	6099	00:56:45	156	0	2446331	173949	173949	Yes
OL220	20	129	0.4	2927	00:58:44	147	-9	2445360	-2242	174111	Yes
OL07L	22	98	0.3	2300	01:00:11	101	0	2444459	171082	171082	Yes

The following prediction is after the addition of one time constraint:

Modify\_WP\_Timeat CMF after 00:27:00 before 00:27:10

- The cruise now consists of
- an initial constant CAS subphase at 148
- an acceleration to the nominal 165
- a continuation constant CAS subphase at 165

Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Dot	Weight	Thrust	Drag	Lmts
	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
	2	92	0.29	3340	00:00:49	88	13	2544367	570149	209030	Yes
	3	92	0.29	3999	00:01:04	90	7	2543207	507171	224784	Yes
	4	126	0.41	5315	00:02:02	136	16	2539103	499176	173924	Yes
	5	126	0.41	6001	00:02:15	139	0	2538210	174567	174567	Yes
	6	126	0.41	6001	00:03:01	139	15	2536886	476612	173509	Yes
	7	126	0.44	8999	00:04:00	149	0	2532976	461108	134621	Yes
	8	139	0.48	8999	00:04:11	162	15	2532253	398597	134033	Yes
	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
	10	139	0.65	25000	00:09:46	208	0	2514279	322295	136607	Yes
	11	148	0.69	25000	00:10:03	221	0	2513462	136995	136995	Yes
	12	148	0.69	25000	00:27:01	224	0	2483848	313874	147041	Yes
	13	165	0.76	25000	00:27:32	247	0	2482392	147252	147252	Yes
	14	165	0.76	25000	00:45:24	244	0	2450232	-5033	138260	Yes
	15	154	0.72	25000	00:45:47	231	-10	2450166	-5820	137911	Yes
	15	154	0.68	22116	00:47:13	220	-10	2449908	-5820	137911	Yes
	15	154	0.64	19111	00:48:45	207	-10	2449608	-6580	138232	Yes
	16	154	0.6	16001	00:50:21	197	0	2449255	138732	138732	Yes
	17	154	0.6	16001	00:50:52	197	-9	2448400	-8099	139051	Yes
	18	154	0.54	10000	00:54:05	181	0	2447573	-4088	129189	Yes
	19	129	0.45	10000	00:54:57	152	-9	2447323	-3418	173746	Yes
	20	129	0.42	6099	00:57:03	155	0	2446662	173917	173917	Yes
	21	129	0.42	6099	00:57:09	156	0	2446490	173879	173879	Yes
	22	129	0.42	6099	00:58:28	156	-9	2444255	-2242	174041	Yes
	23	129	0.39	2300	01:00:37	140	0	2443483	3611	166941	Yes
	24	98	0.3	2300	01:01:25	101	0	2443169	170840	170840	Yes

Print Aircraft State at waypoints

						0					
MR32L	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
MRS03	3	99	0.31	4252	00:01:15	97	7	2542425	507171	224784	Yes
MAR06	5	126	0.41	6001	00:03:01	139	0	2536905	174567	174567	Yes
LOGIS	8	139	0.49	10131	00:04:33	167	15	2530969	398597	134033	Yes
SAURG	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
MTL	11	148	0.69	25000	00:12:55	220	0	2508439	136788	136788	Yes
CMF	12	148	0.69	25000	00:27:01	224	0	2483848	313874	147041	Yes
CHW	16	154	0.6	16001	00:50:22	197	0	2449232	138732	138732	Yes
RBT07	21	129	0.42	6099	00:57:09	156	0	2446490	173879	173879	Yes
RBT	21	129	0.42	6099	00:58:16	156	0	2444583	173879	173879	Yes
OL220	22	129	0.4	2927	01:00:16	147	-9	2443611	-2242	174041	Yes
OL07L	24	98	0.3	2300	01:01:43	101	0	2442710	170840	170840	Yes

The following prediction was after the addition of a further time constraint at CHW.

Modify\_WP\_Timeat CMF after 00:27:00 before 00:27:10

Modify\_WP\_Time atCHW after 00:51:00 before 00:51:10

The total number of subphases here remains the same, but their distribution is different:

- The late time at CHW is met by having an initial descent at 150 instead of 154
- After CHW there is an acceleration and the descent proceeds at the nominal 154.
- Co-incidentally the level which was previously needed to meet the altitude constraint at CHW is no longer included.

Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Dot	Weight	Thrust	Drag	Lmts
	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
	2	92	0.29	3340	00:00:49	88	13	2544367	570149	209030	Yes
	3	92	0.29	3999	00:01:04	90	7	2543207	507171	224784	Yes
	4	126	0.41	5315	00:02:02	136	16	2539103	499176	173924	Yes
	5	126	0.41	6001	00:02:15	139	0	2538210	174567	174567	Yes
	6	126	0.41	6001	00:03:01	139	15	2536886	476612	173509	Yes
	7	126	0.44	8999	00:04:00	149	0	2532976	461108	134621	Yes
	8	139	0.48	8999	00:04:11	162	15	2532253	398597	134033	Yes
	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
	10	139	0.65	25000	00:09:46	208	0	2514279	322295	136607	Yes
	11	148	0.69	25000	00:10:03	221	0	2513462	136995	136995	Yes
	12	148	0.69	25000	00:27:01	224	0	2483848	316691	142782	Yes
	13	160	0.74	25000	00:27:22	241	0	2482831	143026	143026	Yes
	14	160	0.74	25000	00:45:42	238	0	2450227	-4800	135525	Yes
	15	150	0.7	25000	00:46:05	224	-10	2450161	-5421	135208	Yes
	15	150	0.66	22011	00:47:38	213	-10	2449881	-6062	135368	Yes
	15	150	0.62	18898	00:49:17	200	-9	2449550	-6751	135576	Yes
	16	150	0.58	15676	00:51:02	189	-14	2449163	-7497	138031	Yes
	17	154	0.59	14800	00:51:21	192	-9	2449088	-8341	139234	Yes
	18	154	0.54	10000	00:53:56	181	0	2448410	-4088	129234	Yes
	19	129	0.45	10000	00:54:48	152	-9	2448160	-3398	173788	Yes
	20	129	0.42	6099	00:56:54	146	0	2447499	173927	173927	Yes
	21	129	0.42	6099	00:58:08	156	0	2445420	173836	173836	Yes
	22	129	0.42	6099	00:59:29	156	-9	2443114	-2263	173989	Yes
	23	129	0.39	2300	01:01:38	140	0	2442343	3612	166850	Yes
	24	98	0.3	2300	01:02:26	101	0	2442028	170700	170700	Yes

Print Aircraft State at waypoints

	Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Dot	Weight	Thrust	Drag	Lmts
MR32L	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes	
MRS03	3	99	0.31	4252	00:01:15	97	7	2542425	507171	224784	Yes	
MAR06	5	126	0.41	6001	00:03:01	139	0	2536905	174567	174567	Yes	
LOGIS	8	139	0.49	10131	00:04:33	167	15	2530969	398597	134033	Yes	
SAURG	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes	
MTL	11	148	0.69	25000	00:12:55	220	0	2508439	136788	136788	Yes	
CMF	12	148	0.69	25000	00:27:01	224	0	2483848	316691	142782	Yes	
CHW	16	150	0.58	15676	00:51:02	189	-14	2449163	-7497	138031	Yes	
RBT07	21	129	0.42	6099	00:58:08	156	0	2445420	173836	173836	Yes	
RBT	21	129	0.42	6099	00:59:15	156	0	2443513	173836	173836	Yes	
OL220	22	129	0.4	3002	01:01:14	147	-9	2442488	-2263	173989	Yes	
OL07L	24	98	0.3	2300	01:02:41	101	0	2441659	170700	170700	Yes	

The following prediction was after the addition of a further time constraint at OL07L, the approach gate.

Modify\_WP\_Timeat CMF after 00:27:00 before 00:27:10

Modify\_WP\_Time atCHW after 00:51:00 before 00:51:10

Modify\_WP\_Time atOL07L after 01:04:40 before 01:04:50

- There are no extra subphases, but all speeds after CHW have been reduced to the minima allowed in an attempt to meet the final constraint.
- The final constraint cannot be met.

Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Dot	Weight	Thrust	Drag	Lmts
	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
	2	92	0.29	3340	00:00:49	88	13	2544367	570149	209030	Yes
	3	92	0.29	3999	00:01:04	90	7	2543207	507171	224784	Yes
	4	126	0.41	5315	00:02:02	136	16	2539103	499176	173924	Yes
	5	126	0.41	6001	00:02:15	139	0	2538210	174567	174567	Yes
	6	126	0.41	6001	00:03:01	139	15	2536886	476612	173509	Yes
	7	126	0.44	8999	00:04:00	149	0	2532976	461108	134621	Yes
	8	139	0.48	8999	00:04:11	162	15	2532253	398597	134033	Yes
	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
	10	139	0.65	25000	00:09:46	208	0	2514279	322295	136607	Yes
	11	148	0.69	25000	00:10:03	221	0	2513462	136995	136995	Yes
	12	148	0.69	25000	00:27:01	224	0	2483848	316691	142782	Yes
	13	160	0.74	25000	00:27:22	241	0	2482831	143026	143026	Yes
	14	160	0.74	25000	00:45:42	238	0	2450227	-4800	135525	Yes
	15	150	0.7	25000	00:46:05	224	-10	2450161	-5421	135208	Yes
	15	150	0.66	22011	00:47:38	213	-10	2449881	-6062	135368	Yes
	15	150	0.62	18898	00:49:17	200	-9	2449550	-6751	135576	Yes
	16	150	0.58	15676	00:51:02	190	-4	2449163	-3783	129558	Yes
	17	118	0.45	13845	00:53:21	149	-7	2448592	-2433	131624	Yes
	18	118	0.42	10000	00:56:09	140	-8	2447816	-1443	162175	Yes
	19	118	0.39	6099	00:58:35	140	0	2447041	162375	162375	Yes
	20	118	0.39	6099	00:58:56	145	0	2446486	162287	162287	Yes
	21	118	0.39	6099	01:00:18	145	-8	2444322	-483	162308	Yes
	22	118	0.37	3100	01:02:16	137	-8	2443602	-159	162362	Yes
	23	118	0.36	2300	01:02:48	128	0	2443396	4502	179982	Yes
	24	94	0.29	2300	01:03:26	97	0	2443145	182911	182911	Yes

Print Aircraft State at waypoints

MR32L	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
MRS03	3	99	0.31	4252	00:01:15	97	7	2542425	507171	224784	Yes
MAR06	5	126	0.41	6001	00:03:01	139	0	2536905	174567	174567	Yes
LOGIS	8	139	0.49	10131	00:04:33	167	15	2530969	398597	134033	Yes
SAURG	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
MTL	11	148	0.69	25000	00:12:55	220	0	2508439	136788	136788	Yes
CMF	12	148	0.69	25000	00:27:01	224	0	2483848	316691	142782	Yes
CHW	16	150	0.58	15676	00:51:02	190	-4	2449163	-3783	129558	Yes
RBT07	20	118	0.39	6099	00:58:56	145	0	2446486	162287	162287	Yes
RBT	20	118	0.39	6099	01:00:09	145	0	2444562	162287	162287	Yes
OL220	22	118	0.37	3100	01:02:16	137	-8	2443602	-159	162362	Yes
OL07L	24	94	0.29	2300	01:03:49	97	0	2442539	182894	182894	No

The following prediction tries to make the aircraft earlier at CHW while maintaining the constraint at CMF.

Modify\_WP\_Time at CMF after 00:27:00 before 00:27:10

Modify\_WP\_Time at CHW after 00:49:50 before 00:49:59

- The initial descent is now at higher speed
- followed by a shallow descent to nominal

Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Do	t Weight	Thrust	Drag	Lmts
	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
	2	92	0.29	3340	00:00:49	88	13	2544367	570149	209030	Yes
	3	92	0.29	3999	00:01:04	90	7	2543207	507171	224784	Yes
	4	126	0.41	5315	00:02:02	136	16	2539103	499176	173924	Yes
	5	126	0.41	6001	00:02:15	139	0	2538210	174567	174567	Yes
	6	126	0.41	6001	00:03:01	139	15	2536886	476612	173509	Yes
	7	126	0.44	8999	00:04:00	149	0	2532976	461108	134621	Yes
	8	139	0.48	8999	00:04:11	162	15	2532253	398597	134033	Yes
	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
	10	139	0.65	25000	00:09:46	208	0	2514279	322295	136607	Yes
	11	148	0.69	25000	00:10:03	221	0	2513462	136995	136995	Yes
	12	148	0.69	25000	00:27:01	224	0	2483848	312563	149385	Yes
	13	169	0.78	25000	00:27:40	252	0	2482026	151253	151253	Yes
	14	169	0.78	25000	00:44:58	250	0	2450507	-5221	141057	Yes
	15	158	0.73	25000	00:45:21	235	-10	2450442	-6057	140658	Yes
	15	158	0.69	22024	00:46:47	224	-10	2450185	-6918	141072	Yes
	15	158	0.65	18924	00:48:18	210	-10	2449884	-7786	141521	Yes
	16	158	0.61	15699	00:49:55	200	-5	2449531	-7574	139235	Yes
	17	154	0.6	15456	00:50:10	194	-9	2449472	-8213	139159	Yes
	18	154	0.54	10000	00:53:05	181	0	2448711	-4089	129251	Yes
	19	129	0.45	10000	00:53:58	152	-9	2448461	-3399	173800	Yes
	20	129	0.42	6099	00:56:04	146	0	2447800	173968	173968	Yes
	21	129	0.42	6099	00:56:53	156	0	2446395	173875	173875	Yes
	22	129	0.42	6099	00:58:15	156	-9	2444089	-2263	174027	Yes
	23	129	0.39	2300	01:00:24	140	0	2443317	3611	166928	Yes
	24	98	0.3	2300	01:01:12	101	0	2443003	170835	170835	Yes

Print Prediction at wayp

MR32L	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
MRS03	3	99	0.31	4252	00:01:15	97	7	2542425	507171	224784	Yes
MAR06	5	126	0.41	6001	00:03:01	139	0	2536905	174567	174567	Yes
LOGIS	8	139	0.49	10131	00:04:33	167	15	2530969	398597	134033	Yes
SAURG	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
MTL	11	148	0.69	25000	00:12:55	220	0	2508439	136788	136788	Yes
CMF	12	148	0.69	25000	00:27:01	224	0	2483848	312563	149385	Yes
CHW	16	158	0.61	15699	00:49:55	200	-5	2449531	-7574	139235	Yes
RBT07	21	129	0.42	6099	00:56:53	156	0	2446395	173875	173875	Yes
RBT	21	129	0.42	6099	00:58:01	156	0	2444488	173875	173875	Yes
OL220	22	129	0.4	3005	01:00:00	147	-9	2443463	-2263	174027	Yes
OL07L	24	98	0.3	2300	01:01:26	101	0	2442634	170835	170835	Yes

The following prediction adds a slightly later constraint onto the gate.

Modify\_WP\_Time at CMF after 00:27:00 before 00:27:10

Modify\_WP\_Time at CHW after 00:49:50 before 00:49:59

Modify\_WP\_Time at OL07L after 01:01:40 before 01:01:50

- The final descent is now carried out at a lower speed
- There is an extra phase starting after OL220. There is a STAR altitude constraint of between 3000 and 3100 here. The phases before and after OL220 must be at slightly different rates - but the differences are within the resolution of this printout.

Waypoint	Phase	CAS	Mach	Alt	Time	G_Spd	A_Do	t Weight	Thrust	Drag	Lmts
1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes	
2	92	0.29	3340	00:00:49	88	13	2544367	570149	209030	Yes	
3	92	0.29	3999	00:01:04	90	7	2543207	507171	224784	Yes	
4	126	0.41	5315	00:02:02	136	16	2539103	499176	173924	Yes	
5	126	0.41	6001	00:02:15	139	0	2538210	174567	174567	Yes	
6	126	0.41	6001	00:03:01	139	15	2536886	476612	173509	Yes	
7	126	0.44	8999	00:04:00	149	0	2532976	461108	134621	Yes	
8	139	0.48	8999	00:04:11	162	15	2532253	398597	134033	Yes	
9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes	
10	139	0.65	25000	00:09:46	208	0	2514279	322295	136607	Yes	
11	148	0.69	25000	00:10:03	221	0	2513462	136995	136995	Yes	
12	148	0.69	25000	00:27:01	224	0	2483848	312563	149385	Yes	
13	169	0.78	25000	00:27:40	252	0	2482026	151253	151253	Yes	
14	169	0.78	25000	00:44:58	250	0	2450507	-5221	141057	Yes	
15	158	0.73	25000	00:45:21	235	-10	2450442	-6057	140658	Yes	
15	158	0.69	22024	00:46:47	224	-10	2450185	-6918	141072	Yes	
15	158	0.65	18924	00:48:18	210	-10	2449884	-7786	141521	Yes	
16	158	0.61	15699	00:49:55	200	-5	2449531	-6912	135535	Yes	
17	149	0.57	15105	00:50:33	187	-9	2449381	-7397	135361	Yes	
18	149	0.52	10000	00:53:27	175	0	2448617	-3268	129749	Yes	
19	124	0.44	10000	00:54:18	147	-9	2448369	-2467	168510	Yes	
20	124	0.41	6099	00:56:33	143	0	2447660	168711	168711	Yes	
21	124	0.41	6099	00:57:02	151	0	2446864	168619	168619	Yes	
22	124	0.41	6099	00:58:25	151	-8	2444584	-1572	168675	Yes	
23	124	0.38	3100	01:00:14	143	-8	2443924	-1305	168743	Yes	
24	124	0.38	2300	01:00:43	134	0	2443737	4574	181227	Yes	
25	94	0.29	2300	01:01:30	98	0	2443430	182572	182572	Yes	

Print Prediction at wayp

MR32L	1	92	0.27	59	00:00:00	86	20	2549716	771801	205997	Yes
MRS03	3	99	0.31	4252	00:01:15	97	7	2542425	507171	224784	Yes
MAR06	5	126	0.41	6001	00:03:01	139	0	2536905	174567	174567	Yes
LOGIS	8	139	0.49	10131	00:04:33	167	15	2530969	398597	134033	Yes
SAURG	9	139	0.55	15997	00:06:34	178	15	2524288	379017	133716	Yes
MTL	11	148	0.69	25000	00:12:55	220	0	2508439	136788	136788	Yes
CMF	12	148	0.69	25000	00:27:01	224	0	2483848	312563	149385	Yes
CHW	16	158	0.61	15699	00:49:55	200	-5	2449531	-6912	135535	Yes
RBT07	21	124	0.41	6099	00:57:02	151	0	2446864	168619	168619	Yes
RBT	21	124	0.41	6099	00:58:12	151	0	2444949	168619	168619	Yes
OL220	23	124	0.38	3100	01:00:14	143	-8	2443924	-1305	168743	Yes
OL07L	25	94	0.29	2300	01:01:43	98	0	2443076	182572	182572	Yes

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