PERFORMANCE PARAMETERS OF SPEED CONTROL

Rüdiger Ehrmanntraut and Frank Jelinek
EUROCONTROL Experimental Centre (EEC), Brétigny sur Orge, France

Abstract

The effect of speed control to resolve aircraft conflicts has not been well described in literature. Previous investigations on speed control have suggested some performance parameters such as resolution rates. In this paper additional performance parameters such as resolutions per flight, per conflict cluster and constraining aircraft are investigated by the comparison of speed control with other resolutions. This will help to give a better understanding of the effects of speed control on the overall air traffic management system regarding capacity, feasibility, safety, economy and ecology.

I - Speed Control And Automation

Speed control is one of the measures that air traffic controllers may use in conflict resolution. However, clearances involving speed are almost unused in European upper en-route sector control (<<1%) [1], whereas transfers, level changes, direct routing and vectors are most commonly used.

Speed control has not been studied for the purpose of automation yet, or at least there is no significant literature. The literature that treats algorithms for automatic conflict resolution mainly discusses horizontal vectors and, to a lesser extent, vertical resolutions, but very few suggest the use of speed adjustments. Only some project documentation treats speed manoeuvres, e.g. the CORA project [2].

Also, the operational concept of Airborne Separation Assistance (ASAS) investigates the possibility of chaining and spacing aircraft in sequence for easier handling of (arrival) flows [3], so-called station keeping, with a consequence of similarities in speed of the targets, but is not explicitly giving speed instructions. The same spacing principles apply to the procedures over the Atlantic Ocean that space aircraft on in-trail sequences on similar speeds or with a specific radar separation buffer.

All Arrival Manager tools set time constraints on arrival fix points, and aircraft can accomplish the time contract with speed adaptations [4][5]. This concept of metering fixes can further be generalised into the en-route phase to organise aircraft into flows, e.g. [6][7]. Those flow organisers do not include a conflict resolution function using explicitly speed, at least this has not been found documented. The procedures of sequencing aircraft with speed, however, do differ from generic speed instructions, because they only use one dimension of the geometry (along-track conflicts). If, instead, speed-instructions are used for all kind of conflict resolutions, they will be used in all dimensions of the possible conflict geometries.

The Automated En-Route Air Traffic Control (AERA) concept [8] in its very early versions mentions speed restriction measures where the automation system tags traffic that should not be touched by the controllers and pilots, because it is recognised as not being in a conflict situation if nothing happens. This could be regarded as a “maintain speed and heading” clearance, hence a speed instruction that is given by the system.

J. Villiers [9] introduces the notion of speed adjustments as a means to make what he calls “subliminal” control, which
could be considered as an automation system that creates "lucky traffic" so that controllers, who would still be part of the system, would not have to intervene on the traffic. The automation system would use speed adjustments for this, and the controllers would neither see nor have to know about hidden automatic operations, because they would not perceive the speed changes.

The previous study on the potential of speed control [10] has given initially promising results. More knowledge has to be sought on this topic in order to better understand the effects of speed control. This paper analyses additional performance parameters with the help of model simulations and compares speed control with other resolution manoeuvres.

II - Simulation Setup

The Reorganised ATC Mathematical Simulator (RAMS) was used in its version RAMS-Plus5.04 and 5.20. The scenario was reused from the 5 States Fast-Time Simulation [10] with an area extending from London/Paris in the west to Berlin/Prague/Vienna in the east and from Copenhagen/Malmö in the north to Lyon/Milan in the south. More than 140 sectors from 24 ATC Centres were simulated. The measured centres were limited to en-route and to Karlsruhe, Maastricht and Reims, which corresponds to 36 en-route sectors above flight level 245.

The traffic baseline simulates a traffic sample from 12 Sep. 1997, which corresponds to 100%. This was increased to 150, 200 and 300%, which emulates roughly traffic loads for the year 2005, 2010 and 2025 for optimistic traffic growth predictions.
Figure 3: Distribution of speeds per flight level

Figure 3 presents the distribution and variations of speed over the flight levels in the baseline scenario, i.e. without applying speed control.

The radar separation was set to 7NM and 5NM horizontally for the Planning Controller\(^2\) (PC) and the Tactical Controller (TC) respectively, and vertically to RVSM\(^3\). All scenarios set the look-ahead time \(\Delta L_{PC} = 15\) minutes\(^4\) for the PC and to 0 for the TC; and allow a maximal resolution interval of \(\Delta R = 800\) seconds\(^5\) for the implementation of the speed manoeuvres.

Conflict Detection

RAMS includes a tool for conflict detection and resolution. Their modelling influences the performance of the simulator and is briefly described here.

Conflict detection is triggered upon sector-entry events. For each aircraft there is one event for sector entry for the planning controller, and one event for the tactical controller, making two events per aircraft per sector entry. The conflict detection is only successful if the other conflicting aircraft is in the “window” of the respective controller. That means that each conflicting aircraft pair can be detected once or twice.

Figure 4 illustrates an example. If aircraft ac1 enters the PC window at time e1, and ac2 at e2, then e1 will not trigger a conflict, because the other aircraft is not yet in the scope of the PC, but e2 will do. Same applies then for the TC with events 3 and 4.

Resolution Rule Base

RAMS uses a data-driven, rule-base system as a resolution algorithm, which attempts to emulate real controllers’ behaviour. The performance of the rule base is entirely dependant on the way it is programmed, and the default rule base coming with the simulator is not running at optimum. Therefore, the rules have been modified for this study. The logic of the

\(\Delta L_{PC} = 15\) was found to be an optimum for this model.

\(\Delta R = 800\) was found to be an optimum for this model.

\(^2\) The PC is an executive controller issuing clearances and not purely planning.

\(^3\) RVSM – Reduced Vertical Separation Minima

\(^4\) \(\Delta L_{PC} = 15\) was found to be an optimum for this model.

\(^5\) \(\Delta R = 800\) was found to be an optimum for this model.
First, an analysis of the conflict geometry is undertaken with a categorisation of conflicts depending on the angles and attitudes of the aircraft involved. Next the conflict coordination is done, i.e. the aircraft to be penalised is selected. Then the manoeuvre is chosen, and finally additional constraints of the speed manoeuvre are set. The rule base that was created only moves one aircraft, which is very limiting - especially for speed where it would be more logical to increase one aircraft and reduce the other one.

**Uncertainty Emulated With Separation Minima**

Uncertainty in trajectory prediction was approximated with the use of higher separation minima for the Planner. Separation minima $\Delta S$ were set to $\Delta S_{PC} = 7$NM for the Planner, which corresponds to a compensation buffer of 2NM. The look-ahead for the planner is set to 15 minutes from the sector boundary. The average sector crossing time is 8 minutes and therefore the average time to conflict in the sector is assumed to be 4 minutes, i.e. the total time between detection and conflict is on average 19 minutes. The compensation buffer of 2NM corresponds to 1.47% uncertainty per 19 minutes for an aircraft flying at 430 knots (0.77% per 10 minutes), which is possibly slightly optimistic.

**Aircraft Performance Envelopes**

The aircraft performance envelope plays a major role in the ability of the aircraft to speed up or to slow down at the specific flight levels and attitudes where the resolution manoeuvres are applied. Significant improvements have been introduced to use the aircraft performance as given in [12], including over 100 aircraft types. 20 aircraft types have precise speed envelopes, and all other types are mapped to a representative category, i.e. heavy, medium or light. Nevertheless, the simulator was set up to allow for speed variances no higher than 15%, even if the performance profile of a specific aircraft type would allow for it (Figure 6).

**III - Simulations Scenarios**

About 45 simulations were run, each taking between 2 and 5 days on a 2GHz Pentium, and from which only the most significant twenty are presented. Five
resolution rules were used, referenced by A, B, C, D, and E:

[A] Conflict detection enabled, but no resolution manoeuvres at all.

[B] PC set to resolve with speed only, the TC is disabled.

[C] PC set to resolve with vertical only, the TC is disabled. The logic of the vertical resolution searches +/- 2 useable flight levels either for a temporary or a final flight level change.

[D] PC and TC set to resolve with speed only.

[E] PC set to resolve with speed only, the TC set to try a full range of resolutions but with a strong preference for horizontal vectors.

The rationale for scenario B and C is to compare the performance of the single speed and vertical dimensions at the look-ahead horizon. The horizontal dimension e.g. by using parallel offset will be evaluated in a future study. The rationale for scenarios D and E is to compare speed and horizontal manoeuvres of the radar controller in conjunction with the speed manoeuvres of the long planning function. Again other dimensions have not yet been treated. Scenario A is the baseline that treats conflict detection without any resolutions.

IV - Simulation result

Figure 7 presents the main results of this study. It shows the number of conflicts, the number of unresolved conflicts, the resolution rates and the relation of unresolved conflicts per flights for the twenty scenarios.

It can be seen that the conflict and traffic growth rates are non-linear (blue line), but apparently only from a threshold of 200%.

The number of conflicts varies (dark red column, left scale) even for the same traffic samples. Most scenarios with resolution manoeuvres diminish the number of conflicts in comparison to scenario A, which does conflict detection only. Only the speed-speed (D) and speed+horizontal (E) scenarios generate more conflicts for the dense traffic sample. Scenario C with vertical-only manoeuvres generates the smallest number of conflicts.

The resolution rates (dark triangles connected with black lines, right scale) differ largely, and the combination of speed and horizontal resolutions (E) achieve highest resolution rates. Because some scenarios generate more conflicts than others, it is more significant to see the absolute number of unresolved conflicts (light blue column, left scale), i.e. the remaining work to do, then speed-only (B) operating best for low and speed+horizontal (E) for high traffic densities.

The number of unresolved conflicts related to the number of flights (green points, right scale) gives another good indicator for the efficiency of the resolution. The lower this rate is the less remaining conflicts there are per flight and the better the resolution scenario works. Again it can be observed that speed-only (B) and speed+horizontal (E) operate best.

Scenario B where only the planner gives speed clearances performs better than scenario D where both controllers use
speed. It could be expected that the additional controller improves the situation, but this seems not to be the case. On the contrary, the additional TC has a negative effect when using speed only. This is not the case for scenario E where the TC applies horizontal vectors, which does equally well as B and even slightly better for the loaded traffic samples.

Finally, it can be reaffirmed that the resolution rates of the speed manoeuvres are very high ranging from 71 to 84%, but drop with high traffic densities. The vertical resolution gives the lowest results, with 50 to 65% resolution rates and a high ratio of unresolved conflicts per flight. The best candidate for high traffic density is the combination of speed (PC) and horizontal (TC) manoeuvres.

Figure 8: Nr of resolutions per percentage of speed adjustments for 3 speed scenarios.

Figure 8 shows the percentage of speed adjustments for those conflicts that could be resolved by speed manoeuvres, for the three scenarios that use speed as resolution. The distribution of speed adjustments range from plus/minus 15%, which is the threshold from the setup of the simulation. The average speed adjustment is 6.4% reduction and 5.3% increase, which is low. The higher rate of reductions is due to the way the rule base has been programmed, which starts its search with reductions.

Figure 9: Share of resolutions for scenario E.

One can see in Figure 8 that scenarios B, D and E have differing total counts of speed resolutions for the 300% traffic. The difference between B and D is due to the much higher amount of conflicts that D generates; the difference between D and E is that the latter also uses horizontal manoeuvres for about 20% of its resolutions and applies herewith less speed manoeuvres, as depicted in Figure 9.

Figure 10: Environmental parameters for scenario D.

Figure 10 gives an initial indication of environmental performance parameters such as fuel burn, CO, HC, NOx, H2O, CO2 and SO2 emissions for scenario D (ordinate starts at 94%). At 100% traffic level scenario D increases fuel burn and emissions. The increase is not significant and lies at about 0.18% for fuel burn and related pollutants, at about 0.27% for CO, at about 0.17% for HC and at about 0.12% for NOx. With 150% traffic it slightly increases fuel burn and emissions (about 0.2%). The 200% traffic reduces fuel burn by about 2.7%. CO is reduced by about 0.6%,
HC is reduced by about 0.8% and NOx emissions are reduced by about 5%. Therefore it can be concluded that speed control has almost no impact for low traffic levels, but seems to lead to significant environmental benefits of about 3% for fuel burn and directly proportional pollutants (CO2, H2O, SOx) and a reduction of NOx emissions of about 5% for the higher traffic sample. More detailed analysis on the environmental effects of speed control at high traffic levels would be required to confirm these first positive results and their significance level.

Figure 11: Nr of conflicts and resolution rates per encounter angles.

Figure 11 shows the number of conflicts per encounter angles, grouped into three categories: opening angles from plus/minus 0 to 10, 10 to 30, and 30 to 90 degrees. This categorisation is arbitrary. It can be seen that a very high rate of conflicts are in the small angle from 0 to 10 degrees and other studies [13] have found that these are mainly parallel same and parallel opposite direction types. All scenarios have higher resolution rates for the wide angle than for the small and very small angles. It is surprising that speed manoeuvres could resolve many conflicts with parallel directions at all and even the parallel opposite ones: this is due to the high number of climbing and descending aircraft.

Figure 12: Average resolution rates per minimal displacement distance.

Figure 12 depicts the average resolution rate per minimal displacement distance for each scenario. The percentage is related to the range, e.g. on average 67% of conflicts with minimal displacement distance smaller than 1NM could be resolved by scenarios B. All scenarios have more difficulties to resolve conflicts with small distances between the aircraft, which sounds normal. Scenarios B and E seem to resolve critical conflicts most easily, and can herewith be considered the safest!

Figure 13: Average occurrences (log) of sizes of clusters (abscissa) and their average resolution rates.

Figure 13 shows results concerning the cluster sizes and their resolution rates. The cluster is defined as the transitive closure of conflicting aircraft in time and distance [13][15]. The analysis limited the dimensions of a cluster to +/- 5 flight levels and 8 minutes horizontal time-distance, the first value set arbitrarily, and the latter set to the average sector crossing time of the measured centres. Most clusters are
simple conflicts (abscissa value 1) involving two aircraft. The resolution rates are very high for these simple conflicts. The number of conflicts drops exponentially with the cluster size. The resolution rate decreases approximately linearly with the increase of cluster size. It should be noted that there is a very small number of big clusters, so that their resolution rates may not be representative. Scenario E applying speed and horizontal resolution operates best and scenario C with vertical resolutions worst.

This analysis of clusters can be compared to the results from Durand [16]: the French cluster analysis results in more clusters of higher order, which is certainly due to the very high uncertainties that are used, which could be over pessimistic.

Another indicator for the complexity of resolution manoeuvres is the number of constraining aircraft per conflict, i.e. how many aircraft were hindering a resolution process of an aircraft in conflict. The resolution algorithm iterates through possible solutions when resolving a conflict. Every iteration tries out a new trajectory. If this trajectory is invalid because another – constraining – aircraft was in the way, then it continues until it exhausts its programmed possibilities. The number of constraining aircraft per search can be counted; however, it seems more significant to show the growth rates as a function of traffic rather than the simple counts.

Figure 14 therefore normalises to the number of conflicts that had no constraining aircraft in the baseline traffic sample. It can be seen that the number of constraining aircraft strongly increases with the traffic density. Further, scenario C with vertical only manoeuvres has the least constraining aircraft, which is possibly due to the limited solution spaces that the simulation setup allowed for, with only +/- 2 useable flight levels. The inverse applies to scenario E with speed and horizontal manoeuvres, which opens up the solution space and herewith increases the possibility to hit on a constraining aircraft.
Figure 15 illustrates the average resolution rates depending on the number of constraining aircraft for the 300% traffic sample. It is worthwhile to note that resolution rates seem to fall for small and grow for high numbers of constraining aircraft; an effect that is even more accentuated for lower traffic loads.

V - Discussion

Capacity Performance

The speed-only (B) and speed+horizontal (E) resolutions were measured to be the best performing scenarios, with up to around 75% resolution rates for the 2025 traffic. None resolves 100% and it was shown that these unresolved conflicts had higher complexities than the resolved ones. That means in terms of workload that all scenarios still leave a significant part of the work undone.

The model was set up with very long look-ahead and implementation times of about 15 minutes for the PC. The 15 minutes cannot be categorised as a planning task anymore regarding the average sector crossing time of 8 minutes; this means that the PC looks into the sector adjacent to the neighbour and to aircraft that are still grounded. One should rather call that function a Multi Sector Planner (MSP) or, because of its executive nature even better a Multi Sector Traffic Organiser.

Safety Performance

The speed-only (B) and speed+horizontal (E) scenarios are not only the most efficient ones, they are also the safest because they have higher ability: a.) to resolve critical conflicts with close minimal displacement distances between the conflicting partners, and b.) to resolve big clusters of conflicts. It can further be assumed that scenario E is safer than scenario B because it leads to higher average separations between aircraft by the use of the horizontal plane, i.e. an additional degree of freedom:

Figure 17 illustrates the trajectories that scenario E produced for 200% traffic. Many trajectories deviate from their flight plan, and the horizontal plane is well used. I.e. scenario E used the along-track dimension and the horizontal dimension, B and D only the along-track dimension, and C only the vertical dimension. However, the economical and environmental impact...
of scenario E and C should be investigated.

**Figure 17: Trajectories as flown in scenario E (PC speed and TC horizontal vector).**

Another important safety increase is the long look-ahead time of 15 minutes beyond sector boundaries, and the fact that speed resolutions are planned and implemented starting at this time horizon. It means that the entire system will be safe for 15 minutes in case of a breakdown, at least for the proportion of resolved conflicts.

**Economical And Environmental Performances**

It seems that speed control has positive effect on economical and environmental parameters for medium traffic densities; however, the findings need confirmation e.g. by evaluating the other scenarios and the 300% traffic samples.

**VI - Conclusion**

The comparison of different manoeuvres for the Multi Sector Planner and the tactical controller lead to the following conclusions:

- High capacity, safety and environmental gains can be achieved by the introduction of the MSP, a function that actively resolves conflicts at a 15 minutes look-ahead time horizon. Speed manoeuvres have a very high potential for this function ranking from 70 to 75% for the most demanding environment by applying very low speed adjustments.

- Best results are achieved when orthogonal dimensions of degrees of freedom are used, i.e. when the MSP and the radar controller apply different manoeuvres. E.g. when one applies speed and the other one a horizontal manoeuvre (scenario E) performs better than when both apply speed resolutions only (scenario D), which has a negative effect.

- The combination of the MSP and the traditional radar controller is stable and robust. The part of work that the first accomplishes is always high, independent of the work (perturbation) of the latter. This is important if the MSP is an automated function, because it will be reliable independent of human interventions at tactical level.

- This study finds no evidence for the existence of the "capacity barrier", even if the number of conflicts seems to become non-linear with the traffic growth. The conflict resolutions behave graceful with almost linear decrease of performance. Possibly yet higher traffic densities will reveal a saturation process of the different dimensions of the degrees of freedom when the physical airspace capacity is reached. I.e. the capacity barrier simply is a function of airspace characteristics and separation minima.

Future work should continue to investigate single manoeuvres for the MSP: the horizontal manoeuvre should be limited to the PC and compared to these results. Other manoeuvres should be investigated.
e.g. ‘direct-to’, lateral offset and variations in the rate of climb. Only then a combination of the different maneuvers should be envisaged to search for higher resolution rates. The continuation should further evaluate some key resolution parameters such as the duration of implementation and look-ahead time. The conflict resolution algorithm used in the simulator can largely be improved, e.g. maneuver both aircraft, remember when an aircraft is already in a maneuver, try to avoid constraining aircraft with combined rules for the resolution of big clusters etc. And last not least, there may be a requirement for innovative local airspace design to avoid complexity hotspots.

Key Words
MSP, Clusters, Capacity, Safety

The Authors
Rüdiger Ehrmanntraut is a scientist at the EUROCONTROL Experimental Centre in the research area Innovation (EEC-INO). Since 2003 he has been working on a PhD thesis investigating the automation of air traffic management. He has been coordinator of the TALIS consortium, an EC project that finished in spring 2004. From 1999 until 2003 he has been CNS Business Area Manager. From 1996 until 1999 he has conducted several projects on air-ground integration. Before joining EUROCONTROL in 1996 he worked as a software engineer for an industrial company. He holds a diploma of telecommunications engineer from RWTH Aachen, Germany in 1991.

Frank Jelinek is an aviation engineer working at the EUROCONTROL Experimental Centre. Since 2001 he has been responsible for global aviation emissions studies, research and tool development for the EEC research area Society, Environment and Economics (EEC-SEE). Before joining EUROCONTROL in 1994 he worked in the aviation and airport related software industry Lufthansa (LIS) & ABB (former CCS).

Acknowledgements
Many thanks for suggestions and reviews to M. Brochard, M. Bourgois and V. Duong.
Thanks for discussion to Prof. M. Fricke at TU Berlin.
Very special thanks to Ray Dowdall who provided the 5 States simulation setup and re-lecture.

References
for Air Traffic Control Automation
NASA/TM-2000-209586


www.eurocontrol.int/eec/publications.html


