Models of Air Traffic Merging Techniques: Evaluating Performance of Point Merge

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A new technique, Point Merge, for merging aircraft without vectoring in terminal areas (TMA), is modelled, and used in fast-time simulations. Four arrival traffic streams are merged for landing on a single runway. A method for designing fast-time models of vectoring and Point Merge is proposed and validated using real-time simulation trajectories. Relative performances of fast-time simulations of the corresponding models are compared. Interactions with departure traffic are also assessed. Results show the Point Merge model reduces: mean controller task load (20±1%), the number of instructions to pilots (~30%), and fuel consumption (170±14 kg), compared with vectoring.

Nomenclature

ATM	Air Traffic Management	*P-RNAV*	Precision Area Navigation
CDA	Continuous Descent Approach	*SESAR*	Single European Sky ATM Research
FAF	Final Approach Fix	*SID*	Standard Instrument Departure
FMS	Flight Management System	*STAR*	Standard Arrival Route
IAF	Initial Approach Fix	*TMA*	Terminal Control Area

I. Introduction

POINT Merge was developed as an innovative technique aimed at improving and standardising terminal area (TMA) operations[1,2] with a pan-European perspective (systematic use of precision area navigation[3] (P-RNAV) and Continuous Descent Approach[4] (CDA) in high traffic conditions). As it relies on existing technology, it has the potential for implementation in the short term. Potential candidate implementation centres include Oslo (2011), Dublin (2011) and Rome. It is also considered as a sound foundation to support further developments towards the Single European Sky Air Traffic Management (ATM) Research (SESAR) target concept[5] such as trajectory based operations.

Today in most TMAs, the merging of arrival flows relies on the use of open loop radar vectors (heading instructions). This technique is efficient and flexible, however, under high traffic load conditions, it is highly demanding for air and ground sides as it imposes rapid decisions for the controller and time-critical execution by the flight crew. Consequences are peaks of task load, high radio frequency occupancy, lack of anticipation, difficulty to optimise vertical profiles and to contain the dispersion of trajectories.

When considering merging of arrival flows, one of the key difficulties is to maintain some form of flexibility in expediting or delaying aircraft (through path shortening or stretching) so as to maintain capacity. Another difficulty, which may appear as contradictory, is to provide flight path predictability so as to support CDA.

This study is the result of an iterative development based on the RAMS Plus[6] fast-time ATM simulator. The objective was to support the Point Merge concept validation activities and complement the real-time simulations performed at the EEC by quantifying performance benefits with statistical significance. Recordings from real-time simulations of vectoring and Point Merge[1,2,7,10] were analysed for common path stretching patterns. These design patterns for vectoring and Point Merge were prototyped in RAMS Plus and refined iteratively after quantitative comparisons with results from real-time simulations and feedback from operational staff with experience of the corresponding real-time simulations. Based on previous studies[8,9], the first method tried was to model the tracks of both vectoring and Point Merge as a discrete set of alternative predefined arrival routes. There was concern for the error introduced by discretisation and whether the vectoring and Point Merge models were comparable. The tracks of Point Merge were evenly spread with the same angle and distance between each, whereas with vectoring it was difficult to ensure the same incremental distance between each alternate track because of the complexity of the tracks. The solution presented here is to replicate more closely how an air traffic controller performs the technique. Changes in track angle and track length are allowed to vary smoothly within an envelope. The only exception to this is in the case of changes of angle in vectoring where each is restricted to a multiple of 5° to reflect the operational practise of rounding heading instructions before transmission by voice over the radio.

The following chapter presents the theory behind Point Merge and the hypotheses for this study. Chapter III describes the models of air traffic control, the two merging techniques vectoring and Point Merge, the aircraft model and how the models are implemented in fast-time simulation. The validation of the method, scenarios, minimum separation values, traffic and metrics are presented in chapter IV, followed by results and conclusion.

II. Theory

A. Point Merge

Point Merge is a structured technique for merging arrival flows derived from an earlier study on airborne spacing sequencing and merging[11]. It is based on a specific route structure (denoted Point Merge System) that is made of a point (the merge point) with pre-defined legs (the sequencing legs) equidistant from this point for path stretching/shortening (Figure 1). The operating method comprises two main steps:

- Create the spacing by a "direct-to" instruction to the merge point issued for each aircraft at the appropriate time while on a leg.
- Maintain the spacing by speed control after leaving a leg.

The descent may be given when leaving a leg (and clear of traffic on the other leg). It should be a continuous descent as the distance to go is then known by the FMS. The equidistance property is key for the controller to easily and intuitively assess the spacing between an aircraft on the leg and the preceding one (on course to the merge point), with no need for new support tools and solely relying on graphical markers ('range rings').

It should be noted that path stretching is performed without controller intervention by letting the aircraft fly along the leg to the extent required (the published procedure coded in the FMS includes the full length of the sequencing leg). An example of dimensions is: merge point at 6,000 ft, sequencing legs at FL100-FL120 and 20NM from the merge point. An example of staffing is: approach controller in charge of creating spacing ("direct-to"), and final director responsible for maintaining spacing (speed control) and giving the descent instruction.

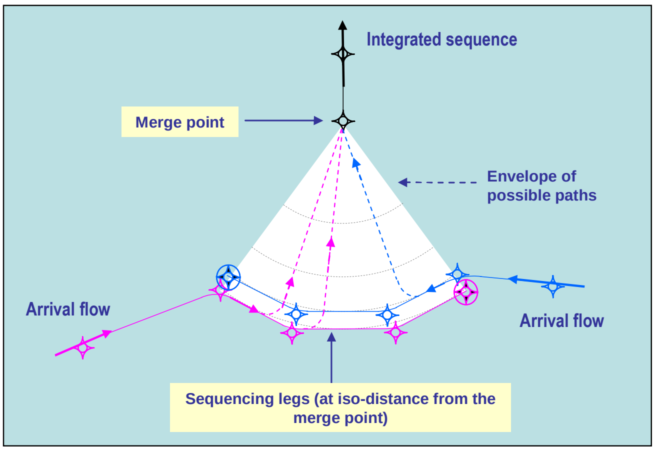

Figure 1: Point Merge system design with two arrival flows

B. Hypotheses

The following hypotheses were derived from results of real-time simulations. Point Merge relative to vectoring:

- results in similar average flight distance and time
- reduces number of instructions (Real-time: by ~ 40%)
- reduces vertical dispersion (Real-time by ~40%)

- increases average altitude (Real-time: by ~100%)

A reduction in controller instructions should lead to a reduction in task load, and aircraft flying higher should lead to lower fuel consumption. Therefore two additional corresponding hypotheses are derived. Point Merge:

- reduces task load
- reduces fuel consumption

These last two hypotheses, related to major indicators such as task load and fuel consumption, are considered to be more specific to modelling activities than to real-time simulation and represent one of the main reasons for conducting fast-time simulations.

III. Apparatus

A. Air Traffic Control Model

The airspace (see Figure 2) is taken from a real-time prototyping session and has four entry points defined by corresponding Initial Approach Fixes (IAFs), one dedicated arrival runway (RWY26L) and one parallel (independent) dedicated departure runway (RWY26R). The runways are operated under configuration where arrivals land and departures take off towards the west.

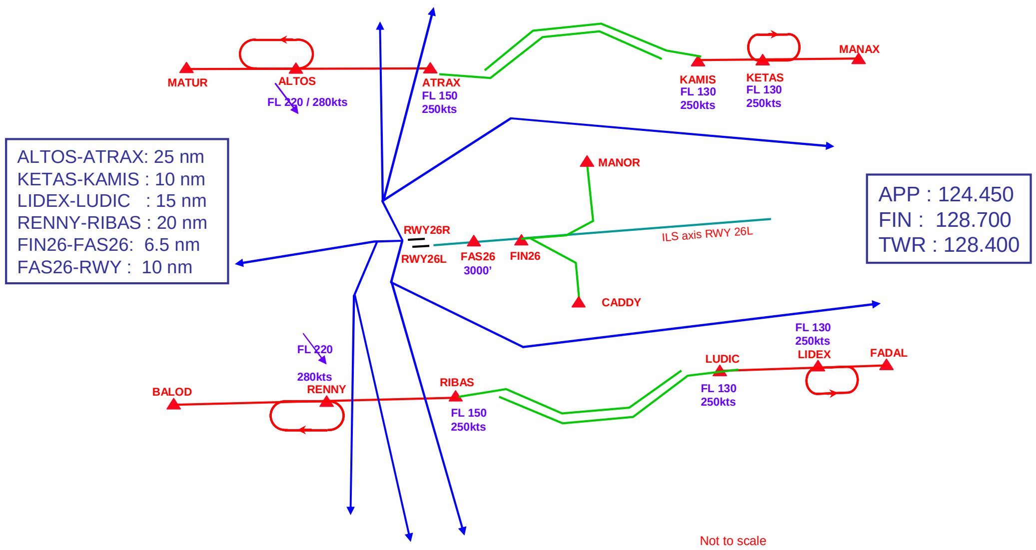

Figure 2: Airspace Design

1. Arrivals

Both arrival sequencing methods (vectoring and Point Merge) use the same basic airspace, but the main differences involve the practises of how the airspace limited by the four IAFs is used for the arrival traffic. Vectoring airspace was based on four standard arrival routes (STARs) corresponding to nominal routes from each IAF to the runway whereas Point Merge airspace was framed by four STARs corresponding to longest routes from each IAF to the runway.

The TMA airspace has two executive arrival controller positions: approach controller and final controller. Planning controllers are not taken into consideration in the experiments.

In vectoring, the approach controller is responsible for initiating sequence integration by path stretching using heading instructions. Final controller is responsible for completing sequence integration using speed instructions and lateral fine tuning if necessary using heading instructions. Descent instructions can be issued by either controller depending on longitudinal progress.

In Point Merge, the approach controller is responsible for initiating sequence integration by path stretching using direct-to merge point instructions. Final controller is responsible for managing the descent and completing sequence integration using speed instructions and lateral fine tuning if necessary using heading instructions.

2. Departures

Departure traffic uses the same airspace/departure routes for both methods. There are 8 Standard Instrument Departure routes (SIDs): one to the west, three to the south, two to the east and two to the north. The altitude restrictions are the same for Point Merge and vectoring models. The altitude restrictions set for the departures are based on the main principle that the departures are restricted to fly below the arrival flows. As an exception, the eastbound departures crossing the Point Merge system or vectoring area are unrestricted because they are considered to have enough time to climb high enough not to intervene with the lower arrival flow.

3. Traffic Feeder

For the purposes of fast-time simulation, feeder sectors and controllers are defined outside of the TMA to cover the area where the flights enter the simulation. The purpose of using these additional controllers is to guarantee that the flights do not arrive at IAFs in conflict.

B. Merging Techniques

Two different merging techniques are used, vectoring (baseline) and Point Merge. A systematic method is applied to provide accurate models appropriate for fast-time simulation of both vectoring and Point Merge techniques:

1. Vectoring

Figure 3 shows how the vectoring technique is implemented for two typical incoming flows. Based on real-time simulation track patterns and airspace/route design by air traffic controllers, there are fixed segments from each IAF and to the Final Approach Fix (FAF). On the downwind flow, there is a choice of several routes from a finite set defined by three consecutive changes in direction. Each change in direction can vary within a range bounded by two angles. The variation is limited to angles which are multiples of 5º to reflect operational limitations of voice communication. The base flow is similar except there are only two changes in direction. For implementation reasons the positions of the change in route direction were fixed e.g. for the north TMA at ATRAX and KAMIS in Figure 3. This was judged to be an acceptable deviation from reality where an infinite set of routes is feasible despite the 5° increment because the start of vectoring is not constrained to a particular point.

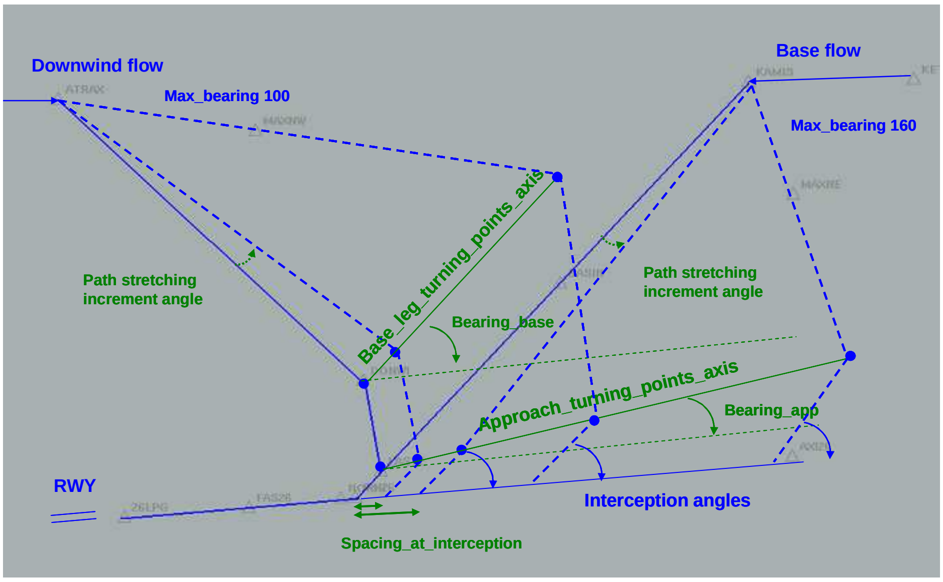

Figure 3: Vectoring method – path stretching with a given increment angle

2. Point Merge

Figure 4 shows how the Point Merge technique is implemented for two typical incoming flow. Aircraft models can fly down a choice of routes similar to those in the real world. There are common fixed segments from IAF and to FAF. In between the routes may vary 'continuously' (within limit of digital computer) with the single degree of freedom being the angle of the 'direct to' the merge point which can vary between two limits.

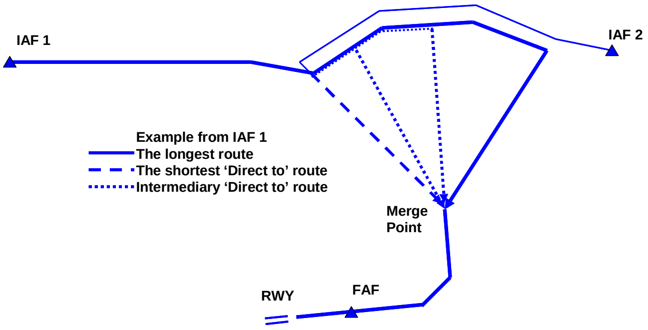

Figure 4: Point Merge method – direct to instruction issued at continuous distance along the leg

C. Aircraft Model

The aircraft performance data used for the study are RAMS Plus performance tables calibrated for BADA[12] 3.6 by EUROCONTROL Maastricht Upper Airspace Control. For each aircraft the airspace performance is defined by level band, with cruise, climb and descent speeds and rates associated with each level band.

These performance data have been modified in few cases when the data do not allow certain aircraft to make certain EEC-defined speed restrictions along the arrival routes. Modifications made are as small as possible to allow the aircraft to obey the modelled restrictions.

A parameter of 10% performance variance with respect to the BADA static tables was applied in all models, which is used, if needed, for aircraft speeds in order to obey restrictions. Sometimes the performance variance is used when aircraft need to be delayed to achieve their slot in the runway sequence.

D. Implementation of Models

These models are implemented in RAMS Plus, using a 'Path Object' design pattern[13,14], where software objects are mapped closely on to corresponding geometrical objects.

IV. Method

A. Validation of Lateral Tracks

To gain confidence in the accuracy of fast-time simulations, the lateral tracks of the models are compared by i) theoretically evaluating route characteristics before implementation in fast-time simulation, and ii) running fast-time simulations.

1. *Pre-simulation*
   - Lateral Deviation Analysis

For vectoring and Point Merge, each real-time simulation trajectory track was split into 100 equally spaced lateral points. For each theoretically possible fast-time simulation track, the great circle distance between equivalent points from a similar set of 100 points was measured. The fast-time track with the smallest maximum distance between points was taken to be the closest to the real-time track and therefore a measure of lateral deviation.

- Path Stretching Distance Analysis

From the airspace/route design, the following potential values characterising the routes are calculated: shortest, longest, maximum number, and average increment in length.

2. *Post-simulation*

Lateral tracks are generated from fast-time simulations for both Point Merge and vectoring and compared with those of real-time simulations.

B. Comparison between Vectoring and Point Merge - Scenarios

1. *Vectoring*

The area where the controllers can give heading instructions to the aircraft begins at the IAFs for the flows coming from the east and, due to departure constraints, 10 NM after the IAF for the flows coming from north-west and south-west, respectively. The vectoring areas for each direction are limited to certain maximum angles off the shortest routes. This results in vectoring areas where north-west/south-west longest routes are continued along the original track before reaching the vectoring area (i.e. flying with magnetic route heading 90°). Similarly for eastern flows, the maximum angle of the vectoring area is set to 160° in the north-east and to 30° in the south-east.

Vector turns are modelled with the angle being a multiple of 5°. The fluctuation of the Base leg axis is modelled with the angle varying between 30 and 50° in north-west, and 130° and 150° in south-west. The interception of the final approach axis is modelled with a fixed 40° angle. Figure 3 illustrates these various model parameters.

2. *Point Merge*

There are two sequencing legs in each of the two Point Merge systems. The length of the outer sequencing legs is approximately 30 NM and the inner sequencing legs are approximately 27.5NM. The radial distance from the inner sequencing legs to the merge points is 26 NM. The incremental distance between each consecutive possible route was set to 0.4 NM for computational efficiency and to be comparable with operational accuracy i.e. air traffic controller/pilot reaction times and navigation system accuracy.

C. Separation

Table 1 shows the separations used for each of the wake vortex category combinations. In addition to the temporal runway separations, a minimum spatial separation of 3.5NM was maintained in the TMA.

Table 1 Wake vortex separation re-used from real-time simulations

Lead Aircraft	Following Aircraft	Runway separation (s)
Heavy Mass >136 tonnes	Heavy Medium	90s 120s
Medium 7 < Mass ≤ 136 tonnes	Heavy Medium	90s 90s

D. Traffic

The same traffic of 72 arrival and 72 departure aircraft is used for Point Merge and vectoring. The initial traffic is derived from a 2008 real-time simulation based on a generic airspace with a 20% heavy / 80% medium mix, throughput of 36 an hour and total time of about 2 hours 30 minutes. The arrival traffic sequence is assumed to have been determined upstream in the extended TMA (top of descent to TMA entry ~10,000 feet) by an arrival manager (AMAN). Therefore sequencing is implicitly defined in the traffic preparation input file. Aircraft enter the simulation with a minimum initial separation of 3 NM.

For departure traffic, altitude constraints are applied (FL120 and FL110) in both vectoring and Point Merge conditions to strategically segregate arrivals on the downwind leg from departures to the south and north. Departure traffic is derived from arrival traffic, by changing airports and times.

Zero wind is assumed for both scenarios.

E. Metrics

The dependent variables measured between IAF and FAF (10NM from runway) are:

- Distance (NM) and time (minutes)
- Number of ATC manoeuvring instructions
- Average altitude and corresponding average standard deviation (flight level)
- Controller task load (%)
- Fuel consumption (kg)

Where standard deviations and sample size are available, some means of metrics for vectoring and Point Merge are compared using a Student t significance test with confidence level of 99%. The t-test assumes that distributions are approximately Normal with equal variances.

V. Results

A. Validation of Lateral Tracks

1. *Pre-simulation*

- Lateral Deviation Analysis

Figure 5 shows the results of the lateral track validation analysis described in section IVA1 for the north-west and south-west arrival flows (results for north east and south east arrival flows are similar and therefore omitted due to lack of space). For each arrival flow, the proportion of total lateral deviation within a given accuracy is shown for heading changes restricted to multiples of 5° and multiples of 10°. For heading changes restricted to multiples of 5°, more than 50% of all lateral deviations are less than 1NM and 95% of all lateral deviations are contained within

3.5NM. These lateral deviations are comparable with those expected from discrete changes in direction of 5° over distances comparable with the route legs.

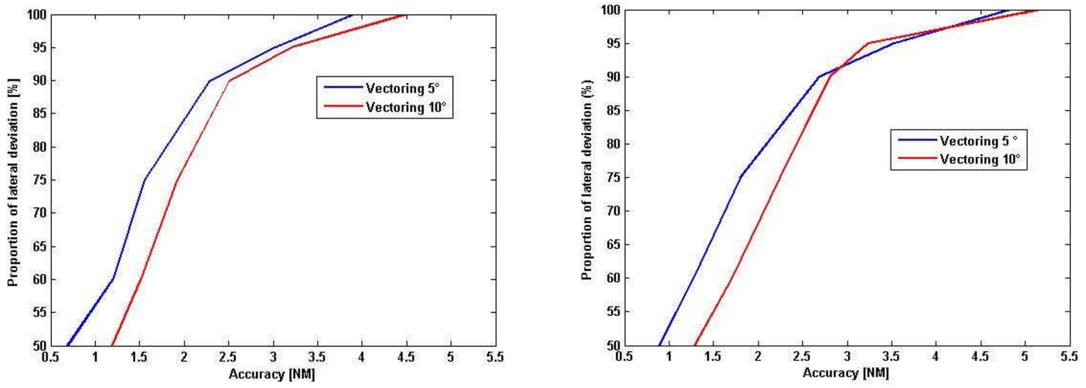

Figure 5: Lateral deviation between real-time and model (left: north-west, right: south-west)

By design, the Point Merge fast-time model should be able to match very closely any real-time track and therefore lateral deviation should be determined by the implementation increment chosen.

- Path Stretching Distance Analysis

Table 2 shows the number of possible routes (IAF to FAF) and variation in lengths calculated for vectoring and Point Merge implementations. Shortest and longest route lengths are similar for both models. The number of possible routes is about double for Point Merge due to the constraint on heading instructions in vectoring. Although the average increments of the models are not exactly the same, they are both judged small enough to be absorbed by small variations in speed (<5 knots) and therefore should have little effect on the relative accuracies of the models.

Table 2 Potential Path Stretching Route Distances

Route characteristics	**Vectoring**		**Point Merge**	
	Base leg	**Downwind**	**Base leg**	**Downwind**
Shortest/Longest route	44.5 / 79.2	66 / 93.5	48.5 / 78.5	68 / 95
Number of possible routes	33	43	75	67
Average increment in length	1	0.6	0.4	0.4

2. Post-simulation

Figure 6 shows the lateral tracks over all simulation time of real-time (left) and fast-time (right) vectoring simulations. The shapes are generally similar but there are slight differences such as the start of vectoring varies within a range of a few miles in real-time simulations whereas it starts at a fixed point for fast-time.

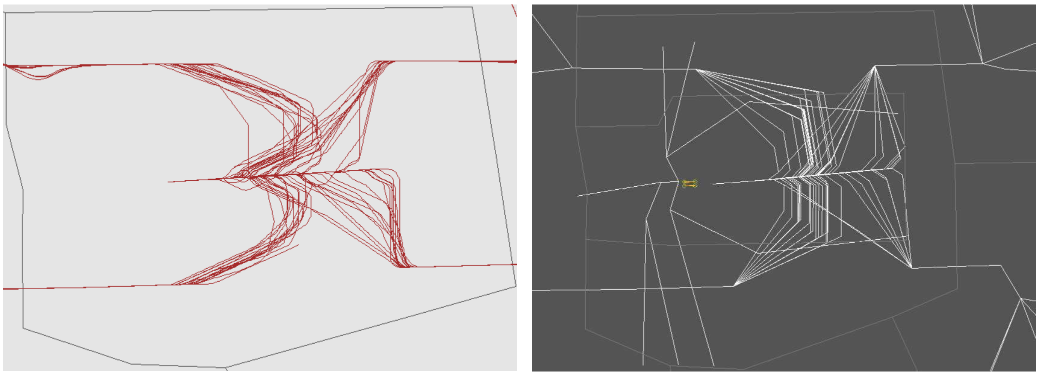

Figure 6: Tracks from vectoring real-time simulation (left) and fast-time implementation of model (right)

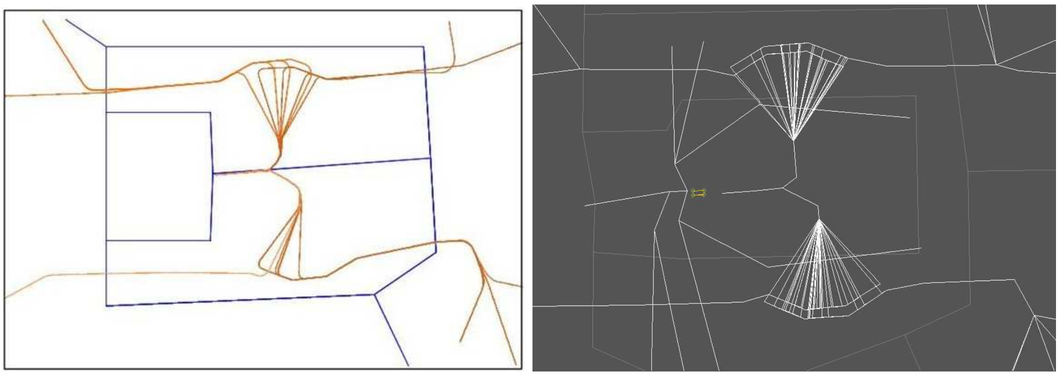

Figure 7: Tracks from Point Merge real-time simulation (left) and fast-time model (right)

Figure 7 shows an example of the lateral tracks of a real-time simulation (left) and fast-time simulation (right) of Point Merge. The shapes are generally similar but there are differences due to route design and an increase of a factor of three in fast-time simulation traffic sample size

B. Comparison between Vectoring and Point Merge

1. Conflict Resolution Performance

The behaviour of the modelled flights in the TMA was driven by the runway schedule and required separations at the FAF. If the model was unable to fit the flights into the arrival runway schedule with the available resolution options (Path Object Vectors), the flight was removed from the runway schedule and all other flights behaved as if the unresolved flight did not exist in the model. Therefore, the number of unresolved runway scheduling conflicts is a measure of how much traffic each model was able to handle. The number of unresolved flights, out of the original 72 arrival flights were the same for each model (5) leaving a total of 67 arrivals for each i.e. model implementations were compared with the same throughput. No conflicts were detected between arrivals and the 72 departures.

2. Distance and Time in TMA

Table 3 shows average and standard deviations of distance and time flown per aircraft between IAF and FAF.

Table 3 Distance and time per aircraft

MODEL	**Distance, mean ± standard deviation (NM)**	**Time, mean ± standard deviation (minutes)**
Vectoring	77±16	19±4
Point Merge	73±13	16±2

Mean flight distances were similar for vectoring and Point Merge as was the case in real-time simulations. The slight trend for shorter flight times with the Point Merge scenario is consistent with aircraft flying on average higher and therefore with higher groundspeeds.

3. Total Instructions per Controller

Figure 8 shows the total number of instructions per controller for vectoring and Point Merge. The combined total number of instructions for both controllers is about 30% less for Point Merge than for vectoring with a more even balance of instructions between controllers. This is comparable with real-time simulations (~40%).

4. Vertical Profile

Figure 9 shows the average flight level and standard deviation of aircraft a given time from landing tends to be higher and narrower respectively for Point Merge compared with vectoring. In addition it can be noted that in Point Merge, the descent profiles are homogeneous between all aircraft (small standard deviation) whereas in vectoring condition the larger dispersion observed suggests that some aircraft flew at relatively low altitude far from the FAF e.g. 5,000 feet with 20 minutes to landing. The median altitude for Point Merge is about twice as high as that for vectoring and the corresponding average standard deviation is about half that of vectoring (comparable with real-time: 100% greater and 40% lower respectively).

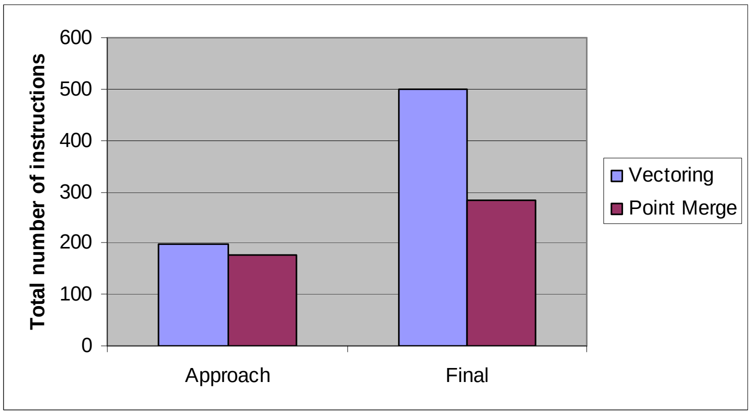

Figure 8: Total number of instructions by approach and final controllers

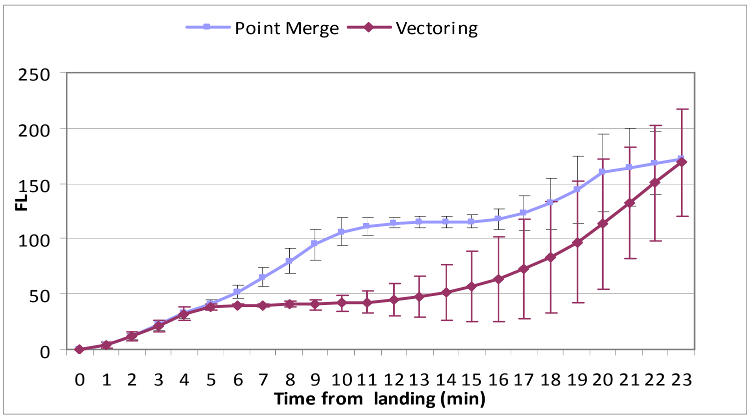

Figure 9: Mean Flight Level and standard deviation

5. Air Traffic Controller Task Load

Figure 10 (left) shows the air traffic controller task load for arrival traffic (task load relative to the departing traffic is not counted). The task load consists of all tasks that were recorded for all arrivals assigned to the approach and final positions during the whole simulation divided by the total simulation time. RAMS Plus has a controller task load model which takes into account coordination, radio communication, flight data management and radar activity. Error bars correspond to the standard error i.e. standard deviation divided by square root of sample size. Task load for the approach controller using Point Merge is not significantly different from vectoring (p-value >

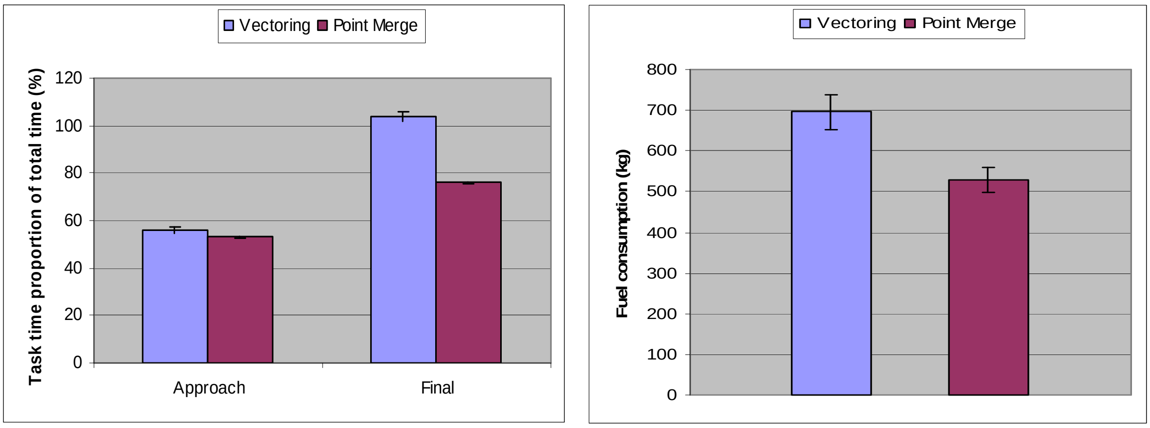

Figure 10: (Left) Task load as proportion of time (Right) Fuel consumption per aircraft

0.29) but task load for the final controller using Point Merge is significantly less (27±1%) than vectoring (p-value < 0.0001). The average task load for both controllers is 20±1% lower than vectoring (p-value < 0.0001, significant). Note the task load of the final controller when vectoring exceeds 100% indicating a potential overload situation.

6. Fuel Consumption

Altitude profiles from initial approach fix to final approach were used with fuel flow rates from corresponding BADA aircraft models to calculate fuel consumed per aircraft. Figure 10 (right) shows mean and standard error of fuel consumption per aircraft for Point Merge and vectoring. Results indicate that mean fuel consumption is 170±14 kg less (25±2%) for Point Merge than vectoring (p-value = 0.0013, significant). Such large reductions with Point Merge could be explained by the large difference in average altitudes.

VI. Conclusion

A method for designing models of the air traffic merging techniques vectoring and Point Merge is described. Models of merging four flows into one are developed for vectoring and Point Merge. Lateral tracks of both models are validated with corresponding tracks from real-time simulations. More than 50% of all lateral deviations are less than 1NM and 95% of all lateral deviations are contained within 3.5NM.

Implementations of the models are compared using fast-time simulation. Results indicate that the Point Merge technique could have significant performance advantages over conventional vectoring. Air traffic controller task load may be reduced by as much as 20±1%. The pilots' task may also be simplified with about 30% fewer tactical manoeuvring instructions. Airlines could save up to 170±14 kg of fuel in the TMA per aircraft which in a busy TMA (single runway with about 36 arrivals per hour) corresponds to the order of 90 tonnes less fuel burned and about 270 tonnes less carbon dioxide produced per day.

Results are consistent with hypotheses derived from real-time simulations and those for controller task load and fuel consumption, therefore all hypotheses are acceptable. Future work could be: to allow the start of vectoring position to vary (known limitation of vectoring model); and validate results further by performing a sensitivity analysis of model performance to variations in path stretching distance increment and traffic sample size.

Acknowledgments

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