Investigating the capacity benefit of airborne speed adjustment

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***Abstract*—In European air traffic flow management, regulation is the assignment of take-off times to prevent the over-delivery of flights to sectors and airports. This paper reports on a validation exercise to quantify the increases in the capacity of regulated sectors to be expected from a SESAR step 1 concept element: airborne speed adjustment to reduce sector entry time errors. Increases in the capacity of regulated sectors are related to reductions in sector occupancy count variance. Fast-time simulations relate sector occupancy count variance (during regulation) to entry time accuracy. Reductions in entry-time standard deviation are calculated. Estimated capacity gains from the use of airborne speed adjustment are reported.**

I. Introduction

A. Context - Air traffic flow management and "regulation"

When excessively high traffic in a sector is predicted, flow managers in European air traffic control centres may send a request to the Network Manager to "regulate" the sector at a specified rate or capacity. "Regulation" is a planning process performed using the CASA (Computer Assisted Slot Allocation) algorithm [3]. This algorithm assigns target sector entry times to flights which would result in entries into the regulated sector at the requested rate, and calculates the corresponding take-off times. The calculated take-off time (CTOT) of a flight (which will fly through a regulated sector) is in general later than the requested take-off time in the filed flight plan, in other words, regulation uses ground delay to achieve the sector entry rate requested by the flow manager.

B. The problem - Planning and reality, bunching and capacity buffers

There are differences between real trajectories and those calculated in the Network Manager's planning. These include:

- differences between actual take-off times and the planned or calculated take-off times, due to airline and airport operations; flights may also be cancelled
- differences due to air traffic control intervention in the real world (changes of standard departure route (SIDs), directs, separation assurance), which are not modelled
- differences between the performance and operation of real aircraft and modelled aircraft
- and differences between real weather and modelled weather

As a consequence of these differences, flights do not reach regulated traffic volumes at the target times planned by the Network Manager. This may result in bunching - periods during which the actual entry rate is greater than the requested entry rate, and periods during which the actual entry rate is lower than the requested rate. To protect sectors from over-deliveries, flow managers effectively build in "capacity buffers" i.e. they request regulation at rates which are lower than the rates that they would request if bunching did not occur [1].

C. A possible solution - Airborne speed adjustment to meet target times

The application of various "real-time anti-bunching" actions to airborne flights, including airborne delay absorption to meet target entry times into congested sectors, was proposed in [1]. Such actions are now known as Short-term ATFCM Measures (STAM).

If flights were to enter regulated sectors more nearly to their planned or target entry times, then bunching could be reduced. A possible solution, considered in SESAR step 1 [4][12], is the use of airborne speed-adjustment to reduce the difference between actual and planned or target entry times. If bunching were reduced, then so too would be the risk of over-delivery into regulated sectors. As a consequence, flow managers could reduce the "capacity buffers" which are used to protect sectors from over-delivery, thereby increasing sector capacity during regulation. Higher capacities would result in reduced ground delay.

Airborne speed adjustment to meet target entry times into terminal manoeuvring areas (TMAs) is also expected to reduce the fuel costs associated with vectoring or holding within TMAs [2].

D. Structure of this paper

Quantification of the capacity benefit mechanism outlined above is broken into the following steps:

- An initial mathematical model of the capacity buffer theory uses a normal approximation to the occupancy count distribution to relate increases in sector capacity to reductions in occupancy count variance (or standard deviation)

- Monte Carlo simulations were used to relate occupancy count standard deviation to entry time standard deviation (with respect to planned entry times)

- Reductions in entry-time standard deviation are calculated for a given speed adjustment policy.

- These relationships are combined to calculate the capacity increases which can be expected from a given airborne speed adjustment policy, for the sectors which were studied.

More recently, Poisson binomial occupancy count distributions have been constructed using mathematical modelling. The probability of exceeding peak levels (and hence capacity gains) can be calculated without making the normal approximation.

II. Relating Capacity Increases to Reductions in Occupancy Count Variance

A. Entry rate during regulation – the capacity buffer theory

Sector capacity is limited by safety considerations. In many control centres, peak acceptable occupancy counts are defined for sectors: the occupancy count (the number of aircraft) in a sector at any instant should not exceed the peak level. The occupancy count at an instant during a regulation can be described by a probability distribution, illustrated by the green curve in Figure 1.

According to the capacity buffer theory, the entry rate during regulation, i.e. the capacity of the sector, is set in such a way that the probability of the occupancy count exceeding the peak acceptable level is less than a certain value. According to this theory, capacity is not set such that the workload created by flights entering at a rate equal to the capacity is manageable by the controller. Rather, the capacity is set in such a way that the probability of an unacceptable situation occurring is lower than a certain value. Further evidence for this theory will be provided later in this paper.

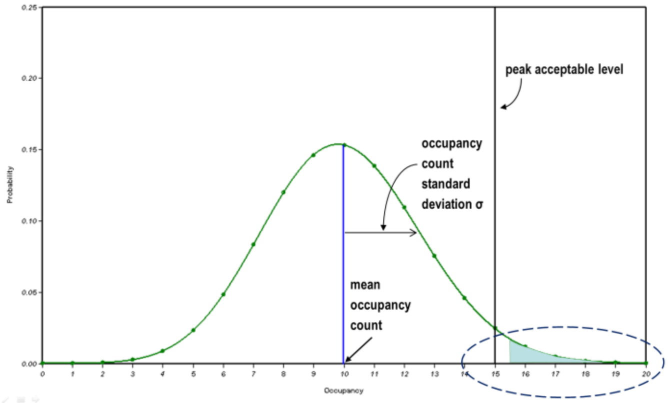


Figure 1 – Occupancy count distribution

If the width or standard deviation of the distribution can be decreased in some way, without changing the mean of the distribution (magenta curve, below), then the probabilities of high occupancy counts would be decreased, bringing an improvement in safety (see Figure 2).

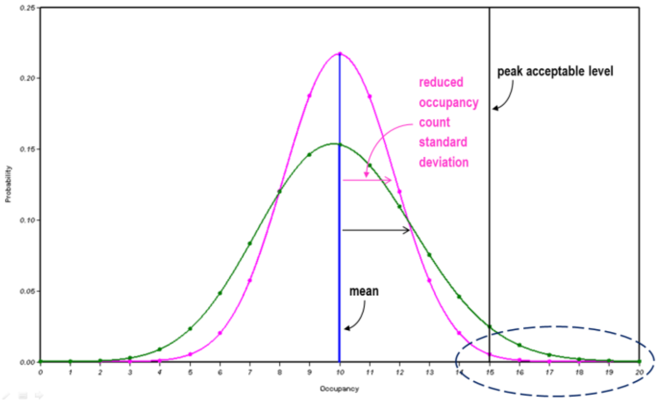


Figure 2 – Reducing the occupancy count standard deviation, leaving the mean unchanged, reduces the probability of exceeding the peak level

Alternatively, the mean of the new distribution can be increased, by increasing the entry rate or capacity, provided the probability of exceeding the peak acceptable level does not increase (see figure 3) (a similar approach to estimating capacity increases due to increases in predictability (due to airport-CDM) was described in [6]). The term “capacity buffer” could be defined as the difference between the mean occupancy (during regulation) and the peak acceptable occupancy.

In order to find out by how much the mean occupancy (and hence the entry rate or capacity) can be increased following a reduction in the occupancy count standard deviation, a model of the occupancy count distribution is needed.

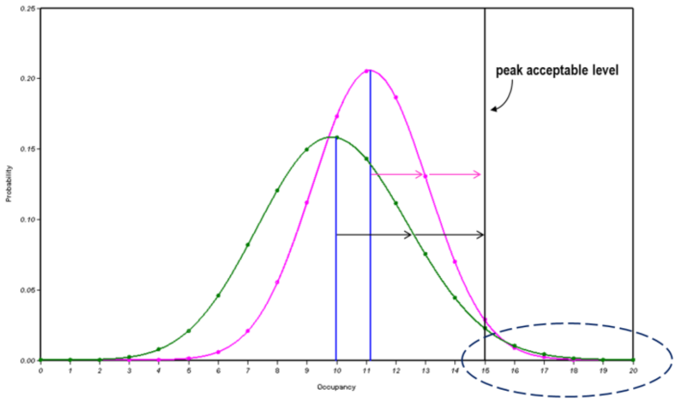


Figure 3 - Reducing the standard deviation allows the mean occupancy to be increased, provided the probability of exceeding the peak acceptable level does not increase

B. Estimating capacity increases due to reductions in occupancy count variance, using a normal approximation to the occupancy count distribution

Whether or not an individual flight will be inside a sector at a future time is a binary random variable. If the probability that an individual flight will be inside a sector at a future time can be calculated, then the (binary) occupancy probability mass function for that flight can be constructed. The sector occupancy count at the future time is also a random variable, equal to the sum of the individual occupancy random variables. If the individual occupancy random variables are assumed to be independent, then the sector occupancy count probability mass function can be found by repeated convolution of the individual probability mass functions. The resulting distribution is a Poisson binomial distribution [15].

Suppose that take-off times for flights which will enter a regulated sector have been planned. Since many flights (of the order of 20 or more) have a significant probability of being in the sector at an arbitrary future time, it is possible to approximate the Poisson binomial distribution by a normal distribution. The approximation may be reasonable near the mean (e.g. within 2 standard deviations) but may not be a good approximation further from the mean, i.e. in the tails of the distribution. This point will be discussed further later in the paper.

With this assumption, then, since normal distributions can be handled analytically, the increase in mean occupancy which could be achieved, without increasing the probability of exceeding the peak acceptable level, can be expressed as follows. Consider an initial situation in which the mean occupancy, $\mu_{initial}$, is k standard deviations below the peak acceptable occupancy, n_{peak}, that is

$$\mu_{initial} \quad = \quad n_{peak} \; - \; k\sigma_{initial} \qquad (1)$$

Assuming that the discrete occupancy count probability mass function (p.m.f.) can be approximated by a continuous normal probability density function, the probability, ε, that the peak acceptable occupancy is exceeded at an arbitrary moment during a regulation, can be approximated by:

$$\varepsilon \quad \approx \quad 1 - \Phi\left(\frac{n_{peak} + 0.5 - \mu_{initial}}{\sigma_{initial}}\right)$$

$$\approx \quad 1 - \Phi(k)$$

$$\text{where} \quad k \quad = \quad \frac{n_{peak} - \mu_{initial}}{\sigma_{initial}}$$

and $\Phi(x)$ is the cumulative distribution function for a normally distributed random variable with zero mean and unit variance. The point here is that, if the approximation by a normal distribution is valid, then the probability of exceeding the peak level depends only upon the value of k, the number of standard deviations between the mean and the peak acceptable occupancy.

Suppose that, for the initial mean occupancy during regulation, $\mu_{initial}$, the occupancy count standard deviation can be reduced by some means (e.g. airborne speed adjustment) to a new value, σ_{new}. The capacity of the sector (i.e. the entry rate during regulation) can now be increased, which increases the mean occupancy proportionately. However, as the entry rate is increased, the occupancy count standard deviation does not remain constant, because there are now more flights which contribute to the occupancy count variance. The occupancy count variance σ^2 increases in proportion to the entry rate or, equivalently, to the mean occupancy. In other words, as a function of mean occupancy:

$$\sigma^2(\mu) \quad = \quad \sigma_{new}^2 \cdot \frac{\mu}{\mu_{initial}}$$

Alternatively, the standard deviation grows as the square root of the mean occupancy:

$$\sigma(\mu) \quad = \quad \sigma_{new} \cdot \sqrt{\frac{\mu}{\mu_{initial}}}$$

If k is held constant, so that the probability of exceeding the peak level is unchanged (i.e. the same safety criterion is respected), the new mean occupancy is given by:

$$\mu_{new} \quad = \quad n_{peak} \; - \; k\sigma_{new} \cdot \sqrt{\frac{\mu_{new}}{\mu_{initial}}} \qquad (2)$$

This is an equation in μ_{new}. Writing

$$\sqrt{\frac{\mu_{new}}{\mu_{initial}}} = \sqrt{1+\frac{(\mu_{new}-\mu_{initial})}{\mu_{initial}}}$$

then, for small capacity gains (e.g. less than 20%), using $\sqrt{1+x} \approx 1+x/2$ for $x << 1$

$$\sqrt{\frac{\mu_{new}}{\mu_{initial}}} \approx 1+\frac{(\mu_{new}-\mu_{initial})}{2\mu_{initial}} \quad (3)$$

Substituting (3) into (2) and rearranging gives

$$\frac{\mu_{new}}{\mu_{initial}} \approx \frac{n_{peak} - (k\sigma_{new}/2)}{\mu_{initial} + (k\sigma_{new}/2)} \quad (4)$$

The increase in mean occupancy is given by

$$\Delta\mu \equiv \mu_{new} - \mu_{initial} \quad (5)$$

and the fractional increase by $\Delta\mu/\mu_{initial}$. To achieve this fractional increase in occupancy, the entry rate during regulation (the capacity) must be increased in the same proportion. In other words, the fractional increase in capacity is the same as the fractional increase in mean occupancy:

$$\frac{\Delta c}{c_{initial}} = \frac{\Delta\mu}{\mu_{initial}} = \frac{\mu_{new}-\mu_{initial}}{\mu_{initial}} = \frac{\mu_{new}}{\mu_{initial}} - 1$$

Using (4) and (1), the fractional increase in capacity can be written

$$\frac{\Delta c}{c_{initial}} = -\frac{k\Delta\sigma}{\mu_{initial}+(k\sigma_{new}/2)} \quad (6)$$

where $\Delta\sigma \equiv \sigma_{new} - \sigma_{initial}$

To estimate the increases in the capacities of regulated sectors which would result from reductions in entry time error variance, we need to be able to relate occupancy count variance (or standard deviation) to entry time error (or standard deviation).

III. Relating Occupancy Count Standard Deviation (During Regulation) to Entry Time Error Standard Deviation, Using Fast-Time Simulation

A. *The simulation*

The AirTOp fast-time simulator was used to investigate the relationship between occupancy count standard deviation and entry time error standard deviation. A number of features have been added to AirTOp to facilitate flow management simulations. Load monitoring during the simulation is used to predict the occurrence of demand and capacity balancing (DCB) problems, such as the number of entries into a traffic volume (over a one hour period) exceeding the declared capacity of the traffic volume. In response to DCB problems, DCB measures, such as queuing, can be activated. A queue sets time constraints on the entry of flights into a regulated sector. The queue can be configured in various ways: in this exercise it inserts a constant time difference between successive planned entries into a traffic volume, such that flights are planned to enter at a specified entry rate. A delay absorption strategy specifies that time constraints set by the queue will be met using ground delay, resulting in the calculation of planned take-off times. During the period of a regulation, i.e. during the period of ground delay queuing, instantaneous occupancy counts can be measured or sampled at regular intervals. A time interval of 20 minutes was used between samples. The flights in a sector change completely over a period of 20 minutes. If a shorter interval were used, the occupancy counts would be correlated because of the continued presence of some flights in the sector at successive sample times. Errors in sector entry time (with respect to the time constraint assigned by a queue) can be simulated by introducing errors in take-off time. Since the flown trajectories are identical with the trajectories assumed by the queue (apart from the difference of take-off time), the statistics of the take-off time error become those of the sector entry-time error. Take-off time errors and hence entry time errors, were simulated using a Gaussian random variable. This does not mean that only departure-time errors are taken into consideration and other sources of sector entry-time error are ignored: within the fast-time simulation, departure-time noise is used to create sector entry-time noise with a controlled magnitude. In the real world, sector entry-time noise has many causes (the main causes were listed in the introduction). There are also causes of occupancy count variance in addition to entry-time noise. These include changes of sector sequence due to horizontal re-routing (e.g. related to deactivation / activation of military areas) and vertical re-routing (flight level requests – up or down).

B. *The method*

A traffic sample (a set of flight plans) was taken from 28th June 2013, the peak day in that year. The regulations which created delay on this day are known. Simulations were created for individual regulated sectors or traffic volumes, in order of decreasing delay due to regulation.

For each traffic volume, the period of regulation was extended artificially by cloning of the flights through the traffic volume. These extended periods of regulation allow the collection of a greater number of occupancy count samples than would be the case if only genuinely filed flight plans were used.

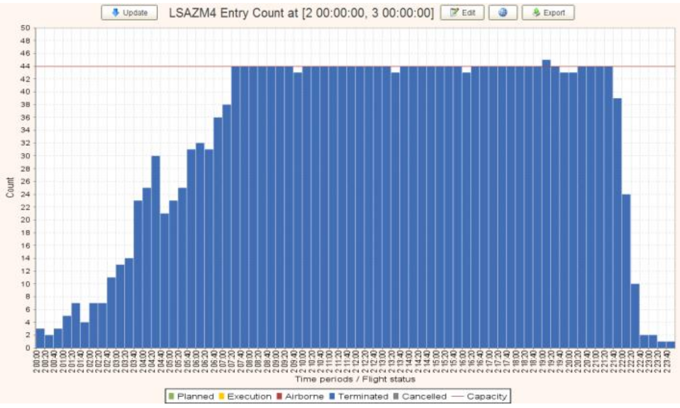
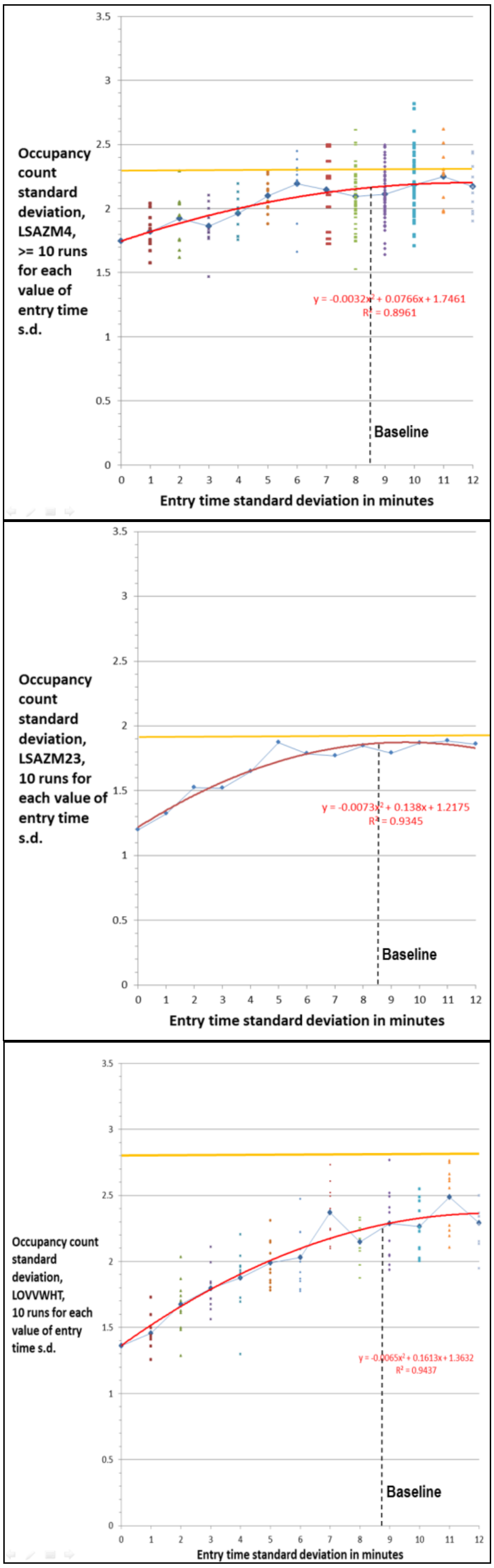


Figure 4 – Planned entry counts per hour during a regulation which has been artificially extended by cloning flights

The first traffic volume investigated was the London TMA, EGTTTC. This traffic volume is defined for a flow which corresponds to arrivals at London Heathrow airport, EGLL. It was realised that the declared capacity of this traffic volume is very similar to the landing rate at the airport. From this, it is apparent, that even if a technique or concept element would allow a sector to accept a higher entry rate during a regulation, in practice this higher entry rate will not be applied if it exceeds the rate at which flights can leave or enter the sector. In other words, where a TMA feeds or is fed by an airport, and its capacity is determined by runway landing or take-off rates, increasing the capacity of such a TMA traffic volume during a regulation has no practical effect. For this reason, it was decided not to consider TMAs, but instead to investigate en-route traffic volumes which are not subject to such limitations.

C. Results of fast-time simulations

For each sector, simulations were performed for entry time error standard deviations ranging from zero to 12 minutes. The randomly generated entry time errors for each flight were normally distributed. Typical baseline values of entry time error standard deviation in the European air traffic management system today are of the order of 8.5 minutes [14]. For each value of entry time error standard deviation, 10 or more runs were performed, the entry time error of each flight varying from one run to the next. This gives a total of at least 120 runs per sector. The following graphs (see Figure 5) show the measured relationships between occupancy count standard deviation and entry time error standard deviation in several sectors. Quadratic curve fits are shown in red.



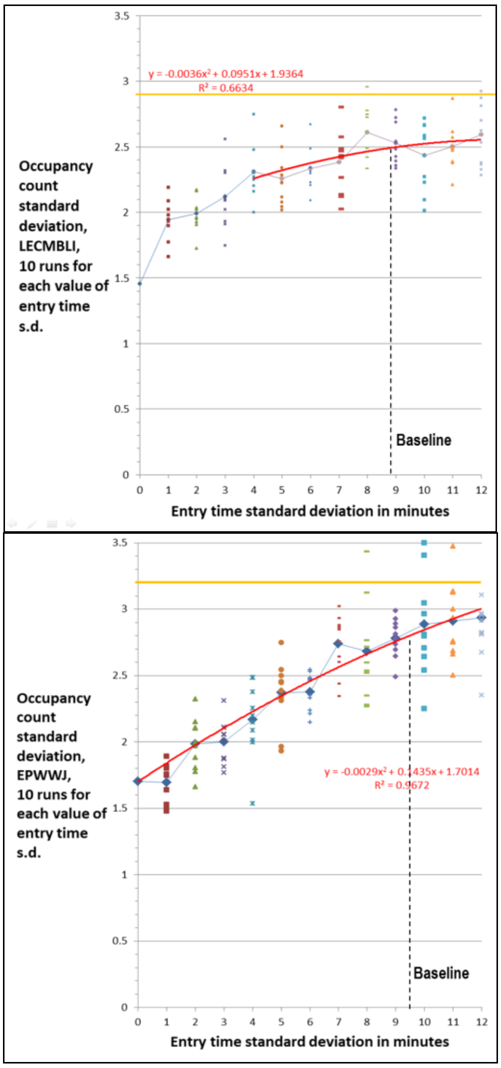


Figure 5 – Occupancy count standard deviation as a function of entry time standard deviation for several sectors

D. Discussion of fast-time simulation results

Qualitatively, these graphs have common features. For most of the sectors simulated, the occupancy count standard deviation appears to tend towards a constant value. As entry time error (standard deviation) increases, sector entry times and occupancy count move from being a deterministic process towards a random process. The long-term average entry rate is constant, and equal to the rate of the regulation, and in this case entry times tend towards a Poisson process [16].

In a Poisson process, the number of events in unit time has a Poisson distribution, with variance equal to the rate ρ. In time intervals of duration τ, the variance in the number of entries is $\rho\tau$. If all flights had the same sector occupancy time T, and we were to consider the number of entries in this time period, then this variance would effectively be that of the occupancy count, so that

$$\sigma^2_{occupancy\ max} = \rho T$$

or

$$\sigma_{occupancy\ max} = \sqrt{\rho T}\ .$$

This value is shown as a horizontal yellow line on the diagrams in Figure 5, calculated using the average sector occupancy time, since real flights spend varying times in sectors.

It can also be noted, that when the entry time error standard deviation is reduced to zero, in other words, when all flights enter the regulated sector exactly at their planned or target entry times, the occupancy count standard deviation does not fall to zero.

This effect was investigated using artificial traffic samples, consisting of identical flight plans. In the case of identical flight plans, as the entry time error standard deviation tends to zero, the occupancy count standard deviation also tends (closely) to zero (see Figure 6). This suggests that the non-zero occupancy count standard deviation, when there is no sector entry time error, is attributable to the different lengths of time spent in the sector by real flights. Depending upon the sector, flights may spend very different lengths of time within a sector. A cruising flight may spend 20 minutes or more in a sector, whereas a descending flight might spend only 1 minute in the sector: the cruising flight contributes to the occupancy 20 times longer than the descending flight. Depending upon the mix and sequencing of traffic, the occupancy count fluctuates, even when all flights enter exactly at evenly spaced planned entry times.

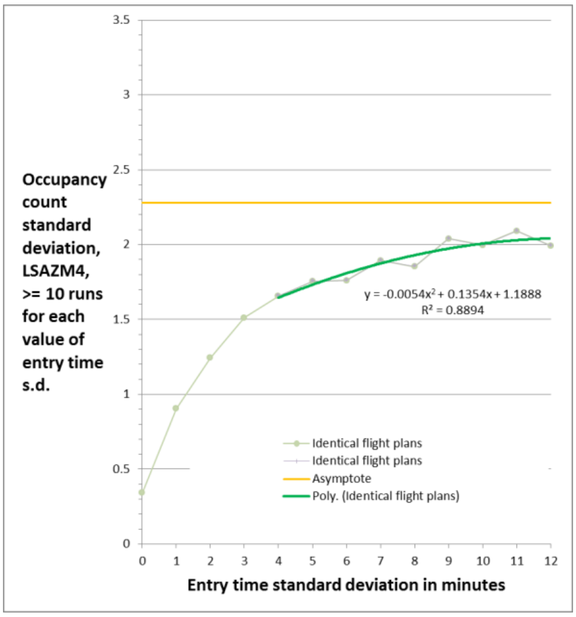


Figure 6 – Artificial traffic sample consisting of identical flight plans – occupancy count standard deviation tends to zero as entry-time standard deviation tends to zero

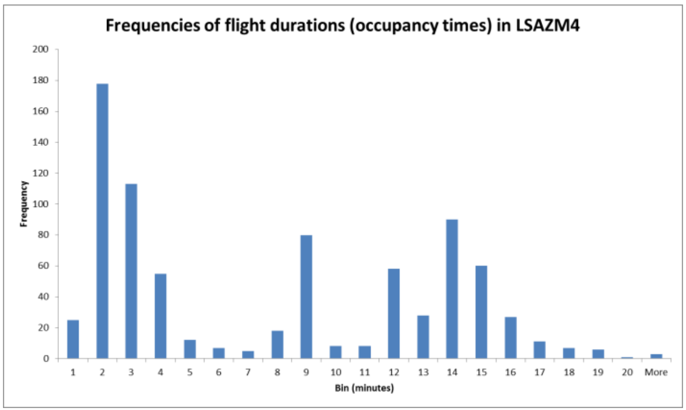


Figure 7 – In some sectors there is a wide variation of sector occupancy times, giving rise to variations in sector occupancy count, even in the case of perfect sector entry time accuracy

IV. Reducing entry time error through airborne speed adjustment, and estimating the corresponding improvement in occupancy count standard deviation

For each sector, simulations were performed with a baseline entry time error standard deviation, based on [14]. For each flight, the flight duration before sector entry and the sector entry time error were recorded. Using a spreadsheet, and assuming speed adjustments from take-off of up to 5%, the maximum correction to each entry time was calculated. Where the initial entry time error was less than or equal to the maximum correction, the new entry time error was set to zero. Where the initial entry time error was greater than the maximum correction, the initial error was reduced by the maximum correction to give the speed-adjusted error.

Traffic volume	Average flight duration on sector entry in minutes (traffic simulation)	Baseline entry time standard deviation in minutes (based on AM study)	Non-baseline entry time standard deviation (5% speed adjustment) in minutes	Improvement in entry time standard deviation (in minutes)	Average improvement in entry time standard deviation (in minutes)
LSAZM4	48	8.50	6.78	1.72	2.14
LSAZM23	44	8.43	6.95	1.48	
LOVVWHT	65	8.78	6.38	2.40	
LECMBLI	70	8.87	6.81	2.06	
EPWWJ	103	9.42	6.38	3.04	

Table 1 – Entry time error standard deviations following speed adjustment

These results are shown graphically in Figure 8.

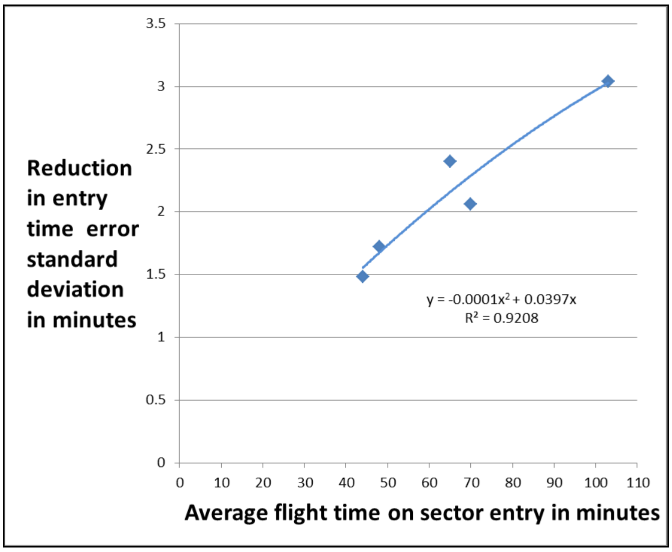


Figure 8 - Reduction in entry time error standard deviation as a function of average flight time on sector entry for a speed adjustment of up to 5%

The improvement which can be obtained in entry time standard deviation depends upon the average duration of flights before sector entry. Consider a flight of duration 1 hour from departure to destination. A regulated traffic volume might be anywhere on its path. Consider the case that the regulated traffic volume is halfway between departure and destination, so that the aircraft will have been flying for about 30 minutes on sector entry. Assuming (symmetrical) speed adjustments of up to 5% from take-off, this flight could make a correction of up to 1.5 minutes to its sector entry time error. Short haul flights can typically make only a small correction to their sector entry time errors. For the sectors considered in this exercise, entry time standard deviations were reduced by just over 2 minutes, on average.

The impact on fuel consumption of airborne speed adjustment has not been assessed.

V. Estimating peak acceptable occupancy counts

In order to calculate the increase in sector capacity, following a reduction in entry-time error and occupancy count standard deviation, we also need to know the peak acceptable occupancy count in a sector. However, this information is not easily available.

Peak acceptable counts were obtained from the Eurocontrol control centre in Maastricht. These values are plotted against mean occupancy counts obtained from simulation. The best straight line fit provides a way of estimating peak acceptable occupancies from mean occupancy counts during regulation, obtained from simulation.

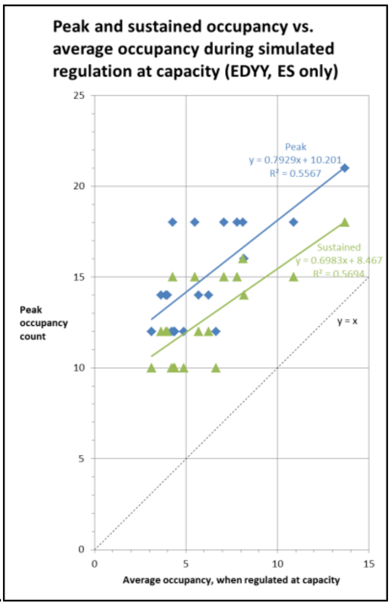


Figure 9 – Mean, sustain and peak levels

The Maastricht data also included "sustain" levels. These are occupancy counts which could be sustained for long periods, provided of course that the peak acceptable level is not exceeded. It can be observed that the sustain levels are only slightly less than the peak acceptable levels, and substantially higher than the mean occupancy counts during regulation. However, the mean cannot be moved to the sustain level, because the probability of exceeding the peak level would then be unacceptably high. This provides evidence for the "capacity buffer" theory described at the beginning of this paper.

VI. Estimating Capacity Increases Due to Airborne Speed Adjustment

The preceding elements can now be put together to estimate the capacity increase for a sector due to airborne speed adjustment. An example is given in the successive rows of Table 2.

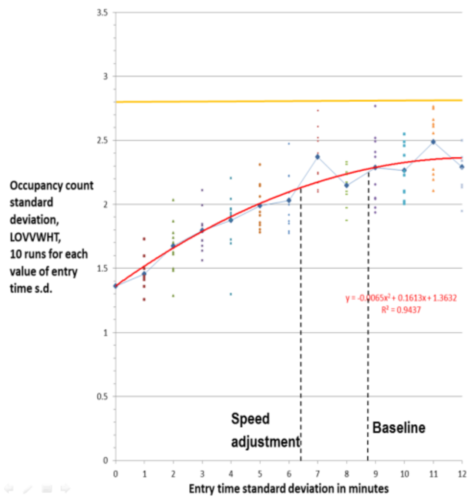


Figure 10 – Reduction in occupancy count standard deviation due to speed adjustment

Traffic volume (regulated sector)	LOVVWHT
Baseline capacity or entry rate ρ	42
Average sector occupancy time T (from simulation)	11.23 minutes
Average occupancy count during regulation, $\mu = \rho T$ (from calculation or simulation)	7.8
Estimate of peak occupancy (based on study of mean and peak levels in Eurocontrol Maastricht)	16.4
Baseline entry time standard deviation (based on [14])	8.78 minutes
Baseline occupancy count standard deviation at 8.8 minutes, σ, (from simulation, see red curve in Figure 10)	2.28
Number of standard deviations between peak and mean occupancy count *k* = (16.4 – 7.8) /2.28 , (safety criterion)	3.8
Entry time standard deviation with 5% speed adjustment (spreadsheet calculation)	6.38 minutes
Occupancy count standard deviation at 6.38 minutes, σ', (from simulation, see red curve above)	2.13
Estimated capacity gain (using normal approximation to occupancy count distribution, equation (6))	4.7%
New entry rate	44

Table 2 – Calculation of capacity increase

Repeating this calculation for the five sectors considered in the study, gives the results in the first column of the following table:

Traffic volume **(sector)**	**Estimated capacity gain %** Using Monte Carlo simulation results, capacity gains calculated assuming normal approximation to occupancy count distribution	**Estimated capacity gain %** Poisson binomial model of occupancy count distribution, capacity gains calculated using normal approximation	**Estimated capacity gain %** Poisson binomial model of occupancy count distribution, capacity gains calculated numerically
LSAZM4	2.6	2.5	4.1
LSAZM23	2.4	2.3	3.8
LOVVWHT	4.7	4.5	7.4
LECMBLI	2.2	3.5	4.3
EPWWJ	6.3	5.3	6.8
Average	3.6	3.6	**5.3**
Standard deviation	1.6	1.2	1.5

Table 3 – Estimated capacity gains due to airborne speed adjustment of up to 5%

Using the normal approximation to the occupancy count distribution, the average estimated capacity gain for these 5 sectors is 3.6% with a standard deviation of 1.6%.

An important point concerns the use of equation (6) to calculate capacity gains due to reductions in occupancy count standard deviation. This equation was based on a normal approximation to the occupancy count distribution. This approximation is unlikely to be valid in the tails of the distribution. In the example given above (Table 2), the peak acceptable level is 3.8 standard deviations from the mean.

Recently, another approach has been taken: the Poisson binomial occupancy count distributions can be constructed using entry time error standard deviations based on [14], and sector crossing time distributions obtained from a single (deterministic) simulation of each sector. This mathematical model is described in [17]. Results from the model are included in Table 3. The results of using the Poisson binomial model but calculating capacity gains using the normal approximation are given in the second column of the table and the average value is again about 3.6%. The results of using the same Poisson binomial model, but calculating the probabilities of exceeding the peak levels (and hence capacity gains) numerically, without making the normal approximation, are given in the third column of the table: the average value is 5.3%, with a standard deviation of 1.5%. This confirms that use of the normal approximation to the occupancy count distribution results in an underestimation of the capacity gains due to airborne speed adjustment.

The number of sectors simulated in this exercise was small, but there appears to be some consistency in the order of magnitude of the capacity gains.

VII. EFFECT OF DIFFERENT SPEED ADJUSTMENT POLICIES

The previous section considered a single speed adjustment policy: speed adjustments of up to 5%, regardless of whether the entry time error to be corrected requires an aircraft to increase or decrease its speed. For the purposes of illustration, a single sector, LOVVWHT, was considered. Two types of speed adjustment were considered:

- "symmetrical" speed adjustments, speeding up or slowing down aircraft by up to n%, as required
- "asymmetrical" speed adjustments, in which aircraft which will enter a sector early are slowed by up to n% (This policy is expected to have a much smaller and possibly even beneficial impact on fuel consumption, compared with "symmetrical" speed adjustments)

Again, a spreadsheet was used to calculate the effects of speed adjustment on the entry time error standard deviation (using departure times from a single simulation).

The reduction in the entry time error standard deviation is almost linear in the magnitude of the speed adjustment percentage (in both the symmetric and the asymmetric case). In the asymmetric case, in which aircraft are slowed to reduce the magnitude of early entries, the reduction in entry time error standard deviation is about half of the reduction which would be achieved with "symmetric" corrections to early and late flights. For any given speed adjustment policy, it is straightforward to calculate the reduction in entry time error standard deviation which can be expected.

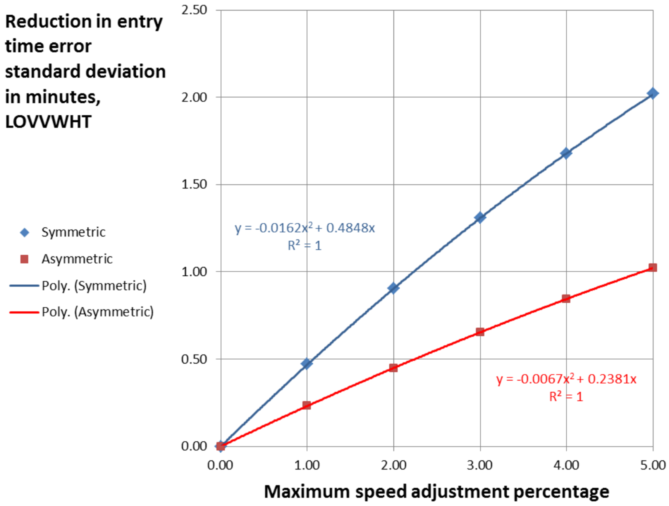


Figure 11 – Effect of different speed adjustment policies

VIII. OCCUPANCY-BASED REGULATION

As discussed earlier, occupancy count variance during regulation at a constant entry rate can be attributed primarily to entry time error, but occupancy time or sector crossing time variance also contributes to occupancy count variance. In the current system, the CASA algorithm plans entries into a regulated sector at the requested entry rate: sector occupancy times are not taken into account.

If flights follow pre-defined routes, then sector occupancy times can be estimated from trajectory modelling in the planning phase. An alternative form of regulation, occupancy-based regulation, could take these known sector occupancy times into account, effectively removing the contribution to occupancy count variance due to differing sector crossing times.

A deterministic occupancy-based planning algorithm is straightforward in principle: planned flights may enter a regulated sector provided the occupancy count is less than a requested level. When the occupancy count reaches the requested level, the sector is full, and another flight may not be planned to enter the sector until the next exit of a planned flight already in the sector. Such an occupancy-based planning algorithm would result in a variable rate of entry into the regulated sector, the rate increasing for flights whose occupancy times are low, and decreasing for flights whose expected occupancy times are high. The possible capacity benefits of occupancy-based regulation have not yet been assessed.

IX. CONCLUSIONS

Estimated capacity increases in regulated sectors were related to reductions in sector occupancy count standard deviation, initially using a normal approximation to the occupancy count distribution.

Monte Carlo simulation was used to relate occupancy count standard deviation to entry time error standard deviation. Occupancy count variance and standard deviation tend towards a horizontal asymptote as entry time error increases, with the corollary that occupancy count variance is fairly insensitive to reductions in entry time error. Even in the absence of entry-time errors, constant entry rate regulation does not result in constant occupancy, because flights spend different lengths of time in the sector. This suggests the possibility of occupancy-based regulation to reduce occupancy count variance.

Airborne speed adjustment of up to 5% (from take-off) reduced entry time error standard deviation in the sectors studied by just over 2 minutes, on average: short haul flights can only make relatively small corrections to entry time errors, and in European airspace there are many more short haul flights than long haul flights.

Using the normal approximation to the occupancy count distribution, the corresponding average capacity increase for the sectors included in this study was estimated to be about 3.6%.

Mathematical modelling has been used to construct Poisson binomial occupancy count distributions. Using the normal approximation to calculate capacity gains again gave an average capacity gain of about 3.6%. Calculating the probabilities of exceeding peak levels numerically gave an average capacity gain for the same sectors of 5.3%, confirming that the normal approximation results in underestimation of the average capacity gain.

The number of sectors simulated in the exercise was small. The study should be extended to provide a more representative assessment of the capacity benefit of airborne speed adjustment in European en-route airspace.

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