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Validation early split & late merge

Report

Aviation Consultants

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1 Context and key findings

As part of the "Transition to high-capacity fixed arrival routes (continued)" subject of KDC's research agenda, and as a question from the Dutch airspace redesign programme (PLRH), KDC has requested To70 to identify and quantify the effect of the position of a merge point (arrival) or split point (departure) on capacity. This resulting report is to be used as a "capacity principle" in future design decisions.

1.1 Context and scope of the analysis

Dutch airspace redesign concepts for the TMA are based on a structure with 3D separated fixed arrival routes and CCO SIDs. To make this concept work, it should provide sufficient TMA capacity. In designing these routes and deciding upon how and where arrival routes should merge and departure routes should split, capacity is an important factor. To facilitate decisions regarding the positions of merge and split points, this report provides capacity relations for different merge/split point locations.

For this analysis the following aspects are in scope:

- Modelling of routes and split/merge point using a schematic setup;
- Modelling departure speed profiles using empiric ADS-B data;
- FTS model with speed control on fixed arrival routes with a 2.3 degrees descent angle[1];
- Separation minima of ICAO Doc 4444 are adopted: 1000ft vertical, 5NM lateral, 3NM lateral at locations where the surveillance systems' capabilities permit this (as is assumed in the TMA) and in-trail separation according to wake-turbulence category applies.

Aspects that are not in scope for this analysis are:

- Interactions between departure and arrival traffic;
- Modelling of routes and split/merge point using actual existing route structure;
- Use of a merging tool and ASAS IM;
- Modelling of wind conditions;
- RECAT/Time-Based separation criteria.

1.2 Key findings

The capacity analysis is divided up in an analysis for the departure split point and an analysis for the arrival merge point. For the departure split point, the results show an increased capacity for an earlier split point. In the analysis split point locations of 3, 5, 10 and 20 NM are tested. Capacity numbers are determined as capacity loss compared to the optimal split point location. The optimal split point location is as early as possible, at 3NM. For later split points the capacity results are:

- At 5NM: A capacity decrease of 0.3 movement per hour;
- At 10NM: A capacity decrease of 1 movement per hour;
- At 15NM: A capacity decrease of 2.1 movements;
- At 20NM: A capacity decrease of 3 movements.

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[1] Descent angle of 2.3 degrees is selected on the basis of the results from: B. Bouwels (2021). *Off-Idle Continuous Descent Operations at Schiphol Airport*

These capacity losses should be regarded as a lower bound, given that in reality an air traffic controller will have to use a larger buffer to handle uncertainty.

Decrease in capacity due to a late split point can be mitigated by imposing a speed restriction. For a speed restriction where flights can fly between 230 and 250 kts from an altitude of 3000 ft, the capacity loss at 10NM can be reduced from 1 to 0.4 movements per hour and the capacity loss at 20NM can be reduced from 3 to 1.9 movements per hour.

For the merge point analysis, the effect of the length of the fixed route and the effect of the merge point location are assessed independently. In the analysis of the fixed route length, the simulation scenario consists of a single fixed route of different lengths where only speed control is possible. Up until the start of the fixed route radar vectors are used. The results show that the longer the fixed arrival route part, the lower the capacity. Capacity numbers are measured in capacity loss compared to the optimal situation, which is a fixed route of 10NM. For larger fixed route lengths the simulation shows:

- At 20NM: No capacity loss with a uniform delivery interval, a capacity loss of 1 movement per hour with a stochastic variation of 60 seconds at delivery;
- At 30NM: A capacity loss of one movement per hour for both uniform delivery and delivery with a stochastic variation of 60 seconds at delivery;
- At 40NM: A capacity loss of 2 movements for a uniform delivery and 7.5 movements per hour for a delivery with stochastic variation of 60 seconds at delivery;
- At 50NM: A capacity loss of 5.5 movements per hour for a uniform delivery and 15.5 movements per hour for a delivery with stochastic variation of 60 seconds at delivery.

For the scenario where the entire inbound TMA operation is performed by fixed arrival routes, an analysis is performed on all aspects that cause capacity effects when the merge point is positioned differently. From the investigated aspects, three aspects were found to play a role for capacity when the merge point location is changed, namely:

- Turn-in error at the merge point: The merge point should not be positioned too close to the threshold. At close proximity to the runway, there is less distance separation close to the merge point and it is harder to correct for the turn-in errors when there is a smaller remaining segment where speed control can be applied;
- Uncertainty in wind conditions: For this aspect it was found that in terms of capacity it is advantageous to place the merge point close to the IAF. This increases the length of the common segment, where the wind component is the same for the flight pair;
- Delivery error: When the merge point is placed too close to the IAF, the control space to correct this error before the merge point is too small. To account for this an additional buffer is required that reduces capacity.

This analysis is followed up by an FTS simulation to validate the findings. Given that this simulation does not incorporate some important aspects such as wind conditions and the anticipatory capacity of real-life ATC controllers, it should not be used to derive exact numbers but merely to validate the found mechanisms for capacity. The simulation results indicate that the merge point should not be placed too close to the IAF, but also not too close to the threshold. There exists an optimum at an intermediate location for the merge point. This confirms the findings in the analysis.

1.3 Reading guide

In chapter 2 an analysis is provided for the capacity effects of changing the location of the departure split point. First the simulation model is explained, after which results of the simulation and a sensitivity analysis are provided. Chapter 3 provides an analysis of the merge point location for arrival routes. This is split up into two parts, where the first part covers the capacity effects of changing the length of a fixed arrival route and the second part cover the capacity effects of changing the merge point location.

2 Split point location for departure routes

TMA design choices for the location of the point where SIDs diverge have an impact on the capacity of the TMA for outbound traffic. To capture this impact, simulations are performed assessing these effects as a function of distance of the split point from the runway threshold.

2.1 Simulation model

To assess the capacity effects of changing the split point location for SIDs, the simulation model schematically depicted in Figure 1 is used. This simulation model uses ADS-B speed profiles of CCO departures at Schiphol, to determine the required buffer for speed variations to maintain miles-in-trail separation along the common segment of SIDs. The longer this common segment, the longer miles-in-trail separation must be maintained resulting in a larger required buffer at take-off.

Outbound runway capacity is determined by the start intervals that can be achieved. These start intervals are determined by the sum of:

- The required minimum separation at take-off;
- The required buffer to maintain miles-in-trail separation, with speed variations;
- An additional safety margin to account for estimation errors.

Separation minima at take-off are determined in the model based on either the minimum radar separation or the wake turbulence categories of flight pairs. For every flight pair, the model then determines the required buffer to maintain miles-in-trail separation using empiric CCO speed profiles for the specific aircraft types. After adding an additional safety margin, the model determines the required start interval between every flight pair. By summing these start intervals it is determined how many aircraft can depart in an hour, c.q. the departure capacity.

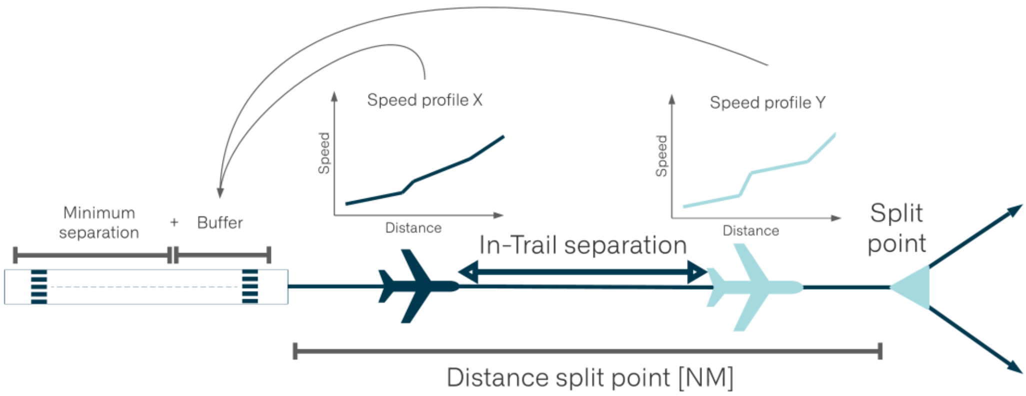

Figure 1 Schematic overview of the departure simulation model

2.2 Simulation scenario

Traffic year 2019 of Amsterdam Airport Schiphol is used to generate a realistic traffic scenario. This traffic year is modelled by using a fleet that represents the aircraft type distribution in this year (see Figure 2). A simulation run scenario is constructed by performing 5000 random draws from this type distribution to establish a sequence of flights.

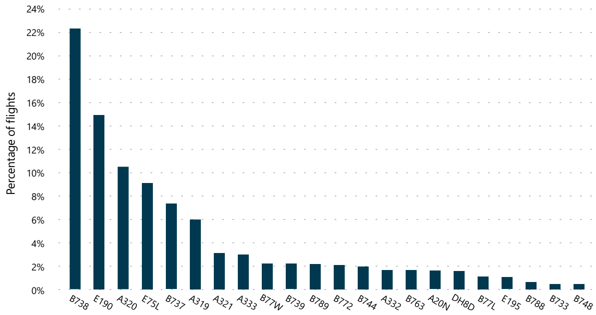

Figure 2 Amsterdam Airport Schiphol departure type distribution in 2019

For every flight in the sequence , the minimum separation time at take-off is determined using the following rules:

- 60 seconds for medium aircraft following medium aircraft;
- 60 seconds for heavy aircraft following heavy or medium aircraft;
- 120 seconds for medium aircraft following heavy aircraft.

Longitudinal separation minima along the common segment, where aircraft pairs are in-trail, are determined based on distance using:

- 3NM for medium or heavy aircraft following medium aircraft;
- 4NM for heavy aircraft following heavy;
- 5NM for medium aircraft following heavy aircraft.

An additional 1NM is added to these lateral in-trail separation minima to account for the safety margin for estimation errors as explained further-on.

2.3 Simulation results

For every of the split point distances as defined in the scenario, ten simulation runs have been performed using a sequence of 5000 randomly selected flights. Capacity results for each run are displayed in figure 3. These results show the capacity decrease in movements per hour for every split point distance compared to the maximum capacity for a split point at 3NM from the runway threshold. These results are predicated on an operational concept where Approach control handles flights up until the merge point.

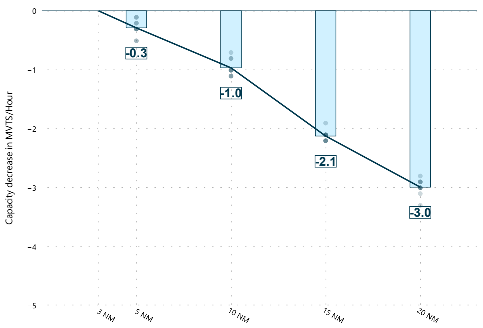

Figure 3: Capacity results for split point locations

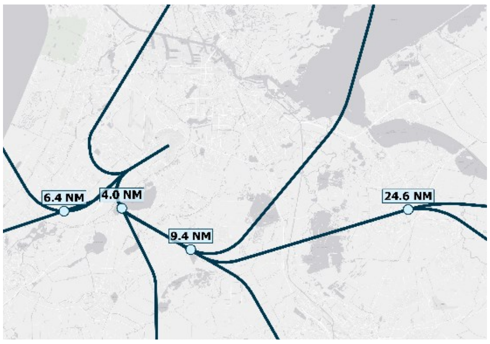

Figure 4: Example of split point distances for runway 24

A split point location at 10NM from the runway threshold results in an average decrease in capacity of one movement per hour. This is further reduced by two movements when the split point is located at 20NM from the runway threshold, leading to a total capacity reduction of three movements. These reductions in capacity result from the required additional buffer at take-off, to account for the differences in speed profiles of trailing flights.

Due to the modelling technique of the required buffer in the simulation, resulting capacity figures will be different than those observed in reality. Buffers are adjusted in the simulation such that they exactly ensure the minimum separation for the randomly selected (and therefore known beforehand) speed profiles of two aircraft types. An air traffic controller cannot do this due to uncertainties in the speed profiles. To ensure that the required minimum separation is maintained at all times, an air traffic controller must factor in the worst case scenario and will apply a buffers to do so. This buffer is approximated in the model by applying a 1NM buffer at all times.

The results are predicated on an operational concept where flights are controlled by approach control up until the merge point. This is leads to underestimated capacity decrease figures for the 15NM and 20NM situation, when the operational concept is based on a hand-over to ACC before reaching the split point. In order to enable this hand-over, a 5NM separation must be established. This is more restricting and will require larger buffers at the start, which will further increase capacity loss for the 15NM and 20NM split point scenarios to 5.7 and 6.4 movements per hour respectively.

2.4 Sensitivity of the results

Given that capacity decreases result from speed differences of trailing flights on the common segment of the SID, this could be mitigated to a certain extent by imposing speed restrictions. To assess the sensitivity of the results a simulation is performed where a speed restriction is imposed on the common segment of the SID. Selecting a suitable speed restriction is done based on the KDC study “CCO and High Altitude SIDs”. This study shows that in terms of effectiveness and feasibility a speed restriction of 230kts to 250kts in the segment of the SID above 3000 feet is the best option. These parameters are therefore applied to select CCO speed profiles and perform new simulation runs.

Simulation results for the same scenario with a speed restriction show a similar pattern as the original scenario, but with less decrease in capacity (see figure 4). The speed restriction effectively reduces the capacity loss from 3 MVTS/Hour to 1.9 MVTS/Hour when the split point is located at 20NM from the runway threshold.

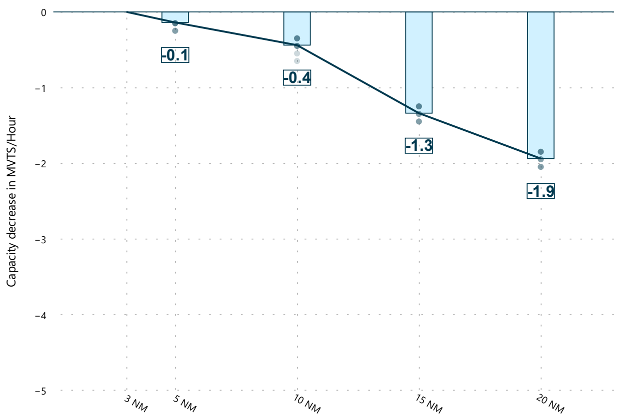

Figure 5: Decrease in departure capacity with a speed restriction

3 Merge point location for arrival routes

Inbound operations for the future airspace design are characterised by a transition from radar vector operations to fixed arrival routes. Transitioning to these operations comes with a set of design choices for TMA design that impact the resulting capacity. This chapter provides an analysis of these capacity effects, for design choices related to fixed route length and merge point location.

3.1 Simulation model

To analyse capacity effects of design choices for future inbound operations in the TMA, a fast-time simulation is developed using the AirTOP simulation platform. This platform provides capabilities to model:

- Speed control instructions;
- Scheduling using trajectory prediction;
- Aircraft dynamics during deceleration;
- Final approach procedures.

Using these capabilities, a simulation model is constructed for inbound TMA operations for a generic airport and TMA structure. In this model inbound flights arrive at the IAF and are controlled through air traffic control instructions to ensure minimum separation and optimise runway capacity. By increasing the traffic demand, the inbound TMA structure is stress tested to determine the maximum demand that can be handled without conflicts occurring. This maximum demand is regarded as the peak capacity of the system.

3.2 TMA structure for APP

Capacity effects for design choices related to fixed route length and merge point location are analysed using different TMA structures. To assess the effect of the fixed route length, a single fixed route is modelled which, due to its letter I shape, is referred to as the 'India' scenario. Whereas effects of the merge point location are modelled using two fixed routes that merge into a single fixed route, looking like the letter Y and therefore referred to as the 'Yankee' scenario.

<u>India scenario</u>

Scenario India consists of one straight fixed route that starts at 10NM, 20NM, 30NM, 40NM or 50NM from the runway threshold, see Figure 6. The TMA is 50NM is in size. This means that in the scenario with a merge point at 50NM from the threshold, the IAF and the merge point coincide. In this scenario there is only one IAF. In scenarios with a shorter fixed route segment, two IAFs are used. Vectoring is performed between the IAF(s) and the merge point. In the initial simulation, AirTOP uses a demand pattern where aircraft arrive at a fixed interval at the IAF. The delivery of aircraft at the start of the fixed route occurs at a simulated EAT by AirTOP. On the fixed route, only speed control is used to maintain separation.

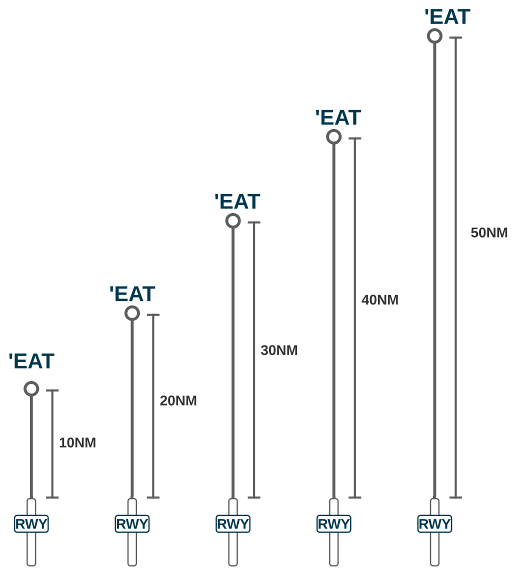

Figure 6 Simulated airspace structure scenario India

<u>Yankee scenario</u>

Scenario Yankee consists of two fixed routes that each start from a different IAF, see Figure 7. The two fixed routes are merging into a common segment at 10NM, 20NM, 30NM or 40NM distance from the runway threshold. The TMA size is 50NM. Both on the common segment and on the two legs leading up to the common segment only speed control is used to maintain minimum in-trail separation.

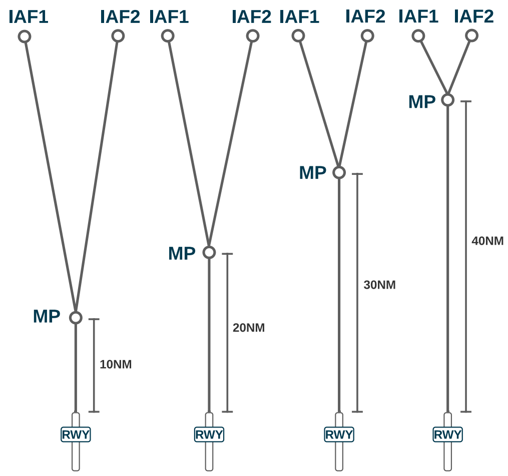

Figure 7 Simulated airspace structure scenario Yankee

3.3 Simulation scenario

The simulation scenario consists of set of 5000 flights with an aircraft type distribution corresponding to the type distribution in 2019. A generic layout for the route structure is modelled using built-in features of AirTOP software in combination with the input of the teams' ATM experts. The resulting AirTOP model features a speed profile that defines a set of minimum and maximum speeds at different distances from the runway and an altitude profile with a descent angle close to 2.3 degrees. This allows for speed control to be performed. Figure 7 shows the comparison between the trajectories simulated by AirTOP (in blue) and ADS-B speed profiles of arrivals (in orange) at Amsterdam Airport Schiphol in 2019. This figure shows that the AirTOP speed profile is resembling real life operations.

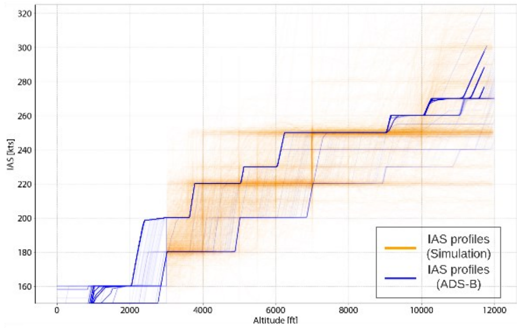

Figure 8: Speed profile in the simulation

The following parameters are used for ATC control and aircraft dynamics in the simulation:

- Minimum vertical separation of 1000ft;
- Minimum lateral separation of 5NM in ACC;
- Minimum lateral separation of 3NM in TMA;
- Minimum in-trail separation according to minimum wake turbulence or radar separation;
- BADA 3 is used to determine aircraft performance characteristics;
- Only speed control is allowed on the fixed route in discrete steps of 10 knots;
- Speed control availability according AirTOP speed profile maxima and minima;

3.4 Simulation results

Simulation results are divided between the India and the Yankee scenario. In the India scenario results are purely based on the simulation results. For the Yankee scenario an analysis is done on the mechanisms that result in capacity effects when the merge point location is changed. This analysis is validated by a simulation.

<u>India scenario</u>

The relationship between the length of the fixed route and capacity is displayed in Figure 9. These are results for a demand scenario where aircraft arrive at a fixed interval. The results show that capacity decreases as the merge point is located further away from the threshold. On the fixed arrival route part, the control space is smaller than in the vectoring part up until the merge point. This means that when the fixed route part is longer, the control space is reduced. With less control space, it is harder to correct for delivery errors leading to flights arriving at more than minimum separation at the threshold. This reduces capacity.

Capacity decrease is highest with a merge point at 50NM from the threshold. In this scenario, there is only one IAF and the TMA structure consists of one long fixed route of 50NM. This scenario shows a capacity decrease of 5.5 movements per hour compared to the optimum situation (10NM or 20NM). By decreasing the length of the fixed route and thereby increasing the space for vectoring, the capacity loss is reduced. From 20NM there is enough vectoring space available and the fixed route is sufficiently short to not cause capacity issues. Shortening the fixed route from 20NM to 10NM does therefore not show any improvements in capacity.

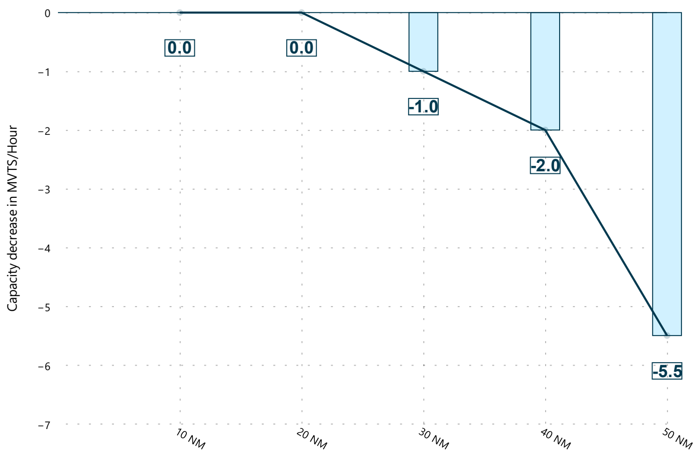

Figure 9 Distance vs. capacity for arrivals in scenario India

<u>Scenario Yankee</u>

In scenario Yankee inbound traffic is controlled solely by use of speed control along a fixed arrival route that has the same length in every scenario. In this scenario the merge point distance towards the threshold is changed. To explain this effect, an analysis is done for separate aspects that may influence capacity when the merge point location is changed.

Variance in speed profiles

Every aircraft type has different performance characteristics, which is reflected in variations of deceleration speeds and speed envelopes during the approach. This leads to speed differences between one aircraft trailing another aircraft, causing an increase or decrease of in-trail separation between the aircraft pair. For a trailing aircraft that is catching the leading aircraft, a separation buffer must be applied at the start of a common segment to ensure the in-trail separation is maintained. With a perfect metering at the start of the common segment, the trailing aircraft is at minimum separation when the leading aircraft is over the threshold and no capacity is lost.

In the opposite scenario where the trailing aircraft falls behind the leading aircraft, the in-trail separation of a flight pair increases along a common segment. An aircraft pair that is at minimum separation at the start of a common segment, will have a surplus of separation when the leading aircraft is over the threshold. A surplus in separation leads to a loss in capacity, which increases with an earlier merge point and longer common segment. This is schematically depicted in Figure 10.

A capacity loss due to a trailing aircraft falling behind a leading aircraft is a phenomenon that only applies in the very last part of the approach. In earlier parts of the approach this phenomenon is mitigated by the compression of arrivals as they get closer to the threshold. This compression effect can be observed by looking at the time space diagrams of subsequent flights in the simulation, see Figure 11. This figure shows a time-space diagram where the surplus of distance separation between flights can be observed as the white space between the light blue areas. As flights get closer to the threshold, the ground speed decreases. As a result, a time separation at the threshold with a low ground speed may correspond with minimum distance separation while at the IAF (where ground speed is higher) this same time separation corresponds to a distance separation that is larger. Similarly at possible locations of the merge points, there is a surplus of distance separation that can be reduced along the segment to correct for capacity loss due to speed variation without violating minimum separation. Speed variations do therefore not introduce capacity effects as a result of changes of the merge point location.

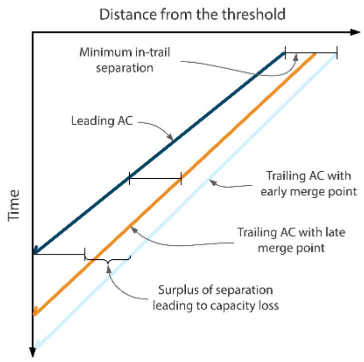

Figure 10: Capacity loss due to speed variation

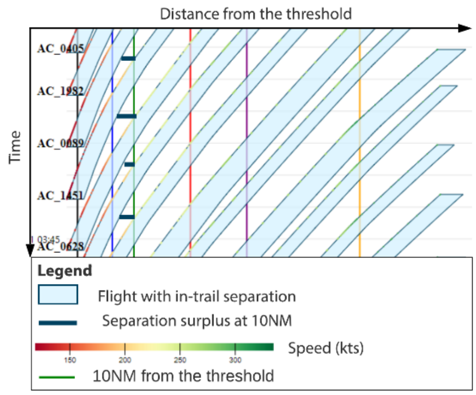

Figure 11: Time space diagram of flights in the simulation

Errors due to discreteness of control instructions

Control instructions in the simulation are provided in steps of 10kts, which results in under- or overcorrection. These errors grow with a longer flight path on a fixed arrival route. For every simulation scenario with different positions of the merge point, the flight path length remains the same. A different merge point position does therefore not cause any capacity effects as a result of inaccuracy of control instructions, unless the selection of a different merge point location changes the flight path length.

Effect of delivery errors

When aircraft are delivered at the IAF, they should be delivered at their exact landing interval plus an additional buffer (corrected for the nominal path duration). It is not always possible to perform an accurate delivery, leading to delivery errors at the IAF. If a flight arrives with a large delivery error at the IAF, this error must be corrected before arriving at the merge point. To do so sufficient segment length between the IAF and the merge point is required to perform speed control. When the merge point is close to the IAF and there is not enough space to perform speed control before the merge point, the buffer for delivery at the IAF must be increased leading to a loss in capacity. To mitigate this loss in error the merge point should be placed further away from the IAF and thereby closer to the threshold.

Effect of turning at the merge point

Changing the location of the merge point, changes the location where aircraft make a turn, to turn in to the common segment. The closer the merge point lies to the threshold, the less space remains for speed control after the merge point. When a turn-in error occurs at the merge point and it is not possible to correct for this error using speed control, this causes either a loss of separation or a surplus in separation. With a higher chance for a loss of separation, a higher buffer must be applied. Applying this buffer leads to a surplus of separation at the threshold, causing a loss of capacity. This loss of capacity can be reduced by positioning the merge point further away from the threshold and thereby closer to the IAF.

Effect of uncertainty introduced by wind

Uncertainty in wind causes uncertainty in the flight profile. The variations in wind typically do not change much over time. This means that two consecutive aircraft over the same path are likely to experience the same wind, and therefore have the same wind uncertainty. However, when the two aircraft are on different paths, the effect of the wind on their 4D profile is also different. For example, the speed of an aircraft is fully affected by wind when it flies into the wind while its speed is hardly affected by wind when it experiences a crosswind.

When the position of the merge point changes, the length of the common segment changes as well. On the common segment an aircraft pair flies the same headings, while in the segment before the merge point each flight in an aircraft pair flies a different heading. This leads to an added uncertainty when the merge point is closer to the runway, because the segment where an aircraft pair flies a different heading is longer. An increased uncertainty requires a larger buffer, which results in capacity loss. To mitigate uncertainty and capacity loss due to wind variation, the merge point should be placed close to the IAF rather than close to the threshold.

Effect of limited control space

To maintain separation and account for speed variations, the only instrument available in this scenario is speed control where flights can be decreased in speed. With a saturated demand, subsequent fights are increasingly slowed down. This process can only continue until a trailing flight cannot be slowed down anymore because of its minimum speed limitations. At this point, a controller essentially runs out of control space and the only remaining option is to apply a holding pattern, which is undesirable in terms of capacity. When this point is reached only depends on the amount of control space that is available. For speed control, this is determined by the length of the fixed route. Given that the for every merge point location scenario the length of the fixed route is the same, the control space will not vary as a function of the merge point location. This aspect will therefore not cause any capacity effects.

Effect of dynamic instability

Dynamic instability can occur due to a positive feedback loop where the trailing object reacts to the leading object and overcorrects. This mechanism for example causes phantom traffic jams. In a scenario where flights are trailing each other on a common segment close to minimum in-trail separation this effect may occur. Changing the merge point location will have an effect on the length of the common segment where this effect may occur. However as shown in Figure 11, flights are only close to minimum separation in the very last phase of the approach at less than 10 NM from the runway. Changing the merge point location will not have an effect on this part of the approach. There will therefore not be any capacity effects of dynamic instability as an effect of changing the merge point location.

AirTOp simulation results

In the AirTOp simulation model, a simulation has been performed to assess the effect of changing the merge point location in a scenario where the entire inbound TMA operation consists of fixed arrival routes. This simulation model incorporates:

- Variation in speed profiles;
- Errors due to inaccurate control instructions;
- Effect of uncertainty in trajectory prediction and planning (partially);
- Effect of limited control space;
- Effect of dynamic instability.

The simulation covers most of the mechanisms that have an influence on the capacity effects of changing a merge point in the Yankee scenario. As explained earlier, exact capacity numbers will be influenced by wind conditions, the exact route structure and the way an actual traffic controller anticipates to optimize capacity. These factors cannot be modelled accurately in the simulation. Results of this simulation should therefore be regarded as a validation of the above described mechanisms rather than absolute capacity number results.

The results show that a merge point location should not be too close to the threshold but also not be too close to the IAF. The ideal location of the merge point is found to be 30NM. These results respond with the expected results for mechanisms that influence the capacity when the merge point location is changed.

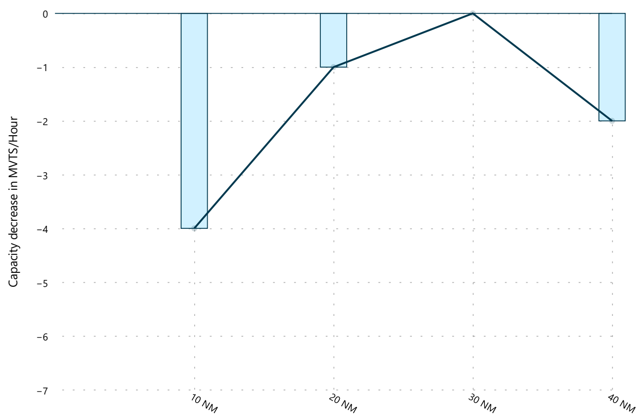

Figure 12: AirTOp simulation results for the Yankee scenario

3.5 Sensitivity to variations in the delivery at the IAF

To assess the sensitivity of the analysis results, a sensitivity analysis is performed for the delivery of aircraft at the IAF. Disturbances in the planning are simulated by delivering aircraft to the IAF with a random uniform distribution between plus and minus 60 seconds from the uniform delivery interval. The random uniform distribution method is selected over a normal distribution to more clearly show the impact of planning disturbances. Due to the limited control space, especially for the India scenario's with a fixed route length of 40NM and 50NM, the capacity loss is respectively 7.5 and 15.5 movements per hour compared to the optimal situation where the fixed route is as short as possible.

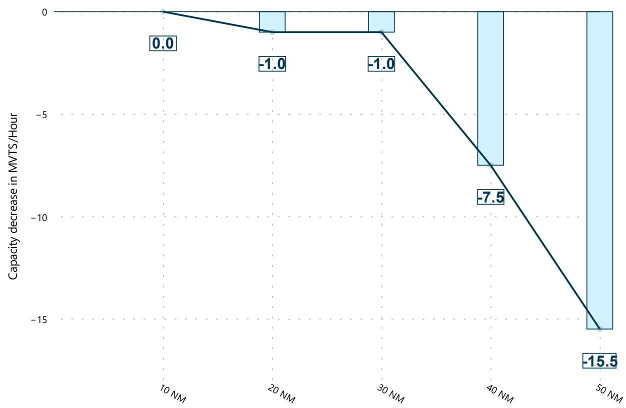

Figure 13: Sensitivity to delivery error for India scenario