



SPEED GATED INTERCEPT PROCEDURE STUDY FOR INTEGRATION OF INCREASING DIVERSE OPERATIONS (IDO) AT EUROPEAN AIRPORTS

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Abstract

The future implementation of Increasing Diverse Operations (IDO) will result in a reduction in capacity at hub airports due to the necessity of inserting larger gaps between aircraft with very different speed profiles. This is due to the large range of different approach speeds that IDO encompasses. Such a development will present a challenge for airports, which are already operating at or near their capacity limit. An alternative routing towards an intercept point at a late stage of the final approach can provide two approach options with relatively low interference for subsequent traffic. This study evaluates the performance in terms of capacity for different constellations of this procedure. The development of an optimized procedure with just one IP on final in order to combine the positive features of all analyzed air traffic scenarios and keep the procedural complexity at a minimum was the main objective of this study. The optimized procedure is based on the advantageous features of the scenarios examined. The selection of the most advantageous scenario determines which option of the approach path the inbound aircraft must fly. Ultimately, an optimized procedure was created that has a higher capacity than to all individual methods.

Keywords: air transport system efficiency; approach procedure; time-based separation; increasing diverse operations; final approach

1. Introduction

Over the past decades, international aviation has grown with the exception of the COVID-19 period almost steadily [1]. Especially airport capacity has become a bottleneck for further growth and the predictions for the future estimate this situation to intensify. At the same time, the German Aerospace Center (DLR) and the National Aeronautics and Space Administration (NASA) are expecting Increasing Diverse Operations (IDO) with very large differences in the flight performance parameters [2]. Due to the almost simultaneous introduction of electrically powered aircraft and supersonic passenger aircraft in the next decades [1], a key flight performance parameter will be the optimum approach speed differences between which are likely to exceed the current variability in terms of speed by a factor of two. The differences in the speed profiles are based on future aircraft designs, which will deviate significantly from those of today's aircraft types due to new propulsion systems and the associated aerodynamic boundary conditions, particularly during the approach phase. The consequence of the very heterogeneous speed profiles of approaching traffic will make it impossible for approach controllers to stagger aircraft as closely and efficiently as today.

Many hub airports are already operating at the limits of their capacity which leads to increasing delays and to rising costs for airlines [3]. Based on the current trend towards more traffic movements, it can be assumed that the number of take-offs and landings will also continue to increase in the coming years, thereby exacerbating the capacity problem, particularly at larger airports.

Physically necessary speed differences on the final approach will lead to an increase in the required separation distances on final in order to ensure the safety-relevant separations between two or more

aircraft during all approach phases. This naturally has an impact on the maximum number of aircraft that can land on a runway system and thus on the overall airport capacity. In addition, due to the CO₂ issue, it is very important to reduce the fuel consumption of each individual aircraft. This can be achieved by giving aircraft along their entire flight path the option of always moving along their own optimized 4d-trajectory. However, this means that aircraft must also follow their own optimized speed profile on final approach, as is the aim of Continuous Descent Operations (CDO), for example. However, this will significantly increase the differences in approach speeds compared to today, with the result that the theoretical capacity of airports will be reduced. In order to prevent the fuel from ultimately being burnt in holdings, thereby achieving CO₂ reductions, new procedures for the optimal staggering and routing of inbound flights must be developed that avoid this loss of capacity or at least compensate for it as far as is technically possible. However, IDO not only involves energy-efficient flying, but also the goal of reducing door-to-door times for passengers and goods. This may also result in completely contradictory requirements for future aircraft designs.

This raises two main questions: Will the technical diversification of aircraft have an impact on the capacity of airspace and airports? And if so, how great is the loss of capacity likely to be and what options do air navigation service providers have to compensate for part of this loss?

Various airspace structures for a Terminal Maneuvering Area (TMA) like Trombone Path Stretching or Point Merge System have already been developed in recent years to ensure safe and optimized approach guidance, but they follow different objectives and boundary conditions that do not necessarily focus on handling different approach speed profiles. For a smooth and safe approach separation of IDOs, we propose a structure consisting of different elements of proven procedures.

2. CURRENT AIRSPACE DESIGN AND PROCEDURES AROUND AIRPORTS

The TMA as the airspace around an airport is the region, where arrival and departure flows converge. Designed to support the organization of traffic in a safe manner by controllers, it may be a source of significant flight inefficiencies, particularly in dense and complex TMAs [4].

The ideal approach procedure keeps aircraft high, at low thrust, and in a clean aerodynamic configuration for as long as possible [5]. In this way, noise impacts on the ground are minimized and fuel burn savings are maximized. Although approximately 80% of the remaining inefficiencies of a flight occur within a 40 NM radius of airports [6], it is particularly difficult in the TMA to meet the specifications of an ideal approach from an aircraft point of view. As a result, Air Traffic Control (ATC) has to make trade-offs between environmental benefits, the technical and aerodynamic realities of the way aircraft must be flown by flight crew, and the need for operational flexibility for a safe and efficient handling of traffic.

All airspace users have to be coordinated and it is obvious, that everybody has to make compromises regarding routes, speeds, and altitudes. Usually, aircraft arrive from all directions to an airport, where they must be merged into several streams based on the number of available runways. For controllers, this is easiest, safest, and most efficient if they clear the same approach speed to all aircraft on merging routes. In addition, identical airspeeds at fixed overflight points ensure that all pilots can reduce their speed safely and in good time to the runway threshold, regardless of current meteorological conditions and the type of aircraft used.

In current day operations, the progressive merging of arrival flows into a runway sequence is often performed with open loop vectoring when path stretching or shortening is required [7]. In case of high traffic, air traffic controllers typically issue a large number of tactical heading-, speed-, and altitude-instructions. The average number of clearances of a route system is an indicator for the complexity of an airspace and therefore is used for its complexity calculation [8]. This guidance method is highly flexible and enabling controllers to synchronize aircraft behavior through speed and altitude advisories. However, this vectoring called procedure results in high workload both for flight crews and controllers and in an intensive use of the radiotelephony. Indeed, it generally requires numerous actions to deviate aircraft from their most direct route for path stretching – and later put

them back towards a waypoint (e.g. the Initial Approach Fix (IAF)) or the center line for integration in the arrival stream on final.

Today, in a number of busy European TMAs, Arrival Management (AMAN) systems have been deployed to support controllers in planning and building of arrival sequences. These systems are important, because some of the busiest airports are determined to use overaged airspace structures and procedures, which were defined in former days with much less air traffic, but may not be suitable for high traffic situations of today. At some airports, restrictions apply due to boundary conditions that cannot be influenced, such as neighboring airports, facilities and residential areas protected from aircraft noise, and high buildings or mountains. Additionally, the runway systems of some of the biggest airports like London Heathrow (EGLL), Paris Charles de Gaulle (LFPG), and San Diego International (KSAN) are running most of the time at their theoretical capacity limit. This can only be achieved through perfect coordination, structuring of the available airspace, excellent training of air traffic controllers, and sophisticated controller support systems tailored to the airport.

When constructing new airspaces and procedures for a specific airport, there are a whole bunch of constraints to consider [9]. Runway topology, obstacle freedom, populated areas, adjacent airports, restricted military areas, or main wind directions are important for new routes and altitudes. So, if one parameter like flight distances is optimized, a downgrade of other parameters, like noise emission around dense populated areas, has to be considered. An AMAN with specific functionalities can optimize parameters in dependence of traffic context or daytime [10].

During the development of new airspaces to support optimized approach procedures, modern AMAN functionalities should be considered to exploit all environmental benefits. In principle, flight management equipment of today's aircraft allows fuel saving and noise reducing CDOs. Without controller and pilot support and in conventional airspaces with narrowed approach routes, CDOs have a noticeable capacity reducing effect on high traffic airports [11]. For the effective and conflict free use of Continuous Descent Approaches (CDA), arrival traffic has to be guided "time-based" instead of "distance-based" [12]. Modern trajectory-based arrival management systems can support approach controllers in arrival sequencing and time-based guidance especially if the scheduling starts very early like Extended AMAN (XMAN) can do [13]. But today's heterogeneous flight management system equipage of civil aircraft needs an integrative concept to use the maximum advantage of the respective technical equipment [14]. During all phases of approach, this requires full support for controllers and pilots [15].

In recent years, a whole series of airspace designs have been developed for the safe and efficient organization of TMAs, which, in addition to the runway topology, must also consider the other mentioned constraints. Theoretical modeling has shown that average arrival and departure delays could be decreased by around 55% and 30%, respectively [16]. Linear programming has also been used to successfully optimize traffic flows in the vicinity of major airports [17]. The total number of conflict resolution advisories also decreases remarkably by analyzing and optimizing TMA traffic. It has become clear that every airport embedded in its environment is unique and therefore there is no global solution for the configuration of TMA procedures. However, it has been shown that certain patterns and procedures can be used again and again in slightly different variations.

2.1 Direct and Fan Approach

The simplest and most frequently used airspace design variants are direct approach routes for low and medium frequented airports [18]. However, there are some bigger airports like Los Angeles International (KLAX) in California or Halle/Leipzig (EDDP) in Germany which use only a direct approach airspace structure for low traffic periods at night times. The benefits of direct routes are the simple design and the easy adaption on different traffic situations. However, the direct approach structures are unsuitable in medium and high traffic situations, because the implementation of an efficient aircraft staggering for the final is almost impossible.

Arrival routes starting in a metering fix and fanned out to fix or virtual points on final exist for medium- and high-frequented airports or airports with a parallel runway system. Overflying the metering fix,

the controller gives a heading instruction in the direction of the centerline [18]. The challenge for controllers is to be able to give the right speed-clearances to the aircraft, because depending on the angle at which an aircraft hits the final or the extended centerline, the remaining flight distance to the threshold is lengthened or shortened.

2.2 Trombone Approach

A path stretching airspace structure using downwind, base leg, and final for the approach procedure is called Trombone. The specific feature of Trombones is the simple way to ensure wake vortex separations when aircraft arrive from more than one direction onto final. Like a zip fastener, aircraft are sorted from both sides on final at the end of the inbound stream or into a gap in case a gap is available. If an aircraft flying on downwind reaches its ideal position to meet the final, the “feeder” controller advises a turn to base and, if possible, clears the aircraft for ILS on final. This Trombone airspace structure is a very common procedure at airports with heavy traffic and therefore introduced on many airports around the world.

2.3 DME-ARC Approach

DME Arcs represent a worldwide used but not very common approach airspace structure. A DME (Distance Measuring Equipment) for air traffic navigation is a transponder-based radio navigation technology that measures the slant range distances by timing the propagation delay of VHF or UHF radio signals. Currently, DME Arcs are in use for example in Delhi (VIDP) in India, Santa Fe (KSAF) in New Mexico, or Clermont Ferrand (LFLC) in France. During DME Arc approach, pilots are guided onto a circle flying on a ring structure around an airport until reaching the final approach path where they are cleared to turn to final. During flight on the arc, aircraft have to stay in level or descend slightly between cleared waypoints.

On airports which are using DME Arcs, aircraft noise may be an issue, because usually glide slope intercepts are at flight levels between 2500 ft and 3500 ft. Another disadvantage of the DME Arc approach are long distances to fly in cases, when aircraft converge the final from the averted side of the final approach path, so they have to fly nearly the complete ring structure without reducing the distance to the airport. Additionally, all aircraft have to fly very long distances on the same route.

2.4 Point Merge Approach

Elaborated by the EUROCONTROL, the Point Merge System (PMS) is the latest development of the approach procedure airspace structures, which are now in operations [7]. A PMS should be defined as an RNAV STAR, transition, or initial approach procedure with a single merge point per threshold used for inbound traffic integration. Pre-defined sequencing legs, designed equidistant from the merge point and defined through FMS-waypoints, are dedicated to path stretching or shortening for each inbound flow. These legs are separated vertically and laterally by design.

The distance to the merge point shall remain (nearly) the same all along the sequencing legs. This is achieved with arcs centered around the merge point and FMS waypoints located at the same distance from the related merge point. Some other possible PMS design options are possible, for example a double PMS, where one PMS feeds the arc of a second PMS [7]. Another solution to feed a parallel runway system, is the Multi-layer PMS with a 90° rotating of the arcs [19].

The benefits of Point Merge operations are the creating of space between aircraft through path stretching with little ATC intervention by leaving aircraft fly along sequencing legs, and a conclusive “direct-to” clearance to the merge point. After leaving the legs, the spacing is maintained through speed control. There are some disadvantages, which prevent the introduction of Point Merge at all bigger airports. For instance, the PMS is a static spacing system that needs a large airspace and is flight time consuming in low traffic periods. It provides only limited Continuous Descent Operations. Another disadvantage is the slightly reduced airspace capacity compared to the Standard Terminal Arrival Routes (STAR) on parallel runway systems [20; 21]. The PMS is set for example in Oslo-Gardermoen (ENGM) and Stavanger (ENZV), both Norway, and Dublin (EIDW) in Ireland. A special variant of PMS was introduced at London City airport (EGLC) in 2016 [22].

2.5 Stacking Patterns

London Heathrow (EGLL) in Great Britain is one of the busiest airports in the world, located in the very cramped airspace around London. Most aircraft coming to land at EGLL are guided into holding stacks, which were established in the 1960s [5]. Each stack acts as a waiting room, allowing the air traffic controllers to gather aircraft for landing efficiently.

With clearances from controllers, the aircraft enter one of the four stacks and then circle and descend at the same time. Once the planes leave the holding stacks, there are defined routes for aircraft moving from the holding stacks to the final approach and Air Traffic Controllers (ATCO) can use the airspace between the stacks and the finals as trombone path stretching areas for fine adjustment of separations. Factors such as geographic positions of the stacks, actual traffic volume, or weather conditions affect how aircraft are sequenced [23]. The advantage of this worldwide unique system is the slight airspace volume needed for inbounds even in high traffic situations.

2.6 Summary Terminal Airspace Design

When designing airways and complex airspace structures, familiar and best practices should always be used whenever possible. This is especially true for the approach into and around the TMA, which is one of the most challenging phases for controllers and pilots due to the reduction of altitude and speed while merging different traffic flows. An ideal design concept is to give pilots as much freedom as possible during the approach so that they can use the onboard Flight Management System (FMS) to calculate and fly an optimal approach profile in terms of time, distance, fuel consumption, and aircraft noise emissions. At the same time, approach controllers face the challenge of coordinating aircraft with their individual profiles in terms of time and space so that the airport is operated safely and efficiently. This requires that at least a minimum of waypoints, routes, and constraints be specified.

Ideally, all aircraft are given clearances for individual approach routes so that, by design, no conflicts can occur. However, on final at the latest, all approaches must be merged, regardless of whether the speed profile they use or were routed. Direct approaches require more precise timing and spacing than structures with an integrated Path Stretching Area (PSA), because there is less space for corrective actions when deviating from the ideal route or predicted speed.

3. CHALLENGE AND SOLUTION CONCEPT

The focus of this study is on the impact of varying airspeeds during the final approach phase of aircraft operations. The need for different speeds stems from various factors such as economic considerations, aircraft design, and noise regulations. However, regardless of the reasons, it's crucial to maintain approach capacity without compromising safety or efficiency.

Currently, there's a significant variance in optimum approach speeds for aircraft flying under Instrument Flight Rules (IFR), ranging from 30 to 550 tons in weight. These speeds can deviate by up to ± 20 knots from conventional approach speeds [24]. Harmonizing these speeds is essential for minimizing air traffic controllers' workload and ensuring safe separation between aircraft. Any deviation from standardized speeds necessitates additional separation, impacting capacity.

The situation is expected to worsen with the introduction of new aircraft models, such as supersonic planes and electric aircraft. These changes in aircraft characteristics are collectively referred to as Increasing Diverse Operation (IDO). Supersonic aircraft will require higher landing speeds, potentially exacerbating noise pollution (Figure 1) [2]. Conversely, electric aircraft, despite their lower cruising speeds, are expected to have different landing characteristics due to their propulsion systems and increased touchdown weights [25; 26].

This study aims to facilitate increased speed differentials to enhance operational efficiency and environmental sustainability, while accommodating diverse aircraft designs. The developed procedure seeks to ensure that aircraft can complete their approaches efficiently, regardless of their

SPEED GATED INTERCEPT PROCEDURE STUDY

speed profiles. Initially, the study considers three speed profiles: Slow, Traditional, and Fast, for simplicity and clarity in calculations and simulations.

The research identifies the 15 Nautical Track Miles (NTM) range as critical for developing a new procedure. Within this range, varying approach speeds necessitate additional separation buffers to prevent capacity losses. This is particularly evident when aircraft with differing speeds share the same route for an extended period, leading to inefficient gaps between them and reducing airport capacity by up to 20%.

Previous studies have investigated the capacity loss associated with differing approach speeds [27; 28]. Factors such as the magnitude of speed differences and merging angles significantly influence capacity. Thus, a comprehensive study of the effects of Increasing Diverse Operations (IDO) traffic is essential to inform future air traffic management strategies.

Increasing Diverse Operation

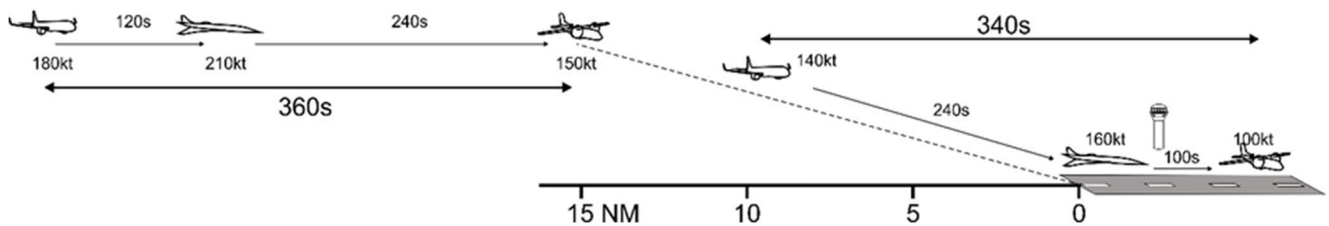


Figure 1 - The challenges that IDO poses for controllers when staggering the approaching traffic due to large differences in speed result from the fact that on final, slower aircraft build up large gaps behind faster aircraft. In addition, slower aircraft have to start with an additional separation buffer to ensure separation to a faster aircraft that is following on approach. Both cases result in a greater utilization of space within the arrival sequence than is observed in aircraft with homogeneous approach speeds. A reduction in possible arrival capacity is the consequence.

4. Solution Concept of Speed Gated Intercept Procedures

The current approach to capacity optimization, which requires equal speeds for all aircraft, doesn't accommodate diverse approach speed profiles. Future traffic will have varying approach speeds, necessitating new TMA guidance procedures. Wider speed ranges require adaptations in air traffic control structures and procedures.

A new approach procedure has been developed that uses relative speeds to guide aircraft on individual flight paths. Different approach speeds impact capacity only if approach paths are correlated or if separation rules apply. Independent movement of aircraft prevents negative separation impacts. Nevertheless, arrival traffic must merge on a common path before landing, which starts latest three Nautical Track Miles (NTM) to meet stabilization criteria.

Speed differences require additional separation buffers, reducing approach segment capacity and increasing the likelihood of holding patterns during heavy traffic. This wastes time and fuel and increases environmental impact.

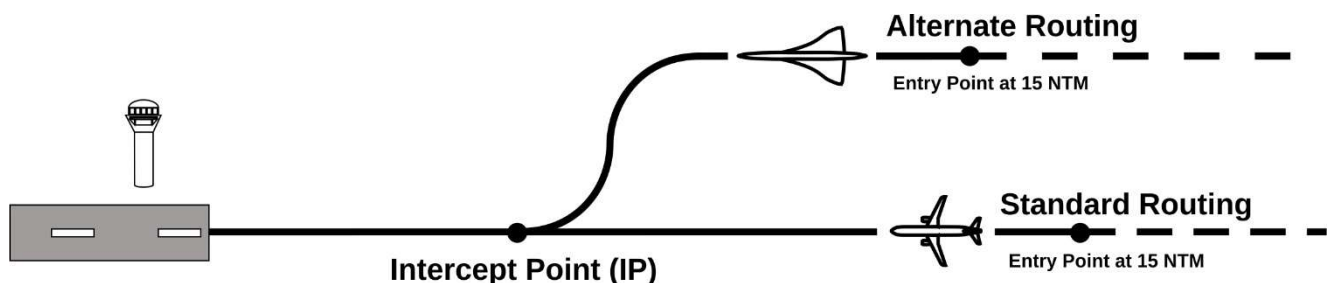


Figure 2: Concept drawing of the SGIP. The alternate Routing offers a deemed separated approach path to the standard routing via lateral separation. The concept study starts at an entry point at 15 NTM.

The Speed Gated Intercept Procedure (SGIP) mitigates capacity reduction by guiding aircraft pairs on separated paths based on speed differences until they reach the Intercept Point (IP) (Figure

SPEED GATED INTERCEPT PROCEDURE STUDY

2Error! Reference source not found.). To guarantee the IP at 3 NTM or more, the distance of the base leg is situated at 4.5 NM to threshold.

Speed gating considers the speed difference to the potentially conflicting traffic, i.e., the preceding and following aircraft. This consideration determines whether the aircraft will follow the alternate routing via the IP or standard routing.

In principle, aircraft with different speed profiles create the need for safety buffers that would not be necessary without IDO. During the approach, unnecessary gaps open up or close. Basically, there are three categories of leader – follower combinations:

1. Same speed schedule,
2. slower-faster and
3. faster-slower.

By enabling the second and third category of aircraft pairing (the introduction of IDO), it creates unnecessary separation which in turn reduces capacity (Table 1(a)).

Table 1: Aircraft pairing categories 1 to 3 and in red the categories that need more than required TBS to meet separation criteria throughout the approach when introducing different speed schedules – IDO scenario (a). SGIP can influence the required separation for category 3 aircraft pairings (in green) positively by an alternate routing via an IP (b). The capacity reduction mitigation of the SGIP is based on the optimization of these three category 3 aircraft pairings 3a, 3b and 3c.

(a)				(b)			
	Fast	Traditional	Slow		Fast	Traditional	Slow
Fast	1	3	3	Fast	1	3a	3b
Traditional	2	1	3	Traditional	2	1	3c
Slow	2	2	1	Slow	2	2	1

In the first category, the TBS remains constant throughout the approach, and in the second category, the gap closes to be at minimum required separation at landing (or in some special cases up to the IP). For the first case there is no need for optimization, corresponding to the minimum required separation as an absolute minimum. The second category generates higher capacity losses and could be avoided by changing the initial approach sequence before commencing the approach. SGIP was developed for the third category of aircraft pairings. During the approach, the separation increases unnecessarily for this category. SGIP is optimizing the category 3 aircraft pairings with regard to the required time interval in the approach by guiding the conflicting aircraft pairings along different flight paths until separation is achieved (Figure 3).

Speed Gated Intercept Procedure

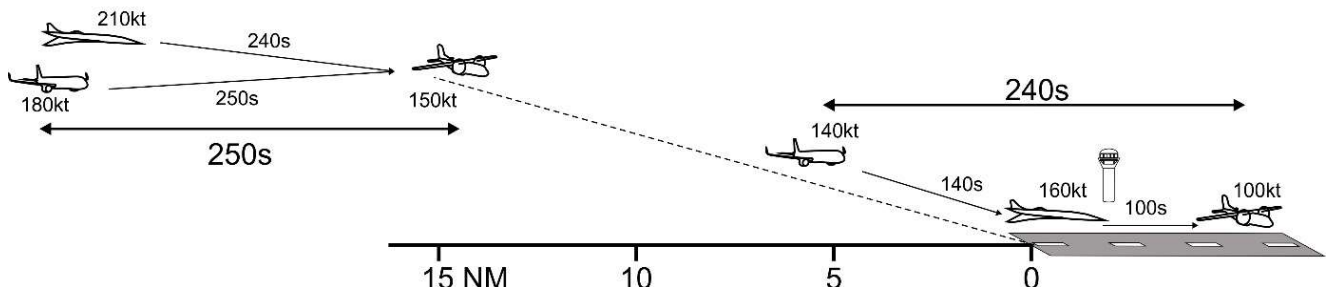


Figure 3 - During the Speed Gated Intercept Procedure specific aircraft or speed schedules join the common approach path via a late Intercept Point (IP). Throughout the approach, the faster speed schedule aircraft gains the required separation while flying on an alternate routing. This reduces the initial required separation at 15 NTM.

For example, a faster aircraft, can fly the approach laterally offset on the alternate routing to achieve the required separation before merging. The merging of the flight paths is pre-calculated and occurs when the required separation rules are met just before joining at the IP. Ultimately, SGIP is optimizing

category 3 aircraft pairings to reduce the negative effects on capacity caused by IDO integration (Table 1(b)). In order to separately address the three category 3 pairings during the further course of the investigations, they are numbered 3a, 3b and 3c.

5. Methodology

The influence of different final approach speeds on the capacity was investigated in the context of the Microwave Landing System (MLS) [27]. In consideration of these findings, the capacity investigations are to be extended to encompass a range of speed profiles, traffic mixes and approach layouts. Consequently, the capacity study is divided into four types of scenarios. For each scenario, a range of capacity calculations is performed and the results are evaluated for capacity differences, developments and patterns.

The first type of scenario is the Baseline for all other scenarios and is based on present speed profiles until finally decelerating to Final Approach Speed¹. All aircraft fly on the same track to the same runway.

The same applies to the second type of scenario, the IDO scenario. This time each aircraft can choose one of three possible speed schedules: Fast, Traditional and Slow. The Traditional speed schedule profile is derived from relevant approach speed analysis for major European airports. For the IDO scenario, the Fast and Slow speed schedules are faster or slower throughout the entire approach.

The third type of scenario implements SGIP and evaluates in three different scenario setups the pros and cons of integrating one specific speed schedule out of the three possibilities via the IP.

The fourth type of scenario finally combines the best results in terms of capacity from the third scenario and combines them to a theoretical optimum called SGIP Max.

To ascertain the resulting capacity for a multitude of potential combinations, capacity calculations are conducted with a statistical equal distribution of aircraft combinations. Consequently, the capacity of a virtually infinite traffic stream is obtained. The calculations are based on an ideal traffic scenario with constant traffic pressure and without interactions with departing traffic or traffic from other runways. The standard for this study was set by EGLL, as one of the busiest airports in Europe, with two independent parallel runways in which one runway is mainly used for arrivals and the other for departures.

5.1 Procedure Constraints

The given constraints are decisive for the resulting capacity. Conversely, this means that the absolute capacity values are not as meaningful as their relationship to each other under the same constraints. A fundamental limiting factor in this analysis is the angle at which the aircraft are routed from the alternate routing to the common final around 4.5 NM before threshold. An optimization of the intercept angle would offer the potential for improving the absolute capacity [27], but doesn't impede the considerations for the optimization of SGIP.

5.2 Speed Profiles

The Traditional speed schedule profile is derived from studies on major European airports [24] and US airports [29], whereby the European data set, which exhibited high traffic pressure, was deemed more relevant for the purposes of this study.

¹ Final Approach Speed represents the final speed for landing.

SPEED GATED INTERCEPT PROCEDURE STUDY

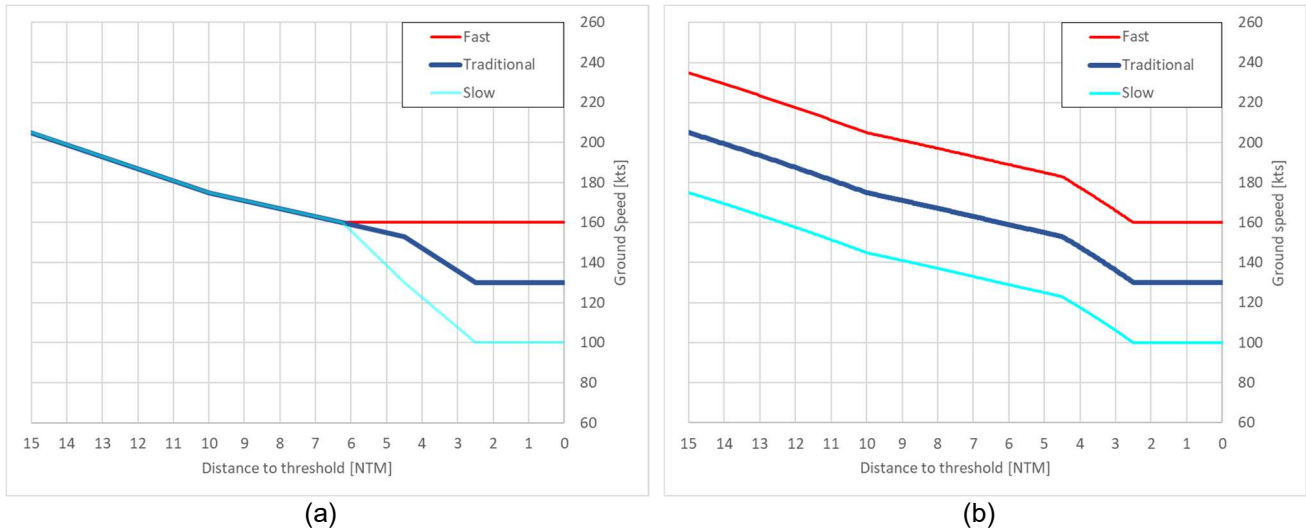


Figure 4 - Speed schedules of IDO traffic (Fast, Traditional and Slow) for the last 15 NM to threshold. The Baseline scenario integrates traffic like today, with a speed reduction to each's aircraft individual final approach speed as late as possible (a). The IDO scenario as well as all other scenarios facilitate an individual optimized speed schedule throughout the entire 15 NTM (b).

The calculations use the derived speed profiles modified in two distinct ways, each with its own unique set of variables:

1. Within the Baseline scenario, the speed schedules were only altered for final deceleration to Final Approach Speed after 6 NTM (**Error! Reference source not found.**(a)).
2. For all other scenarios, Fast and Slow speed schedules deviate continuously by the same speed difference throughout the entire segment of the last 15 NTM (**Error! Reference source not found.**(b)).

For the IDO and SGIP scenarios, the arriving flights select one of the three speed profiles (one traditional speed schedule (Traditional), one faster schedule (Fast) and one slower schedule (Slow)). By communicating this to the ATCO, the necessary safety buffer can be kept as small as possible. Otherwise, all approaches would require an additional separation buffer. In terms of facilitating optimal approach speed schedules, the arriving traffic approximates its own optimal speed profile by selecting one of the three speed profiles. In addition, the ATCO (or ATCO support system) has a basis for planning the Time-Based Separation (TBS) via Time-to-fly (T2F).

Since the polar of an aircraft shifts with the aircraft weight, the aircraft weight determines the optimum speed (wing shape kept constant) and thus the optimum speeds for the approach [30]. Furthermore, the aircraft type and manufacturer have an impact on speed on final, due to their selection of high-lift devices [31]. Accordingly, for aircraft with higher weight, which can be expected in the RECAT-EU Classes B, C, and D, it was assumed that some aircraft in this group would ideally have a higher than traditional approach speed. Extreme cases of IDO, such as new supersonic aircraft, would also be in this group based on the known approach speeds of the Concorde. On the other hand, some current and future aircraft designs are assumed to have lower landing weight than average and they can be found in the RECAT-EU weight categories Class D and E. Accordingly these aircraft would ideally seek to fly at a lower than traditional approach speed. For example, the integration of electric aircraft can be part of this category [25; 26].

5.3 Scenarios for Investigations

The investigations (Table 2) include the Baseline and IDO scenario, with all aircraft on the standard routing. Scenario 1 to 3 are scenario setups evaluates the performance of integrating one specific speed profile group via the IP. SGIP Max was developed out of all investigated scenarios.

SPEED GATED INTERCEPT PROCEDURE STUDY

Table 2 - Scenario specifications for separations calculation. IDO represents the integration of IDO traffic with three different speed schedules (Fast, Slow and Traditional). The objective of Scenarios 1 to 3 is to investigate the capacitive effects of integrating Fast, Slow, and Traditional speed schedule aircraft via a late IP. The SGIP Max is a unique solution that combines the advantages of the different variants, resulting in the theoretical maximum of the SGIP.

	Joining via IP	Speed Schedule
Baseline	-	Speed schedules variable during the reduction to final approach speed
IDO	-	Constant speed difference to Traditional speed schedule for Fast and Slow
Scenario 1	Fast	Constant speed difference to Traditional speed schedule for Fast and Slow
Scenario 2	Slow	Constant speed difference to Traditional speed schedule for Fast and Slow
Scenario 3	Traditional	Constant speed difference to Traditional speed schedule for Fast and Slow
SGIP Max	Fast/Traditional/Slow	Constant speed difference to Traditional speed schedule for Fast and Slow

5.4 Conditions for SGIP Max

It is crucial to emphasize that the outcomes of SGIP Max represent a theoretical maximum. In order to facilitate the optimal routings for all aircraft, for some speed schedule combinations of arrival traffic there needs to be either an independent second IP (Option A) or a change in the initial arrival sequence (Option B). SGIP Max opts to work without a second IP because a second IP makes the procedure structure much more complicated and, in addition, a second IP needs to be more than 3 NM separated from the first IP, in order to be independent in terms of lateral separation. This forces the aircraft with different speed schedules to fly along the same track for almost twice the time as needed with a separation solution with one IP. As a consequence, the realization of option A would mean a reduction in capacity compared to the optimum. Accordingly, option A fails to meet the SGIP Max specifications.

In principle, option B is therefore to be regarded as the preferable alternative. In order to evaluate if option B is the right solution to this problem, it is initially necessary to estimate the quantity of the necessary sequence changes and their extent. The equation for determining the quantity Q of required initial arrival sequence changes to facilitate a single IP is as follows:

$$Q \text{ (Sequence changes)} = \sum_{z=1}^{n-1} ((n-1-z) \cdot z)$$

With n representing the number of available speed schedules. **Error! Reference source not found.** shows that for low numbers of available speed schedule profiles the quantity of sequence changes is relatively low. With an expected capacity of 35 to 45 arrivals per hours and three available speed schedules this will result in roughly 1 to 2 arrival sequence changes per hour.

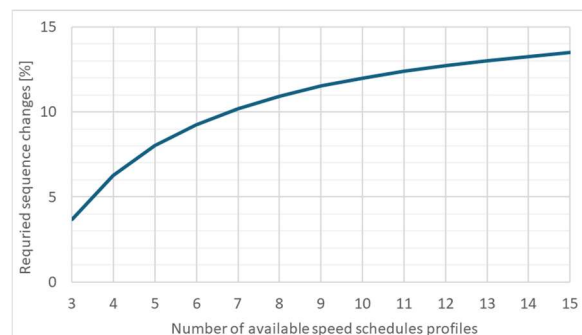


Figure 5: Quantity of required arrival sequence changes in relation to number of available speed schedules to facilitate SGIP Max with one single IP for low procedure complexity. Hypothesis is an equal distribution of traffic on all speed schedule profiles.

This quantity will increase for higher numbers of available speed schedules, e.g. 4 to 5 sequence changes for 10 speed schedules. As a consequence, with low numbers of speed schedules, option B seems to be the preferable solution in terms of quantity of changes.

SPEED GATED INTERCEPT PROCEDURE STUDY

As far as the extent of the changes is concerned, the individual cases of sequence change and their underlying rules must be considered. The implementation of speed gating at the point of arrival commands the two fundamental principles underlying the operation of SGIP Max:

1. In the event that the leader of an aircraft pairing is faster than the follower, the leader flies via the alternate routing.
2. In the event that three consecutive aircraft request to fly at a slower speed schedule than the preceding one, it is necessary to implement a change in the sequence of aircraft, with the intention of changing the sequence towards a single pairing with a reduction in speed schedules (example in Table 3).

Table 3: Example of a sequence change. Sequence in the Baseline or IDO scenario compared to the SGIP Max sequence (highlighted in yellow).

	Aircraft 1	Aircraft 2	Aircraft 3
Baseline / IDO Scenario	Fast	Traditional	Slow
SGIP Max	Fast	Slow	Traditional

Concerning the extent of the sequence changes, the extent is found to be very limited, thus selecting option *B* the optimal solution for SGIP.

The probability of being gated via an alternate routing is around 30% for the scenarios under investigation. How much this depends on the scenarios used and the given constraints will be part of future investigations.

5.45.5 Traffic Mix

The traffic mix is based on actual predictions for the next 20 years [32]. Since the focus of this study is the evaluation at large congested airports, the predicted traffic mix for the most likely traffic case at Europe's five largest airports (EDDF, EGLL, EHAM, LDMD and LFPG) in terms of large aircraft arrival numbers was used.

Table 4 – Traffic mix prediction of DEPA 2070 for the five largest European airports in terms of large aircraft arrival numbers (EDDF, EGLL, EHAM, LDMD and LFPG) and only for EGLL. A development towards higher WTC Classes is predicted: Class E aircraft are predicted to experience a decline in traffic share, while Class B aircraft are expected to gain in traffic share. EGLL is already ahead of this transition.

WTC (RECAT-EU)	Five Largest European Airports			EGLL		
	2025	2035	2045	2025	2035	2045
B	19%	24%	29%	27%	35%	36%
C	1%	1%	2%	1%	2%	2%
D	59%	63%	60%	62%	62%	61%
E	22%	11%	8%	9%	1%	1%

For these airports a traffic mix development towards higher WTC classes is predicted. The reason for this transition is the increasing scarcity of slots which will inevitably lead to a shift towards larger aircraft, especially a move away from the lighter WTC categories [33]. With the highest traffic volume, EGLL is already experiencing a prominent scarcity of available slots, consequently resulting in a traffic mix composition similar to the average of the five largest European airports 15 to 25 years into the future.

5.55.6 Separation Constraints

The basis for separation in this study is TBS which is based on RECAT-EU with 2.5 NM Minimum Radar Separation (MRS). TBS has capacity advantages in strong wind conditions, but for this study with low wind conditions, it is by definition the same as Distance-Based Separation (DBS) [34].

The spacing buffer of 0.5 NM was adopted from the mean spacing buffer evaluated for five large European airports [24]. The compression effect is considering by the use of T2F calculations [35].

Furthermore, the Runway Occupancy Time (ROT) is incorporated [35]. Further constraints, such as dependent runways, were not considered in the calculations.

6. Evaluation on the basis of Constant Separation Distance

As a basis for the capacitive comparability of the last 15 NTM, a minimum separation at the beginning of the considered approach segment is calculated for each possible aircraft pairing. The spacing value is used in terms of TBS but is ultimately providing a separation based on the RECAT-EU DBS values. Together with the separation buffer and the statistical probability of the respective aircraft pairing, the statistically average separation time is determined. For the scenarios in Table 2, these calculations are conducted with the parameters speed difference (difference to traditional speed schedule) and traffic mix. The calculations are based on the equations used for the Leading Optimized Runway Delivery (LORD) ATCO support system for the practical application of TBS [37] and EUROCONTROL guidelines on TBS [34; 35]:

For application at threshold:

$$TBS_{(leader,follower)} = T2F_{follower}(DBS_{(leader,follower)})$$

For application with distance x between separation critical point and threshold:

$$TBS_{(leader,follower)} = T2F_{follower}(DBS_{(leader,follower)} + x) - T2F_{follower}(x)$$

Where $DBS_{(leader,follower)}$ is the RECAT-EU DBS and x is the distance between separation critical point and threshold. The separation critical point is the point at which the aircraft on the same flight path encounter the minimum separation. This needs to be examined for the entire approach segment under investigation (here: the last 15 NTM). The separation in time refers to the T2F of the following aircraft and accordingly results from the speed profile of the following aircraft.

For succeeding aircraft not following the same flight path a minimum lateral separation of 3 NM is ensured by the calculations [38].

6.1 General Results – Constant Traffic Mix

In order to facilitate a more comprehensive evaluation and interpretation of the subsequent results, it is helpful to consider the relationship between the results and the three aircraft pair categories presented in Chapter 4. In particular, the aircraft pairings in category 3 must be linked to the mitigation performance of the different scenarios when evaluating the results.

The range of 20 to 50 kts difference between the speeds of the Traditional speed schedule aircraft and the Fast aircraft with correspondingly higher speeds, as well as the Slow aircraft with correspondingly lower speeds, is examined. This range was selected because it encompasses the potential range of speed differences observed in contemporary contexts. In scenarios where the speed difference is less than 20 knots, the influence of the scenario layout can be greater than the influence of the speed difference, making these results inconclusive.

SPEED GATED INTERCEPT PROCEDURE STUDY

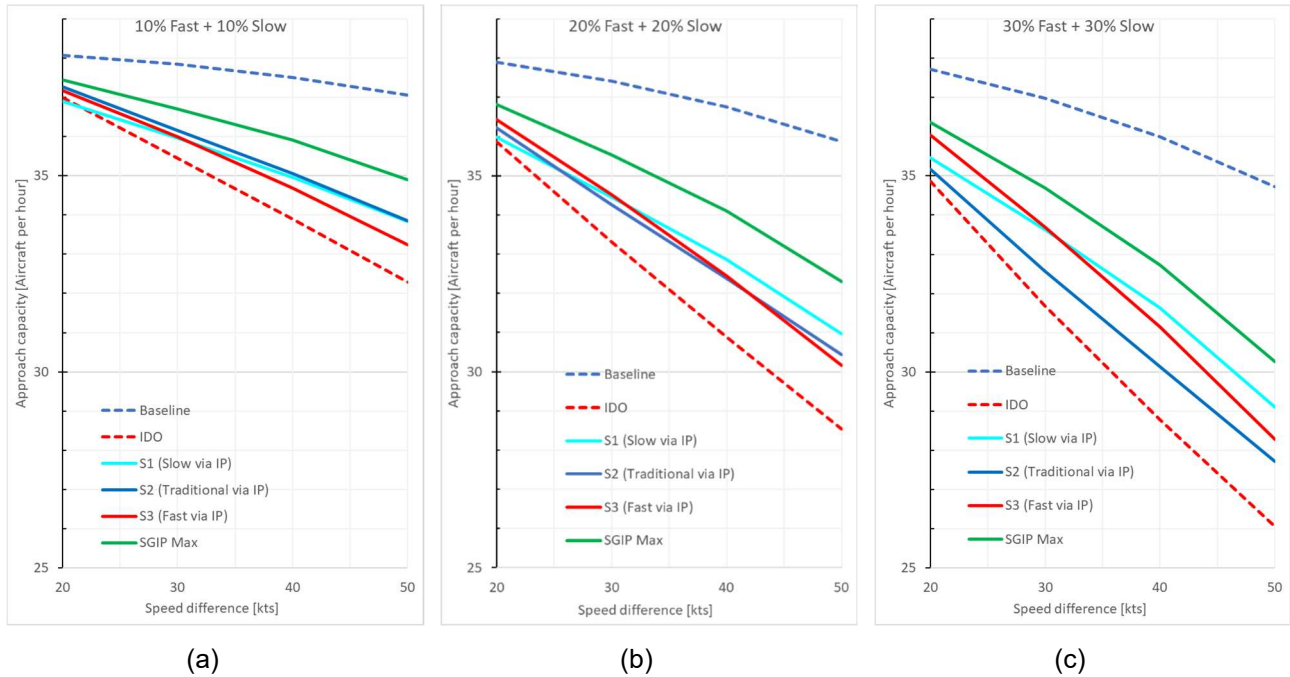


Figure 6: Different shares of IDO traffic (20% (a), 40% (b) and 60% (b) IDO traffic) consisting of Fast and Slow speed schedule aircraft in equal parts. The speed difference is the difference in speed compared to the traditional speed-scheduled aircraft. With higher IDO traffic shares the reduction caused by IDO traffic shows by the widening of the gap between Baseline and IDO scenario (b and c). With all traffic shares and speed differences SGIP Max has a relevant mitigation advantage compared with all other scenarios.

Figure 6 (a) to (c) show that the approach capacity is increasingly reduced with increasing speed differences and with increasing proportion of IDO traffic. Starting with 20% IDO traffic (Figure 6(a)), the approach capacity will be reduced by 1 to 5 aircraft per hour, within the speed difference range of 20 to 50 kts. With 60% IDO traffic (Figure 6(c)), the approach capacity will be reduced by 3 to 9 aircraft per hour, or up to 25%. The different SGIP concepts under investigation can mitigate up to 57% of the capacity loss due to the introduction of IDO traffic. However, the capacity mitigation changes for different speed differences as well as for every scenario concept and can even become negative for the wrong scenario concept at distinct traffic mixes and speed differences.

Scenario 1 is integrating Slow speed schedule aircraft via the alternate route. With increasing speed differences and higher shares of IDO traffic, the capacity mitigation increases and Scenario 1 is showing the best capacity results out of the three test scenarios. This emphasises the impact of integration of slower aircraft. Finding a solution to reduce the impact of aircraft with particularly slow speed schedules on capacity is essential. Looking at the possible aircraft pairings, each of the three test scenarios can improve separation times for specific aircraft pairings. Scenario 1 can improve type 3b and 3c aircraft pairings (Table 1(b)). Improving two out of three possible aircraft pairing types, as well as the aircraft pairing with the largest relative speed (type 3b: Fast followed by Slow) explains the good capacity results of Scenario 1.

Scenario 2 is separating Traditional speed schedule traffic via the alternate routing and achieves good capacity results for environments with low shares of IDO traffic. As the percentage of Traditional aircraft with higher shares of IDO traffic reduces, the results of Scenario 2 degrade as well. The rationale for this can be attributed to the fact that Scenario 2 is designed to optimize type 3c aircraft pairings. As the proportion of Fast and Slow traffic increases, the influence of type 3a and 3c on the total capacity shifts towards a greater influence of type 3b.

Scenario 3 separates Fast aircraft via the alternate routing and thus optimizes type 3a and 3b aircraft pairings. The capacity results are among the best or the best for lower speed differences up to about 35 kts speed difference. Optimizing two out of three pairing types explains the good performance for low speed differences. In addition, the required separation times for type 3b pairing is the lowest out of all three test scenarios. For higher speed differences, the negative effect Slow speed schedule

aircraft on the common path with Traditional aircraft becomes increasingly relevant for the total capacity.

6.2 General Results – Changing Traffic Mix

The influence of the composition of IDO traffic was examined using an example with 50% traditional traffic and 30 kts speed difference to the traditional traffic speed schedule (Figure 7). Shares of Fast and Slow traffic with 0% to 50% underwent investigation. At the extreme ends of traffic mix two scenarios show the same capacity as SGIP Max: Scenario 1 for 0% Slow traffic and Scenario 3 for 0% Fast traffic. The explanation for this lies in the concept of SGIP Max. SGIP Max optimizes all category 3 aircraft pairings and Scenario 1 optimizes only the 3a and 3b pairings (Table 1(b)). If there are no 3c pairings because there are no Fast aircraft (0% Slow traffic), then Scenario 1 and SGIP Max ultimately operate identically, which explains the same resulting capacity. The same applies to Scenario 3 and SGIP Max at the other end of the scale (0% Fast traffic).

In between these extremes SGIP Max constantly has a higher capacity with for different share mixes of IDO. In this case SGIP can mitigate 43% to 76% of capacity loss induced to IDO introduction. Mitigation increases with a higher proportion of Slow traffic.

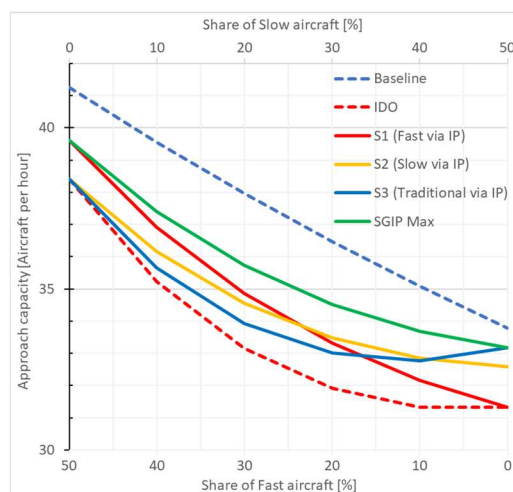


Figure 7: Development of capacity with constant 50% share of Traditional speed schedule traffic. Shares of Fast and Slow traffic are changing throughout the graph, representing together 50% of the total traffic. The speed difference between Fast, Traditional and Slow speed schedules is constant at 30 kts.

In summary, this analysis highlights that the loss of capacity is caused by two things. On the one hand, the integrating of Slow traffic with slower average speeds and thus lower capacity. And on the other hand, the combination of multiple speed schedules. The steep drop in the capacity curves from 0% to 20% Slow traffic shows that the combination of Fast and Slow traffic has a significant negative effect on capacity. The major capacity reduction is induced by a broad speed bandwidth. This is particularly noticeable when looking at the capacity curve from 20% towards 0% Fast traffic. In this range, there is only a minor change in total capacity. Instead, in Scenario 3, the capacity increases with the reduction from three toward two speed schedules (50% Slow and 50% Traditional).

6.3 SGIP Max

Each scenario has its pros and cons in different scenario configurations. SGIP Max is the combination of the best features of all scenarios. In accordance to the relative speed of each approaching aircraft pairing, the most beneficial routing in terms of capacity is chosen for each aircraft. Throughout the whole scale of different speed and traffic mixes SGIP Max can mitigate around 40% to 76% of the IDO induced capacity loss. Most of the time the mitigation is more than 50% with a constant enhancement compared to all test scenarios.

7. Conclusion and Outlook

Due to increasing traffic figures in aviation worldwide, large airports and air navigation service providers are trying to get as close as possible to the theoretical airport capacity in terms of aircraft movements. Among other things, this requires all approaching aircraft to be brought to the same airspeed over ground at an early stage and at every merge point, so that once separation between aircraft has been established, the separation remain constant.

Currently, new aircraft are being developed worldwide. This also includes hypersonic aircraft to enable very fast transportation of people and goods to follow the principle of short door-to-door times. On the other hand, electric aircraft are being developed which, due to their design constraints, will require slower speeds. Future approach speed schedule shall enable short door-to-door times as well as energy-efficient flying. According to our simulations, these changes, summarized as IDO, will result in a capacity reduction of up to 25% depending on the predicted traffic mix and airspace.

At the same time, due to the homogenized approach speeds, many aircraft are already operating well outside their optimal approach performance today. Compared to an ideal approach profile, this results in increased fuel consumption and thus also increased CO₂ and NO_x emissions.

The mitigation of IDO capacity loss by our Speed Gated Intercept Procedure (SGIP) concepts studied is up to 76%. However, the capacity mitigation varies for different speed differentials and for each scenario concept, and may even be negative for the wrong scenario concept for different traffic mixes and speed differentials. Nevertheless, an optimized procedure with superior characteristics in all traffic and speed difference scenarios under investigation has been identified.

Fundamentally, the separation of divergent speed schedules is essential for the overall capacity. SGIP Max was developed with just one IP on final in order to combine the positive features of the considered air traffic scenarios and keep the procedural complexity at a minimum. In addition, practical ways to implement SGIP Max were identified and evaluated. The selection of the best validation scenario used to formulate SGIP Max also determines which aircraft will operate on the alternative route. To achieve this, minor sequence changes are required. The number and extent of these changes have been evaluated and deemed feasible.

Moreover, during the development of SGIP Max and also SGIP in general, it became evident that the calculations are complex. Consequently, another objective would be the development of an extended air traffic controller support system (AMAN) to ensure the procedure remains manageable in its complexity.

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