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# Airspace Structure Study with Capacity Compensation for Increasing Diverse Operations

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**Abstract:** Future aircraft designs with a wide range of performance parameters, such as electric and supersonic aircraft, will have to be accommodated in traditional airspace designs in the future. Allowing an individual optimization of traditional approach speed profiles has a similar, broadening effect on approach speed characteristics. The resulting necessity of integrating Increasing Diverse Operations (IDO) will lead to a reduction in capacity at hub airports, as larger gaps will have to be inserted 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 low interference for subsequent traffic. Based on traffic data from London Heathrow, this study evaluates the performance in terms of runway capacity for different constellations of this procedure. Moreover, the biphasic evaluation, conducted through theoretical calculations for a constant separation distance and a fast-time simulation for a constant separation time, yielded key findings that facilitated the development of an optimized procedure for a traffic mix with significant speed differences to compensate IDO-related capacity losses as far as possible.

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



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## 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 especially in lower airspace and the Terminal Maneuvering Area (TMA) will be the optimum approach speed, where the relative variation on approach speed is the key criterion for environmentally friendly approach trajectories. These 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. Already today there are significant differences in approach speed within a group of the same aircraft type [3], for example, the A320 family with its wide range of possible landing weights. This group represents a significant proportion of traffic share and is forecasted to grow with future aircraft designs [4]. 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 rising costs for airlines [5]. 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 [6]. It can be assumed that under these conditions it will be particularly difficult to implement individual optimized approach trajectories with regard to environmental influences.

Physically necessary speed differences on the final approach will lead to an increase in the required separation distances on the 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 within a defined time interval and thus on the overall airport capacity. In addition, due to the $CO_2$ 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 and speed profile. However, this will significantly increase the differences in approach speeds compared to today, with the long-established result that the theoretical capacity of airports will be reduced [7]. Trials at Schiphol Airport in Amsterdam have shown that the introduction of Continuous Descent Operations with individual approach speed profiles reduces the throughput and thus the maximum approach capacity of runways by a factor of two [8]. In order to prevent the fuel from ultimately being burnt in holdings and long downwind legs, thereby achieving $CO_2$ reductions, new procedures for the optimal staggering and routing of inbounds 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 [9]. This may also result in completely contradictory requirements for future aircraft designs.

Various airspace structures for TMAs like Trombone Path Stretching or Point Merge Systems 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 TMA airspace structure consisting of different elements of proven procedures.

After estimating the influence of different approach speeds on runway capacity for actual flight traffic regarding capacity and controllers' guidance operations, the development objectives of this procedure were

- work with today's traffic patterns and guidance principles,
- to consider future electric and supersonic aircraft with high variable flight and speed characteristics,
- to enable individual approach speeds to reduce fuel flow and $CO_2$ emissions, and
- to minimize capacity loss by different approach speeds at busy airports.

In order to achieve these objectives, Section 2 presents airspace structures and approach procedures that are currently used and implemented internationally, together with their advantages and disadvantages, and describes their applicability under different approach conditions. Section 3 describes the challenges and solutions that make it difficult to use different speed profiles, especially on the final approach. Section 4 presents our concept of the Speed Gated Intercept Procedure, which is specifically tailored to IDOs in order to achieve all of the above objectives. Section 5 defines the baseline scenario, the traffic mix, the considered speed profiles, and separations. Sections 6 and 7 analyze the fast-time simulations of the procedure, once with the separation distances and once with the separation times held constant. The paper concludes with Section 8, where simulation results and limitations are discussed critically, and future activities and applications of the Speed Gated Intercept Procedure are outlined.

## 2. Current Airspace Design and Procedures at Major 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 [10].

The ideal approach procedure keeps the aircraft high, at low thrust, and in a clean aerodynamic configuration for as long as possible [11]. 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 [12], 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 the flight crew, and the need for operational flexibility for 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 at 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 optimal approach procedure of 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 [13]. In case of high traffic, air traffic controllers typically issue a large number of tactical heading-, speed-, and altitude instructions [14]. The average number of clearances of a route system is an indicator of the complexity of an airspace and therefore is used for its complexity calculation [15]. This guidance method is highly flexible and enables controllers to synchronize aircraft behavior through speed and altitude advisories. However, this vectoring procedure results in multiple, instantaneous clearances in comparison to a fixed approach scheme which increases task load and reduces the possibility of pre-plan and configuring the aircraft optimally in advance Another disadvantage is that it is hardly possible for pilots to fly an optimal trajectory and speed profile to the runway threshold in terms of environmental impact and kerosene consumption. 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 the final.

Today, in a number of busy European TMAs, Arrival Management (AMAN) systems have been deployed to support controllers in planning and building arrival sequences [16,17]. These systems are important to utilize the existing capacity optimally and support controllers in building and guiding arrival streams. 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 multiple constraints to consider [18]. 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 densely populated areas, has to be considered. In recent years, a whole series of airspace designs (introduced in detail in Section A below) 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 [19]. Linear programming has also been used to successfully optimize traffic flows in the vicinity of major airports [20]. 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 routes and procedures. However, it has been shown that certain patterns and procedures can be used again and again in slightly different variations.

### *2.1. Commonly Used Airspace Designs and Procedures for Approach Guidance*

The simplest and most frequently used airspace design variants are direct approach routes for low and medium-frequented airports. The benefits of direct routes are the simple design and the easy adaption to different traffic situations, but a direct approach structure is unsuitable in medium and high traffic situations because the implementation of an efficient aircraft staggering for the final is almost impossible. For medium- and high-frequented airports or airports with a parallel runway system arrival routes start in a metering fix and fanned out to virtual points on the final. Overflying the metering fix, the controller clears a heading in the direction of the centerline. As an additional guidance instrument, controllers have the possibility of varying the time when they clear the transition from the base onto the centerline resulting in a different angle of final intersection. An airspace structure using downwind, base leg, and final for the approach procedure is called Trombone which is an efficient way to fit target times and wake vortex separations when aircraft arrive from more than one direction onto the final. Like a zip fastener, aircraft are sorted from both sides on the final at the end of the inbound stream or into a gap if available. During the DME Arc approach, pilots are guided onto a circle, flying on a ring structure around an airport until reaching the final approach path. Here, the Air Traffic Control Officer (ATCO) clears the turn to final. During the segment along the arc, aircraft have to stay at level or descend slightly between cleared waypoints.

The Point Merge System (PMS) from EUROCONTROL is the latest development of approach procedure airspace structures, which are now in operation [13]. 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. The legs are separated vertically and laterally by design. The benefits of Point Merge operations are the creation of space between the aircraft through path stretching with little ATC intervention. EGLL is one of the busiest airports in the world, located with two independent runways 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 [11]. Each stack serves as a waiting room, enabling air traffic controllers to efficiently gather aircraft for landing. Factors such as geographic positions of the stacks, actual traffic volume, noise restrictions, and weather conditions affect how aircraft are sequenced by air traffic controllers to leave the stack and make their way to the final approach [21].

### 2.2. 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.

One crucial point of this study is the observation that already today, there's a significant variance in optimum approach speeds for aircraft flying under Instrument Flight Rules (IFR). For the same aircraft type, final approach speeds can deviate by up to ±20 knots mostly depending on aircraft weight [3]. In this case, optimum means that the best speed profile in terms of stability on final, fuel consumption, and noise emission can deviate by up to ±20 knots from the approach speeds usually flown due to restrictive clearances today. Equal speed profiles mean the best solution both for the controllers' workload and for maintaining minimum separation in order to bring as many aircraft as possible to land as safely as required per time unit. Any deviation in individual speed requires additional separation, which means that low-noise CDAs at busy airports are only possible in the less busy off-peak hours of the day [22]. Consequently, the optimization of other criteria is sacrificed for the throughput of an airport.

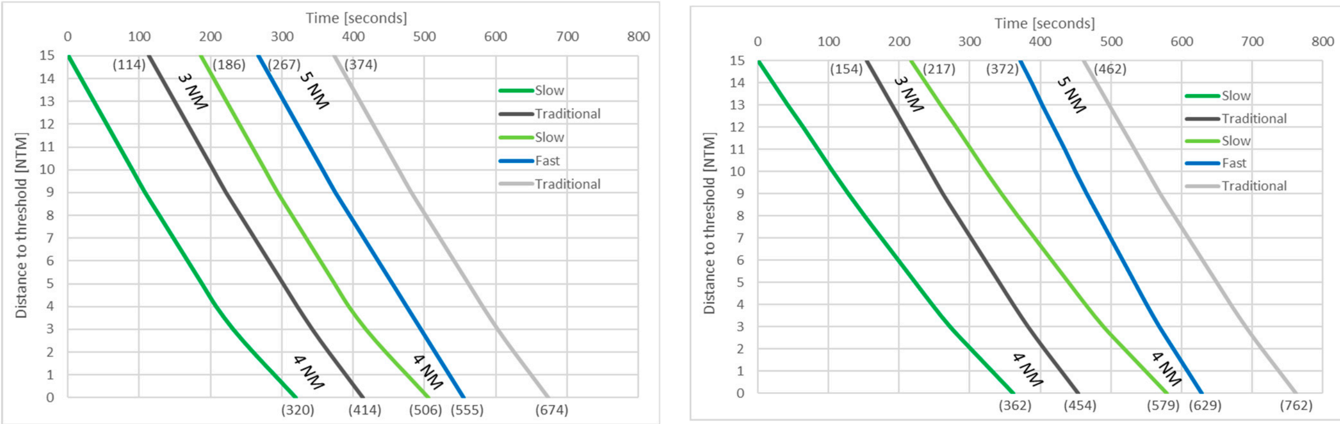
Additionally, this situation will worsen in the coming decade when new aircraft models with completely different flight characteristics for today's conditions come into use [2]. These include supersonic aircraft already under development, which will require significantly higher take-off and landing speeds due to their aerodynamic flight characteristics being similar to those known from the Concord. If these supersonic aircraft are technically capable of approaching an airport at speeds similar to those of an Airbus A320, for example, this will likely not be a configuration that minimizes the emitted aircraft noise.

On the other hand, aircraft with a completely new propulsion system are being developed worldwide that are equipped with electric motors instead of combustion engines [23,24]. Although the weight of batteries to power the engines is currently still a challenge given the size of the aircraft to be built, it is foreseeable that electric aircraft will be in use within a decade, which in turn will have different flight characteristics to those we are used to from today's aircraft. It is assumed that not only the regular cruising speed will be lower than that of today's jet aircraft [24] but also their landing and touchdown speeds will differ This is partly due to different aerodynamic designs for electric aircraft, as well as the challenge that the touchdown weight of electric aircraft will be significantly greater than is the case with today's combustion aircraft, as batteries do not lose weight during discharge as is the case with kerosene tanks, resulting in a higher optimum approach speed and, depending on the choice of high lift devices, a possibly higher final approach speed.

Accordingly, the focus of this work is to enable increased speed differentials in order to fly efficiently and thus more environmentally friendly, and to enable more economical aircraft designs without causing negative effects on the overall arrival capacity of major hub airports.

The objective of the developed and evaluated procedure is to ensure that all arriving aircraft, whether traditional or future, can complete their approach regardless of their individually optimized speed profile, without undue impact on runway capacity. One challenge in implementing this is to provide the air traffic controller with sufficient situational awareness and, consequently, controllability of the situation. This can be solved by focusing on three options for speed profiles. The traditional speed profile (**Traditional**) is formed based on the evaluated average of the approaches of the ADS-B data (see Section 5.1.2). In addition, there is a profile that is faster across the entire range of approach speeds (**Fast**) and one that is slower (**Slow**). Further details on the evaluation and selection of all three speed profiles are provided in Section 5.1.2. At this point, however, it should already be mentioned that for better comprehensibility, the calculations and simulations both follow the use of these three profiles.

The range up to 15 Nautical Track Miles (NTM) (Nautical Track Miles (NTM) represents the distance to the threshold in nautical miles) from the runway threshold and has been identified as particularly interesting for a new procedure because aircraft are following each other here on correlating approach paths. As described in the former subsection, the same speed profiles prevent negative interactions in terms of capacity loss within subsequent aircraft. However, if a broad band of approach speeds is essential due to environmental or economic reasons, additional separation buffers are required for the speed differentials between each pair of aircraft (Figure 1). This applies in particular when aircraft with different speeds move along the same route at the same altitude for a long time. This ultimately drastically reduces the capacity of airports, as the minimum separation must initially be established when flight paths are merged. Particularly in the case of the fast-slow combination, the aircraft flying ahead causes an inefficient gap between the two aircraft after a few miles. Especially if aircraft are allowed to fly an individually optimized approach profile in order to save fuel and reduce aircraft noise as much as possible, our simulations show that, depending on the traffic scenarios, this will result in a significant capacity loss of up to 20% at busy airports as described in the results section.




(**a**) (**b**)

**Figure 1.** The time-space diagram of five randomly selected consecutive aircraft shows the differences in the sequence of today's traffic (**a**), the baseline, and the IDO case assumed for the future (**b**). In both cases (**a**,**b**), the same required separation minima apply. In the IDO case (**b**), however, it can be seen that the curves through various speed profiles increase the maximum spacing throughout the approach. As a result, the entire approach sequence requires a longer time interval for safe operation (in this example: 762 s compared to 674 s). A reduction in possible arrival capacity is the consequence.

In general, the capacity loss due to the introduction of different approach speeds has already been investigated [25,26]. Studies have shown that the loss of capacity is mainly determined by the amount of the speed difference on the same route. In addition, the way in which traffic flows at different speeds are merged and the angle at which they merge have a significant impact on capacity. It can be concluded that a comprehensive study of the actual effects of the introduction of IDO traffic is necessary.

## 4. Solution Concept of Speed-Gated Intercept Procedures

International hubs such as London Heathrow, which have to process a high volume of traffic, work with strict speed limits [27]. These speed limits apply equally to all approaching traffic. However, a considerable proportion of the future traffic participants is anticipated to approach at different relative speeds in between successive pairs of aircraft. This change calls for a different approach to TMA guidance procedures. The wider the range of airspeeds in the approach area, the more the structure and the procedures of air traffic control have to adapt to the new situation. To make this possible, a new approach procedure has been developed that explicitly uses these relative speeds, compares them with the relative speeds of the predecessor and successor aircraft, and uses this analysis to guide aircraft on individual flight paths.

The new approach is based on the principle that different approach speeds only have an impact on capacity as long as the approach paths are correlated or there is a dependency based on separation rules between aircraft with different flight speed profiles. However, if aircraft move independently of each other, there are no negative interactions in terms of separation issues and the speed differences have a neutral effect on capacity. Since the aircraft must always be reunited on a common flight path before landing, this independence is subject to certain limitations. On the last few miles before landing, aircraft require a certain amount of time to stabilize in order to ensure a safe landing. Today, 1000 ft or about 3 NTM are considered the standard for stabilization and will therefore be considered the minimum in this study [28]. To guarantee the location of the IP at 3 NTM or more, the distance of the base leg is situated at 4.5 NM to the threshold.

In a world where speed differences are necessary for environmental and economic reasons, additional separation buffers are required for the speed differentials between each pair of aircraft, which ultimately drastically reduces the capacity of the approach segment. As a result, there is a major risk that aircraft will have to be sent to holding patterns more often during high-traffic periods, which not only wastes time and fuel but also leads to a significant increase in environmental impact caused by $CO_2$ and other air pollutants. In order to mitigate this capacity reduction, our Speed Gated Intercept Procedure (SGIP) guides aircraft pairs on a separated alternate routing, depending on the speed difference, until they reach the Intercept Point (IP) (Figure 2).

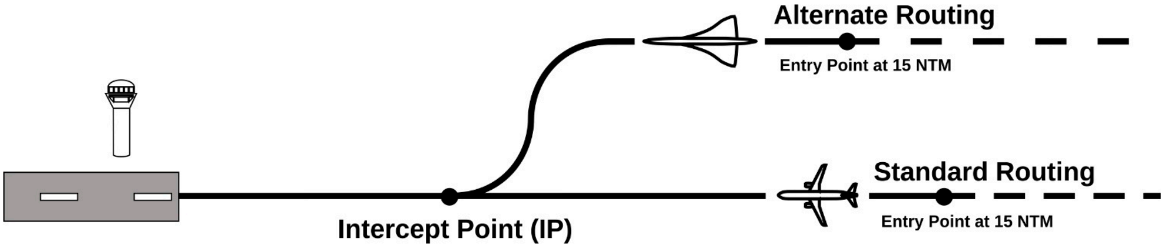
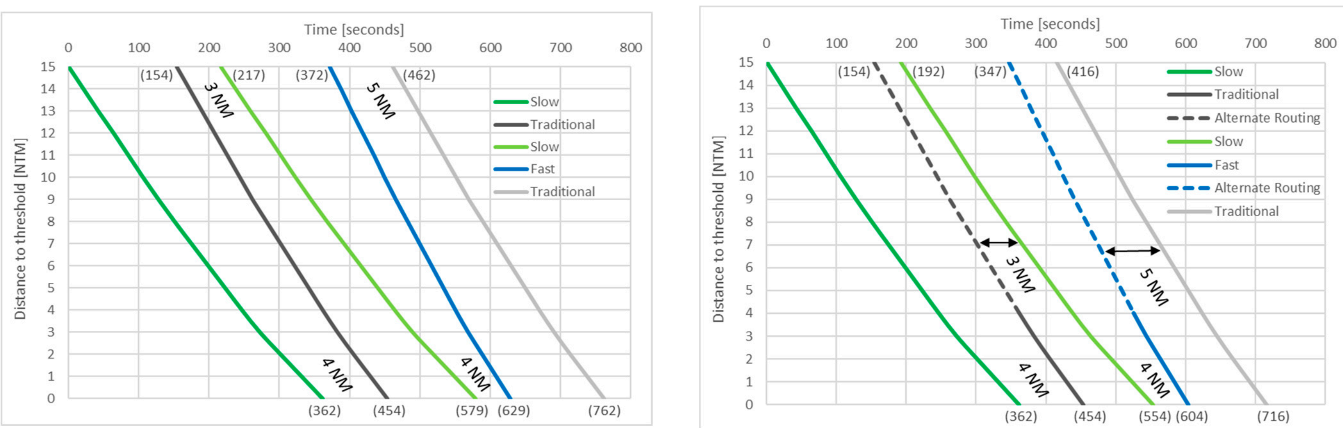



**Figure 2.** Concept drawing of the SGIP. The alternate Routing offers a deemed separated approach path to the standard routing via lateral separation. The concept study starts at an entry point at 15 NTM.

Speed gating considers the speed difference to the potentially conflicting traffic, i.e., to the preceding and following aircraft. With the help of this consideration, it is determined whether the aircraft moves on a separate flight path to the IP or follows the conventional approach path. For example, a faster aircraft, for example, can fly the approach laterally offset on an alternative route to achieve the required separation. The merging of the flight paths is pre-computed and occurs when the necessary separation regulations are fulfilled (Figure 3).




(**a**) (**b**)

**Figure 3.** For the same traffic sequence as in Figure 1, a comparison of the IDO (**a**) and the SGIP case (**b**) is shown in this figure using a time-space diagram. In the second case (**b**), the necessary minimum separation values are only reached later (indicated by the double arrows). In order to nevertheless maintain the necessary separation, the affected aircraft pairings move along separated flight paths. The corresponding portion of the approach on the alternate routing (flown by the faster aircraft of the aircraft pairing) is shown as a dashed line. This exemplary comparison of IDO and SGIP shows how SGIP can reduce the time interval required for traffic scenarios (716 s (**b**) compared to 762 s (**a**)).

SGIP also presents an opportunity to facilitate other scenarios involving significant variations in speed, such as forced landings, environmental phenomena, or the implementation of new, unconventional aircraft designs.

## 5. Methodology

In the context of the investigations on the Microwave Landing System (MLS), the influence of different final approach speeds on the capacity was fundamentally investigated [25]. The capacity investigations are based on these results but extended by variable speed profiles of IDO throughout the entire final approach and specific up-to-date traffic examples. Thus, the capacity study is divided into the following three scenarios:

1. Present demands with traditional speed profiles using present approach procedures;
2. Future demands with Fast, Traditional, and Slow speed profiles using present approach procedures;
3. Future demands with Fast, Traditional, and Slow speed profiles using future Speed Gated Intercept Procedures (SGIP).

In order to determine the resulting runway capacities for a large number of possible combinations, analytical capacity calculations are carried out with a statistical distribution of aircraft combinations. Thus, receiving the capacity of an arithmetically infinite traffic stream. Furthermore, in order to validate the outcomes of the analytical calculations, the introduction of IDO and SGIP is simulated and evaluated in the final step using the BlueSky (Version 20240701) fast-time simulation program [29]. Furthermore, it is of interest to consider the effect of constant separation of time and distance on the outcome of this study. In order to evaluate the effect of constant time, it is recommended that a simulation be conducted using BlueSky. In order to evaluate the effect of constant separation distance, a calculation-based evaluation is performed.

The proposed solution belongs to the class of multi-criteria optimization with numerous possible constraints, and given the uniqueness of airports, it will be necessary to solve the implementation of IDO for each of them. This will ultimately require the development of a new standard and new procedures, and ATC will require new software to support air traffic as seamlessly and safely as today. The complexity and expense of this undertaking are considerable, and this paper proposes a methodology that simplifies the process by selecting a number of constraints. These constraints not only streamline the process but also facilitate analytical calculations and simulations of a particularly dense traffic situation, characterized by constant traffic pressure on the runway. In order to achieve this objective, the approach of EGLL was selected. EGLL is equipped with two independent parallel runways, one of which is primarily designated for arrivals, while the other is allocated for departures.

### *5.1. Constraints*

In order to ensure the validity of the statistical calculations and the simulation, a realistic speed profile determined from the average speed profile of the real traffic scenario is used for both. The basis for the real-life traffic scenario is a ADS-B data package (purchased Flight Radar 24 ADS-B data of the terminal area of London for the timeframe July–September 2019). The analyzed data shows gaps in the approaching traffic that are longer than the required minimum separation, and therefore do not correspond to consistently high traffic pressure. With regard to the comparison of simulated and calculated total approach capacity, a discrepancy can already be assumed due to this circumstance. Despite this, a relative comparison of the calculated and simulated capacities should provide validation. To make this possible, the traffic pressure gaps in the simulation were kept constant and were not used to optimize the capacity, which would have resulted in a distortion of the capacity comparability.

5.1.1. Selecting the Baseline Scenario

The capacity calculations are based on a representative approach speed profile at EGLL for the last 15 NTM. A representative traffic scenario at EGLL was selected for this purpose. The scenario was selected by analyzing ADS-B data. All approach traffic data for the highly frequented summer months of July, August, and September 2019 within the Terminal area of EGLL were screened for a scenario with an average traffic mix, high traffic load, and as little data-distorting weather phenomena as possible. The study will focus on the investigation of approach traffic on a single runway, hence another important factor for the selection of the scenario was a time frame with primarily single-mode operation and no runway change. It is imperative that all possible aircraft pairings occur multiple times within the scenario, as this is fundamental to the study. The relevant weight turbulence categories (WTC) for aircraft using RECAT EU are classes A–D. Of the 16 possible aircraft pairings, those with class A aircraft in particular should be noted due to their low number. Consequently, the designated time frame for the scenario selection must encompass a sufficient number of class A aircraft to facilitate a comprehensive examination of all potential aircraft pairings with the class A aircraft, thereby ensuring sufficient analysis of the effects of different study setups. To this end, four class A aircraft were designated as the minimum requirement.

The ADS-B data was filtered for further selection using the software Rouge (Version 2021-07), resulting in approximately 700 approaches per day with a standard deviation of 22. Subsequently, the data was compared between weeks and individual weekdays according to traffic share and absolute aircraft movements per hour. This revealed insignificant deviations between the individual weeks and also between the weekdays. In particular, the traffic share fluctuates within the RECAT EU WTC throughout the day. During the morning hours, the traffic share of Class A, B, and C aircraft reaches a maximum of up to 100%, after which it experiences erratic and wave-like fluctuations until the end of the day, sometimes reaching 0%. Conversely, the share of Class D aircraft exhibits a reciprocal trend over the course of the day. On average, the data show 3% Class A, 36% Class B and C, and 61% Class D aircraft. The average traffic load prior to 5 UTC is in the low single digits but subsequently exceeds 39 aircraft per hour for the first time after 6 UTC, and remains at this level (with the exception of a midday low between 13 and 15 UTC, with 37–38 aircraft per hour) until around 20 UTC (Figure 4). At peak times, the data shows up to 50 aircraft per hour on individual days. However, it should be noted that these peak levels are only achieved when both runways are operational for approaches.

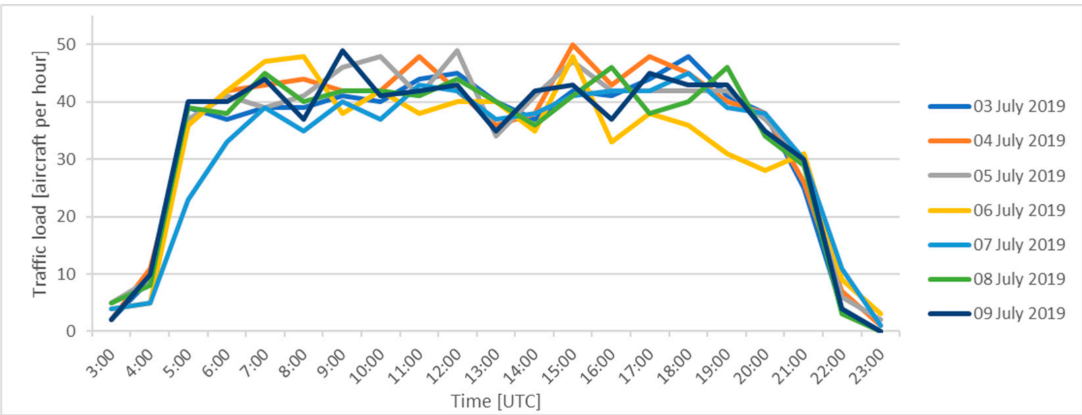



**Figure 4.** Traffic load per hour throughout the week at EGLL.

According to the specification outlined before a timeframe of two hours was selected on 4 July 2019. The time window 12–14 UTC provides an average traffic mix, largely single-mode operation (only two aircraft landing on RWY 09R, all other aircraft landing on RWY 09L), and no runway change.

#### 5.1.2. Speed Profiles

With the speed data from the ADS-B dataset within the time frame of the baseline scenario speed averages were evaluated (see Figure 5). Within the chosen scenario, the ground speed is about 200 kts up to 10 NTM, followed by a reduction and an average ground speed of 180 kts, until a very late reduction to the final approach speed starting at 4 NTM the data of the 64 aircraft within the baseline scenario were further simplified by evaluating speed averages for two sections of the final approach: 15–10 NTM and 10–4 NTM. This simplification is consistent with the speed constraints given by ATC within the last 15 NM (confirmed by the evaluated ADS-B data) [27]. In addition, the effect of partially inaccurate data could be compensated. From 4 NTM until the threshold, the ADS-B data no longer provides reliable data for each aircraft due to their proximity to the ground. However, this is of little relevance for further investigation in the context of the stabilized criteria after 1000 ft above the threshold.

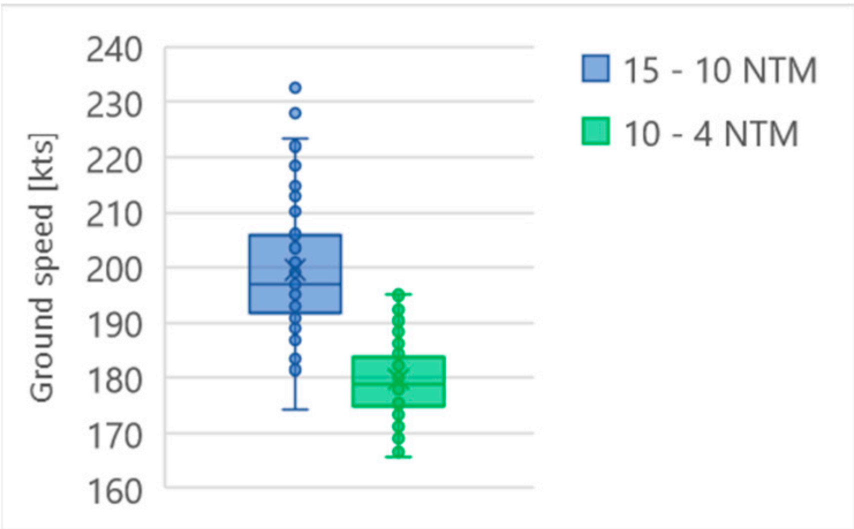
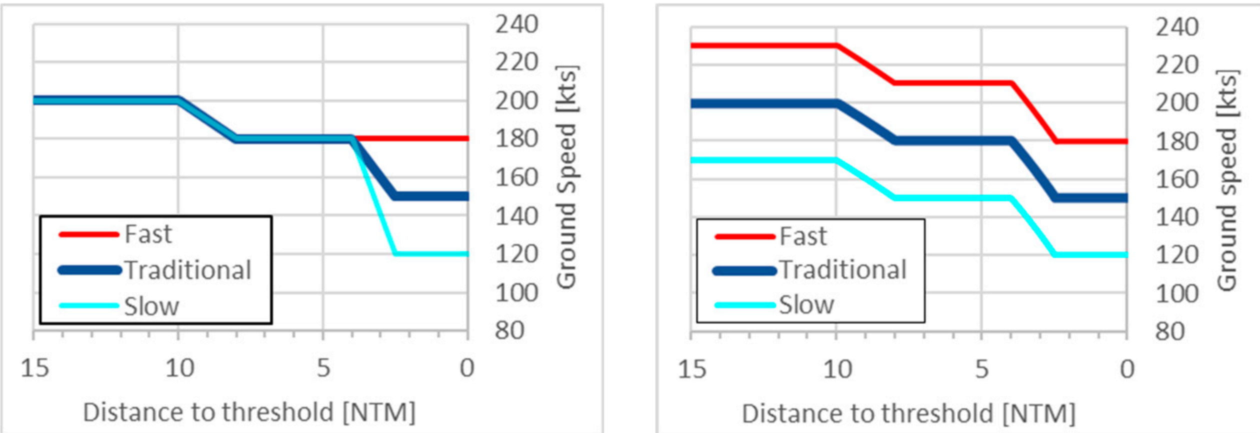



**Figure 5.** Speed data from the ADS-B dataset within the baseline scenario and the resulting average speeds of aircraft between 15–10 NTM and 10–4 NTM.

Distinct speed restrictions were observed during data analysis. However, the final approach speed already varies as expected. Individual speed depending on aircraft type, manufacturer, and landing weight has to be achieved for a safe final approach [30]. This difference in final approach speed within the last few miles to the threshold leads to a difference in time-to-fly (T2F). Since this variance is difficult for the controller to predict, a safety buffer on top of the required minimum separation is added and thus approach capacity is degraded. With the help of distinct speed restrictions, for as long as possible, the difference in T2F can be kept at a minimum causing the necessary buffer to be optimized as well. An example of an airport with strict speed restrictions and low safety buffers is EGLL [3].

In a future IDO scenario, it is assumed that the aircraft fly their individual optimum speed profile during the entire approach. In this case, the uncertainty for the ATCO about the expected speed profile would be drastically increased. In the case of EGLL, the necessary safety buffer is minimized by advising strict speed limits. The introduction of IDO has exactly the opposite effect, which is why the use case at EGLL airport appears so relevant. For this study, the option of selecting two alternate speed schedules is introduced for all scenarios other than the baseline. A proportion of the traffic can fly a Fast or a Slow speed schedule that varies by a predetermined speed difference compared to the Traditional speed schedule used at EGLL today.

For the SGIP scenarios, the arriving flights select one of the three-speed profiles (see Figure 6) and communicate it to the controller, thus keeping the necessary safety buffer as small as possible. By selecting one of the three-speed profiles, the arriving traffic approximates its own optimal speed profile and the controller (or controller support system) has a basis for planning the Time-Based Separation (TBS) via T2F. The aircraft weight determines the optimum speed and thus the optimum speed profile for the approach for a given wing and aircraft design, as the polarity of an aircraft shifts with the aircraft weight [15]. Accordingly, for aircraft with higher weights and the same aerodynamic design, it can be assumed that these aircraft ideally have a higher-than-average approach speed. The same applies to vice versa. The other case of IDO is represented by new designs, such as new supersonic aircraft or electric aircraft. The implementation of novel approach speed schedules has the potential to enhance the viability of these innovative designs, thereby facilitating their real-world deployment.




(a) (b)

**Figure 6.** Fast, Traditional, and Slow speed profiles used for the calculations with 30 kts speed difference (as an example of a speed difference). Within the baseline, all aircraft maintain the same restrictive speed schedule until they have to reduce (or maintain) their speed for final approach speed (**a**). Within all future scenarios (IDO and SGIP) the approach speed is selectable and maintains a constant off-set based on the selected profile throughout the entire last 15 NTM (**b**).

*5.2. Scenarios for Investigations*

Based on the described baseline scenario, an IDO scenario and further scenarios with different traffic merging via an IP will be examined. The IDO scenario is today's approach layout but with the option to fly the Fast or the Slow speed schedule. Furthermore, another five scenarios (Table 1) with various separation options were examined. As illustrated in Table 1, each scenario examines a different speed schedule setup allocation to separate different speed schedule groups via an alternate routing.

**Table 1.** Scenario specifications for separations calculation. Each scenario has procedure design options (specific speed schedules via one or two specific IPs). The IDO scenario and Scenarios 1 through 5 have the three different traffic mix options in addition.

| | Joining via IP 1 | Joining via IP 2 | Speed Schedule |
|---|---|---|---|
| **Baseline** | - | - | Today's EGLL speed schedule |
| **IDO** | - | - | EGLL speed schedule with options Fast and Slow |
| **Scenario 1** | Fast | - | EGLL speed schedule with options Fast and Slow |
| **Scenario 2** | Slow | - | EGLL speed schedule with options Fast and Slow |
| **Scenario 3** | Traditional | - | EGLL speed schedule with options Fast and Slow |
| **Scenario 4** | Fast + Slow | - | EGLL speed schedule with options Fast and Slow |
| **Scenario 5** | Slow | Traditional | EGLL speed schedule with options Fast and Slow |

#### 5.2.1. Traffic Mix

The basis for separation in this study is TBS based on RECAT-EU with 2.5 NM Minimum Radar Separation (MRS). TBS has capacity advantages in strong wind conditions but is by definition the same as Distance-Based Separation (DBS) in low wind conditions [31]. RECAT-EU was in use at EGLL during the time period of the baseline scenario [32]. The observed traffic mix during the baseline scenario time window was 5% Class A, 32% Class B, and 63% Class D aircraft—very close to the assessed average at EGLL throughout July–September 2019 (see Section 5.1.1). Furthermore, previous studies at EGGL confirm this traffic mix [33]. For better comparison, this traffic mix is the reference for all calculations.

The traffic mix according to RECAT EU WTC is the same in each scenario examined. However, depending on the IDO share, the aircraft approach follows one of three different speed schedules. The distribution of IDO traffic among the WTCs is proportionate to the share of the respective WTC. Proportionate because each RECAT EU WTC can contain aircraft-type families with the same aerodynamic lift devices but with very different approach weights.

#### 5.2.2. Spacing Buffer

For the calculations, the spacing buffer is the mean spacing buffer for EGLL just before the threshold with 0.2 NM [3]. The compression effect is considered by time-to-fly calculations [34], thus only the spacing buffer at the threshold has to be considered.

### *5.3. Simulation Setup*

The simulation was conducted on a standard computer using the BlueSky open-source air traffic simulator, incorporating an adjusted OpenAP (BlueSky Version 20240701) performance model [35]. Additionally, BlueSky was extended with a major plugin and six smaller plugins. These extensions were specifically developed to simulate approach traffic and to facilitate both visual and analytical evaluation of the simulation data.

Each simulation run covers a real-time duration of two hours and includes 64 aircraft. The set of aircraft starts the simulation from different directions, entering the final 15 NTM of their approach at varying altitudes and speeds. The simulation is based on real ADS-B data of the baseline scenario. Utilizing BlueSky's fast-time simulation capabilities, each scenario was simulated in approximately four minutes.

## 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 ultimately provides 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 1, 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 [36] and EUROCONTROL guidelines on TBS [31,34].

Another consideration is the temporal decay of wake vortices on which distance separations are generally based. If the separation time of the underlying baseline scenario is maintained, the following aircraft should be exposed to the same wake age compared to that observed in the baseline. From the perspective of this study, a broad bandwidth of disparate approach speeds necessitates a comparison of the principle of constant separation distances as well as times. To compare this consideration with the calculations based on EUROCONTROL equations, a simulation based on constant separation times was performed using BlueSky. Furthermore, this serves to validate the calculations of the mathematical evaluation of constant separation distances.

### 6.1. Separations Calculation

For all aircraft on the same trajectory, RECAT-EU DBS transferred to TBS is valid, and for all other conditions, the minimum lateral separation in the TMA range of 3 NM [37]. The TBS separation is based on the following Equations (1) and (2) [34,36]:

For application at threshold:

$$TBS_{(leader,\ follower)} = T2F_{follower}\left(DBS_{(leader,\ follower)}\right) \tag{1}$$

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

$$TBS_{(leader,\ follower)} = T2F_{follower}\left(DBS_{(leader,\ follower)} + x\right) - T2F_{follower}\ (x) \tag{2}$$

where $DBS_{(leader,follower)}$ is the RECAT-EU DBS and $x$ is the distance between the separation critical point and threshold. The separation critical point is the point at which the aircraft on the same flight path encounters 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 trailing aircraft and accordingly results from the speed profile of the trailing aircraft. The time of minimum separation depends on the speed profiles of the conflicting traffic pairs. There are generally three types: Type 1 represents aircraft pairs within the same speed schedule category. Both aircraft need the same time to cover the 15 NM of the final approach. Type 2 and 3 consist of aircraft pairings with different speed schedules. The leading airplane is faster than the following airplane and hence needs less time for the 15 NM than the following airplane (Type 3) or vice versa (Type 2). Depending on the type, the time of minimum separation in the determined speed profiles is at the beginning or end of the phase with the same flight path. The relative speed of the speed profiles is therefore decisive. Discrete path-time tables are used for all speed profiles to calculate the T2F difference that results in the minimum DBS as defined by RECAT-EU.

The first criterion to maintain the required separation is a lateral separation of 3 NM for all aircraft not moving on the same trajectory [37]. This minimum is a radar minimum and must be maintained for all aircraft that are not vertically separated by more than

1000 ft within the terminal area. The critical area, where an aircraft pair with different speeds within SGIP has the minimum lateral distance from each other, is within the IP area. In order to find out where the airplanes of the aircraft pair are located at the time of minimum lateral separation, a series of considerations and calculations is performed, with all calculations based on standard rate turns of 3 degrees per second and the depicted speed schedules.

In general, there are two different scenarios for minimum lateral separation of aircraft pairs:

Case 1: Slower aircraft joins via IP.
Case 2: Faster aircraft joins via IP.

In the case that the faster aircraft joins via the IP (Case 2—Figure 7), the necessary calculations are different from Case 1. The minimum lateral distance is determined by means of a geometric analysis of the development of the separation. The Equation (3) shows the distance between the planes of the aircraft pair as a function of the intercept angle $\alpha$ and turn radius $r$:

$$d^2(\alpha, r) = \left\{ r * (1 - \sin\alpha) - r * \left(1 - \frac{\pi * \alpha}{180}\right) + 3 \right\}^2 + \{ r * (1 - \cos\alpha) \}^2 \tag{3}$$

Due to the fact that the leader is in the middle of the turn at the moment of minimum lateral separation (Figure 7), thus resulting in constantly changing speed components along the $x$-axis and the $y$-axis, the integration of the $y$-axis component of the movement of the leader is done via a numerical approximation. The solution reveals the angle $\alpha$.

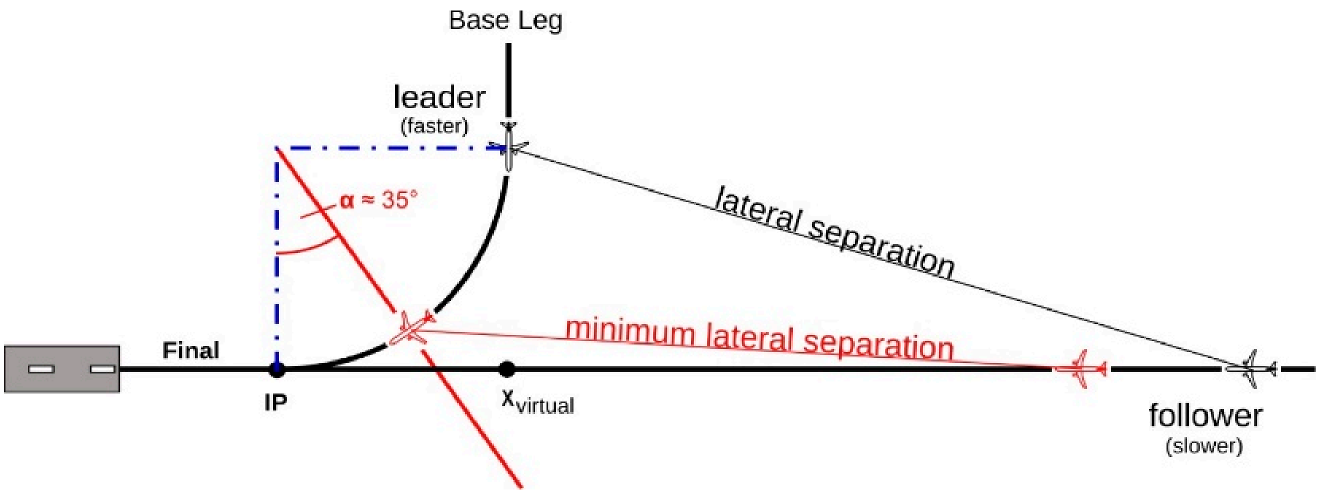



**Figure 7.** Moment of minimum lateral separation for Case 2 and the Fast—Slow aircraft pair.

The geometry of Case 2 is more beneficial for capacity than the geometry of Case 1. The reason for this advantage is the difference between lateral separation distance and distance on track (Figure 8). With the following, slower aircraft flying orthogonally towards the flight path of the leader, the moment of minimum separation is before the follower begins its turn onto the final. The follower is more than the required 3 NM behind the leader. Looking at the separation calculations, the on-track distance between the aircraft pairs is up to 4 NM with realistic approach speeds—an unnecessary separation leading to capacity loss.

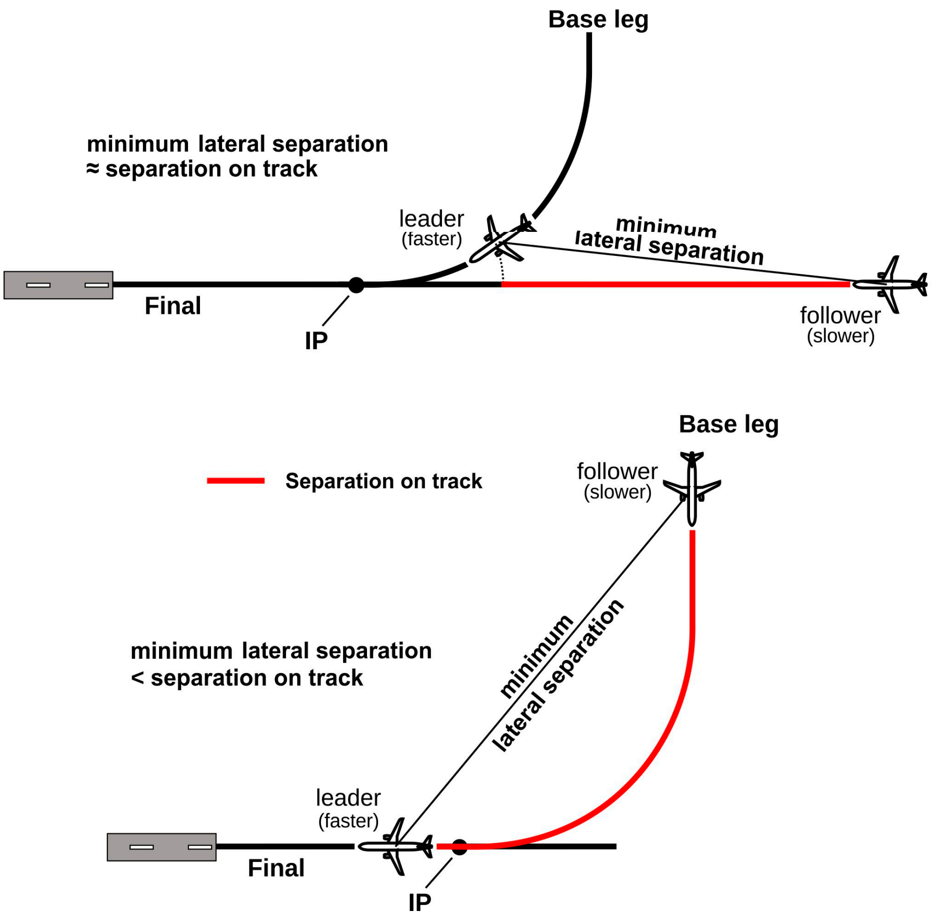



**Figure 8.** Graphic illustration of the geometric advantage of guiding faster aircraft via the IP on final (top of the two figures). Clearly recognizable is the shorter separation on track to obtain the same separation laterally. In the case of the slower aircraft via IP, there is a significantly different geometric constellation at the time of minimum separation.

### *6.2. Results—Constant Separation Distance*

The range of 20–50 kts difference between the speeds of the Traditional speed schedule aircraft and the Fast aircraft with correspondingly higher speed, as well as the Slow aircraft with correspondingly lower speed, is examined. This range was selected because it encompasses the potential range of speed differences observed in contemporary contexts. The upper end of the range examined (40–50 kts speed difference) serves primarily to illustrate the trend as the speed differences increase. 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. This makes the results of the scenario no longer relevant for interpretation. The same difference in key figure speeds exists during the entire last 15 NTM.

The baseline scenario consisting of recorded radar data from EGLL as the basis for comparison allows two comparisons to be made simultaneously. On the one hand, the decrease in approach capacity caused by the introduction of IDO becomes visible (the capacity gap between the dashed lines in Figure 9a–d). On the other hand, the achieved mitigation of capacity caused by the proposed solution scenarios (continues lines in Figure 9a–d).

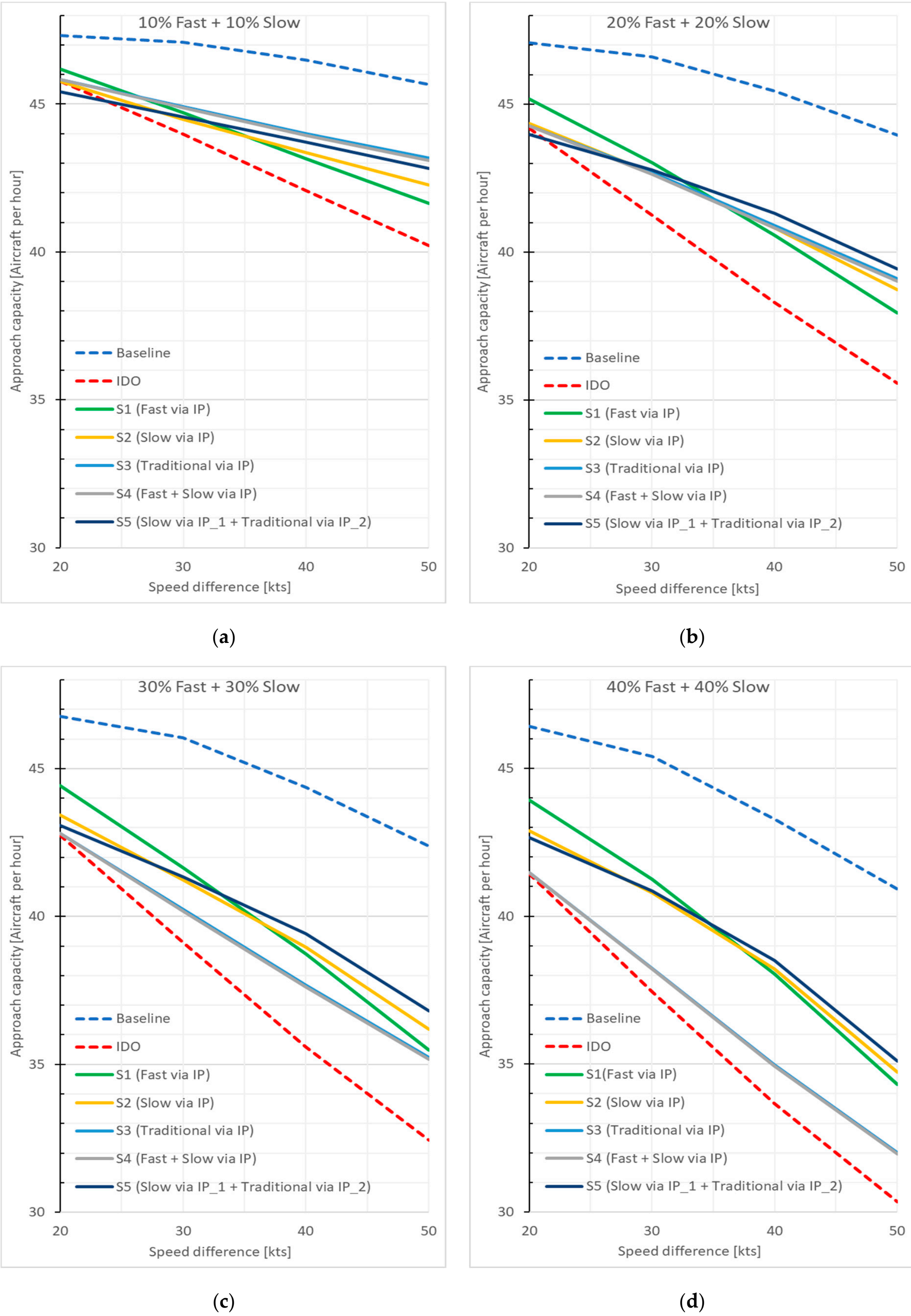



**Figure 9.** Different shares of IDO traffic (20 (**a**)–80% (**d**) IDO traffic) consisting of Fast and Slow speed schedule aircraft in equal parts. The Speed Difference is the difference in speed compared to the traditional speed-scheduled aircraft. With 40% IDO traffic (**b**) the capacity reduction caused by IDO traffic shown by the widening of the gap between baseline and IDO scenario. At 60 percent IDO traffic (**c**), a combination of scenario 1 and scenario 5 begins to show its superiority. With 80% IDO traffic (**d**), this is even more pronounced.

Figure 9a–d shows that the approach capacity is increasingly reduced with increasing speed differences and with increasing proportion of IDO traffic. Starting with 20% IDO traffic (Figure 9a), the approach capacity will be reduced by 2–6 aircraft per hour, within the speed difference range of 20–50 kts. With 80% IDO traffic (Figure 9d), the approach capacity will be reduced by 5–11 aircraft per hour—or up to 25%. The different SGIP concepts under investigation can mitigate up to 55% of the capacity lost due to the introduction of IDO traffic. However, the capacity mitigation changes for different speed differences and for every scenario concept and can even become negative for the wrong scenario concept at distinct traffic mixes and speed differences.

Scenario 1 reveals the best results in mitigating the capacity loss induced by IDO at low-speed differences (Figure 9b–d). The capacity advantage between scenario 1 and the other scenarios reduces to almost zero for a speed difference of more than 27–35 kts. The higher the IDO traffic share the longer the advantage of scenario 1. For higher IDO traffic shares, scenario 1 is still within the range of best-performing scenarios, thus revealing the advantage in terms of the capacity to separate faster traffic as long as possible and also confirming the previously described advantage of integrating fast traffic via an IP (Case 2).

Scenario 2 never shows the best results, but with increasing speed differences or with higher shares of IDO traffic, capacity mitigation becomes increasingly relevant. This shows how important the separation of aircraft with particularly slow speed schedules is. Even if a simple extraction from the general approach path does not lead to the best results, the findings from scenario 2 are remarkable, as they provide indications for optimizing the future approach distribution between traditional and alternative routes. The results of scenarios 1 and 2 essentially show that aircraft flying consecutively on the same flight path with descending speed schedules are highly capacity-reducing. Separating the faster aircraft via the alternate routing (Scenario 1) has a greater effect than separating the slower aircraft (Scenario 2). The magnitude of the effect increases the greater the speed difference and, most importantly, the slower the absolute speed of the trailing aircraft. This means that for traffic combinations with descending speed schedules, it is essential to make use of the alternative flight path in order to optimize capacity.

In scenario 3, Fast and Slow speed schedule aircraft fly throughout the approach on the same track and interact in a negative manner due to their largest possible speed difference. Traditional speed schedules join via the alternate routing. Scenario 4 is the same allocation in terms of speed schedule groups on the same routing, but vice versa in terms of routing allocation. This explains the (almost) same results. The advantages and disadvantages of separating different speed schedules, as well as the geometry during the integration of both traffic streams, equal out.

Scenario 5 is most beneficial for high-speed differences and high IDO traffic shares due to the separation of all speed schedules. On the other hand, due to the disadvantages of the more complex procedure with two IPs scenario 5 has a lower capacity than the IDO scenario, with low-speed differences and low shares of IDO traffic.

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 10) Shares of Fast and Slow traffic with 0–50% underwent investigation. Scenarios 1 and 4 are de facto identical with a 0% share of Slow traffic, which explains the same capacity. Scenario-specific integration of Fast traffic via the IP explains the particularly higher capacity of the two scenarios. The result is stringent with the previous results.

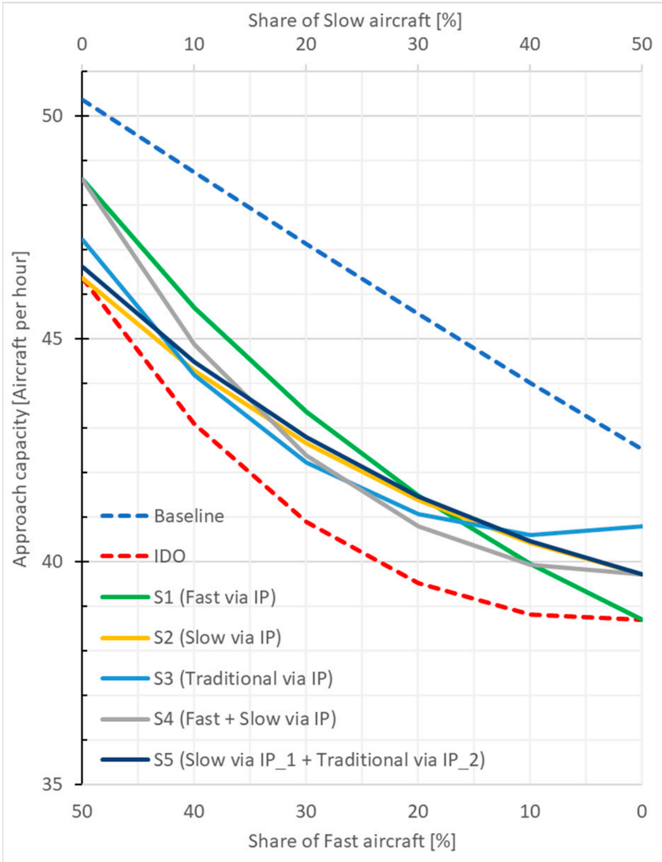



**Figure 10.** Development of capacity with constant 50% share of Traditional speed schedule traffic. Shares of Fast and Slow traffic are changing throughout the graph, representing together 50% of the total traffic. The speed difference between Fast, Traditional, and Slow speed schedules is constant at 30 kts.

The mitigation performance of scenario 3 in the range of 40–50% slow traffic is particularly compelling. In this range, scenario 3 exceeds the capacity of scenarios 2, 4, and 5. The difference resides in the integration of a faster flying leader via the alternate routing. The separation of the higher speed schedule category aircraft from slower aircraft via the alternate routing is the decisive point that results in an advantage.

In addition, scenario 5 displays a solid mitigation performance in only a narrow traffic mix range. The concept of separating all speed schedule groups is only effective if there are sufficient shares of each speed schedule group. Otherwise, the disadvantages predominate once again, demonstrating the fragile advantage of a more complex procedure.

In summary, this analysis highlights that the loss of capacity when integrating IDO is mainly influenced by the average speed of arrival traffic. Accordingly, the integration of Slow traffic reduces the average arrival traffic and thus reduces the capacity. The other capacity influencing factor is the speed bandwidth between Fast and Slow traffic. The steep drop in the capacity curves from 0–20% Slow traffic shows that the combination of Fast and Slow traffic brings a significant negative impact on capacity, due to the even greater speed bandwidth. This is particularly noticeable if you look at the capacity curve from 0 to 20% Fast traffic. In this range, there is only a minor change in total capacity for most scenarios. Instead, in scenario 3, the lower capacity limit is even achieved at 10% Fast traffic. With 0% Fast traffic (only Slow and Traditional traffic) the capacity is slightly higher, even though the share of Slow traffic has increased.

## 7. Evaluation on the Basis Constant Separation Time

After the capacity for constant distances (converted to TBS) has been examined, the capacity for constant time interval separation will be examined in the following. BlueSky is ideally suited for this, as the simulation scenarios are set up based on time. This was done using a case study with EGLL airspace and traffic. In order to be able to correctly reproduce the different speed profiles, intercept procedures on the final, and analyze the data, BlueSky was expanded by seven software modules for the realistic simulation of the measured traffic and for the simulation of SGIP. As a further outcome, the results of the simulation should be used to validate the results of the calculative evaluation of IDO and SGIP in Section 5.

### *7.1. Simulating Baseline*

As the baseline traffic scenario, a day during summer with times when the airport was operating at its capacity limit was chosen. The meteorological boundary conditions were a low-wind and high-pressure situation with no thunderstorms or rain showers and therefore no weather-related anomalies. The qualitative evaluation of the verification method was carried out using the time deviation of the BlueSky simulation compared to reality. In the baseline traffic scenario, it amounted to an average of 1.5 s with a standard deviation of 0.9 s at the runway threshold (Figure 11). This provides a sufficiently accurate representation of reality for IDO integration evaluation and SGIP concept evaluation.

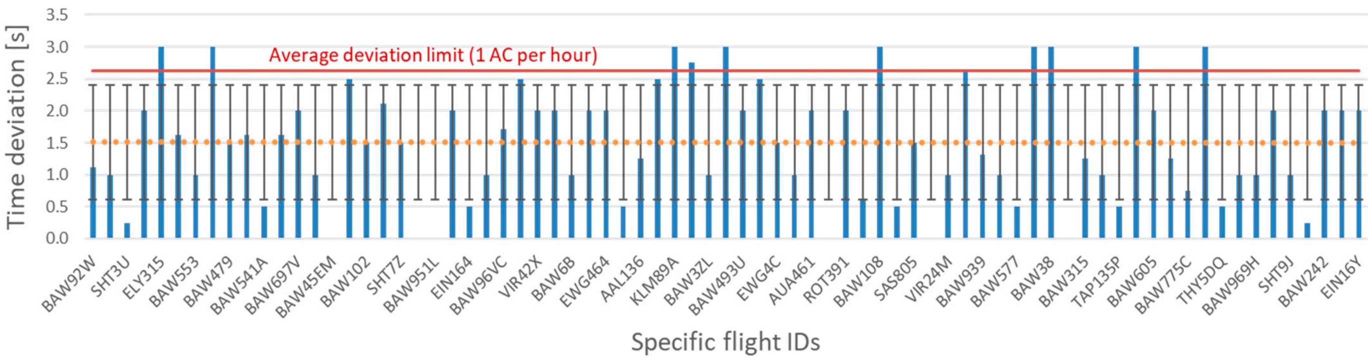



**Figure 11.** The average deviation limit is selected to be one aircraft per hour (red solid line). The average deviation error (dotted orange line) as well as its standard deviation (black vertical extensions) of the selected baseline case study simulated with fast time simulation program BlueSky remain below this limit.

### *7.2. BlueSky Simulation*

To simulate an increasing integration of Fast-only, Slow-only, or Fast and Slow speed schedule traffic, individual aircraft types were successively replaced in the baseline scenario by correspondingly Slow and Fast speed schedule aircraft. Their influence on the hourly capacity of the runway system was simulated by adding only Fast, and only Slow as well as by adding Fast and Slow aircraft at the same time. In order to rule out the possibility that the choice of the replaced aircraft has a decisive influence on capacity, several simulations were carried out with different setups of Fast and/or Slow replacements.

In terms of the speed difference for the BlueSky Simulation and Fast speed schedule, an aircraft was chosen that is 20 kts faster than today's aircraft. The basis for the Fast aircraft template was the Concorde speed schedule (Derived from interviews with former Concorde pilots and original Concorde speed schedule procedures). For the Slow speed schedules, the extreme value of 40 kts speed difference was deliberately chosen in order to test the limits of the speed variants that appear likely. Thus, purposely stretching the range about 10–20 kts than today's already existing speed range [3].

The simulation is based on the approach structure of a real traffic scenario and is therefore different in some respects from the calculation, which is based purely on what is mathematically feasible. The already mentioned gaps in the traffic pressure in the simulation baseline were also maintained for the simulations of the IDO and SGIP scenarios. The baseline has a capacity of about 10 aircraft per hour less than theoretically possible, which means that the unit of measurement is no longer shown as capacity (i.e., the maximum possible), but as approach flow. For the evaluation of the capacity after the integration of IDO traffic with different proportions of IDO traffic, it is expected that this will lead to a parallel shift of the calculated IDO curve by a value of approximately 10.

The maintenance of the time-based intervals between successive aircraft will have two effects that are of critical importance in differentiating the results of the simulation from those of the calculation. In the calculation, the T2F separation between successive aircraft represents the DBS of RECAT-EU. In contrast, maintaining the time-based separation of successive aircraft as the minimum time of separation even with different speed schedules means that the separation for the respective Slow aircraft will be smaller (in terms of DBS) compared to a specific aircraft pair with constant separation distance. Correspondingly, for Fast aircraft, the separation will be larger (in terms of DBS). In the combination of Fast and Slow traffic with similar proportions of traffic mix and speed difference, the differences are sufficiently compensated to ensure comparability in terms of validation. For this reason, the graphs showing the Fast and Slow traffic are the only ones used for validation purposes.

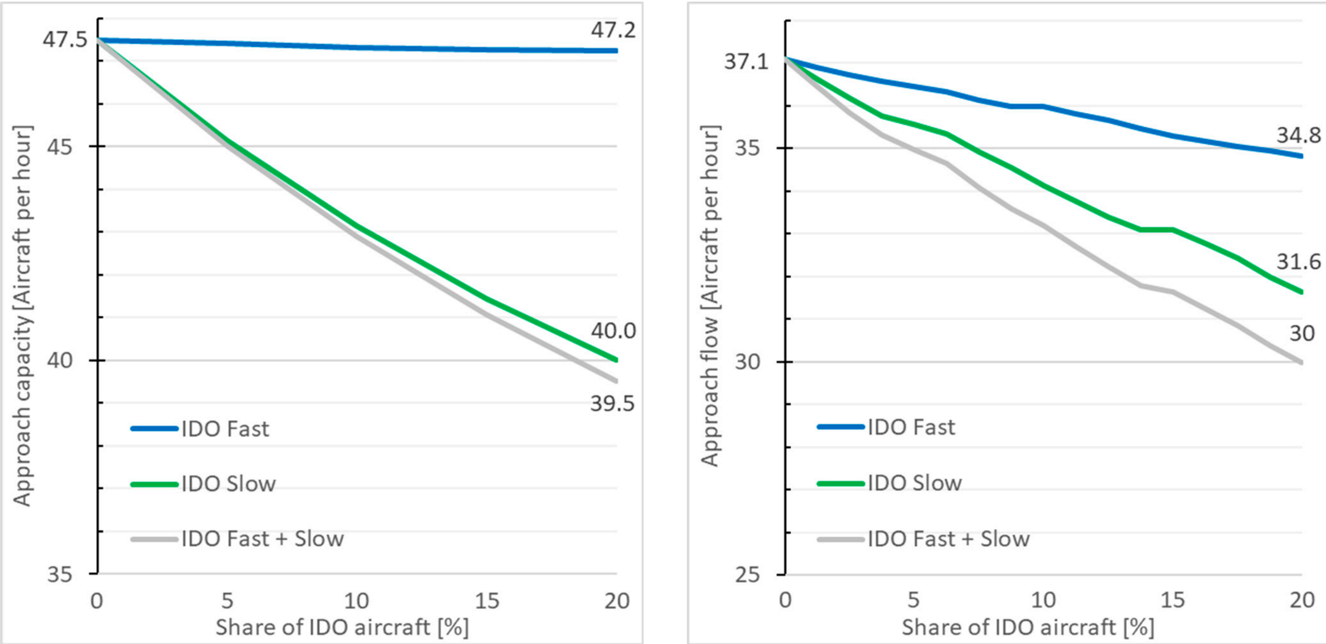
### *7.3. Results—Constant Separation Time*

When examining the results of the simulation in comparison to the theoretical calculation, the assumptions are generally confirmed (Figure 12). When integrating IDO traffic, the capacity reductions for Fast-only and Slow-only speed schedule aircraft are different in the simulation than in the calculation. As described in the last subchapter, this is caused by the fact that it was decided to maintain the time interval of separation for the simulation. However, this led to the required separation being undercut or exceeded. Overall, these effects offset each other and balance each other out in the case of equal speed differences. For the validation, the comparison of the graphs with Fast and Slow traffic is therefore the basis for the validation (grey line in Figure 12a,b).

When considered collectively, the capacity loss resulting from IDO Fast and Slow traffic remains largely consistent in both the calculation and the simulation. For Fast and Slow traffic with 20% each, for example, the calculation and the simulation result in a very similar capacity loss of 8.0 and 7.1 aircraft per hour. In relative terms, these results are comparable, with capacity loss percentages of 17% and 19%.

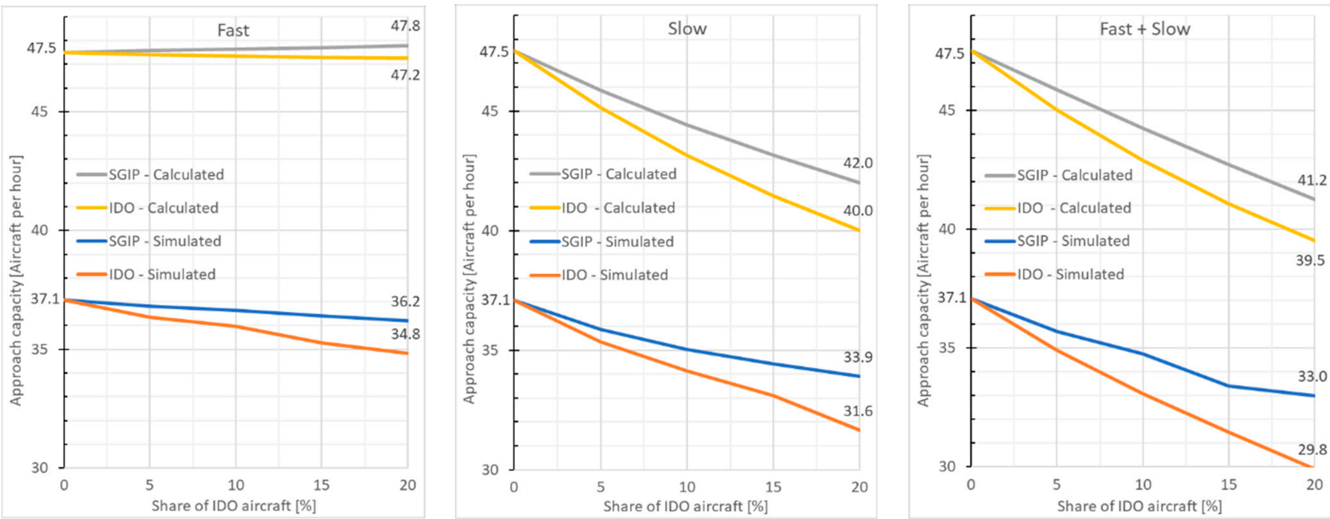
Interestingly, with separation times kept constant, the capacity losses of Fast only and Slow only are converging compared to the calculation with constant distance. Fast only is responsible for more capacity loss and Slow only is no longer responsible for over 90% of the capacity loss (Figure 12a), as was the case in the calculations, but for 73% less approach flow (Figure 12b). Despite the higher approach speed, which is generally conducive to capacity, the Fast speed schedule aircraft contribute to 27% of the approach flow loss (Figure 12b).

A comparison of the SGIP capacity development (Figure 13) of the calculation and simulation shows similar characteristics, again. The scenario setup and deviating constraints have some influence on the SGIP capacity, which must be considered when comparing the results. For example, it is noticeable that the absolute capacity gain through SGIP in the simulation is about 17% greater (Figure 13a) than in the theoretical calculation (at 20% IDO). On the other hand, for Slow traffic (Figure 13b) there is only a 15% higher approach flow gain in the simulation compared to the calculation. Once more, the rationale for this discrepancy can be attributed to the temporal separation, which results in a larger spatial separation for the Fast aircraft in comparison to the calculation. This ultimately has the effect of enhancing the capacity of the SGIP due to the increased spacing of succeeding aircraft when turning into the IP.




(**a**) (**b**)

**Figure 12.** Calculated (**a**) and with BlueSky simulated (**b**) capacity for increasing shares of IDO traffic for Fast aircraft (20 kts speed difference), Slow aircraft (40 kts speed difference), and Fast + Slow. The difference of approximately 10 aircraft per hour between (**a**,**b**) is caused by traffic pressure gaps within the baseline of the simulation.




(**a**) (**b**) (**c**)

**Figure 13.** Approach capacity with increasing shares of (**a**) Fast (20 kts faster), (**b**) Slow (40 kts slower), and (**c**) Fast + Slow traffic. The two upper graphs show the difference between IDO and SGIP scenarios in a calculated optimized environment. The lower two graphs show the difference between IDO and SGIP for a specific scenario, simulated with BlueSky.

In conclusion, the simulation demonstrates that SGIP is an effective method for mitigating the capacity loss caused by IDO traffic. The mitigation achieved is notably higher than that observed in the calculation, which can be attributed to both the simulation setup and the different separation approach with constant temporal spacing. The subsequent chapter will present the findings of this analysis.

## 8. Conclusions 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 the ground at an early stage and at every merge point so that once separations between aircraft have been set, they remain constant as long as possible.

Meanwhile, 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 weight and engines, will require slower approach speeds, especially on the final. 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.

One of the main concerns of this paper is homogenized approach speeds, which are commonly used, but already force many aircraft to operate well outside their optimal approach performance even today. Compared to an ideal approach profile, this results in increased fuel consumption and thus also increased $CO_2$ and $NO_x$ emissions.

The mitigation of IDO loss by our Speed Gated Intercept Procedure (SGIP) concepts studied is up to 55%. 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, some scenarios with good characteristics have been identified.

Regarding the validation of the calculation, the comparison of the results shows that the BlueSky simulation has sufficiently validated the results of the theoretical calculation. In addition, the resulting conclusions from the two evaluations of the constant separation time and the constant separation distance provide a valuable gain in knowledge. The importance of the details regarding the setup and the constraints for the performance of SGIP becomes evident. Furthermore, our calculations and simulations have shown that it could make sense to switch more consistently from the distance-based staggering normally used today to time-based staggering for IDO. For a future traffic mix with predominantly slower aircraft compared to today, this would be an advantageous approach in terms of capacity; conversely, for future traffic with faster aircraft, a time-based approach would be rather disadvantageous.

Fundamentally, the separation of divergent speed schedules is essential for the overall capacity. One example of this is the simulation with a second approach path towards the IP, which resulted in a significant improvement in relative SGIP performance compared to the relative SGIP performance of the calculation. The key findings from the calculated results provide an idea of which aircraft should be separated via an alternate routing and integrated via a late IP. The first key finding shows that integrating faster traffic over IP is better for capacity. The second key finding shows that for traffic combinations with descending speed schedules, it is essential to use the alternate approach path for capacity optimization. The third key finding shows that if there are large speed differences and relatively large groups of traffic participants with different speed profiles, an additional intercept point is useful for optimizing capacity. However, the third finding is heavily dependent on the respective traffic mix constellation and its influence on capacity is not as great as the first two findings.

Together with the conclusions from the validation, this leads to a concept for an optimized SGIP version with adaptive and selective separation control. The rules for the adaptive selection should be kept as simple as possible for implementation in practical use and shall be the next step of development. During the setup for the BlueSky simulations, it already became evident that T2F is difficult to gasp for an air traffic controller. Furthermore, the calculations revealed that new software is needed to support ATC due to the complexity of the expense of this procedure. Therefore, another development goal would be an air traffic controller support system (AMAN) to keep the procedure manageable in its complexity.

Ultimately, further challenges are already emerging in the area of hardware and software for implementing the new procedure on the part of the aircraft, as well as the associated crew training.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| AMAN | Arrival Manager |
| ATC | Air Traffic Control |
| ATCO | Air Traffic Control Officer |
| CDA | Continuous Descent Approach |
| CDO | Continuous Descent Operations |
| $CO_2$ | Carbon Dioxide |
| DBS | Distance Based Separation |
| DLR | German Aerospace Center |
| DME | Distance Measuring Equipment |
| EDDF | Frankfurt Airport, Germany |
| EDDM | Munich Airport, Germany |
| EDDP | Leipzig Airport, Germany |
| EDVE | Braunschweig Airport, Germany |
| EGLC | London City Airport, UK |
| EGLL | London Heathrow Airport, UK |
| EIDW | Dublin Airport, Ireland |
| ENGM | Oslo-Gardermoen Airport, Norway |
| ENZV | Stavanger Airport, Norway |
| FL | Flight Level |
| FMS | Flight Management System |

| | |
|---|---|
| IDO | Increasing Diverse Operations |
| IP | Intercept Point (of the Speed Gated Intercept Procedure) |
| KLAX | Los Angeles Airport, USA |
| KSAF | San Francisco Airport, USA |
| LFLC | Clermont Ferrand Airport, France |
| LFPG | Paris Charles de Gaulle Airport, France |
| LORD | Leading Optimized Runway Delivery (System) |
| MTOW | Maximum Take-off Weight |
| MRS | Minimum Radar Separation |
| NASA | National Aeronautics and Space Administration |
| NM | Nautical Miles |
| NTM | Nautical Track Miles |
| $NO_x$ | Nitrous Oxide |
| PMS | Point Merge System |
| P-RNAV | Precision Area Navigation |
| PSA | Path Stretching Area |
| RECAT-EU | European Wake Turbulence Re-Categorization |
| SGIP | Speed Gated Intercept Procedure |
| STAR | Standard Arrival Route |
| T2F | Time to Fly |
| TBS | Time-Based Separation |
| TMA | Terminal Maneuvering Area |
| UHF | Ultra-High Frequency |
| UTC | Universal Time |
| VHF | Very High Frequency |
| VIDP | Delhi Airport, India |
| XMAN | Extended AMAN |

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