Take-off Support Lights: A Pilot Support System for Super Close Runway Operations (SupeRO)

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***Abstract*—In order to cope with future capacity bottlenecks, the Institute of Flight Guidance of the German Aerospace Center (DLR) is developing the Super Close Runway Operations (SupeRO) concept. In the near term, this concept provides for segregated operation of two very closely spaced parallel lanes, i.e. arrivals on one runway and departures on the other. A precisely timed beginning of the take-off run will support the capacity increasing effects of SupeRO significantly. For this reason, a pilot support system, the so-called Take-off Support Lights, was developed and subsequently validated with airline pilots in the Generic Experimental Cockpit Simulator of the DLR. The trials showed that a large proportion of pilots would prefer the Take-off Support Lights to the current procedure using radiotelephony. Evaluation of the simulator data also supports the use of Take-off Support Lights when operating the SupeRO concept. The times between the transmission of the respective signal for take-off clearance and the subsequent reaction of the pilots in the form of applying thrust could be reduced by an average of up to 77 percent compared to the standard procedure via radiotelephony. In the case of a request to abort the take-off, which can also be signaled by the Take-off Support Lights, the braking reaction times could be improved by an average of up to 27 percent compared to the standard procedure.**

Keywords: take-off support lights; runway capacity; pilot support; take-off procedure.

I. Introduction

Runway capacity has been and will continue to be one of the main bottlenecks in air traffic development. Eurocontrol's Challenges of Growth 2018 study predicted a capacity gap of 1.5 million flights by 2040 [1]. Even the severe drop in air traffic in the wake of the COVID-19 pandemic did not eliminate this problem, but merely postponed it for a few years [2].

For example, the project DIAL2050 from the DLR forecasts for the London airports Heathrow and Gatwick an hourly peak demand which is more than twice as high as the current capacities of these airports [3].

Therefore, an increase in runway capacity is urgently needed.

The two common methods for increasing runway capacity are building new runways or reducing longitudinal separation between runway operations. Building new runways is associated with political and legal problems, particularly due to the need to maintain the required minimum centerline spacing between runways and the associated expansion of airport land use.

Increasing runway capacity by reducing longitudinal separation of aircraft is not technically feasible without limitations at this time. For example, re-categorizing wake-vortex separation has resulted in a 3 to 5 percent increase in runway capacity for arrivals [4]. Due to the aforementioned expected growth of demand in the future, it is apparent that sufficient capacity increases seem currently not possible via a reduction in longitudinal separation alone.

To address this issue, the Institute of Flight Guidance of the German Aerospace Center (DLR) is developing a new concept to increase runway capacity at airports called "Super Close Runway Operations (SupeRO)". In the near term, this concept provides for segregated use of the two runways for arrival and departure. It allows the insertion of a departure between two consecutive arrivals where, under current operational concepts, no further operation would have been possible. For this concept to work, a precise begin of the take-off run of the inserted departures is necessary to achieve the benefits of the concept. In order to assist the pilots of departing flights in achieving a precisely timed beginning of the take-off roll, a prototype pilot support system was developed as part of a master's thesis: the so-called Take-off Support Lights (TSL).

The second section of this paper provides a brief summary of the operation in the near term of the SupeRO concept.

Section 3 presents the newly developed Take-off Support Lights in connection with required procedural changes and explains its working mechanisms.

A series of human-in-the-loop simulator trials is described in Section 4 and its results are presented in Section 5.

The conclusion summarizes the conceptual introduction of the Take-off Support Lights as well as the results of the trials and provides an outlook on possible further developments.

II. Near-term SupeRO

The SupeRO concept is designed to increase the capacity of single runways by adding a second parallel runway lane very close to the existing one. The target for the centerline distance between the two runways is well below 200 meters. This distance is intended to allow the second runway to be inserted into existing airport sites without having to expand the total area of the airport. While in the far-term of the SupeRO concept will provide for simultaneous take-offs and landings on both runways, in the near term the SupeRO concept is using the two runways in a segregated mode. This means that take-offs will take place exclusively on one runway and landings exclusively on the other.

In the near term, the SupeRO concept is intended to reduce the blocking of time for departures caused by the runway occupancy time of the preceding arrival. Whereas in a conventional single-runway system the departure has to wait for the runway occupancy time to clear the runway in front of it, the SupeRO concept allows the departure to start its take-off run as soon as the arrival has landed safely and only has to taxi away. Fig. 1 illustrates this principle. The upper part of the figure shows a single runway. There, it can be seen that the take-off run can only be started after the arrival has left the single runway. The lower part shows the near-term configuration of the SupeRO concept. In this case, the departure can start its take-off run immediately after the arrival has landed safely.

With a strictly sorted supply of the SupeRO runways with alternating departure and arrival, up to 50 percent more operations per hour could already be possible with the near-term configuration of the SupeRO concept compared to a single runway. Reference [5] gives a more detailed description of the SupeRO concept as well as the capacity estimation and the main challenges of the concept.

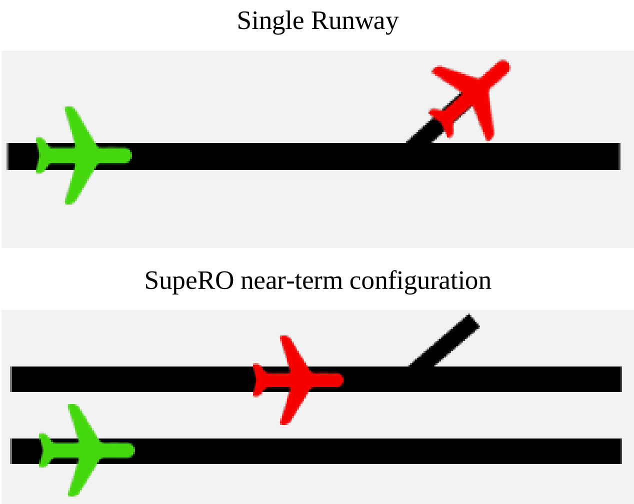

Figure 1: Single Runway (above): Departure (green) has to wait until the arrival (red) has left the runway.
SupeRO near term (below): Departure can begin the take-off roll directly after safe landing of the arrival.

III. TAKE-OFF SUPPORT LIGHTS

In current operations, the take-off clearance is given by the air traffic controller via radiotelephony. The responsibility for the take-off clearance lies completely with the air traffic controller [6]. It is assumed that a couple of seconds expire while the air traffic controller is reading the take-off clearance phraseology with corresponding information about runway identification, wind and potential conditions. In the case of an interference, a repetition of the take-off clearance could become necessary, which needs additional time.

If there is a visual signal, such as the Take-off Support Lights, the departure pilots immediately receive the take-off clearance without noteworthy delay. Thus, the time needed for reading the take-off clearance phraseology can be saved.

The Take-off Support Lights must meet a number of requirements in order to be able to signal pilots the correct moment to take-off as well as a request to abort the take-off, if necessary:

- Lights must be visible along the entire runway
- Lights must be visible even in poor visibility conditions
- The number of lights must be high enough to ensure that a failure of individual lights does not affect the functionality

To meet these requirements, the physical design of the Take-off Support Lights will be oriented to the Take-off Hold Lights and Runway Entry Lights, which are part of the Runway Status Lights developed by the FAA [7]. Another reason for orienting the Take-off Support Lights to the Runway Status Lights is the operational evaluation of the Runway Status Lights released by Eggert et al. [8]. Therein, a pilot acceptance of 92 percent is given for the Runway Entry Lights. Therefore, the Take-off Support Lights will be recessed into the runway in pairs at fixed intervals along the entire runway. This ensures visibility along the entire length of the runway. The distance between the respective pairs of lights should be chosen lower than the lowest visibility at which the SupeRO concept is applied. Thus, at least one pair of lights can always be seen from every position on the runway. The large number of individual lights resulting from this design ensures functionality, thus meeting all requirements. An exemplary design from the pilot's point of view in poor visibility is shown in Fig. 2.

Figure 2: View from the cockpit to the Take-off Support Lights at poor visibility (aircraft model by ToLiss Simulation Solutions Inc.)

The light signals emitted by the Take-off Support Lights are oriented to a classic street traffic light. A red signal prompts pilots to stop or abort the take-off run if it has already begun. A yellow signal indicates an imminent take-off clearance. When the yellow signal is given, the pilots should
begin to slowly run up the engines in order to stabilize them. The duration of the yellow signal must therefore be individually adapted to the respective aircraft. If the duration is too short, pilots could be tempted to take off without stabilizing the

engines sufficiently. A duration that is too long, on the other hand, would keep the engines at a medium RPM level for an unnecessarily long time, which would have a negative economic impact. The yellow signal is ultimately followed by a green signal. This signals that the optimum take-off time has been reached. The pilots should now start the take-off run.

Ideally, the Take-off Support Lights are activated semi-automatically. To do this, the air traffic controller first gives a conditional take-off clearance by radiotelephony to the departure. The phraseology must be changed for this purpose. The phraseology for this conditional take-off clearance could be, for example: "At green TSL, cleared for take-off, at green TSL". In this way, the controller retains responsibility for the actual take-off clearance, but passes the decision on the exact take-off time to the Take-off Support Lights. Following the conditional take-off clearance, the controller arms the Take-off Support Lights by selecting the aircraft involved via a suitable interface and thus initiating a SupeRO departure. This sets the Take-off Support Lights to red.

Take-off Support Lights will also be elements of a future pilot support system. The system will process information such as runway dimensions, centerline distances and current weather information in order to perform a risk analysis, e.g. in the context of a veer-off, and thus calculate a safe separation time between the touchdown of an arrival and the take-off clearance for the departure.

The detection of the arrival touchdown, a go-around or a veer-off can be undertaken by the air traffic controller. The transformation of the detection into a steering information for the Take-off Support Lights will be performed manually via a suitable interface for the air traffic controller. To achieve a higher degree of automation, the development of an automatic detection system that provides the required information to the Take-off Support Lights is recommended.

In the event that Take-off Hold Lights are already installed at an airport, a compatible solution must be found for the simultaneous usage of both systems. Initial considerations in this regard are aimed at a shared use of the lights. For example, the Take-off Hold Lights could have higher priority than the Take-off Support Lights and set the lights to red should the corresponding signal be received.

IV. Simulator Study

In May 2022, a real-time human-in-the-loop simulator study to validate this support system was conducted [9]. The trials were performed in the Generic Experimental Cockpit Simulator at the Institute of Flight Guidance of the German Aerospace Center (DLR). For this purpose, an additional super close departure runway was added to an existing runway scenario of a German airport in the simulation environment and then provided with the Take-off Support Lights. The simulation environment was developed with X-Plane 11 from Laminar Research. An illustration of the super close runway and the associated Take-off Support Lights can be seen in Fig. 3.

A total of seven airline pilots took part in the study trials. The participants are commercial pilots from three different German airlines. The participants' work experience ranged from 1 to 29 years, with an average of 14.7 years. They had completed an average of 6,500 commercial flight hours. Their average age was 41.6 years. These characteristics of the participants are listed in Table I.

Figure 3: Simulation environment with every possible signal from the TSL (aircraft model by ToLiss Simulation Solutions Inc.)

TABLE I. CHARACTERISTICS OF THE PARTICIPANTS

Characteristic	Mean	Min.	Max.
Age	41.6 a	33 a	55 a
Professional experience	14.7 a	1 a	29 a
Commercial flight hours	6,500 h	<500 h	11,000 h

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TABLE II. SCENARIO COMPONENTS

Weather	Take-off Clearance Time	Take-off Clearance Procedure
CAVOK	Early (10 s after line-up)	Standard procedures via radiotelephony
ILS CAT II	Late (20 s after line-up)	Take-off Support Lights
		Take-off Support Lights without yellow phase

Each participant went through two weather scenarios, each with an early and a late take-off clearance time, each with three different take-off clearance procedures. The three procedures consisted of the standard radiotelephony procedure, the Take-off Support Lights procedure and the Take-off Support Lights procedure without a yellow phase. This resulted in twelve trial runs with complete take-off. In addition, take-off aborts were performed under two different weather scenarios, each with two different procedures resulting in four additional runs and a total number of 16 trial runs per participant. Table II shows an overview of the weather scenarios used, the take-off clearance times and the take-off clearance procedures. To keep the focus of the trials on the Take-off Support Lights, no arrivals were simulated in the trials, so for simplicity the separation time in the trials is measured from the end of the line-up and not from the touchdown. The end of the line-up was therefore chosen to ensure that in the same scenarios, all pilots waited the same amount of time for the take-off clearance.

In addition to the participant as pilot flying, two employees of the Institute of Flight Guidance were involved in the trials as pilot monitoring and air traffic controller.

After a few test runs, the pilots went through the 16 trial runs one after the other. Each trial run began with a short taxiing to the runway. For this, the pilots were given line-up clearance via radiotelephony. The taxiing is important in order to give the pilots a realistic feeling for the actual waiting time on the runway.

In the trial runs with standard procedures, take-off clearance was given by radiotelephony after the respective separation times (10 or 20 seconds) had elapsed. In the take-off abortion scenarios, when the aircraft reached a specified speed of 115 knots, the request for take-off abortion was also given to the pilots via radiotelephony.

When the Take-off Support Lights were used, the conditional take-off clearance was transmitted by radiotelephony from the air traffic controller to the pilot during the line-up ("At green TSL, cleared for take-off, at green TSL"). After the line-up, the pilots saw a red signal from the Take-off Support Lights on the runway. In the trials, the Take-off Support Light signals were controlled manually by the air traffic controller in a simplified manner. The duration of the subsequent yellow phase was simplified to five seconds for these trials. Accordingly, the Take-off Support Lights switched to yellow 5 seconds before reaching the respective separation time, i.e. 5 or 15 seconds after the line-up. From this point on, the pilots generally stabilized the engines at 50 percent. At the end of the five-second yellow phase, the Take-off Support Lights switched to the green signal. From that moment on, it was up to the pilots to release the brakes and run the engines to take-off thrust. In the case of a take-off abortion scenario, the Take-off Support Lights switched the signal back to red when the specified speed of 115 knots was reached. The pilots then executed the take-off abortion.

If the Take-off Support Lights were operated without a yellow phase, the yellow phase was simply omitted. In these scenarios, pilots received green signals directly following the red signal at the respective take-off clearance times. The pilots then performed engine stabilization, brake release and take-off thrust in one step. Since take-off abortion is not dependent on the yellow phase, no take-off abortion was performed during these trial runs.

During the trials, selected simulator data were recorded at a frequency of ten hertz, from which the times between the green start signal and the subsequent reaction of the pilot could be determined. This reaction is identified on the basis of applying thrust. Furthermore, the times between the red take-off abortion signal and the subsequent braking reaction of the pilot were measured. This reaction was identified based on the onset of braking power.

V. RESULTS

The simulation data were examined for the reaction times of the pilots to the respective signal. The focus was on the pilot-reaction time and not on the actual take-off time of the departures, since the take-off time depends on the aircraft type, weight, weather and other influences.

Table III shows the average reaction times to the green take-off signal for the trial runs with good visibility (CAVOK). In addition to the absolute values for the respective release procedures, the table also shows the absolute as well as percentage change in the average reaction times when the Take-off Support Lights are used compared to the standard procedure. The table shows that the average reaction times were reduced from between 4.4 and 5.0 seconds for the standard procedure to between 1.0 and 1.8 seconds when the Take-off Support Lights were used. This corresponds to a relative improvement of 59 to 77 percent. Thus, up to more than three quarters of the reaction time can be saved by using Take-off Support Lights.

The reaction times for the trial runs with poor visibility (ILS CAT II) are shown in Table IV. This shows similar values for the standard procedure as for good visibility. These are 4.5 to 5.9 seconds, while the reaction times when using the Take-off Support Lights are 1.5 to 2.0 seconds. The improvement over the standard procedure here is between 56 and 75 percent. This is also similar to the improvements with good visibility. However, it is noticeable that the improvement is higher with late clearance than with early clearance. Nevertheless, even with early clearance, the reaction time is more than halved.

TABLE III. REACTION TIMES AND CHANGES COMPARED TO STANDARD PROCEDURE AT GOOD VISIBILITY

Good visibility	Late clearance	Early clearance
Standard procedure	5.0 s	4.4 s
Take-off Support Lights	1.8 s	1.0 s
Absolute change compared to standard	-3.2 s	-3.4 s
Relative change compared to standard	-64 %	-77 %
Take-off Support Lights without yellow phase	1.8 s	1.8 s
Absolute change compared to standard	-3.2 s	-2.6 s
Relative change compared to standard	-64 %	-59 %

TABLE IV. REACTION TIMES AND CHANGES COMPARED TO STANDARD PROCEDURE AT POOR VISIBILITY

Poor visibility	Late clearance	Early clearance
Standard procedure	5.9 s	4.5 s
Take-off Support Lights	1.6 s	2.0 s
Absolute change compared to standard	-4.3 s	-2.5 s
Relative change compared to standard	-73 %	-56 %
Take-off Support Lights without yellow phase	1.5 s	1.9 s
Absolute change compared to standard	-4.4 s	-2.6 s
Relative change compared to standard	-75 %	-58 %

Finally, Table V shows the braking reaction times of the pilots after they have received a red signal during the take-off run and thus the request to abort the take-off. For the standard procedure, the braking reaction times are considerably shorter than the reaction times after the take-off signal. These also differ only insignificantly, with 1.5 seconds for good visibility and 1.6 seconds for poor visibility. Since the braking reaction times are already very low with the standard procedure, only minor improvements can be expected at this point. This is confirmed by the data in Table V. The braking reaction times when using the Take-off Support Lights are between 1.1 and 1.4 seconds. The relative improvements are 13 to 27 percent.

TABLE V. BRAKING REACTION TIMES AND CHANGES COMPARED TO STANDARD PROCEDURES

Take-off abortion	Good visibility	Poor visibility
Standard procedure	1.5 s	1.6 s
Take-off Support Lights	1.1 s	1.4 s
Absolute change compared to standard	-0.4 s	-0.2 s
Relative change compared to standard	-27 %	-13 %

An open questioning of the pilots showed that six of the seven participants preferred the Take-off Support Lights to the standard procedure. In particular, the use of the Take-off Support Lights during take-off abortion met with great approval. In addition, four of these six pilots preferred the Take-off Support Lights with yellow phase, as they felt better prepared for the actual take-off time by the yellow phase. This means that the pilots are not surprised by a sudden green signal, thus reducing the risk that the pilots will not properly stabilize the engines. The remaining two pilots who opposed a yellow phase cited an inappropriate length of the yellow phase as the reason. This confirms the assumption that the length of the yellow phase must be individually adapted for each aircraft and for each configuration and therefore requires further investigation.

From the questioning of the pilots and the analysis of the simulation data, it further emerges that for the optimal use of the Take-off Support Lights, more detailed definition of the take-off clearance procedure is required. This applies, for example, to the use of the aircraft's brake, as there was uncertainty among the pilots as to when they should release it. However, special situations also need to be defined more precisely. For example, during the trials, the situation occurred where the pilots had already been given the green light, but had not yet received conditional take-off clearance from the air traffic controller. Another possible special situation could occur when there is a discrepancy between the signal displayed by the Take-off Support Lights and the announcement by the air traffic controller. Clear rules still need to be developed for these cases. Another aspect pointed out by the pilots is the usability of the Take-off Support Lights outside the SupeRO context. For example, they could initially be used as additional information to the controller's announcements for conventional take-off clearances.

VI. Conclusion and Outlook

The SupeRO concept is under development in order to solve the predicted runway capacity challenges of the future. The near-term part of this concept provides for segregated use of the runways for take-off and landing. Successful operation of this near-term part requires a precisely timed start of the take-off run of the departures, which is inserted between two arrivals in direct succession.

In order to assist the departure pilots in starting the take-off run at the correct time, the Take-off Support Lights were developed. These are pairs of lights, similar in design to the Take-off Hold Lights, which are set into the surface of the entire departure runway at fixed intervals along its length. They signal the pilots with a red signal that the aircraft must hold or, if necessary, abort the take-off run if it has already begun. A yellow signal indicates that take-off is imminent and prompts the pilots to stabilize the engines. Finally, a green signal indicates the final take-off time.

A series of trials with seven participants in the Generic Experimental Cockpit Simulator at the Institute of Flight Guidance showed that the Take-off Support Lights serve their purpose. Most pilots would prefer a take-off with Take-off Support Lights to a current standard take-off. The evaluation of the respective pilot reactions also speaks in favor of the use of Take-off Support Lights. In all trial scenarios, the improvement in take-off reaction times averaged at least 56 percent. Maximum improvements of 75 percent on average were achieved. During take-off abortion, the comparatively fast reaction times already achieved with the standard procedure were improved by an average of at least 13 percent and a maximum of 27 percent. The Take-off Support Lights are therefore able to ensure a precisely timed beginning of the take-off run of the departing aircraft, which is necessary for the near-term SupeRO concept.

The next steps will initially involve specifying the take-off process, which has been modified compared with the standard procedure, especially for specific situations. Furthermore, the development of an automatic touchdown as well as a veer-off and go-around detection system is an option for a higher degree of automation, with which the pilot support system is automatically informed about the status of the arrival and can thus independently determine the take-off clearance time and, if necessary, request a take-off abortion from the departure.

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