

Assessment of Segmented Standard Taxi Route Procedure to Integrate Remotely Piloted Aircraft Systems at Civil Airports using Fast-Time Simulations

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Abstract— The introduction of unmanned aircraft systems into various domains of civil aviation led to the necessity to develop suitable integration concepts to coordinate flight movements of manned and unmanned aircraft especially regarding surface operations at civil airports. These remotely piloted or automatic / autonomous unmanned aircraft do not have the same capabilities as manned aircraft. However, to achieve a wide commercial success, they will have to use the same infrastructure. Air traffic control has to maintain a safe, orderly and expeditious flow of air traffic, considering this new mixed traffic constellation. In order to do so, new operational procedures were defined. Within the scope of the SESAR 2020 project 'Surface Management Operations' (SuMO), a procedural concept for ground movements of unmanned aircraft together with manned aircraft has been developed and evaluated in gaming sessions. This concept introduces so-called segmented standard taxi routes as a first and easy solution to enable mixed traffic while maintaining the same level of safety and very low system requirements for unmanned aircraft systems. In 2017, this concept was successfully validated in a dedicated workshop with operational experts, air traffic controller, remote and conventional pilots. The results of this evaluation have been published at the 37th Digital Avionics Systems Conference in September 2018. Based on this success, a fast-time simulation has been conducted in the beginning of 2019 to investigate quantitatively the operational performance of this solution in terms of the key performance areas capacity, efficiency and environmental impact. According to project objectives, the simulation scenarios were set up using as example the international airport of Stuttgart. Towing operations were used as a baseline scenario for RPAS ground movements. Selected performance parameters were then compared with those being calculated for the application of the segmented standard taxi route procedure in the solution scenario. The share of remotely piloted aircraft systems varied between 0% and 50% of the whole traffic. This paper provides a detailed description of the setup of this fast-time simulation, conducted simulation runs, defined metrics and results. In addition, these results are correlated with the recently published outcomes of the validation workshop of 2017. The paper closes with a summary and an outlook.

Keywords— *unmanned aircraft systems; airport operations; integration; segmented standard taxi routes, fast time simulations, operational towing*

I. INTRODUCTION

A. Background

Although larger unmanned aircraft systems are operational and used for military purposes since decades [1], their civil use is still subject to research and development. The commercial interest in unmanned air transport with remotely piloted aircraft systems is high as it promises several advantages against manned air transport, like more flexibility in the use of personnel resources, higher payload capacity and no more operational limitations brought about by an on-board flight crew like restricted flight endurance or maneuverability. However, when commercial unmanned air transport is going to be introduced it will most likely have to use the existing ground infrastructure together with manned passenger and cargo flights to avoid additional infrastructure costs and an inefficient use of available aerodrome capacity. This immediately leads to the necessity for an integration concept of remotely piloted or maybe even automatic aircraft systems into the existing aerodrome traffic.

B. Related works

In the frame of the SESAR project PJ03a "Surface Movement Operations" (SuMO) a detailed integration concept has already been developed and published on the Digital Avionics System Conference in 2018 [2]. This concept foresees the use of so called segmented standard taxi routes (SSTR) for ground movements of unmanned aircraft while the guidance and ground movement procedures of all other conventional traffic remain basically unchanged. With SSTR there are fixed and published taxi routes for RPAS with mandatory stop points and can only be passed if air traffic control (ATC) gives a "go". This way, the allocation of a taxi clearance and the interaction of the unmanned aircraft system with ATC is very much simplified, but still offers sufficient possibilities to control all traffic – manned and unmanned – and enables ATC to guarantee safety and de-conflict the ground movements. In addition, this procedure implies very low system requirements to the unmanned aircraft, e.g. a detect-and-avoid system is not required. Further, the concept is very deterministic to allow a high degree of automation and offers a safety net in case of a contingency situation, e.g. loss of C2 link. In practice, this procedure has similarities with the dynamic virtual block control procedure [3], but the main difference is that taxi routes are fixed for unmanned aircraft while all other flights



are guided with conventional taxi procedures at the same time. More details regarding the segmented standard taxi route procedure are provided in section II.

The segmented standard taxi route procedure has already been validated in a dedicated gaming workshop performed in November 2017 at DLR premises in Cologne, together with 2 airliner pilots, 2 pilots of the remotely piloted aircraft system "Heron" from the German Air Force, one civil tower controller, one military tower controller and one ATC expert from the German Air Navigation Service Provider DFS. Different traffic situations have been 'played' through using the airport topology of Stuttgart (EDDS) as operational environment. Hereby, the segmented standard taxi route concept has been compared against full RPAS segregation on ground (designated as Baseline I) and RPAS towing operations (designated as Baseline II). This activity was a V1 validation according to E-OCVM [4] whose main results have already been published [2].

C. Motivation

The main outcome of the Cologne workshop was that the segmented standard taxi route concept seems to be feasible and realistic. The Baseline I scenario (=full RPAS segregation) was rated the worst while the Baseline II scenario (=RPAS towing operations) and the segmented standard taxi route scenario was almost equally rated, considering the Key Performance Areas (KPA)s safety, access and equity, interoperability and human performance. One conclusion was that both seem to be realistic options while the segmented standard taxi route solution sometimes has advantages against baseline II and vice versa, e.g. in terms of needed aerodrome resources. Therefore, it was recommended and considered promising by the V1 workshop expert team to further investigate the segmented standard taxi route concept with additional KPA)s. This recommendation has been followed and led to the next validation activity in the first half of 2019, this time as V2 validation stage. For this reason, a fast-time simulation has been set up with Simmod PRO! to investigate the quantitative operational performance of the Baseline II and the segmented standard taxi route concept in terms of aerodrome capacity, efficiency and environment and additional indicators like the usage of aerodrome resources. Further details on the simulation setup and V2 validation campaign are provided in section III. The results and the conclusions are provided in section IV with a summary and an outlook to future work in section V.

II. OPERATIONAL CONCEPT OF SEGMENTED STANDARD TAXI ROUTES

Within this section, more detailed information are provided regarding the segmented standard taxi route concept to enable ground movements of unmanned aircraft at an aerodrome surface, together with conventional manned aircraft.

This concept seeks for a first-and-easy integration of RPAS into controlled aerodrome ground traffic and involves the following items:

- All remotely piloted aircraft (RPA) are only allowed to taxi along standard taxi routes which are defined and published for every Runway - Parking Spot Pairing.
- These standard routes are segmented by implementing mandatory holding points at taxiway hotspots or before crossing a runway.
- These segmented standard taxi routes are designed according to the one-way-principle where possible.
- ATC issues clearances separately for every segment in the form of a "go"-command (routing and stop points are standardized and published).
- ATC issues this "go"-command for one segment when it is ensured that it is clear and will remain clear of other traffic (manned and unmanned).
- ATC ensures that only one RPA is using the same route segment at the same time
- The rule is: no unmanned behind manned; manned behind unmanned ok
- The RPA has to stop at a mandatory holding point except it already received the "go"-command for the next segment.
- The way of transmitting this "go"-command is not further specified as this is not relevant for the concept itself. Due to the simple and very short message content, even a message of the size of 1 bit is sufficient.
- Segmented standard taxi routes are checked by ground personnel regularly as it is done today to ensure a safe use avoiding the need of appropriate on-board sensors.
- The navigational performance of the RPA (without specifying the concrete method of navigation on ground) must fit to the taxiway / runway dimensions.
- The RPA should be marked with a special color scheme to enable controllers and pilots to identify it as an RPA on the first look.
- In case of contingency, the RPA should show red flashing lights or any other visual warning signal to indicate the situation and to alert other aerodrome users and the tower controllers (especially in case the remote pilot isn't able to communicate the situation).
- If the runway exits assigned for RPA arrivals are occupied by another preceding RPA, the RPA has to fly a missed approach maneuver.

It is expected that the collision avoidance task for ground movements is taken over by ATC similar to the dynamic virtual block control concept [3]. Due to the very definite procedure, a high level of automation on board of the RPA is thinkable. Further, this procedure should be very transparent and predictable to other aerodrome users and to ATC.

Finally, it introduces additional safety in case of contingency situations such as a loss of pilot-ATC-communication as the RPA or C2 link loss will in any case stop taxiing at the next mandatory holding point at the latest [2]. In any contingency the RPA will be towed back to the parking position if there is not a recovery in a specific timeframe (to be configurable). Therefore contingency situations are handled by 'going back' to the baseline situation.

III. SIMULATION SETUP

For this V2 validation exercise the objective is the further evaluation of the mentioned concept of segmented standard taxi routes. The V2 Validation Exercise was a set of fast time simulation scenarios modelling Stuttgart Airport. Simulation runs were conducted with the ‘Simmod PRO!’ fast time simulation tool available at DLR Braunschweig. ‘Simmod PRO!’ which was developed back since 1997 with its true rules-based modelling capability is very flexible for different concept applications. User-defined rules to control each step of the flight and the enabling of dynamic decision making is one of the assets of this tool. This is done through a generalized simulation scripting language and the possibility to define user- and application specific rules [5]. This ability allows the modelling of e.g. advanced operating concepts like segmented standard taxi routes or dedicated RPAS towing. Because ‘Simmod PRO!’ is a fast time simulation tool, it can simulate thousands of flights in one minute.

The primary focus of this V2 validation was the operational performance of the segmented standard taxi route procedure,

especially the impact on aerodrome capacity, efficiency and environmental sustainability in comparison to RPAS towing operations referred to as baseline scenario and the pure manned reference scenario. Concerning contingency or non-nominal situations (C2 link loss and loss of communication) the fall-back procedure is the baseline (see section II).

A. Airport

To build upon and continue the investigation of the previous V1 validation activities of 2017, again the topology of Stuttgart Airport (EDDS) was chosen as operational environment, see Fig. 1. Summarized, this is an airport with a single runway and a non-complex surface layout (cf. [6]). This airport already surpasses the airport class targeted in the V2 validation activity in the SuMO project in terms of network function and traffic composition. However, this does not negatively affect the applicability of results for smaller airports. The departure and arrival routes for SSTR are shown in Fig. 1 for runway direction 25 and in Fig. 2 for runway direction 07.

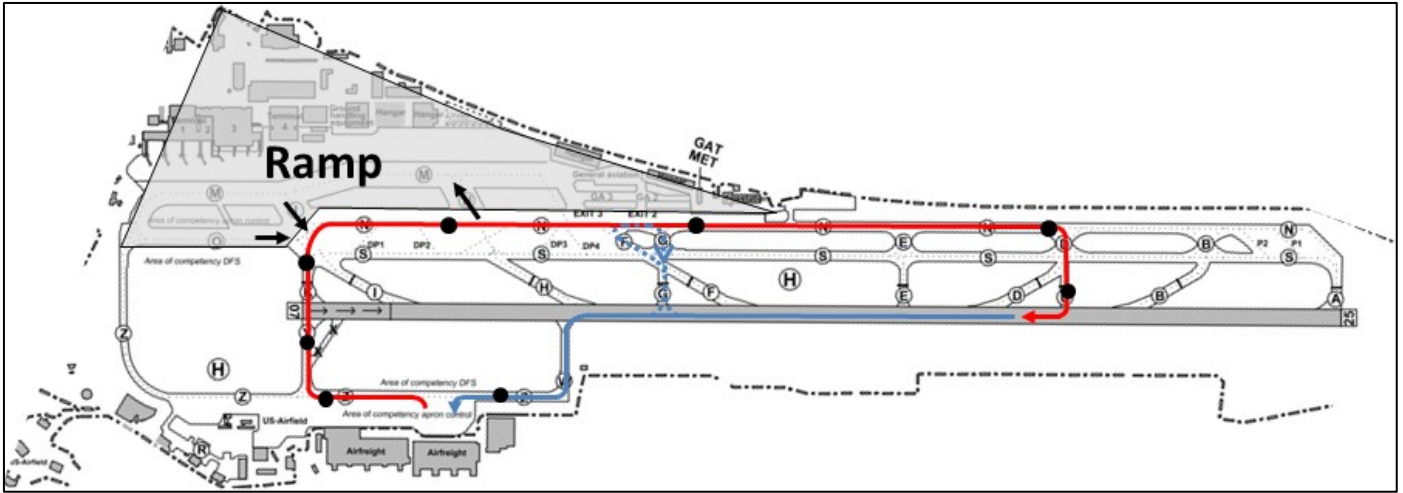


Fig. 1: Stuttgart International Airport with the SSTR departure procedure (red) and the SSTR arrival procedure (blue) for runway 25 starting from and arriving in the southern ramp and the mandatory holding points, arrival taxi route diversions are blue dotted, based and adapted from [7]

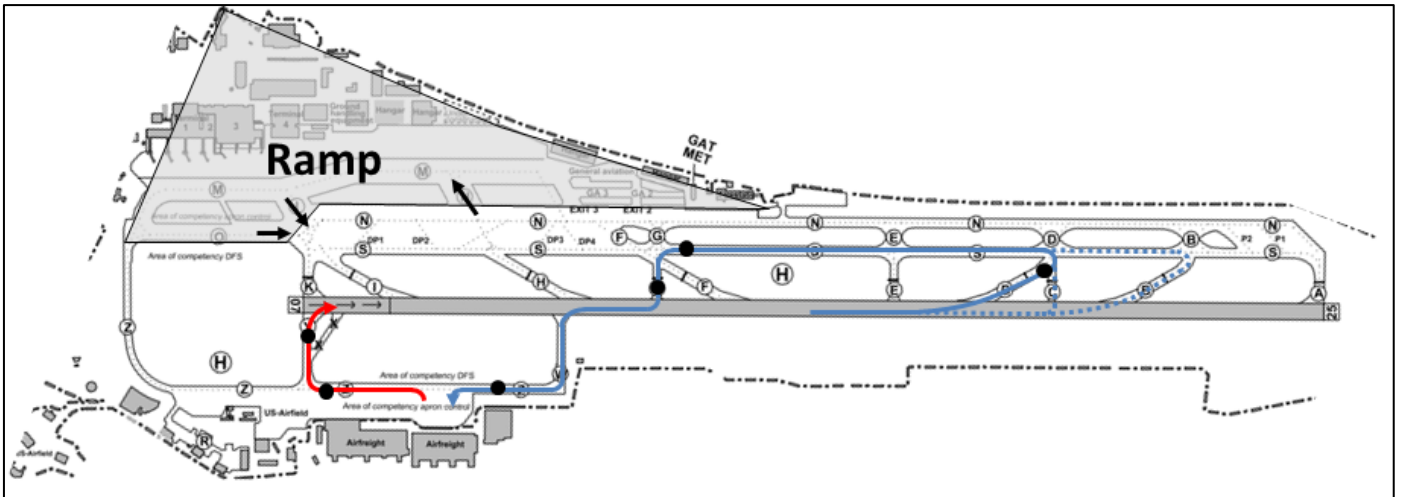


Fig. 2: Stuttgart International Airport with the SSTR departure procedure (red) and the SSTR arrival procedure (blue) for runway 07 starting from and arriving in the southern ramp and the mandatory holding points, arrival taxi route diversions for towing operations are blue dotted, based and adapted from [7]

The ramp area in the northwestern part of the airport was not fully modelled for the simulation scenarios. Stand allocation and gate conflict issues were modelled with the rule of one aircraft per stand. To simplify the modelling the it was only defined as an area where arrivals enter and departures leave the ramp.

B. Traffic scenarios

Several traffic scenarios with a different share of unmanned aircraft have been developed based on real operational traffic data of November 1st 2018 departing from or arriving at Stuttgart Airport. Data was extracted from EUROCONTROL's Demand Data Repository (DDR2) including 4D trajectory information for the recorded flights. The derived traffic scenarios are:

- 0% RPAS share (pure manned traffic - no application of RPAS towing operations or segmented standard taxi route concept) also called 'reference',
- 10% RPAS share, used in both RPAS towing operations (baseline) and segmented standard taxi route (solution) simulations,
- 25% RPAS share, used in both RPAS towing operations (baseline) and segmented standard taxi route (solution) simulations,
- 50% RPAS share, used in both RPAS towing operations (baseline) and segmented standard taxi route (solution) simulations.

In order to create the RPAS traffic share, the number of RPAS flights, based on the share and the total amount of flights, were evenly distributed by 'Simmod PRO!' by simply replacing existing manned flights. All RPAS flights were operating from Stuttgart's Cargo Area South. The reference scenario has no RPAS traffic and contains pure manned aircraft movements as it is the case nowadays.

The baseline scenario consisted of RPAS towing operations. These aircraft were towed from their parking position to the runway holding point of the departure runway and from the runway holding point of their landing runway (after having vacated it) to the parking position by ground supporting equipment or towing vehicles referred now as "tugs". For the simulation, the routes those tugs use were fixed for simplification. When ATC clears the tug to tow the aircraft to their runway holding positions the towing process was considered as a taxiing aircraft with its own detect and avoid capability (DAA).

The solution scenario consisted of remotely piloted aircraft that followed the procedure of segmented standard taxi routes performing stops at mandatory holding points.

For a whole day of traffic (typically incl. peak and off-peak traffic situations) different traffic situations are to be investigated. Under nominal traffic conditions without contingency, two different runway directions, westbound operations (runway in use 25) and eastbound operations (runway in use 07), were analyzed with different shares of RPAS traffic, see also Table 1, where the "X" denotes one conducted simulation run.

TABLE 1: Simulation matrix for nominal traffic situations

RWY Mode	Reference	Baseline				Solution		
	0%	10%	25%	50%	10%	25%	50%	
25	X	X	X	X	X	X	X	
07	X	X	X	X	X	X	X	

The results are analyzed for both runway operation modes separately because of the different complexity of departure and arrival taxi routes.

C. Further Assumptions

For the validation activity the following assumptions were made.

1) RPAS Category and Performance

All RPAS were defined to be of EASA "Certified Category" [8]. In addition, they have been considered class V and VI of EUROCONTROL's classification [9]. RPAS performances were assumed to comply with air traffic rules and airport use and to be similar to those of comparable commercial manned aircraft.

2) Communication and contingencies

Data link was assumed to be available to enable clearance transmission between ATC and the RPAS. The communication between ATC and tug driver and between tug driver and remote pilot was assumed to be functional all the time. When investigating non-nominal conditions, the focus was on the implications when experiencing a loss of communication between remote pilot (RP) and ATC to reduce the complexity of the implementation of the contingency use cases.

3) Towing operations

Tugs were assumed to be able to turn around on the taxiway if there is no RPA attached to them (after detaching the RPA and before attaching the RPA). Tugs were also assumed to be able to hook up the RPA independently from the RP, for instance in case of a C2 link loss. The time required to attach or detach the RPAS is assumed to take three minutes.

4) Ground Movement

For modelling purposes a set of predefined towing routes was applied to the fast time simulation. The modelling of ATC guidance was required to facilitate towing operations based on the traffic situation, which was done by using existing ATC techniques of 'Simmod PRO!' (collision avoidance by enforcing rules of separation). Aircraft having vacated the runway may block their exit in case they have to wait for a tug (Baseline or Contingency) or the subsequent taxi route segment to become available (Solution). A succeeding RPA would have to use an alternative runway exit or if also occupied have to follow a missed approach procedure (modelled as a simplified traffic pattern). Based on the items denoted in section II standard runway exits were defined for each runway direction dedicated to be used by RPA (blue lines of Fig. 1 and Fig. 2). The limitation of one runway exit per runway direction available for RPA carries a risk to increase the number of missed approaches. Due to the characteristics of the SSTR procedure there is kind of an imbalance in the operations of the runway directions. Using runway 25 even the second approaching RPA would have to go around in case

there is congestion in the southern cargo ramp area whilst in direction 07 the taxiway system can accommodate three more RPA (on the segments north of the runway) before initiating a missed approach procedure. To mitigate this effect, a set of arrival taxi route diversions was implemented (see e.g. blue dashed line in Fig. 1).

5) Weather

In order to evaluate this specific procedure the varying parameters should be kept at a minimum. Therefore, good weather conditions, i.e. Ceiling And Visibility OK (CAVOK), were assumed for all simulations.

D. Performance metrics

The performance metrics shown in Table 2 were measured in this validation activity, based on the required KPAs from the SESAR 2020 Validation Strategy [10]. The metrics address in particular the operational performance and environmental aspects of RPAS towing operations and expected stop and go movements by SSTR procedure.

TABLE 2: Performance metrics

KPA	Metric	Definition
Capacity	Departure runway throughput	Number of take-offs in 1h intervals
Capacity	Arrival runway throughput	Number of landings in 1h intervals
Efficiency	Departure taxi out times	Time from off-block to line-up
Efficiency	Arrival taxi in times	Time from touchdown until on-block
Environment	Fuel consumption	Amount of consumed fuel in kilograms
Environment	Gaseous emissions	Amount of gas emissions (CO ₂ , NO _x) in kilograms

Regarding the assessment of the consumed fuel and the gaseous emissions the following data and assumptions were used and applied. The fuel consumption and the emissions were evaluated based on the engine types of the aircraft in the scenario based on their registration. The ICAO Aircraft Engine Emissions database, provided by the European Aviation Safety Agency (EASA) [11] for jet engines, and the piston engine database from the Swiss Federal Office of Civil Aviation (FOCA) [12] were used to assess the fuel consumption and the NO_x emissions. The CO₂ emissions were calculated based on the ratio of 3.155 kg emitted CO₂ per kg fuel which is the mean value of various publications, [13]-[15].

Approximately 11% of the engines types of the traffic scenario are turboprop engines and are not listed in the ICAO database and therefore publicly not available. For this reason the publicly available performance data regarding maximum take-off power and corresponding revolutions per minute of for these turboprop engines were researched to derive their fuel consumption for maximum takeoff performance [16].

Based on the fuel consumption and the defined ICAO thrust setting percentages an engine with similar fuel consumption from the ICAO database was chosen to derive the NO_x emission indices.

The most emission contributing taxi phases are the engine idle phases and the acceleration phases [17] and were therefore considered for this calculation. The fuel consumption and the NO_x emissions of the acceleration phases were calculated with an average thrust index of 11.77% for departures and 7.56% for arrivals using empirical accelerations for the A320 aircraft family [18]. The basic emission calculation methodology was taken from ICAO [19] and adapted to consider acceleration phases via curve fitting methods [20].

Emissions of tugs were also considered and calculated based on the aircraft weight, a tug weight of 22.5t and 191kW power¹ using the fuel consumption and the NO_x emission index for diesel towing vehicles from [22] and the same CO₂ calculation factor compared to kerosene which can be seen as a worst case calculation. The required load factor for the tug power was assumed to be 100% when towing and 50% in an empty run [23].

IV. SIMULATION RESULTS AND DISCUSSION

For the initial simulation the amount of tugs for the baseline scenarios was set to three tugs. This is based on a pre-study in 2018 where the amount of tugs to handle 10% of evenly distributed RPAS was found to be two. An intermediate evaluation with three tugs showed that the arriving RPA had to wait for the tugs in average over 15 minutes when runway 07 is in use and over 7 minutes for runway 25 in use incl. attaching time. These waiting times also implied that RPA often occupied the runway exit and following RPAs had to fly missed approach procedures. To reduce waiting time and to avoid missed approach maneuvers, the initial number of available tugs was therefore set to ten for the final evaluation as estimation.

A. Runway throughput

Regarding the evaluation of runway throughput the number of take-off run beginnings and touchdown times were counted in 1 hour timeframes. The departure and arrival runway throughput figures for a whole day are shown in the same diagrams, respectively. The departure throughput is displayed above and the arrival throughput below the x-axis. The throughput of the reference scenario for both arrivals and departures are depicted as black dashed lines.

¹ Because of public available data, the biggest tow bar less truck from the Chinese company CarToo was chosen [21].

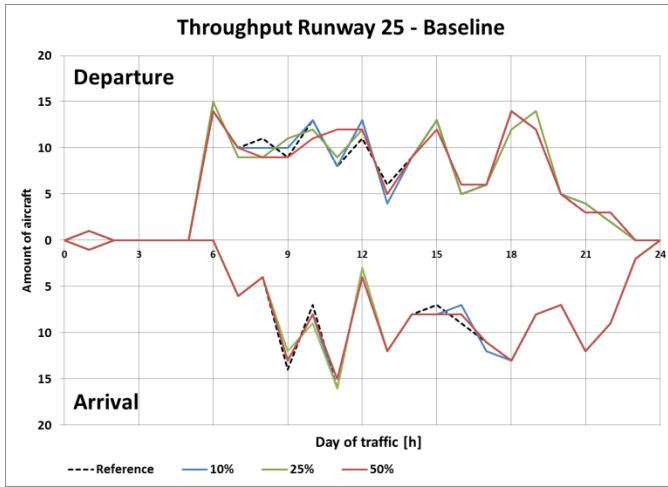


Fig. 3: Runway throughput for the baseline of arrivals and departures for runway 25 in use

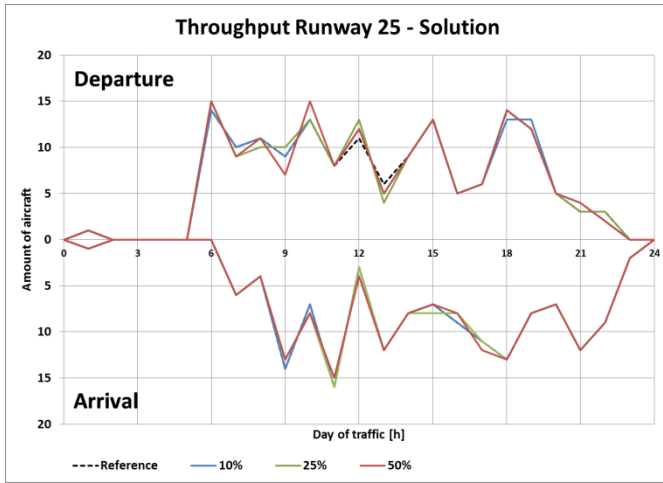


Fig. 4: Runway throughput for the solution of arrivals and departures for runway 25 in use

When comparing the reference (pure manned traffic) and the baseline scenarios (towing operations) for runway 25 in Fig. 3 there are some differences for both, arrivals and departures, in particular concerning the 50% traffic share scenario. The departure throughput curve is more even concluding that the traffic was delayed. The reason could be waiting times at the runway because of several detaching processes of many RPAS from tugs in shorter time frames.

When comparing the reference (pure manned traffic) and the solution scenarios (segmented standard taxi routes) for runway 25 in Fig. 4 the departure throughput is very similar having higher peaks with rising RPAS traffic share around 10:00h and 12:00h.

When comparing the reference (pure manned traffic) and the baseline scenarios (towing operations) for runway 07 in Fig. 5 there are some small differences, in particular concerning the 50% traffic share scenario of the departure throughput. This again is due to many RPA that have to be detached from their tugs using the same runway holding point.

In Fig. 6 the reference (pure manned traffic) and the baseline scenario (segmented standard taxi routes) are again very similar.

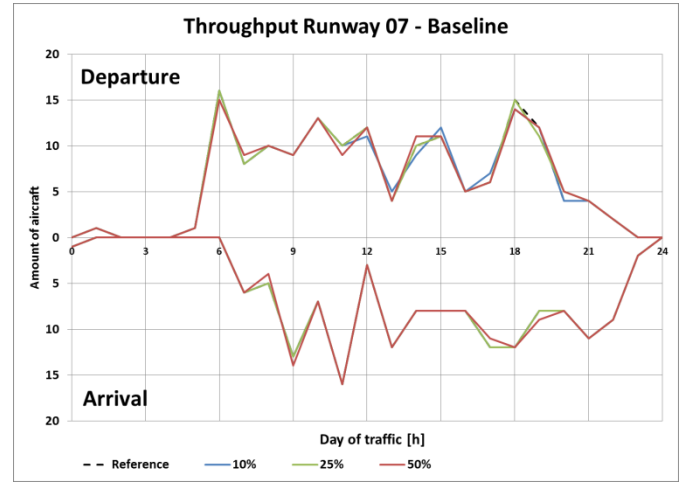


Fig. 5: Runway throughput for the baseline of arrivals and departures for runway 07 in use

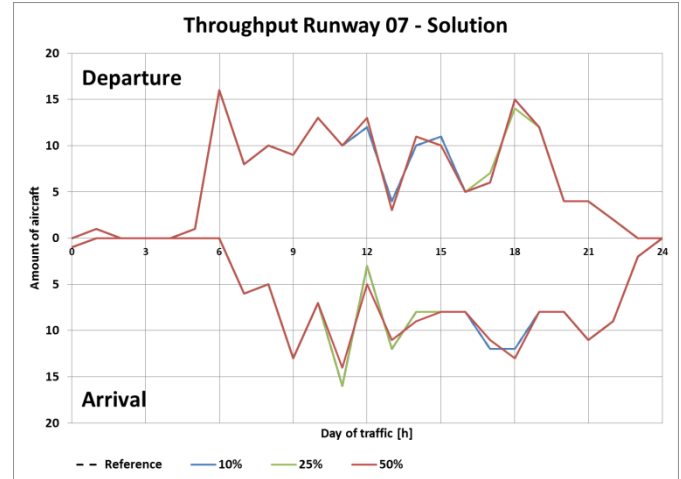


Fig. 6: Runway throughput for the solution of arrivals and departures for runway 07 in use

However, for both runway directions the departure throughput of SSTR is handled within the operating hours and is equal to the baseline and the reference although there is interaction between manned and unmanned traffic because both use the same taxiway resource north of the runway.

As mentioned it can sometimes be the case that RPA waiting for a tug in the baseline scenario resp. RPA waiting for the 'go' for the next taxi segment may block runway exits, leading to go-around maneuvers of succeeding RPA arrivals.

Table 3 lists all flown missed approach maneuvers that occurred in the simulation runs.

TABLE 3: Flown missed approach maneuvers

RWY Mode	Reference	Baseline			Solution		
	0%	10%	25%	50%	10%	25%	50%
25	-	-	1	2	-	-	1
07	-	-	-	-	-	-	4

The reason for the high number of flown missed approach maneuvers in the solution scenario of runway 07 with 50% RPAS is because of the blocking of all segments of the arrival taxi route (see Fig. 2). Since the RPAS arrivals when runway 07 is in use have to cross their landing runway a backlog happened blocking all runway exits assigned for RPAS. The arrival standard taxi route for runway 25 consists of two different routes, both with only two segments and one of them with a runway crossing to reach the parking position while for runway 07 there are 5 segments and one of them includes a runway crossing. This seems to occur just when the share of RPAS is 50% or higher. This can be resolved with a pre-planning either done by a system or an air traffic controller.

B. Taxi times

The total taxi times of manned and unmanned traffic were also measured. They are defined as the time span from off-block to line-up resp. touchdown to on-block. The results are displayed in Fig. 7 for all scenarios (DEP = departure taxi time, ARR = arrival taxi time).

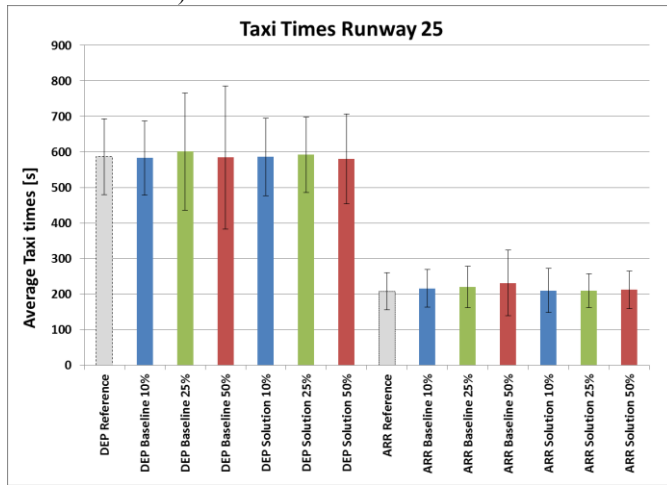


Fig. 7: Average taxi times for baseline and solution of arrivals and departures in operation mode runway 25

There are only small variations of the taxi times in Fig. 7. Taxi times for 10% RPA traffic share are surprisingly almost identical to the reference. Longest taxi times for departures are observed for the towing operations with a 25% RPAS traffic share; shortest taxi times for departures are observed for SSTR operations at 50% RPAS traffic share. For towing operations, the standard deviation increases with increasing RPAS share of arrival and departures while it is similar for SSTR. The unmanned aircraft had a 15% longer taxi distance and had to cross the runway 25 which caused waiting times. The taxi times for runway 07 in use in Fig. 8 vary stronger than for runway 25 in use (Fig. 7). The reduction of the taxi out times with the rising traffic shares is due to the homogenization of the traffic movements with SSTR. Coming from the southern ramp the taxi distance and subsequently the taxi time for the RPAS is shorter than for the manned traffic coming from the northern ramp. The standard taxi route length for manned departure traffic with runway 07 in use is 700m compared to

300m for unmanned which is a difference of 40%. Compared to that, the difference between departure traffic with runway 25 in use, the manned aircraft taxi 3400m whereby the unmanned aircraft taxi 3900m which is a 15% difference. The increase for the taxi in times when runway 07 is in use (Fig. 8) is due to the taxi routes whereby the runway must be crossed for a length of 300m opposite to the runway direction (see Fig. 2). However, for runway 07 the average taxi out times are always shorter for all scenarios compared to the reference scenario. For the taxi in times, the increase with increasing RPAS traffic share is less steep for SSTR.

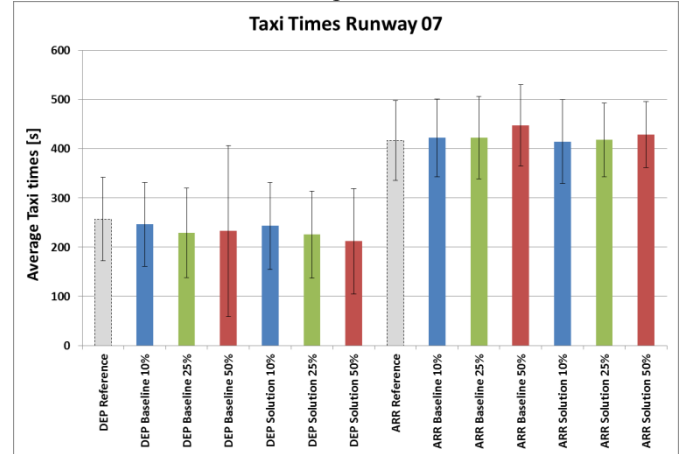


Fig. 8: Average taxi times for baseline and solution of arrivals and departures in operation mode runway 07

C. Fuel consumptions and gaseous emissions

The evaluation for fuel and CO₂ emission is combined in one diagram whereby the NO_x emissions are shown separately because of the different axis scale. The analysis again distinguishes between runway 25 and runway 07 in use.

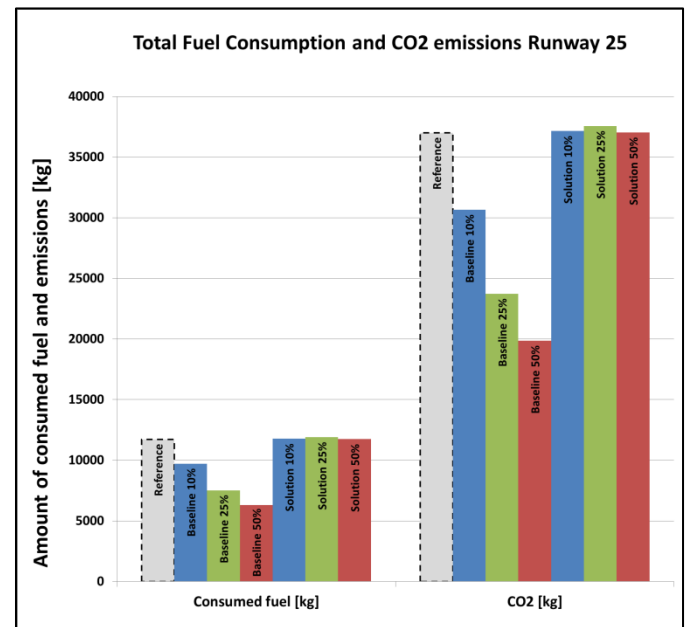


Fig. 9: Total fuel consumption and CO₂ emissions for baseline and solution of arrivals and departures in operation mode runway 25

Looking at Fig. 9 and Fig. 10, the fuel consumption, the CO2 emission and the NOx emission decreased almost proportionally when runway 25 is in use with the rising RPAS traffic share in the baseline scenario compared to the reference scenario almost by 50%. The reason is the lower fuel consumption of tug operations instead of autonomous aircraft taxiing.

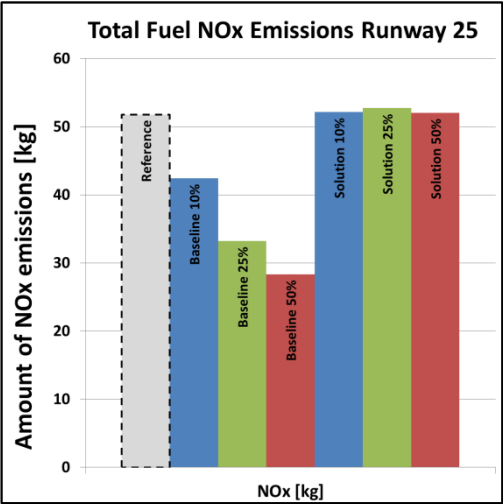


Fig. 10: Total NOx emissions for baseline and solution of arrivals and departures in operation mode runway 25

In the solution scenario the fuel consumption and all emissions slightly increased compared to the reference scenario by 0.5% with small differences between the different RPAS traffic shares. The reason for that might be the slightly higher number of stop-and-go's for the SSTR procedure compared to reference, while the maximum is observed at 25% traffic share.

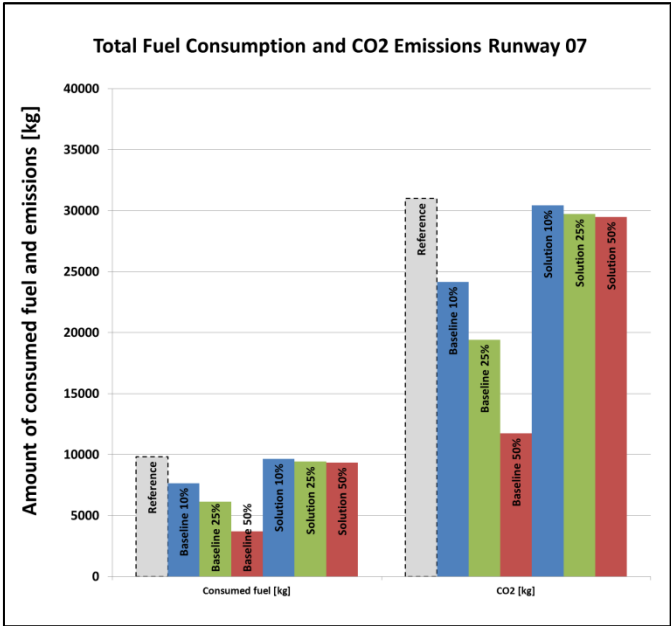


Fig. 11: Total fuel consumption and CO2 emissions for baseline and solution of arrivals and departures in operation mode: runway 07

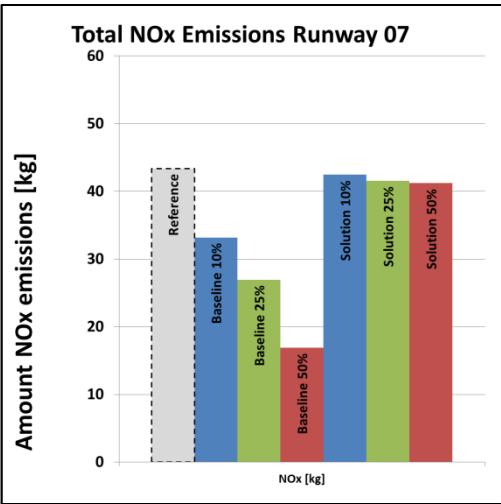


Fig. 12: Total NOx emissions for baseline and solution of arrivals and departures in operation mode runway 07

Looking at Fig. 11 and Fig. 12, the fuel consumption, the CO2 emission and the NOx decreased almost proportionally when runway 07 is in use with an increasing RPAS traffic share in the baseline scenario compared to the reference, similar to runway 25 in use by more than 50%. In the solution scenario the fuel consumption and the emissions were higher compared to the baseline scenario which was expected due to lower fuel consumptions of tugs. However, compared to the reference, the solution also shows a slight proportional reduction of up to 5% which might be also due to the shorter taxi distance.

It was assumed that the mandatory stops induced by SSTR contribute greatly to the emissions. Fig. 13 shows the overall number of stops in-between runway entry or exit and parking position under nominal conditions for both runway 07 and 25 in use. The numbers include stops after pushback for manned aircraft, stops before crossing a runway or lining up for all aircraft, stops for attaching and detaching the RPA in Baseline scenarios, stops of RPAs at mandatory holding points in the Solution scenarios and other stops caused by congestion within the taxiway system.

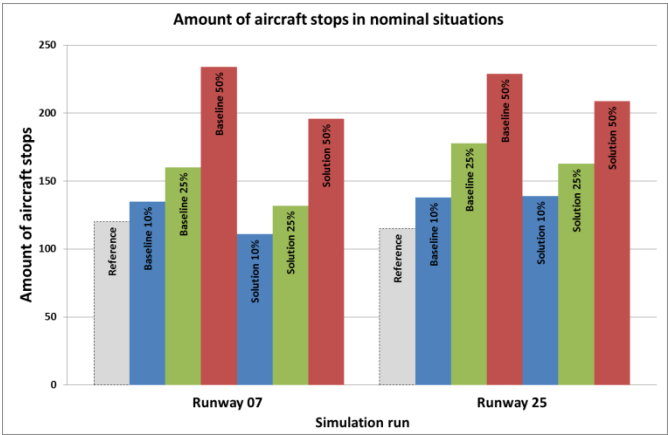


Fig. 13: Amount of aircraft stops per simulation run

The number of stops for the solution scenario is lower than the baseline and higher than the reference with at least 25% RPAS

for runway 07 in use. For runway 25 in use the stops of the solution scenario is equal or lower than the baseline but always higher than the reference. These numbers confirm the emission values in the previous figures. Therefore SSTR does not contribute to higher emission with more stops as expected compared to the baseline. The impact of the flown missed approach maneuvers could not be quantified due to high and variable set of parameter that needed to be considered. Therefore the benefit of the solution scenario with runway 07 with 50% RPAS need to be further assessed.

D. Final conclusion

Concerning runway throughput there were no significant differences between the reference, the baseline and the solution scenarios. Both towing operations and SSTR are feasible solutions.

Concerning the taxi times, neither the stop-and-go's nor the attaching and detaching times of the tug had a negative impact on the total taxi times. Regarding runway 07 in use there are more deviations than with runway 25 in use. It can be concluded that the differences between baseline and solution are in general for the benefit of the solution which is even better when comparing it to the reference.

Towing operations have a less environmental impact than the pure manned traffic and SSTR, what was expected. However, the solution was not worse than today's reference.

Both, towing operations and SSTR are still equal solutions that work with the topology of Stuttgart airport and the corresponding traffic. The most important decision making criteria are the investigation with human in the loop and the resource demand for towing operations in contrast to the total fuel consumption. For towing operations the fuel consumption is lower but in the simulation runs there were ten tugs available and reserved just for RPAS ground movements.

V. SUMMARY AND FUTURE WORK

As part of the SESAR 2020 Industrial Research Project PJ03a 'SuMO', a concept for the integration of RPAS in the airport surface traffic was evaluated using fast time simulation. The concept of segmented standard taxi routes was evaluated before in a gaming workshop and now implemented with the 'Simmod PRO!' fast time simulation environment at DLR. The topology and a realistic whole day scenario of Stuttgart International airport was implemented and applied for this simulation exercise.

The simulation was split up into reference (current day operations without RPAS), baseline (towing operations) and solution simulation runs (segmented standard taxi routes), considering several RPAS traffic shares between 10% and 50% and two different runway operation modes: runway 25 and runway 07.

For all simulation runs, KPAs and recommended metrics from the SESAR 2020 Validation Strategy including capacity, efficiency and environment, were measured and compared.

It could be shown that the overall departure and arrival throughput of both runways is not affected which is also due to the homogenization of the traffic situation for both runway operation modes with the rising RPAS traffic share. The

difference of the taxi times is higher when runway 07 is in use because the taxi distances of manned and unmanned traffic vary stronger compared to runway 25 in use. Considering the emissions the comparison between reference and the concept of segmented standard taxi routes (SSTR) is for the benefit of this new developed SSTR procedure although the mandatory stop points forced the RPAS to stop more often due to the traffic situation; forcing it also to accelerate more often. Based on the workshop output from the V1 exercise the idea was to have a combined application of towing operations and SSTR based on the traffic demand and the RPAS traffic share [1]. The segmented standard taxi routes have to be defined and optimized for every airport specifically. Therefore, the benefit of the implementation of SSTR could only be shown for Stuttgart airport topology for this day of traffic while neglecting gate and potential ramp area traffic conflicts and having 10 tugs in store that are reserved for RPAS towing operations only. The SSTR procedure element to fly missed approach procedures when all published exits are occupied is seen as a tentative solution which was set up for the fast time simulation. Considering the control and guidance by an air traffic controller these traffic situations would most probably have been avoided more often as ATC traffic preplanning was not modelled in the fast time simulation.

Further research activities may include more data analysis to estimate human performance issues which can be derived on a high level from the fast time simulation. For instance the airport congestion and the amount of given commands can help to estimate how the task load of ATC and subsequently the workload could change when implementing segmented standard taxi routes. In addition the optimal amount of tugs has to be assessed in more detail from an economic point of view. For saving resources, optimization strategies and tug scheduling concepts should also be developed and applied here.

ACKNOWLEDGMENT

This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement number 734153.

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*38th Digital Avionics Systems Conference
September 8-12, 2019*