Performance Evaluation of Conflict-Free Trajectory Taxiing in Airport Ramp Area Using Fast-Time Simulations

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***Abstract*—The German Aerospace Center (DLR) and the National Aeronautics and Space Administration (NASA) have been collaborating to conduct joint research addressing future surface traffic management challenges. The surface management tool from DLR, called Taxi Routing for Aircraft: Creation and Controlling (TRACC), was adapted to be integrated in NASA's fast-time simulation environment called Surface Operations Simulator and Scheduler (SOSS). The research described in this paper 1) applied TRACC to trajectory-based ramp traffic management, where TRACC generates conflict-free aircraft trajectories in a congested ramp area, 2) investigated the feasibility of the concept through the integrated TRACC-SOSS fast-time simulation, and 3) evaluated the performance of the integrated system. For this activity, TRACC was adapted for ramp operations at Charlotte Douglas International Airport, called TRACC_PB (TRACC for pushback optimization). TRACC_PB provides four-dimensional taxi trajectories with a command speed profile for each aircraft following standard taxi routes within the ramp area. In this study, departures are given the Target Movement Area entry Times (TMATs) provided by the baseline surface metering scheduler based on NASA's Spot and Runway Departure Advisor (SARDA). TRACC_PB also calculates optimal pushback times for departures, as well as the times when arrivals shall enter the ramp, the Target Movement area Exit Times (TMETs). The initial results showed that the TRACC_PB successfully generated conflict-free trajectories for the ramp area taxi operations and improved taxiing efficiency compared to the baseline results. TRACC_PB aimed to provide conflict-free taxi routes avoiding any stops while taxiing. This resulted in longer gate hold times for departures and postponed throughput values compared to the baseline simulation without trajectory optimization. Having conflict-free routes without stoppage also created shorter taxi times but required renegotiation of the given TMATs. TRACC_PB also achieved reductions in both fuel consumption and engine emissions (17% for departures and 10% for arrivals), which correlate with the ramp taxi time reduction.**

Keywords—trajectory-based taxi operations, TRACC, SARDA, fast-time simulations

I. INTRODUCTION

A. Background

Airports represent key nodes of the air transport network, and its airport surface is undoubtedly one of the most complex and challenging areas. The Next Generation Air Transportation System (NextGen) [1] program and the Single European Sky ATM Research program (SESAR) [2] initiatives, respectively, are dealing with these challenges. To jointly address this research area, the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) established a research collaboration in 2012 entitled "Coordinated Arrival, Departure and Surface Operations" to develop harmonized concepts of operations and simulation tools to improve airport surface traffic operations by reducing delays and environmental impacts, such as emissions and noise pollution.

In recent years, innovative processes for airport surface operations have been introduced: Airport Collaborative Decision Making (A-CDM) in Europe [3] and Surface Collaborative Decision Making (S-CDM) in the U.S. [4]. A-CDM and S-CDM facilitate information sharing between the involved airport stakeholders, increasing situation awareness while decreasing negative environmental impacts [5]. In addition, with A-CDM, the pre-departure sequence planning concept was introduced to calculate off-block times to reduce runway queues and surface congestion. In S-CDM, the metering of departure traffic flows during times of imbalances between capacity and demand is activated based on a target queue length of the considered departure runways, and target times for departure aircraft to enter the Airport Movement Area (AMA) are provided to the user. NASA and DLR have independently investigated CDM concepts, developed required technologies, and tested prototype decision support tools in their own operational environments.

The analysis in this paper will focus on the ramp area at U.S. airports, called the non-movement area (equivalent to the apron area in Europe), which includes gates (or stands), whereby the traffic is controlled by the ramp control tower(s) commonly managed by airlines (in Europe airport ramp/apron operations are managed by the airport or Air Traffic Control (ATC) depending on the size of the airport). The Air Traffic Control Tower (ATCT) managed by the U.S. Federal Aviation Administration (FAA) is responsible for the traffic in the movement area, which includes taxiways and runways (equivalent to the maneuvering area in Europe). The spots are the locations where control of traffic is transferred between the ramp control tower and ATCT. The sequence resulting from the handover of departure aircraft between these two control entities greatly affects the departure sequence at the runway. In the S-CDM environment, departure aircraft subject to metering are assigned with Target Movement Area entry Times (TMATs) provided by the metering tool, which are derived from the runway schedule [4]. Better conformance of the TMATs by departure flights leads to higher chances of the aircraft taking off from the runway at their predicted Target Takeoff Times (TTOTs). However, in current operations, due to uncertainties in the pushback process and traffic conditions in the congested ramp area, it is quite challenging for the ramp control personnel to meet TMATs. Therefore, the S-CDM procedure allows a relatively large compliance window (e.g., ±5 minutes).

B. Related works – DLR's Surface Research

Addressing airport surface congestion, DLR developed a research prototype for ATCT ground and local controllers to meter aircraft at the gate and the runway by introducing ATC clearance times for pushback, engine start-up, taxi, line-up and takeoff based on nominal taxi-out and taxi-in times [6]. The Controller Assistance for Departure Optimization (CADEO), which is an implementation of a departure management system (DMAN), was developed as part of European research project for the optimization of airport surface traffic. CADEO provides an optimal runway schedule with the objectives of increased throughput and reduced taxi delay and emissions [7][8]. DLR recently developed a tool generating conflict-free taxi trajectories implemented by speed advisories based on the principle of a surface management system (SMAN) [9]. The Taxi Routing for Aircraft: Creation and Controlling (TRACC), DLR's SMAN implementation, is one of the enabling technologies for A-CDM along with the Advanced Surface Movement Guidance and Control System (A-SMGCS). The speed advisories and the routes are shown to the controller who guides the aircraft via radio [10]. This prototype was successfully evaluated via human-in-the-loop (HITL) simulations at DLR in 2013 [11]. Because TRACC is able to generate optimized taxi-out and taxi-in times, it was integrated with the runway scheduling capability of CADEO [12] and tested in a HITL simulation [11]. With some enhancements made to the CADEO-TRACC system, the performance of the integrated system was assessed in automated real-time simulations. The results showed that the runway queue length did not exceed more than one aircraft and the departures received their line-up clearances shortly after reaching the runway holding point [13].

C. Related works – NASA's Surface Research

Similarly, there has been ongoing research in the U.S. focused on efficient and safe surface operations through development of schedule optimization and enhanced flight deck capabilities. NASA has developed the Spot and Runway Departure Advisor (SARDA), a research prototype decision support tool to provide tactical advisories to ramp and ATCT controllers. Initially, SARDA's spot and runway sequence advisories were evaluated for ATCT ground and local controllers [14]. Later, the SARDA capabilities were extended to the ramp area and provided gate pushback advisories to the airline ramp controllers [15]. In both cases, SARDA was tested in a HITL simulation environment at NASA. The runway schedule of departure flights was generated through a combination of optimization and heuristic algorithms, which aimed to maximize runway throughput [16]. The HITL experiments showed promising results concerning the performance of the tool (i.e., taxi delays and environmental impacts), as well as human factors metrics (e.g., workload, usability, and situational awareness) [14][15].

More recently, under NASA's Airspace Technology Demonstration 2 (ATD-2) subproject, the Integrated Arrival, Departure, and Surface (IADS) system was developed in coordination with the FAA and aviation industry. Since September 2017, the Phase 1 ATD-2 IADS system has been deployed at various facilities in Charlotte Douglas International Airport (CLT), North Carolina, including the FAA's ATCT and American Airlines Control Center (i.e., ramp tower), CLT Terminal Radar Approach Control (TRACON), and Washington Air Route Traffic Control Center (ARTCC) for field evaluation. One of the core capabilities in the Phase 1 IADS system is surface metering. The tactical surface scheduler generates the runway schedule based on airlines' Earliest Off-Block Times (EOBTs) and provides gate pushback advisories to the ramp controller according to the surface metering strategies set by the user [17].

NASA's flight deck research on the NextGen Surface Trajectory Based Operations (STBO) has been focused on conformance of 4D taxi clearances through investigation of various options for displaying information to the pilots and evaluating pilot performance and related human factors in high-fidelity flight simulations [18][19]. In Ref. [19] SARDA was integrated with the flight deck, where pilots were presented with a graphical representation of a four-dimensional taxi trajectory (4DT) and speed advisory to support conformance to the surface schedule generated by SARDA. Simulation results showed that pilots were able to follow the 4DT under manual control with a time deviation of ±15 seconds from target takeoff times shown on the flight deck display [19].

D. Motivation

NASA and DLR jointly developed a concept of operations for trajectory-based taxi operations where 4DTs are generated, combined with an optimized runway schedule supported by conformance monitoring and supporting flight deck technologies to execute 4DTs on the airport surface [20]. Based on this concept, NASA and DLR conducted joint research where independent, parallel simulations were conducted to compare the performance of CADEO-TRACC and SARDA tools [21]. In both simulations, a common traffic scenario from Hamburg International Airport (Germany), was used under the same traffic conditions. Also, a set of common performance metrics was jointly developed based on the International Civil Aviation Organization (ICAO)'s Key

Performance Areas (KPAs) and Key Performance Indicators (KPIs) proposed by the Civil Air Navigation Services Organization (CANSO). Simulation results showed that both CADEO-TRACC and SARDA tools were able to improve taxi efficiency while maintaining runway throughput under normal traffic conditions.

The study presented in this paper investigates the TRACC conflict-free taxi capability applied to a relatively larger US airport (CLT), but constrained to the ramp operations, and compares the performance with that of a nominal baseline capability. NASA's Surface Operations Simulator and Scheduler (SOSS) [22], a fast-time surface traffic simulation environment, was used for the study.

The application of the TRACC tool in this study is envisioned to enable a much tighter TMAT compliance by providing conflict-free trajectories for aircraft in real-time. The outcome of this conflict-free trajectory calculation can be provided to the ramp controller and flight deck in the form of gate pushback times for departures, also referred to as Target Start-up Approval Times (TSATs), Target Movement area Exit Times (TMET) for arrivals, and speed commands for both arrivals and departures. This paper describes the technical approach in detail and the results of the simulation experiment of ramp taxi operations at CLT. The operational benefits that can be achieved include improved predictability, reduced taxi delays, and reduced fuel/emissions in ramp operations. Ideally, the conflict-free taxi scheduling should be extended to cover the entire span of taxi operation on the surface to provide downstream benefits, such as reduced airborne delays, fuel savings and increased predictability, thus enabling gate-to-gate trajectory-based operations (TBO).

The remainder of this paper is organized as follows: Section II introduces the operational concepts and tools of NASA and DLR that were the basis for this investigation. Section III describes the simulation setup including the chosen performance metrics. Section IV presents the simulation results and discussion, followed by section V with a summary and future research plans.

II. OPERATIONAL CONCEPTS AND TOOLS BY DLR AND NASA

A. *Surface Optimization Tools of DLR*

DLR developed TRACC as an implementation of an SMAN: create, control and always maintain conflict-free taxi trajectories for all aircraft ground movements. These requirements fulfil the following procedure stated in [6]: Plan => Execute => Measure => Adapt.

Enabling technologies for TRACC include the following assumptions: The aircraft positions are always known; 4DTs are sent to the flight deck via datalink; and the aircraft are able to comply with speed advisories. TRACC uses speed advisories for controlling aircraft in accordance with the calculated trajectory. Alternative aircraft taxiing systems, such as electric taxi [23], the usage of Taxibots (e.g., ZETO project at University of Darmstadt, Germany) [24], and additional support tools, will make it possible for the pilots to meet prescribed taxi speeds.

TRACC is designed as a generic tool which can be easily adapted to any airport layout using a special editor tool for the creation of datasets where all necessary information is mapped. This model with an underlying node-link system is used together with flight plan information to create conflict free, optimized and time-based taxi routes (4DTs), each including a speed profile, for all aircraft on the airport. For the creation of these trajectories an Evolutionary Algorithm is used. Besides the trajectory creation, TRACC provides Air Traffic Controllers (ATCOs) with necessary taxi advisories resulting from the proposed trajectories. In addition, conformance monitoring (i.e., location and time) of each aircraft is carried out. In case of nonconformance, the trajectory is adapted to the aircraft's actual position and speed and recalculated, if necessary. This requires an automatic conflict detection and resolution (CD&R) function for TRACC. For trajectory recalculation two main principles are applied in TRACC: the "Principle of Lowest Workload" and the "Principle of Smallest Modification." For the first, actual commands are sent to the controller only when changes are caused by trajectory deviations. The second principle means that trajectories should stay as close to a set of standard trajectories (predefined) as possible, and that only aircraft deviating from the advised taxi trajectory are penalized.

The management of pushback time is an essential part of SMAN because off-block times may influence the duration of every aircraft moving on the ground. For example, aircraft pushing back can block taxiways for other aircraft (i.e., pushback conflicts), resulting in negative environmental impacts and excessive fuel burn [25]. Therefore, a sophisticated combination of pushback management and Target Start-up Approval Time (TSAT) management is implemented in TRACC which calculates the best TSAT for every aircraft, considering taxiing aircraft and TTOTs created by a DMAN. The main goal is not only to hold departures as long as possible at the parking positions (i.e., gates or stands), but to reach the departure runway in time with conflict-free taxi routes. In case TRACC cannot find a solution to meet the runway schedule, the runway scheduling function in DMAN (i.e., CADEO) has to adapt the schedule [12]. Details are available in Ref. [13]. The main difference from conventional ramp management is holding aircraft at the parking position as opposed to releasing them as they are ready.

Reducing uncertainty in arrival times at the departure runway is one of the most important tasks for a surface management system like TRACC [26]. It is accomplished by monitoring all aircraft movements, updating the trajectories using the actual position and speed, and creating new trajectories in case of conflicts or missed arrival times at the departure runway.

TRACC has an integrated CD&R functionality to monitor conformance to the original 4DT and maintain conflict-free separation. TRACC's CD&R functionality consists of the following components:

1. Identification of deviations from the planned trajectory
2. Adaptation of the planned trajectory to the actual deviation in position and speed

3. Test of the adapted trajectory for conflicts
4. In case of conflicts or significant deviations from the given time constraints: creation of a new conflict-free trajectory with respect to current position, time and Target Line-up Time (TLUT) (only departures)

An important prerequisite for conflict detection is the minimum distance allowed between two taxiing aircraft. The minimum distance used by TRACC is determined by the aircraft weight class, aircraft length, and wingspan to reflect aircraft engine blasts of different wake vortex classes and the aircraft sizes.

B. *SOSS - NASA's Fast-Time Analysis Tool*

NASA developed the Surface Operations Simulation and Scheduler (SOSS) fast-time simulation tool to provide a simulation platform to support development and testing of surface schedulers, such that any schedulers showing promise can be further tested in real-time systems. Fig. 1 shows the architecture diagram of SOSS.

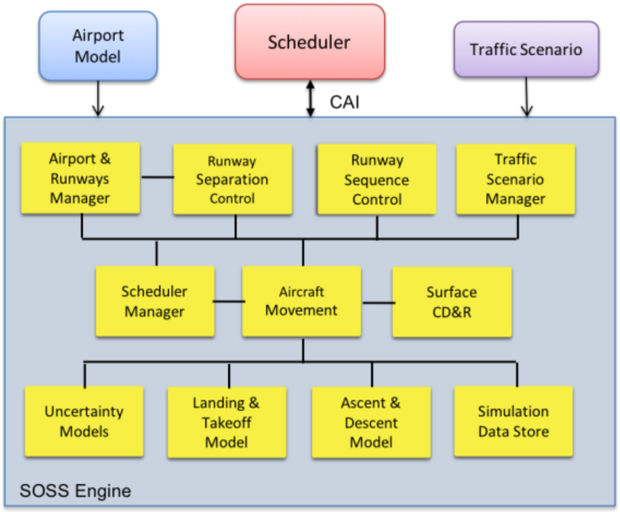

Fig. 1. SOSS architecture

SOSS models the airport surface as a node-link network representing gates, spots, taxiways, crossings, and runways. SOSS maintains a database of aircraft performance characteristics, such as taxi speed, acceleration, and deceleration for a variety of aircraft types. SOSS also has wake-vortex separation matrices for runway operations, so that two consecutive runway operations are temporally separated based on the weight class of aircraft. SOSS has a built-in surface CD&R logic that prevents aircraft from loss of separation in trail or head-on collisions while taxiing on the airport surface. SOSS also has capabilities to model uncertainties, including pushback process, taxi speed, and flight ready time, via different types of probability distributions. SOSS connects to surface schedulers through a socket and uses a protocol called the Common Algorithm Interface (CAI), which allows the researchers to test different schedulers without changing the simulation engine (see Fig. 1).

The scheduler receives current locations of aircraft, speed, routes, and estimated arrival times at key positions, including spots and runways through CAI and returns release times of aircraft at key airport locations, such as gates, spots, and runways. The SOSS simulation engine has been validated against operational data from multiple airports [22][29], where key performance metrics, such as taxi in/out times, departure throughput, and departure rates, are compared between simulation results and operational data. Initial location and time on final approach for arrival aircraft are prescribed in a traffic scenario according to the operational data.

The SOSS fast-time simulation tool has been utilized for NASA's surface research to assess the surface metering concepts developed for SARDA and ATD-2. Traffic scenarios generated from real operations were used for simulations to evaluate scheduler performance and operational benefits in efficiency, predictability, and throughput [21][30][31][32].

C. *Integration of NASA and DLR Tools in SOSS*

The purpose of the integration of TRACC with SOSS in this study is to explore optimized 4D trajectory-based surface traffic management at busy hub airports in the U.S. based on the TRACC functions: TSAT and pushback management. As a first step, ramp area traffic management was considered. The rationale for restricting the application to the ramp area is to make the problem size for optimization by TRACC manageable. In addition, the traffic in the ramp and Airport Movement Area (AMA) are separately managed by airlines and ATC. TRACC is expected to achieve reduction in taxi delay by holding aircraft at parking positions instead of risking an overcrowded ramp area and to ensure a reliable departure time. With a decreased number of active aircraft taxiing in the ramp area, safety will also be improved.

For the integration of TRACC into SOSS several changes were carried out: 1) a set of prescribed taxi trajectories between each combination of origin and destination nodes on the surface was constructed and stored, where only speed changes are allowed for optimization instead of creating new routes; 2) because the application area was restricted to the apron / ramp area, TMATs were used as targets for optimizing departure trajectories in the ramp area instead of using TLUTs at the runway as was the case in the original TRACC implementation; and 3) SOSS was adapted in such a way that speed changes are linear to ensure the same speed profiles are used in SOSS simulation as for the calculation of trajectories implemented by TRACC. The adapted version of TRACC was called TRACC_PB (TRACC for pushback optimization).

TRACC_PB receives target times at assigned spots (i.e., TMATs for departures and TMETs for arrivals) from an external source (i.e., SOSS) for departures/arrivals to exit/ enter the ramp area. It will then generate conflict-free taxi trajectories and calculate engine start-up times for all departures from assigned TMATs and, similarly, the expected gate-in time for the arrivals from TMETs. The start-up time is the time a departure aircraft should leave the parking position in order to reach the spot at its assigned TMAT without interfering with other aircraft and reaches the TMAT in time. If TRACC_PB is unable to obtain a conflict-free trajectory for the aircraft with the given TMAT, SOSS informes it of the next earliest time the aircraft can reach the assigned spot. If necessary, arrival aircraft will be held at the entering spot until a conflict-free trajectory in the ramp exists.

SOSS requests for TRACC_PB trajectory updates are event driven. Each time a new flight needs a taxi trajectory, SOSS calls TRACC_PB with the new request. TRACC_PB performs a trajectory optimization for the considered aircraft to accommodate the new trajectory without changing the existing trajectories of other flights. This ensures that there are no adjustments to the trajectories that have already been calculated. This way, all optimized trajectories of conformed aircraft become a constraint to the new trajectory optimization of the non-conformed aircraft. Otherwise, a global optimization could lead to an unstable system of trajectories, where trajectories are changed too often.

TRACC_PB exercises flexibility by varying speeds, pushback times and ramp entry time, if necessary.

The following assumptions have been made for connecting TRACC_PB and SOSS:

- Standard routes with associated speeds must be known including a list of nodes with coordinates, and nominal and maximum taxi speeds.
- The time between beginning of start-up / pushback and decoupling the towing vehicle must be known.
- Because the route between each parking position and spot is predefined, only speed optimization is carried out.
- For each aircraft the positions on its trajectory as well as parking position and spot should be known to TRACC_PB for conflict calculation.
- The earliest possible TSAT, set by Scheduled Off-Block Time (SOBT) in this study, for each aircraft, must be known as a lower bound for the calculation of the appropriate TSAT to meet the TMAT.

The coordination between TRACC_PB and SOSS is carried out in the following way:

- SOSS sends trajectory updates of aircraft to TRACC_PB in case of substantial spatial deviations or speed changes of the taxi trajectory.
- SOSS sends new or updated TMATs to TRACC_PB with the actual positions of all moving aircraft for the conflict detection algorithm of TRACC_PB.
- TRACC_PB executes the following steps, when receiving a new or updated TMAT:
    - Calculate the appropriate TSAT by using the unimpeded taxi time between parking position and spot.
    - Check whether it is possible to leave the position at this time and meet the TMAT.
    - If not, start a search for the closest possible TSAT with the earliest possible TSAT as a lower bound.
    - Optimize the speed profile of the trajectory in such a way that the new TMAT is met or calculate a new TMAT, in case of traffic congestions or blocked pushback path, as close as possible to the TMAT provided by SOSS.
    - Transmit the new TSAT, Calculated Movement Area entry Time (CMAT) (i.e., same as the new TMAT), and a new speed profile for the flight to SOSS.
- TRACC_PB executes the following steps, when receiving a new TMET from SOSS:
    - Assign the predefined standard trajectory to the arrival.
    - Optimize the trajectory, so that the aircraft arrives at the parking position at TMET plus unimpeded taxi time. If this is not possible due to traffic congestions or blocked taxi-in path, use the earliest possible spot arrival time (TMET) and increase the TMET to allow the creation of a conflict-free trajectory.
    - Transmit new Calculated Movement area Exit Time (CMET) and new speed profile to SOSS.
    - SOSS tests the CMET and recalculates the sequence if necessary.

Flight data is transmitted to TRACC_PB when an aircraft receives the first TMET / TMAT. Updates can be sent with the same type of message and structure as the first flight data. The same data structure is used to send the necessary information from TRACC_PB to SOSS (e.g., CMAT / CMET and new speed profile).

Because the taxi routes are predefined, only position and spot need to be included in the flight information along with the type (arrival / departure), status (inactive / moving / leaving / update), actual position, and a list of speeds for every waypoint.

III. SIMULATION SETUP

A. Airport and traffic scenario

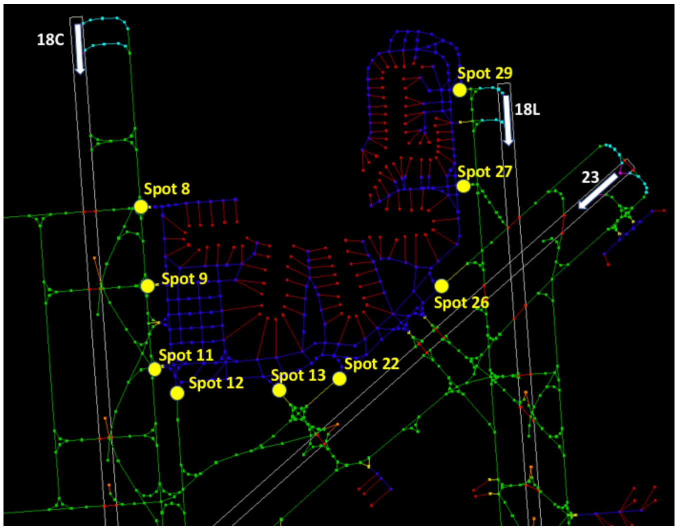

Fig. 2. Node-link model in SOSS for CLT in south flow configuration

Fig. 2 shows the SOSS node-link graph that models CLT airport operations. Ramp area nodes are depicted in blue (taxi nodes) and red (gate nodes). Spot nodes are shown in yellow.

The test traffic scenario, created from real operations data, has a total of 138 flights, 62 departures and 76 arrivals, in south flow operations. It is a medium traffic density for about 2.5 hours. In this scenario, runway 18L is a departure-only runway, runways 18R (not shown in the figure) and 23 are arrival only runways, and runway 18C is a dual usage runway. Arrivals enter the ramp area via four spots: Spot 11, Spot 12, Spot 13, and Spot 22. Departures use five spots to enter the movement area: Spot 8, Spot 9, Spot 26, Spot 27 and Spot 29.

B. Joint system setup of integrated simulation

Two simulations were set up for this evaluation. They were run in sequence, as shown in Fig. 3. The first one, called baseline simulation, used an emulated SARDA runway scheduler connected to SOSS. The scheduler computed the runway departure schedule, and then calculated the gate pushback times (TSATs) and TMATs. The same TMATs and TMETs for departures and arrivals, respectively, were then imported to the second simulation, called TRACC_PB simulation, where TRACC_PB was connected to SOSS. The simulation results from the TRACC_PB simulation are compared with the baseline simulation results.

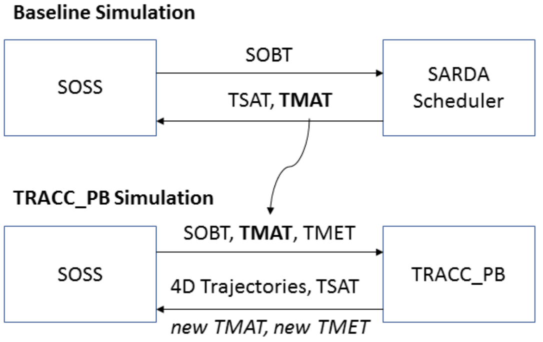

Fig. 3. Simulation setup, top: Baseline simulation, bottom: TRACC_PB simulation; parameters in italic are only sent when necessary.

Baseline simulation - SOSS calls the runway scheduler every ten seconds. The scheduler first creates three priority groups for those flights that need to use runways. The first priority is for landing arrivals, the second for those departures that have already left the gate and are taxiing to the runways, and the last priority group contains departures still at gate. Arrival runway use times (first priority group) are scheduled at their given landing times per the scenario. Scheduling of the flights within the second priority group is ordered by their estimated runway arrival times. Flights in the last priority group still at the gate are ordered by the SOBTs.

Each runway sequence is calculated according to the ordered flights in the priority groups and must satisfy the wake vortex runway separation criteria set by the International Civil Aviation Organization (ICAO). Each flight in the runway sequence is assigned a target runway use time. The TSAT and TMAT are backward computed from the assigned target take off time. Once a departure is ready to push back, its TSAT and TMAT are frozen and sent to SOSS for execution. The frozen TMATs are saved and used for the TRACC_PB simulation.

Each arrival’s TMET is estimated as the earliest time of the arrival at its assigned spot, ready to enter the ramp area. The TMETs are saved and used in the TRACC_PB simulation. Aircraft taxi at nominal speeds as long as there is no conflict with other aircraft. SOSS’s CD&R function was used to maintain aircraft separation to avoid conflicts.

TRACC_PB simulation - SOSS is connected to TRACC_PB without a runway scheduler. Instead, the TMAT and TMET values recorded from the baseline simulation are sent to TRACC_PB for conflict-free trajectory calculation in the ramp area. For departure flights, TRACC_PB also receives the SOBTs as the lower bound of TSAT calculation. TRACC_PB sends back to SOSS the calculated taxi trajectory with a speed profile for each flight. If the TMAT cannot be met, TRACC_PB advises SOSS with a delayed (new) TMAT and the corresponding TSAT. Similarly, TRACC_PB may hold arrival aircraft at the entering spot until a delayed (new) TMET is reached, see Fig. 3.

In the TRACC_PB simulation, SOSS’s CD&R is turned off. Aircraft taxiing in the ramp follow the speed profiles by TRACC_PB. Movement of aircraft is monitored by TRACC_PB, and trajectories are adjusted in case of conflict.

C. Performance metrics

A set of performance metrics was defined for a meaningful evaluation of the simulation runs, as shown in Table 1.

TABLE 1. PERFORMANCE METRICS

Metric	Definition	KPA
Departure ramp throughput	Number of “ramp out” movements; actual movement area entry times (in 10-minute intervals or in accumulation)	Capacity
Arrival ramp throughput	Number of “gate in” movements; actual in-block times (in 10-minute intervals or in accumulation)	Capacity
Departure ramp taxi time	Time from pushback start to spot passing (AMAT-TSAT)	Efficiency
Arrival ramp taxi time	Time from spot passing until arriving at gate (AIBT-AMET)	Efficiency
Gate hold time	Time between actual off-block time (pushback start) and scheduled off-block time (TSAT-SOBT)	Efficiency
Aggregate departure spot queue size	Number of flights in ramp area taxiing to their assigned spots	Efficiency
Departure TMAT compliance	Time between actual and original/updated target movement area entry times (AMAT-TMAT)	Predictability
Fuel consumption	Amount of consumed fuel in kilograms	Environment
Gaseous emissions	Amount of gas emissions (CO_2, NO_x, CO, HC) in kilograms	Environment

These metrics were derived from the KPAs identified by ICAO [27] and the KPIs recommended by CANSO regarding the operational performance of air navigation service provider [28]. Departure and arrival ramp throughputs are calculated based on Actual Movement Area entry Times (AMATs) and Actual In-Block Times (AIBTs), respectively.

IV. SIMULATION RESULTS AND DISCUSSION

A. *Ramp throughput*

Fig. 4 shows the histogram of ramp throughput for arrivals and departures resulting from the baseline and TRACC_PB simulations shown in 10-minute intervals during the 2.5 hour-long scenario. The black dashed line indicates the number of departures based on the TMATs as a reference for departure demand.

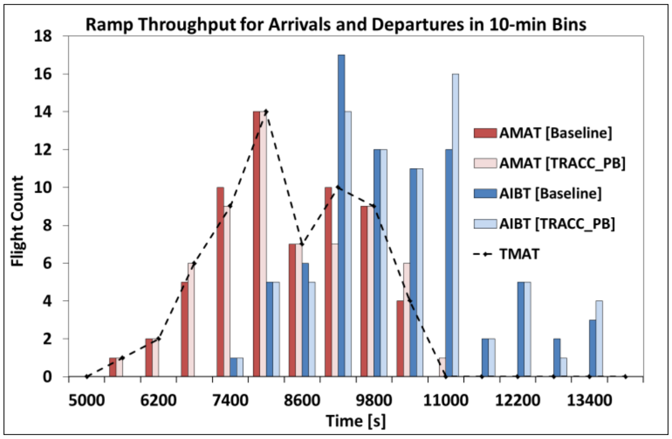

Fig. 4. Ramp throughput for arrivals (blue) and departures (red); the departure demand is shown by the TMAT (dashed black line).

The ramp throughputs are comparable in the beginning of the departure bank until when the arrival bank starts. The main difference in the departure ramp throughput can be seen during the arrival peak at around 9,200 secs into the simulation. The baseline model maintains the demand (black dashed line) while TRACC_PB shifts the demand to a later time (around 10,400 secs into the simulation). Similarly, the baseline simulation shows higher arrival throughput through the middle of the arrival bank (9,200 secs into the run). With TRACC_PB, on the other hand, arrival entry into the ramp area is delayed in the beginning of the arrival bank and the throughput regains later in the simulation (11,000 secs into the run). The operational concept for both baseline and TRACC_PB tools is to hold aircraft at the gates with engines off by shifting some excess taxi time from runway queue to the gates. The goal of TRACC_PB, in particular, is to provide conflict-free routes whereby the aircraft is able to taxi without stoppage. Therefore, the difference in throughput values will be reflected in the ramp taxi and gate hold times.

B. *Ramp taxi times*

Fig. 5 shows the ramp taxi times for baseline and TRACC_PB simulations for departures (Out) and arrivals (In). It is evident that the TRACC_PB simulation shows shorter ramp taxi times compared to the baseline simulation. The average and total values of ramp taxi times are shown in Table 2.

In the baseline simulation, departure aircraft spent 36 secs more on average and 2,296 secs (38.27 minutes) more in total for taxi in the ramp area compared to TRACC_PB, which has a reduction of 16.9% in average and 17.3% in total. Similarly, in the baseline simulation, arrival aircraft spent 20 secs more on average and 1,502 secs (25.03 minutes) more in total for taxi in the ramp area compared to TRACC_PB which shows 9.3% reduction on average and 9.2% in total.

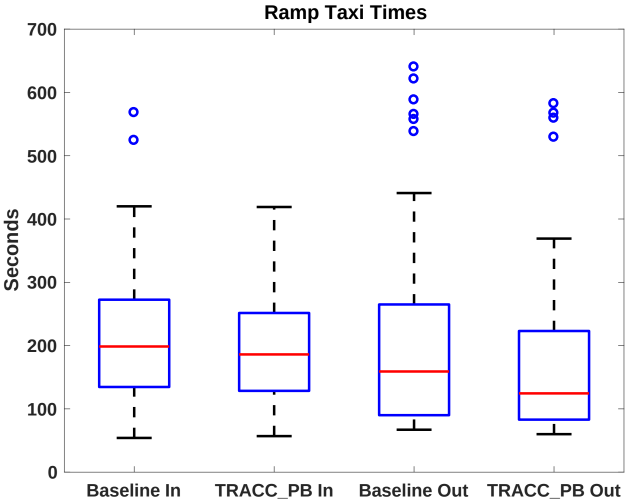

Fig. 5. Ramp taxi times of departures (Out) and arrivals (In)

TABLE 2. AVERAGE AND TOTAL RAMP TAXI TIMES (SECONDS)

	Baseline	TRACC_PB	Difference	
Average taxi-out time	213	177	36	16.9%
Total taxi-out time	13,238	10,942	2,296	17.3%
Average taxi-in time	215	195	20	9.3%
Total taxi-in time	16,370	14,868	1,502	9.2%

The CD&R function in SOSS was used in the baseline simulation to resolve conflicts between taxiing aircraft in the ramp area, which may slow down and stop the aircraft to avoid a conflict situation, thus resulting in longer taxi times.

TRACC_PB first attempts to solve for conflict-free ramp taxi routes for arrivals with the TMETs given by the baseline run. In the case that TRACC_PB is not able to produce a conflict-free route, TRACC_PB adjusts the TMET and holds the aircraft at the spot until the new TMET is reached, so that the aircraft is able to taxi to the gate without stoppage.

It is important to note that the baseline simulation used SOSS' nominal ramp taxi speed that depends on the aircraft type with 12 knots as the maximum speed. TRACC_PB, on the other hand, allowed the aircraft to taxi up to 15 knots to take advantage of conflict-free trajectories.

C. *Gate hold times*

Both baseline and TRACC_PB concepts provide operational benefits in terms of taxi efficiency and fuel/emissions savings by shifting some of the excess taxi time from runway queue to the gates. Fig. 6 shows the distribution of departure gate hold times realized by the baseline and TRACC_PB. The mean and total values of departure gate hold times, and the numbers of aircraft held at the gates are shown in Table 3. In the TRACC_PB simulation, departures were held at their gates 91 secs longer on average and 5,687 secs (94.78 minutes) longer in total compared to the baseline. It is evident that the gate hold times with TRACC_PB are longer (at least 20%) because TRACC_PB holds departures at the gates until conflict-free routes are available, whereas the baseline model tends to push back aircraft close to their assigned pushback times (TSATs). Interestingly, TRACC_PB held less aircraft at the gate than the baseline (i.e., 49 vs. 62), indicating the tendency to adhere to the original departure schedule, which may be seen as counter-intuitive. However, the number of aircraft held at the gate for a considerable amount of time (e.g., > 60 secs) was similar between the two simulations (i.e., 42 for TRACC_PB vs. 43 for baseline, numbers not shown in the table).

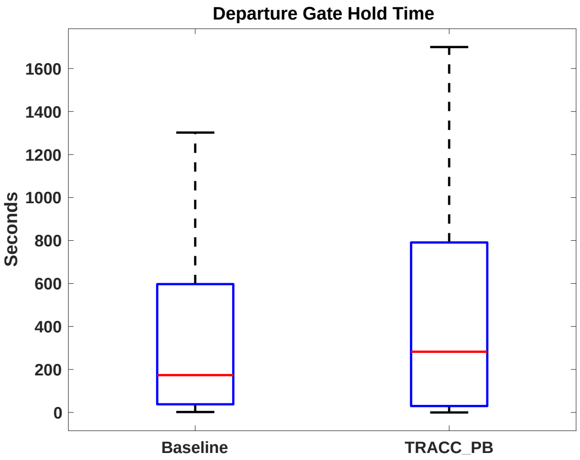

Fig. 6. Departure gate hold times

TABLE 3. AVERAGE AND TOTAL GATE HOLD TIMES

	Baseline	TRACC_PB	Difference	
Average gate hold times (sec)	360	451	91	20.2%
Total gate hold times (sec)	22,304	27,991	5,687	20.3%
Number of aircraft held	62 (all)	49	13	21.0%

It is important to note that the amount of gate hold times associated with each departure gate generated by TRACC_PB depends on the taxi route that leads to the assigned spot because every taxi route for the gate-spot pair has a different potential for conflicts due to ramp traffic patterns, which can cause the aircraft to stop.

D. Aggregate departure spot queue size

Fig. 7 shows the total number of departure aircraft taxiing in the ramp area between the baseline and TRACC_PB simulations at each instance of time, which also indicates the level of ramp congestion.

It is important to note that this is a cumulative view for all five departure spots (Fig. 2) without separating the result by departure spot. The figure shows that the numbers of taxiing aircraft between the two simulations are similar early in the departure bank until approximately 8,200 secs into the run. As the bank progresses, more departure flights are scheduled to push back, and the number of taxiing aircraft for the baseline remains high whereas that of TRACC_PB decreases. The aggregate queue size for TRACC_PB continues to decrease until 9,000-9,100 secs, where the difference between the two simulations reaches six aircraft, after which the queue size increases again. This occurs approximately at the same time when the difference in ramp throughput for departures and arrivals together between the two simulations has reached the maximum (Fig. 4). It is shown that the ramp departure queue/congestion period for TRACC_PB lasts six minutes longer than for the baseline (approximately 10,700 secs vs. 10,300 secs → difference of 400 secs) due to the fact that TRACC_PB's conflict-free routes have caused longer gate hold times, leading to taking more time to flush departures out of the ramp.

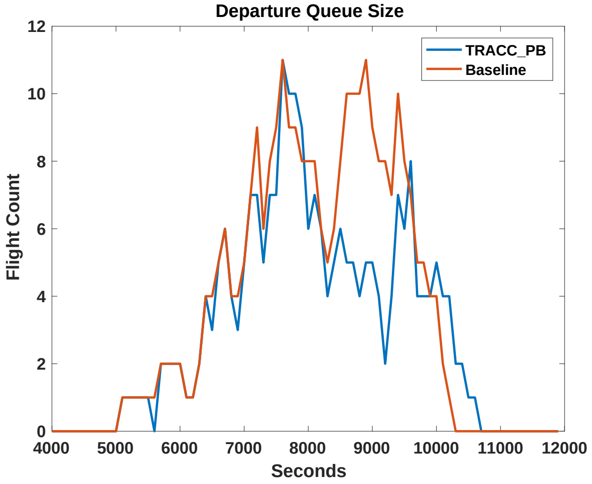

Fig. 7. Aggregate departure spot queue size

E. TMAT Compliance

TMAT compliance is defined as the difference between the TMAT and Actual Movement Area entry Time (AMAT) for individual aircraft. In this study, it indicates how the automation tool enables departures to meet their TMATs at assigned spots. The lower values indicate better compliance.

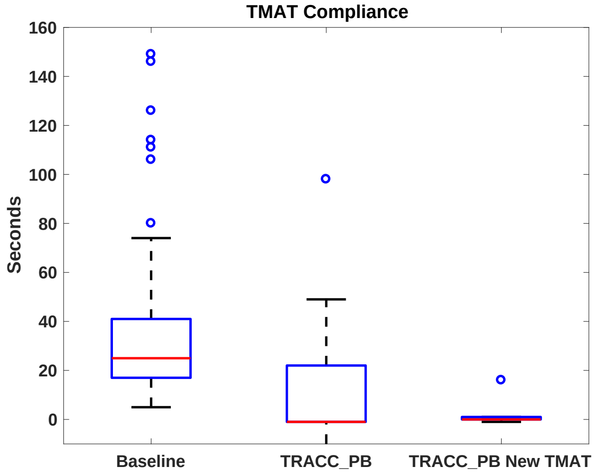

Fig. 8. TMAT Compliance of Baseline and TRACC_PB; The middle boxplot has eight more outliers going up to 1,200 secs and was cropped to improve readability.

Fig. 8 shows the comparison of TMAT compliance between the baseline and TRACC_PB simulations. The middle box plot shows the TMAT compliance of TRACC_PB with the original TMATs given by the baseline run. TRACC_PB shows the better compliance with the baseline given TMATs than the baseline case itself. Table 4 shows the comparison of TMAT compliance in percentile values up to the 90th percentile. It is noted that TRACC_PB outperformed the baseline in 80% of the situations.

TABLE 4. PERCENTILE VALUES OF TMAT COMPLIANCE (SECONDS)

Percentile	25th	50th	75th	80th	90th
Baseline	17	25	41	43	87
TRACC_PB	0	0	22	44	279

The right box plot in the figure shows the same metric of TRACC_PB with adjusted TMATs, which shows almost perfect compliance (except for one situation) as the aircraft are capable of following the command 4D trajectory precisely.

F. Environmental benefits

To estimate the environmental benefits, the total amounts of fuel burn and gas emissions in the ramp are computed for the baseline and TRACC_PB simulations, as shown in Table 5. These calculations are based on ramp taxi times from two simulations and engine emission certification data from ICAO [33], with the assumption that two engines are running at a 7% thrust setting during the taxi phase.

TABLE 5. TOTAL FUEL BURN AND EMISSIONS (KG)

	Simulation	Fuel	CO_2	HC	CO	NOx
Departure	Baseline	2,116.05	6,517.43	4.27	46.28	9.42
	TRACC_PB	1,739.68	5,358.21	3.36	37.55	7.76
	Difference (%)	376.37 (17.8%)	1,159.22 (17.8%)	0.91 (21.3%)	8.73 (18.9%)	1.66 (17.6%)
Arrival	Baseline	2,680.64	8,256.36	6.84	64.13	11.88
	TRACC_PB	2,410.19	7,423.38	5.59	56.56	10.65
	Difference (%)	270.45 (10.1%)	832.98 (10.1%)	1.25 (18.3%)	7.57 (11.8%)	1.23 (10.4%)

In Table 5 it is shown that with TRACC_PB there is a reduction of fuel and emissions by at least 10% for arrivals and 17% for departures. Because emissions are directly proportional to the taxi time, their reduction fits to the ramp taxi times of both departures and arrivals.

V. SUMMARY AND FUTURE WORK

As part of the collaborative research investigating different airport traffic management concepts and tools developed by the research teams of DLR and NASA, an integrated simulation using NASA's fast-time simulation engine, SOSS, together with DLR's surface management tool for ATC ground control, TRACC, was conducted. As the first step of the integrated simulation study, feasibility and potential benefits of conflict-free taxi trajectories in ramp operations at a busy airport using DLR's TRACC were analyzed. In doing so, TRACC_PB was derived from the TRACC tool to facilitate conflict-free taxi trajectories using speed profile variations on fixed standard taxi routes in the ramp. Two simulation runs were conducted for the ramp area of Charlotte Douglas International Airport. The baseline simulation, representing a near-term surface management tool, was conducted using a runway scheduler derived from components of NASA's surface scheduler connected to SOSS that calculated the runway departure and gate pushback schedules (i.e., TSATs, and TMATs). The simulation for TRACC_PB was connected to SOSS and the TMATs from the baseline simulation were used as a constraint.

For both simulation runs, a set of metrics adapted from ICAO KPAs and CANSO's KPIs, including capacity, efficiency, predictability and environment, was measured and compared. Both scheduling tools aimed to reduce the environmental impact and increase efficiency by holding aircraft at the gate with engines off. The simulation results showed that TRACC_PB achieved shorter taxi times, and thus less fuel consumption and engine emissions, than the baseline case by facilitating conflict-free taxi routes, enabling aircraft to taxi at higher speeds without stoppage in the ramp area. However, the ramp throughputs for departures and arrivals were shifted to later times because of aircraft holding longer at the gate and the entering spot. It was noticed, however, that the sum of total times of both departures and arrivals for TRACC_PB simulation, including ramp taxi time, and arrival spot waiting time, was higher than those from the baseline simulation. The idea of holding arrival aircraft at the entering spot was regarded as a tentative solution for TRACC_PB to enable conflict-free ramp taxi routes for arrivals. Ideally, TRACC_PB would have solved for conflict-free trajectories with both route and taxi speed as decision variables for optimization. Further investigation is warranted to explore better solutions that would avoid aircraft waiting at the entering spot. Both baseline and TRACC_PB simulations showed a good TMAT compliance according to the current S-CDM suggestions (e.g., ±5 minutes). Results indicated that TRACC_PB achieved a better compliance than the baseline in 80% of situations.

The concept of TRACC_PB is still regarded as a far-term 4DT concept even though TRACC_PB was simplified from the more sophisticated TRACC to only provide the speed variations on standard taxi routes for gate-spot pairs to facilitate conflict-free taxi. The implementation of 4D taxi trajectories with speed control exceeds the scope for current day airport surface operations. However, the research community has already begun exploring new technologies for achieving 4DT surface operations that can bring significant benefits in terms of environmental and economic impacts. For example, Taxibots and electric taxi are currently being explored to support the implementation of command speed profiles. On the flight deck side, pilot-in-the-loop simulations have been conducted and showed promising results where pilots with a proper guidance display were able to follow the 4D taxi routes generated by the TRACC tool with high conformance [34].

Further research activities under the collaboration between NASA and DLR include the investigation of uncertainties in the taxi process to provide robust taxi schedules and the investigation of off-nominal conditions. One of the critical aspects in implementing the concept of trajectory-based taxi operations, described in [20], is the execution of 4D taxi trajectories by the flight deck. Further analysis will be conducted to balance the research between ground-based decision support tools and the flight deck automation.

ACKNOWLEDGMENT

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