GREENER CONFLICT-FREE TAXI TRAJECTORIES USING GENETIC ALGORITHMS

L. Tyburzy*, M. Schaper*, L. Nöhren*, K. Muth*

* German Aerospace Center, Controller Assistance, Institute of Flight Guidance, Lilienthalplatz 7, 38108, Braunschweig, Germany

Abstract

In order to reach the goals of the Paris Agreement, it has become evident that it is necessary to reduce the impact of the whole aviation sector on the environment. The project GreAT (Greener Air Traffic Operations) aims to showcase how a combination of advanced air traffic management tools and procedures for departure, en-route, arrival and surface operations can support this reduction of aviation's environmental impact. For the surface operations of aircraft at the airport, the surface management system TraMICS+ (Traffic Management Intrusion and Compliance System Plus) has been developed to support ground controllers with a security situation assessment and trajectory advisories for taxi operations. TraMICS+ uses a genetic algorithm to plan and adjust taxi-trajectories in real time to resolve conflicts between aircraft on the ground, with the aim to reduce holding time after engine startup as well as preventable braking and acceleration actions due to other traffic. This paper presents a case study, comparing different configuration profiles for generating conflict-free trajectories using TraMICS+ and Hamburg airport topology. By using a trajectory configuration profile with higher penalties for holds during the taxi phase, it was possible to create more efficient taxi trajectories with 80 percent fewer holds.

Keywords

Air Traffic Management; Controller Support; Surface Management; Environment

1. GREENER SURFACE OPERATIONS FOR AIRCRAFT

Within the European funded project GreAT [1], different procedures and assistance systems for air traffic controllers (ATCOs) are investigated, to showcase the potential improvements towards more climate friendly air traffic operations. One of the areas concerned with the increasing need to lower environmental impact are the surface operations of aircraft at airports, specifically the taxi movements from an aircraft's assigned gate to its assigned runway and vice-versa. While in comparison with other flight phases (take-off, climb, en-route and descent) the fuel consumption during taxi operations is much lower [2], there is also lot of potential to reduce the environmental footprint of taxi operations, by delaying engine startup, reducing idle engine running time and optimizing taxi trajectories.

When observing taxi operation at airports, the default technique used by ATCOs to resolve conflicts during taxi operations is often "hold short and give way to...", meaning aircraft will frequently stop at intersections to let other aircraft pass. While this technique makes use of the fact that aircraft on the ground — unlike airborne counterparts — can actually stand still, it also means that aircraft lose their momentum and need to accelerate again. Depending on engine type, aircraft weight or surface properties, this can require an additional amount of thrust compared to constant aircraft movement, leading to more wear and tear on the engines and increased fuel consumption. Both commonly used models to estimate fuel consumption, Eurocontrol´s Base of aircraft data (BADA) [3] and the Landing and Take-off (LTO) cycle [4] published in the International Civil Aviation Organization (ICAO) engine emission database [5], do not consider the impact of these stop-and-go phases on fuel consumption. Nonetheless, a recent study estimates that up to 18 percent of the fuel consumed during the taxi phase can be attributed to stop-and-go actions [6].

This paper investigates how a modern surface manager (SMAN) can be configured to calculate taxi trajectories that are conflict-free and additionally minimize the number of stops, which can be used by ATCOs to provide safe and efficient taxi instructions to aircraft.

2. THE TRAFFIC MANAGEMENT INTRUSION AND COMPLIANCE SYSTEM PLUS

The TraMICS+ software has been developed by DLR as a prototypical SMAN connected to a surface traffic situation display for the usage in different research

doi: 10.25967/610520

projects. It consists of a security component with conformance monitoring and an SMAN component providing the trajectory calculation.

2.1. Conformance Monitoring

The security component with conformance monitoring allows the system to monitor aircraft behavior and generate alerts for non-conformant behavior, such as route deviation or taxiing without clearance. The number of alerts is monitored and used to calculate a security situations indicator, which can help the ATCO and other stakeholders to detect possible security incidents. For a more detailed description of this security component, see [7] and [8].

2.2. Taxi Trajectory Calculation

For the purposes of this paper, the relevant functionality of TraMICS+ are the automatic planning and calculation of taxi trajectories for aircraft, that are part of the SMAN component. Genetic algorithms have been shown to be an efficient technology in the calculation of conflict-free taxi trajectories [9–11]. TraMICS+ builds on this technology with an adapted algorithm: In a first step, TraMICS+ calculates the shortest route from an aircraft's designated stand to the designated runway entry (or runway exit for arrivals, respectively), using a multiobjective A*-algorithm [12]. This algorithm optimizes the initial route for distance and sharpness of turns, preferring routes with fewer and less sharp turns. In a second step, the initial routes are used to generate initial trajectories, by computing the necessary taxi times assuming a standard speed of 15 kt as well as considering available planning times in the flight plan. These planning times are either estimated landing times (ELDTs) for arrivals, or target take-off times (TTOTs), scheduled off-block times (SOBTs) or target off-block times (TOBTs) for departures, depending on configuration and availability.

In a last step, all generated trajectories are checked for conflicts with other trajectories. If a conflict is found, a genetic algorithm is used to generate new modified trajectories based on the initial trajectory to solve conflicts. Modifications for new trajectories can include holds, route changes, or speed changes for certain taxiways. Holds can be inserted in the trajectory at the gate before engine startup, in front of intersections or at certain points on taxiways to enable pushback operations. The speed changes include fast taxiing (about 20 kt), slow taxiing (about 10 kt) or use the default speed of 15 kt. Lastly, changes to the initial taxi route can be made to avoid conflicts. The new trajectories are then evaluated using a penalty function to find the best trajectory. This penalty function uses different parameters that can be configured, thus enabling the creation of different trajectory profiles. The following parameters are configurable (adapted from [13]):

- W1 – Conflict weight: The weight for all remaining conflicts that exist in the solution. Each conflict has a severity between one and two which are summarized and afterwards multiplied with this weight. The severity of a conflict is defined as follows:

$$S = \left(1 - \frac{sDist_C}{sDist_T} + 1 - \frac{tDist_C}{tDist_T} + 2\right)/2 \tag{1}$$

  Where $sDist_C$ is the spatial distance of the two flights in the conflict, $sDist_T$ is the spatial distance threshold, $tDist_C$ is the temporal distance in the conflict and $tDist_T$ is the temporal distance threshold for conflicts.
- W2 – Duration weight: This weight is multiplied with the increase of the taxi duration due to additional holding time along the trajectory compared to the initial trajectory calculation.
- W3 – Hold weight: The number of holds that were inserted in the solution is multiplied with this weight. Holds that are operationally necessary, like the hold at the end of the push back until all engines are up, are not considered.
- W4 – Speed change weight: This weight is added for every time the speed of the flight changes. This does not include necessary speed changes for curves, but rather just changes to the base speed.
- W5 – Fast point weight: The weight for every point in the trajectory where the flight should move fast, which is assumed to increase fuel consumption.
- W6 – Slow point weight: The weight for every point in the trajectory where the flight should move slow.
- W7 – Existing trajectory weight: This weight is applied for every previously calculated trajectory that was modified by the genetic algorithm to create this solution.
- W8 – Route change weight: This weight is multiplied with the number of flights for which the optimal route calculated by the multiobjective A* algorithm was changed during the optimization.
- W9 – Stand hold weight: This weight is multiplied with the sum of additional waiting times at the stand of departures.
- W10 – Big delay weight: A threshold can be configured at which the taxi delay calculated for W2 and W9 is considered as "big delay", ensuring that no single flight is simply delayed by a very large amount of time to solve conflicts.

TraMICS+ achieves an average calculation time per trajectory of under 0.5 seconds on standard consumer hardware, allowing the software to solve most conflicts in real time. A more detailed description of the technical background of the whole trajectory calculation process, including the evaluation of trajectory calculation times, can be found in [13].

3. CASE STUDY

To evaluate the reduction of holding times after engine startup as well as preventable braking and accelerating actions, a case study consisting of several simulation runs with three different traffic scenarios and two different configurations of the penalty function used during the trajectory calculation was conducted.

3.1. Simulation Environment

The simulations were conducted using the NARSIM (NLR ATC Research Simulator) [14] configured for Hamburg airport (EDDH/HAM). For this case study, the simulation runs were conducted in an automatic fashion, without humans in the loop. For the result analysis, it was assumed that the trajectories planned by TraMICS+ are followed by the pilots, and that no delays or non-conformant behavior occur, that could cause a replanning of the trajectories.

3.2. Traffic Scenario Configuration

Three different traffic scenarios with a duration of one hour were used for the evaluation of the trajectories. Based on real traffic mix, a low traffic density scenario with 23 aircraft and a medium traffic density scenario with 36 aircraft were created. For the medium traffic density scenario, two hours of traffic were matched to one hour. Additionally, a high traffic density scenario with 45 aircraft was designed artificially, but with a comparable traffic mix. All scenarios contained roughly a balanced ratio of departures and arrivals.

The flight plans for the departing aircraft contained SOBTs as well as TOBTs. The SOBTs were grouped in five minute blocks, as is often the case with regular static flight plans. This means that for each five-minute block, it was possible that multiple departures were scheduled with identical SOBTs, leading to potential trajectory conflicts during pushback or the subsequent taxi phase. In contrast, TOBTs are better separated in time, so that the potential for conflicts during taxi is lower if TOBTs are followed instead of SOBTs. For the case study, the TOBTs in the flight plans were precalculated and frozen before scenario start. For each scenario, two separate configurations were used: The default configuration used SOBTs as starting point for the trajectories, whereas the *precision* configuration used the TOBTs. For the arrivals, the ELDTs were used as the starting point to calculate the trajectories. These ELDTs remained the same for both default and *precision* configuration.

3.3. Trajectory Profiles

As mentioned before, the penalty function for TraMICS+ trajectory generator can be configured using different parameters, allowing for the creation of different trajectory profiles. Based on previous experiments with TraMICS+ [13], a *conventional* profile and a *green* profile have been developed. The *conventional* profile focuses on planning the trajectories relatively close to the SOBTs or TOBTs, minimizing the delay at the stand at the cost of possibly having to introduce some holds in the trajectory to let other aircraft pass. The *green* profile increases the penalty for stops during taxi, while simultaneously lowering the penalty for delayed startup at the stand, thereby aiming to reduce the number of necessary holds. The values chosen for the *conventional* and *green* profiles can be found in table 1.

TAB 1. Overview of the weights of the penalty function for the *conventional* and *green* trajectory profiles. Changes in parameters from the *conventional* profile in the *green* profile are marked in bold type.

Penalty Weight	Conventional	Green
W1 – Conflict weight	10000	10000
W2 – Duration weight	10	**5**
W3 – Hold weight	500	**2000**
W4 – Speed change weight	200	200
W5 – Fast point weight	25	**50**
W6 – Slow point weight	25	25
W7 – Existing trajectory weight	1000	1000
W8 – Route change weight	1000	1000
W9 – Stand hold weight	5	**2**
W10 – Big delay weight	1000	**500**

3.4. Analysis

For the evaluation of the trajectories, the TraMICS+ software was started with either the *conventional* or the *green* profile in both default and *precision* configuration, yielding four different setup combinations(see 1). Each of these setup combinations was run with each of the three traffic scenarios. Since the genetic algorithm used for conflict resolution works non-deterministically, leading to slightly different trajectories, each combination of setup and traffic scenario was run five times and the results averaged over these five runs. Upon receiving the flight plans and aircraft data, the initial trajectories were generated and conflicts resolved. The conflict-free trajectories were exported in JSON-format and used for the result analysis.

4. RESULTS

As main indicator for the comparison of the different scenario/trajectory profile combinations, Figure 2 shows the total number of holds during the taxi phase, averaged over five executions of the trajectory planning and conflict resolution for each combination. Here, a hold is defined as an aircraft being completely stationary for any amount of time after engine startup, which would require braking and subsequent acceleration.

The results are grouped into three blocks, corre-

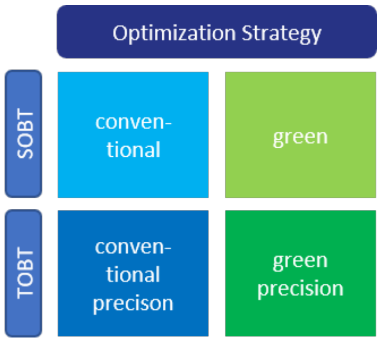

FIG 1. Overview of the four different setup combinations for TraMICS+ software used in the analysis

sponding to the different traffic scenario runs with low (left), medium (middle) and high (right) traffic density. Within each block, the two bars on the left show the number of holds with departure trajectories calculated based on SOBTs (light blue and light green), while the two bars on the right (dark blue and dark green) show the number of holds for trajectories calculated based on TOBTs in the (*precision*) scenario configuration. The (light and dark) blue bars correspond to the *conventional* trajectory profile and the (light and dark) green bars correspond to the *green* trajectory profile, which was optimized for reducing the number of holds.

Not unexpectedly, the low-density traffic scenarios required nearly no holds to resolve conflicts in any configuration. The medium and high density scenarios however indicate a significant reduction in the number of holds for the *green* profile in comparison with the *conventional* profile, for both SOBTs and TOBTs. In this particular case study, one low density traffic scenario and *precision* planning times actually required a hold in one of the trajectories to resolve a conflict for both trajectory planning profiles. Since the other runs of the same configuration did not contain a hold at all, this can be attributed to the non-deterministic calculations by the genetic conflict-solving algorithm used by TraMICS+. The slightly higher number of holds in some configurations in the medium traffic scenario indicates, that the pre-calculated TOBTs in the *precision* configuration used as basis for the trajectory calculation, did not lead to a major reduction of the number of holds. Nonetheless, the *green* profile did lead to a reduction of the number of holds, even with sub-optimal planning times as basis. The most significant difference can be seen in the comparison of the *conventional* and *green* profiles in the high density traffic scenario using SOBTs as planning times, leading to a reduction of the number of holds from 4.4 to only 0.8 on average. The corresponding precision planning in the high density traffic scenario resulted in only 1.0 holds on average with the *conventional* profile and 0.2 holds for the *green* profile.

Over the total 30 simulation runs that used the *green* profile paired with different traffic density and planning times combinations, only one run with the *green* profile produced a higher number of holds compared to runs using the *conventional* profile with the same combination. This indicates that despite the non-deterministic genetic trajectory calculation algorithm, the *green* profile quite consistently produces more efficient trajectories in regards to the number of holds than the *conventional* profile.

An additional analysis of the total engine-on taxi time revealed, that on average the *green* profile led to a small increase in overall taxi-time. A probable explanation for this is, that instead of inserting a hold at an intersection, the *green* profile is more likely to calculate a different route with a slightly longer distance or sections with reduced taxi speed. For the trajectories based on SOBTs, the maximum increase was 4.39% (see table 2), while the trajectories based on TOBTs did only increase the taxi time by a maximum of 3.87% (see table 3).

TAB 2. Avg. Total Taxi Time for SOBT-based Trajectories [s]

	Conventional	Green	Change [%]
Low	293.6	306.5	+4.39
Medium	315.1	320.1	+1.59
High	316.3	324.1	+2.47

TAB 3. Avg. Total Taxi Time for TOBT-based Trajectories [s]

	Conventional	Green	Change [%]
Low	286.1	295.9	+3.42
Medium	291.6	302.9	+3.87
High	297.2	306.1	+2.99

Unfortunately, the results of the trajectory analysis could not be used to conduct a meaningful quantification of the estimated fuel consumption. The available model by BADA uses only the taxi times as a parameter to calculate fuel consumption. Therefore, the improvements in number of holds would not have been considered at all. The same goes for the ICAO approach of using the fuel consumption at idle thrust settings, which also only considers taxi time. However, the lower number of average holds with only a minimal increase in taxi time is a clear indication that the *green* profile is more efficient and can contribute to more environmental-friendly taxi operations.

5. CONCLUSION AND OUTLOOK

The case study presented in this paper has shown that assistance tools for surface management like TraMICS+ can improve the efficiency of taxi operations by calculating conflict-free trajectories. By using a conflict resolution algorithm with a parameterized optimization function, it was possible to use a *green* profile for the trajectory generation. This profile was

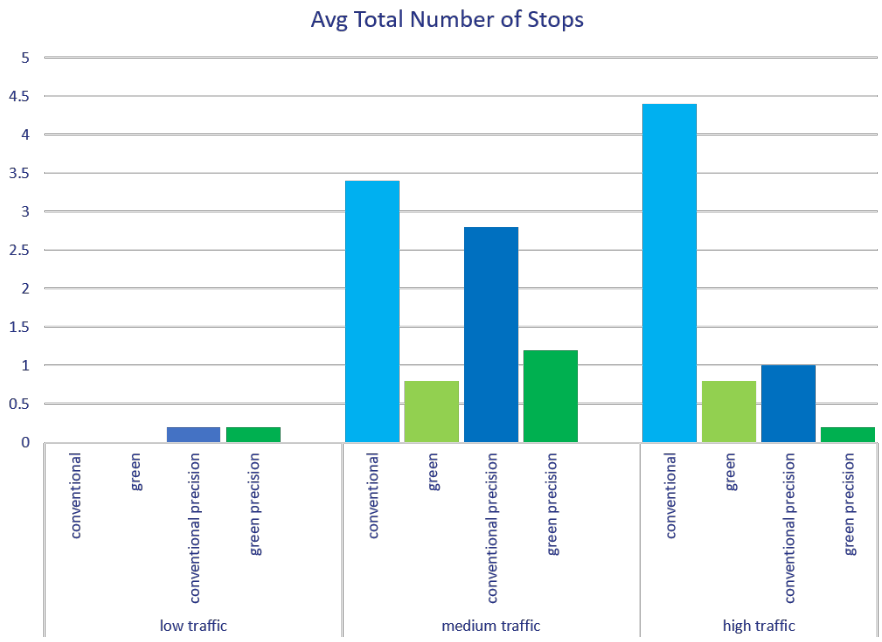

FIG 2. Average total number of planned stops in the taxi trajectories for each scenario

configured to prefer holding aircraft at their stand before engine startup and includes higher penalties for holds during normal taxi. This resulted in a reduction of the number of holds by 80% in high-density traffic scenarios, compared to a *conventional* optimized trajectory profile. Furthermore, the *green* profile consistently produced trajectories with fewer holds than the *conventional* profile, regardless of traffic density and planning times. Meanwhile, the total taxi time did increase only marginally. This suggests a decrease in the environmental impact of taxi operations by saving the fuel needed for frequent braking and subsequent acceleration with higher thrust settings.

These results encourage further exploration of the potential of SMAN software to enable greener taxi operations. It is worth mentioning that both the *conventional* profile as well as the *green* profile presented here represent optimized taxi trajectory solutions. Therefore, it can be expected that the benefits are even greater when compared to non-optimized solutions. Specifically, a validation of the planned conflict-free trajectories calculated by TraMICS+ in human-in-the-loop simulation and a comparison with a baseline traffic scenario without optimized trajectories could provide more information about the benefits offered by such a system, but was outside the scope of this paper. To more precisely evaluate the improvement of the environmental impact, however, it is also imperative to create a more precise model than BADA or ICAO´s LTO cycle for estimating the fuel consumption during taxi operations, that can indicate the additional fuel consumed with higher thrust settings during acceleration.

Other opportunities to expand on this work include the development of new assistance features for ATCOs and pilots alike, such as advisory indications, that allow them to precisely execute the planned trajectories, thus ensuring an optimal taxi traffic flow that follows the initial planning.

Acknowledgment

The project on which the presented research is based has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 875154. The responsibility for the content of this publication lies with the authors.

Contact address:

lukas.tyburzy@dlr.de

References

[1] Great: Greener air traffic operations. https://www.project-great.eu/. Accessed: 2023-08-24.

[2] Paola Di Mascio, Maria Vittoria Corazza, Nicolò Rocco Rosa, and Laura Moretti. Optimization of aircraft taxiing strategies to reduce the impacts of landing and take-off cycle at airports. *Sustainability*, 14(15), 2022. ISSN: 2071-1050. DOI: 10.3390/su14159692.

[3] Eurocontrol. Base of aircraft data (bada) product management document. Technical Report 2009-008, 2009.

[4] International Civil Aviation Organization. International standards and recommended practices, annex 16, environmental protection: Aircraft en-

gine emissions, vol. 2, 4th ed. Technical report, Montreal, 2017.

[5] International Civil Aviation Organization. Aircraft engine emissions databank. https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank. Accessed: 2023-08-24.

[6] Tasos Nikoleris, Gautam Gupta, and Matthew Kistler. Detailed estimation of fuel consumption and emissions during aircraft taxi operations at dallas/fort worth international airport. *Transportation Research Part D: Transport and Environment*, 16(4):302–308, 2011. ISSN: 1361-9209. DOI: https://doi.org/10.1016/j.trd.2011.01.007.

[7] Meilin Schaper, Olga Gluchshenko, Kathleen Muth, Lukas Tyburzy, Milan Rusko, and Marián Trnka. The traffic management intrusion and compliance system as security situation assessment system at an air traffic controller's working position. In *31st European Safety and Reliability Conference, ESREL 2021*, pages 2825–2831, 2021.

[8] Meilin Schaper, Hilke Boumann, Lennard Nöhren, Lukas Tyburzy, Kathleen Muth, and Nils Carstengerdes. Validation of the traffic management intrusion and compliance system as security-awareness-component at the controller working position. In *Deutscher Luft- und Raumfahrtkongress (DLRK) 2022*, 2022.

[9] Meilin Schaper and Ingrid Gerdes. Trajectory based ground movements and their coordination with departure management. In *2013 IEEE/AIAA 32nd Digital Avionics Systems Conference (DASC)*, pages 1B4–1–1B4–9, 2013. DOI: 10.1109/DASC.2013.6712510.

[10] Ingrid Gerdes and Annette Temme. Taxi routing for aircraft: Creation and controlling. *The Second SESAR Innovation Days*, 2012.

[11] Ingrid Gerdes and Meilin Schaper. Management of time based taxi trajectories coupling departure and surface management systems. In *11th ATM Seminar*, Juni 2015.

[12] Peter E. Hart, Nils J. Nilsson, and Bertram Raphael. A formal basis for the heuristic determination of minimum cost paths. *IEEE Transactions on Systems Science and Cybernetics*, 4(2):100–107, 1968. DOI: 10.1109/TSSC.1968.300136.

[13] Lennard Nöhren, Meilin Schaper, Lukas Tyburzy, and Kathleen Muth. Real-time calculation and adaption of conflict-free aircraft ground trajectories. In *33rd Congress of the International Council of the Aeronautical Sciences, ICAS 2022*, September 2022.

[14] J.M. ten Have. The development of the nlr atc research simulator (narsim): Design philosophy and potential for atm research. *Simulation Practice and Theory*, 1(1):31–39, 1993. ISSN: 0928-4869. DOI: https://doi.org/10.1016/0928-4869(93)90009-F.