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SUSTAINABLE GROUND MOVEMENT AND ITS OPERATIONAL IMPACT

Presented by TOC

SUMMARY

A new procedure called sustainable ground movement is being considered, wherein a TaxiBot pulls the aircraft towards the runway. This essentially allows the aircraft to taxi out, without turning on its engines. This aims to reduce emissions and improve local air quality. This working paper examines its viability and how this will impact the operations of both air traffic controllers and pilots.

1. INTRODUCTION

1.1. In response to the 2015 Paris Agreement, the Dutch Government established a Climate Agreement with an emission reduction objective for the Netherlands. The country aims to reduce national greenhouse gas emissions by 49% in 2030 relative to the 1990 level[1]. All sectors shall contribute to this including the aviation sector.

1.2. The Dutch aviation industry created a plan called 'Slim én Duurzaam' or 'Smart and Sustainable'[2]. The objective is to lower the CO_2 emissions in 2030 relative to 2020. One plan is to introduce electric alternatives for heavy equipment such as cargo and ground. Another plan is to focus on the electric pushback/taxi concept for an aircraft, planned between 2021 and 2025[3]. Pushback and taxiing an aircraft are some of the contributors to carbon emissions.

1.3. The Netherlands' aviation sector presented the Minister of Infrastructure and Water Management with a roadmap to significantly reduce fuel consumption, CO_2, nitrogen, and ultra-fine particulate matter from aircraft taxiing to the active

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[1] Air Transport Action Group, Waypoint 2050, 2021 [PDF] Retrieved from https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

[2] Actieplan Slim én Duurzaam, 2022 [PDF] Retrieved from https://www.nlr.nl/wp-content/uploads/2022/06/Slim-en-duurzaam-update-2022.pdf

[3] Luchtvaart Nederland. (2018). Slim én duurzaam. Retrieved July 9, 2024 from https://acn.nl/wp-content/uploads/2019/11/Actieplan-slim-en-duurzaam.pdf

runway. The goal is to make sustainable taxiing a standard procedure at Amsterdam Schiphol Airport by 2030 at the latest.

1.4. This paper presents Schiphol Airport's sustainable ground movement pilot program in Amsterdam, the Netherlands. The methods, materials, and proposed procedures will be studied to determine how they will affect the air traffic procedures at Schiphol Airport, the benefits and net gain from offsetting carbon emissions and reducing harmful emissions to create a ‘green zone’, and the effects of implementing this new procedure with the air traffic controllers and pilots operating at Schiphol Airport.

2. DISCUSSION

2.1. CONCEPTUALIZING SUSTAINABLE GROUND MOVEMENT

2.2. According to Lukic et al., the pushback/taxi concept will be the technology that will help in lowering carbon emissions. There's a need for support of on-board or external systems[4]. Therefore, it is paramount to know the following:

2.2.1. The airport industry emission contribution of ground support equipment and airport aircraft movements.

2.2.2. Several pushback/taxi concepts.

2.2.3. The sustainable propulsion by biodiesel, hydrogen, or green electricity on which the pushback/taxi concept is propelled to make it sustainable.

2.3. The pushback procedure contributes to carbon emissions by using fossil fuel power to propel the pushback truck to push the aircraft on the apron towards the start-up points, while attached to the nose landing gear. The amount of emissions depends on the needed power, size, and speed of the truck, aircraft type, and the airport’s infrastructure[5]. Greenhouse gases such as Carbon monoxide and dioxide (CO and CO_2), nitrogen oxide (NO_x), hydrocarbons (HC), hydrogen (H_2), sulphur dioxide (SO_2), and particulate matter (PM) are emitted during the usage of Ground Support Equipment (GSE) and movement of aircraft[6].

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[4] Lukic, M., Hebala, A., Giangrande, P., Galea, M., & Nuzzo, S. (2019). Review, Challenges, and Future Developments of Electric Taxiing Systems. IEEE Transactions on Transportation Electrification, 5(4), 1441-1457.

[5] Skybrary. (2019, June 23). Pushback. Retrieved July 9, 2024, from Skybrary: https://www.skybrary.aero/index.php/Pushback

[6] Xu, H., Fu, Q., Yu, Y., Liu, Q., Pan, J., Cheng, J., Liu, L. (2020). Quantifying aircraft emissions of Shanghai Pudong International Airport with aircraft ground operational data. Environmental Pollution, 261, 114-115.

2.4. Winther et al. stated that GSE contributes to about 9% of the total Nitrous oxide emissions of aircraft main engines, Auxiliary Power Unit (APU), and handling equipment at Copenhagen Airport[7]. It is noted that the taxiing procedure accounts for the most actual operational fuel mass consumed in the Landing and Take-off (LTO) cycle[8]. The LTO Cycle consists of phases representing landing, approach, taxi/idle, take-off, and climb of an aircraft up to 915-metre height above the runway. Nevertheless, the taxi phase is responsible for 70% of total emissions in the LTO cycle[9].

2.5. Several actions already have been taken to reduce emissions of GSE and aircraft movements, such as single-engine taxiing, operational tow-outs, advanced queue management, pushback rate control, collaborative departure queue management, spot and runway departure advisor, and various other optimization techniques[10]. All of these contribute to reduced fuel usage and emissions, still, fossil fuel power and engines are used, which results in emissions.

2.6. PUSHBACK PROCEDURE

2.6.1. After boarding and/or loading up the cargo, the crew will close the doors, and the air bridge will be disconnected from the aircraft. In most airports, the aircraft is unable to leave the nose-in parking stand while facing the terminal building. Jet-engine aircraft are prohibited to reverse thrust from a parking stand due to increased noise levels, CO_2 production, maintenance costs, and risks of Foreign Object Damage (FOD), which causes safety risks and damage to the aircraft stand.

2.6.2. During this procedure, the pushback truck also consumes fuel and produces emissions. The pushback truck is part of GSE which the consumed fuel and emissions depend on[11]:

2.6.2.1. number of movements at the airport;

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[7] Winther, M., Kousgaard, U., Ellermann, T., Massling, A., Nøjgaard, J. K., & Ketzel, M. (2015). Emissions of NOx, particle mass and particle numbers from aircraft main engines, APU's and handling equipment at Copenhagen Airport. Atmospheric Environment, 100, 218-229.

[8] Balakrishnan, H., & Deonandan, I. (2010). Evaluation of strategies for reducing taxi-out emissions at airports. 10th AIAA Aviation, Technology, Integrations, and Operations Conference. Fort Worth.

[9] Kesgin, U. (2006). Aircraft emissions at Turkish Airports. Energy, 31(2-3), 372-384. Retrieved July 9, 2024

[10] Ashok, A., Balakrishnan, H., & Barret, S. R. (2017). Reducing the air quality and CO2 climate impacts of taxi and takeoff operations at airports. Transportation Research Part D: Transport and Environment, 54, 287-303.

[11] Postorino, M. N. (2010). Environmental effects of airport nodes: a methodological approach. International Journal of Sustainable Development and Planning, 5(2), 192-204.

2.6.2.2. flight schedules;

2.6.2.3. airside size and configuration;

2.6.2.4. vehicle configuration;

2.6.2.5. aircraft type;

2.6.2.6. GSE type;

2.6.2.7. fuel type;

2.6.2.8. GSE operating time;

2.6.2.9. horsepower;

2.6.2.10. load factor; and

2.6.2.11. age.

2.6.3. For context, based on the published study by Postorino[12] et al., and Yang[13] et al., 1% of airport CO_2 emissions was produced by GSE in 2016 at Bologna Airport and 4.3% at Beijing Capital International Airport. This is directly proportional to the number of aircraft movements. Bologna only had 69,697 movements in 2016, while Beijing Capital International Airport had 590,169 aircraft movements in 2015.

2.6.4. Consequently, GSE emissions at Beijing Airport are higher than those at Bologna Airport due to the volume of aircraft movements. This is attributed to Beijing Airport's larger airside size and configuration, more extensive flight schedule, greater variety of aircraft types, and longer GSE operating times.

2.6.5. However, these emissions pertain to GSE rather than pushback equipment. Pushback equipment contributes 9.5% of NO_x and PM emissions from all handling equipment, but only 0.8% of NO_x and PM emissions from the total airport emissions[14]. This is similar to the 1% of total airport GSE CO_2 emissions observed at Bologna Airport.

2.7. TAXIING

[12] Ibid.

[13] Yang, X., Cheng, S., Lang, J., Xu, R., & Lv, Z. (2018). Characterization of aircraft emissions and air quality impacts of an international airport. Journal of Environmental Sciences, 72, 198-207.

[14] Winther, M., Kousgaard, U., Ellermann, T., Massling, A., Nøjgaard, J. K., & Ketzel, M. (2015). Emissions of NOx, particle mass, and particle numbers from aircraft main engines, APU, and handling equipment at Copenhagen Airport. Atmospheric Environment, 100, 218-229.

2.7.1. When the aircraft is pushed back from the stand, it is therefore ready to taxi towards the active runway. This procedure is called taxi-out, while taxi-in refers to an aircraft taxiing to the stand after landing. The taxi procedure is a phase within the flight and LTO cycle, consisting of the landing, approach, take-off, and climb phases[15]. Conventionally, the aircraft moves on its power by using its engines, hence, no additional vehicle is needed to move the aircraft.

2.7.2. There are two methods of taxiing: conventional and single-engine taxiing. The conventional pushback procedure starts with the aircraft being connected to a tug, and the flight crew coordinating with ground control and the tug operator for clearance. The tug then moves the aircraft in reverse, guiding it safely away from the gate and aligning it with the taxiway, while engines are started if required. Once complete, the tug is disconnected, and ground personnel ensure the area is clear before signalling the flight crew to proceed. Using single-engine taxiing, the life of the engine is extended, less fuel is used, and fewer emissions are produced[16]. This measure is used to make airports and airline companies more sustainable. However, fuel is still consumed, and emissions are still produced nonetheless.

2.7.3. The emissions and fuel consumption from taxiing at an airport depend on:

2.7.3.1. aircraft movements;

2.7.3.2. aircraft age, type, and size;

2.7.3.3. aircraft characteristics;

2.7.3.4. airport congestion;

2.7.3.5. airside size and configuration;

2.7.3.6. number of times the aircraft has to stop from taxiing;

2.7.3.7. number of times the aircraft has to accelerate from taxiing;

2.7.3.8. number of times the aircraft has to turn;

2.7.3.9. number of times the aircraft is at a constant speed or brakes from taxiing;

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[15] ICAO. (2011). Airport Air Quality Manual. Retrieved July 11, 2024, from https://www.icao.int/publications/Documents/9889_cons_en.pdf

[16] Guo, R., Zhang, Y., & Wang, Q. (2014). Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. Transportation Research Part C: Emerging Technologies, 44, 98-109.

2.7.3.10. engine thrust;

2.7.3.11. type of engine;

2.7.3.12. number of engines used;

2.7.3.13. fuel flow; and

2.7.3.14. operating time.

2.8. TAXIBOT

2.8.1. A TaxiBot is a towing tractor equipped with specialised gear for attaching to the aircraft's front wheel. This system is designed to slightly lift and secure the front wheel while allowing it to be controlled from the cockpit.

2.8.2. Once the aircraft is secured on the TaxiBot, control is transferred from the tractor driver to the pilot, who then taxis the aircraft as if using its engines. The TaxiBot slightly lifts the front wheel, allowing it to steer left or right, with sensors transmitting these movements to the tractor, which steers accordingly[17]. Similarly, when the pilot applies the brakes, the TaxiBot detects the increased drag and stops, despite the aircraft not using the front wheel for braking. Upon reaching the designated Tug Release Points (TRP), the TaxiBot releases its clamps and returns to the terminal, allowing the pilot to start the engines in preparation for departure. At this point, the TaxiBot is now operated by a driver.

2.8.3. Actual fuel savings depends on the aircraft type and engine manufacturer. For A320s, the fuel burn rate is about >0.1 kg of fuel per second. Bigger aircraft such as the A380 consume 1.2 kg of fuel per second[18]. Aside from direct savings in fuel, there is a significant decrease in carbon emissions. During taxiing, the A380 emits about 5 kg of carbon dioxide per second. Lastly, TaxiBots are ready to taxi after pushback, eliminating a bottleneck in the gate areas. TaxiBots also allow higher taxi speeds than classic tow-bar trucks. In 2014, a TaxiBot reached a taxiing speed of 23 knots while attached to an A320 aircraft[19].

2.8.4. However, one of the main disadvantages of a TaxiBot is its price. A unit of TaxiBot is three times more expensive than a towing tractor. To prevent delays, airports need multiple TaxiBots, as a single taxi operation takes about twenty minutes at major European airports.

[17] Hospodka, Jakub. (2014). Electric taxiing – TaxiBot system. MAD - Magazine of Aviation Development. 2. 17. 10.14311/MAD.2014.10.03.

[18] Ibid.

[19]Australian Aviation (2014, February 6). Retrieved July 11, 2024, from https://australianaviation.com.au/2014/02/iai-TaxiBot-sets-new-tug-speed-mark/

Including pushback and preparation, one complete cycle is approximately 40 minutes. For an airport handling 30 movements per hour, around 20 TaxiBots are required to ensure smooth operations and maximise airport efficiency[20]. Another issue is the ground movement of TaxiBots on the manoeuvring area and taxiways between taxiing aircraft. TaxiBots will return from runway holding points and sometimes wait for arriving aircraft on the taxiway. This increased vehicle activity on taxiways could raise the risk of accidents, especially in busy airports with complex ground movements, such as Schiphol Airport.

2.8.5. To establish sustainable taxiing as a standard procedure at Schiphol by 2030, various modifications and changes will be necessary, including to the airport's infrastructure and layout. This will entail widening the taxiways to enable the safe and efficient decoupling of a TaxiBot from the aircraft. Additionally, the taxiways will need adjustments to allow the TaxiBot to navigate freely, and the aircraft stands must be modified to ensure the TaxiBot can safely park the plane at the gate.

2.8.6. Although the TaxiBot is not yet entirely emission-free due to its diesel-electric drivetrain, it significantly reduces the carbon footprint of airport operations. Smart Airport Systems is developing a fully electric version, incorporating technical enhancements to increase the TaxiBot's reliability[21].

2.9. AMSTERDAM-SCHIPOL AIRPORT LAYOUT

2.9.1. Amsterdam's Schiphol Airport is the main international airport of the Netherlands. Located 9 kilometres southwest of Amsterdam, Schiphol Airport is the fourth busiest airport by passenger traffic in 2023, handling 67.5 million passengers.

2.9.2. On busy days, Schiphol Airport can handle up to 108 aircraft movements per hour[22]. As one of the main hubs in Europe, the airport has six runways and one large terminal split into three departure halls. The airport covers a total land area of 2,787 hectares.

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[20] Hospodka, Jakub. (2014). Electric taxiing – TaxiBot system. MAD - Magazine of Aviation Development. 2. 17. 10.14311/MAD.2014.10.03.

[21] Smart Airport Systems. Schiphol Feasibility Study Confirms ‘TaxiBot’ as Integral to Sustainable Taxiing Program (2021). Retrieved July 12, 2024. https://www.smart-airport-systems.com/schiphol-feasibility-study-confirms-taxibot-as-integral-to-sustainable-taxiing-program/

[22] Royal Schiphol Group. Traffic and transport figures. (2023). Retrieved July 11, 2024 from https://www.schiphol.nl/en/schiphol-group/page/transport-and-traffic-statistics/

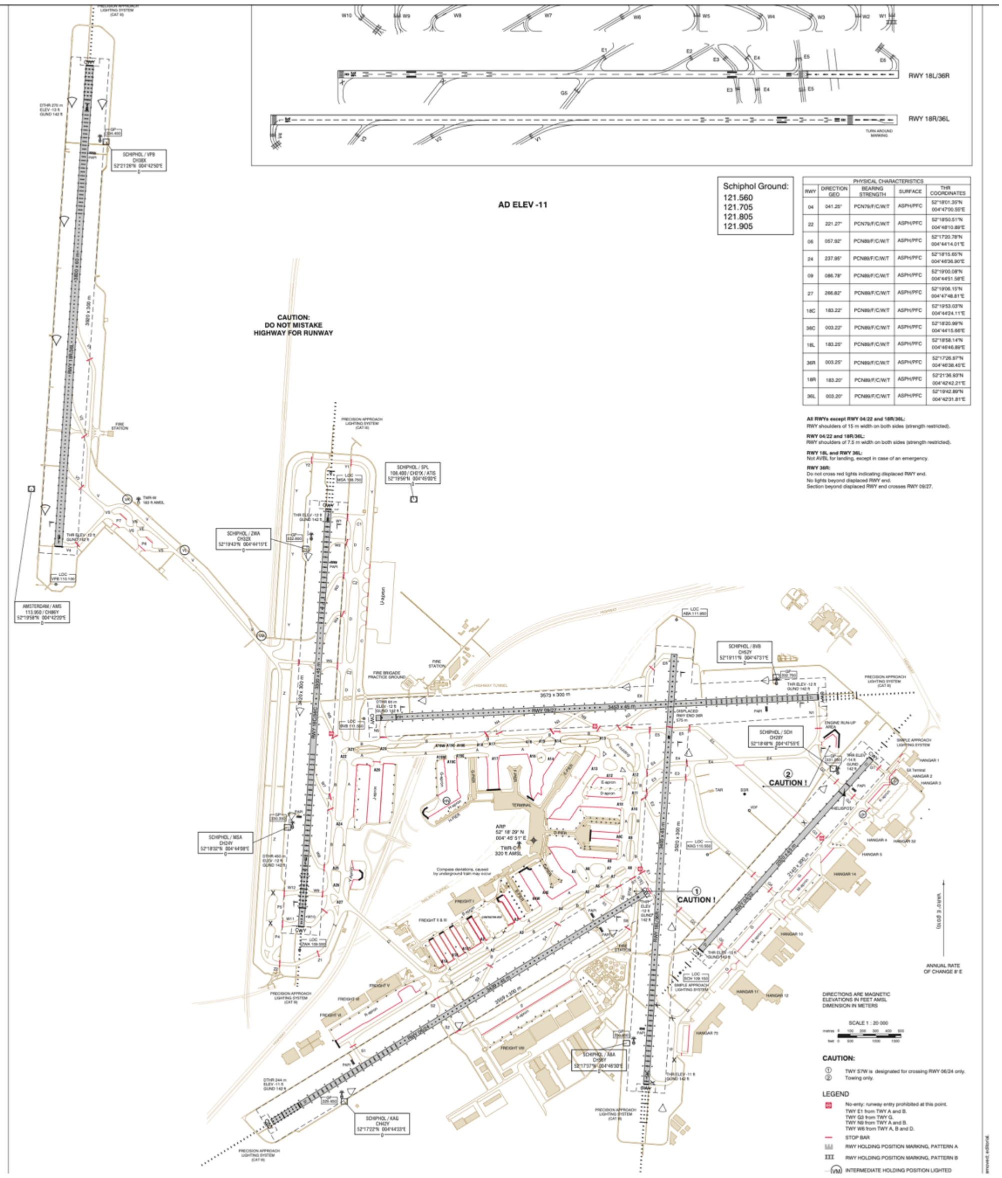

Fig 1. Schiphol Airport layout and its six runways. Source: AIP Amsterdam.

2.10. POLDERBAAN (RWY 18R/36L)

2.10.1. Amsterdam's RWY 18R/36L is their newest runway. Opened in 2003, it was named *Polderbaan* runway. *Polder* is the Dutch word for land reclaimed from a body of water, and the airport is situated in a polder. Polderbaan is located 3 miles (4.5km) from the terminal building. It takes around 20 minutes or more for an aircraft to taxi from Polderbaan to the gate (and vice versa).

2.10.2. Runway 18R-36L is frequently used but not exclusively: last year, 24% of all aircraft took off and 39% landed here. However, the other four runways are also regularly utilised. The choice of runway depends on weather conditions, current traffic levels, and agreements with the residents[23].

2.11. PILOT RUN 2020

2.11.1. In the 2020 pilot program, narrow-body aircraft were transported to and from the runway using a TaxiBot, a specialised semi-robotic aircraft towing vehicle created by Smart Airport Systems and developed by Israel Aerospace Industries. This system allowed aircraft to keep their engines off for most of the taxiing process, leading to fuel savings of approximately 50%, varying by the runway used. When taxiing to the Polderbaan, the runway with the longest taxi time, fuel savings could reach up to 65%[24].

2.11.2. Schiphol developed the roadmap in collaboration with Air Traffic Control the Netherlands (LVNL), KLM, Transavia, Corendon Dutch Airlines, and ground handling agents DNATA and KLM Ground Services. Sustainable taxiing is included in the industry-wide Smart and Sustainable plan and the Sustainable Aviation Agreement between the Ministry of Infrastructure & Water Management and the aviation sector. Additionally, it is one of the goals outlined in the Ministry's Aviation Policy Memorandum[25].

2.11.3. This pilot will involve several aircraft sustainably taxiing to and from the Polderbaan as part of the ALBATROSS[26] project, a European initiative to develop and demonstrate more sustainable flight operations from gate to gate. The project uses various strategies and solutions to save fuel at each stage of a flight. Previous studies at Schiphol have shown that sustainable taxiing reduces fuel consumption by 50% and decreases emissions of CO_2, nitrogen, and ultrafine particulate matter. Fuel savings can reach up to 65% when taxiing to and from the Polderbaan due to the distance.

2.11.4. On December 11, 2024, another test run was conducted at the Amsterdam Schiphol Airport. The same test was applied to a KLM Boeing 737-8MAX aircraft to RWY36L (Polderbaan runway).

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[23] Schiphol Newsroom. Why do I always fly from 'de Polderbaan'?. (2017). Retrieved July 12, 2024 from https://news.schiphol.com/why-do-i-always-fly-from-de-polderbaan/

[24] Schiphol Newsroom. Aviation sector presents sustainable taxiing roadmap
d (2021). Retrieved July 12, 2024 from https://news.schiphol.com/aviation-sector-presents-sustainable-taxiing-roadmap/

[25] Ibid.

[26] SESAR Joint Undertaking. ALBATROSS - The most energy-efficient flying bird (2022). Retrieved July 12, 2024 from https://www.sesarju.eu/projects/ALBATROSS

2.12. 

Fig. 3. A KLM B737-8MAX with the TaxiBot, at the end of its taxiing phase to RWY 36L (Polderbaan RWY). Photo taken by Benjamin van der Sanden.

2.12.1. According to the ATCs on duty, it was observed that the aircraft seemed to be performing similarly when its engines were on. As the aircraft nears the holding point of RWY 36L, the TaxiBot disengages and is positioned at P6 (a remote holding point for RWY 36L). From starting its engines until taxiing, the entire procedure took 3 minutes and 57 seconds.

2.13. WORKLOAD EFFECTS ON AIR TRAFFIC CONTROLLERS

2.13.1. Tower controllers are greatly affected by sustainable taxiing since they are responsible for the ground movements of aircraft. In busy airports like Schiphol Airport in Amsterdam, implementing this new procedure requires more workload, especially in coordination with the airport ground personnel. While the control of the TaxiBot lies with the pilot, delays are anticipated.

2.13.2. Another concern is the infrastructure of the airport's movement area. Ideally, several units of TaxiBots would operate simultaneously within the movement area. These TaxiBots may have safety issues, as they may be hazardous and cause runway or taxiway incursions. The likelihood of this unwanted scenario is generally high.

2.13.3. According to the pilots from the first TOC-IFALPA meeting held in Madrid last September 23, 2024, members from IFALPA shared their concerns regarding sustainable ground movement. While it significantly reduces emissions of harmful gases and saves fuel, the time for an aircraft to start its engines once it's in position at the holding point of the departure runway depends on the aircraft type. Narrow-body jets such as the A320 take at least five minutes to start, but the Airbus A350-900 takes more than nine minutes. This would create a bottleneck effect, which can affect the operations due to delays brought about by this new procedure.

2.14. IFATCA POLICY

2.14.1. <u>ATS 3.20 Environmental Issues in ATM</u>

As of this writing, this policy is under revision by TOC and PLC.

3. CONCLUSION

3.1. While the trial run of sustainable taxiing has already commenced in 2020, it is still in its infant stage. It is paramount for the aviation sector to participate in environmental sustainability by diminishing carbon emissions and promoting a cleaner and greener work environment. IFALPA is very supportive of this endeavour. However, two things need to be considered: (i) the effects on the operations of air traffic control and (ii) the varying engine performances during the start-up procedure of different aircraft.

3.2. Amsterdam’s Schiphol Airport is big. With six runways and several taxiways, implementing TaxiBots in the pushback and taxiing procedures will have huge setbacks and adjustments in the air traffic control procedures, particularly in managing ground movements. It is important to note that the intention of implementing this procedure is noble, but it will create more problems than solutions. If other airports want full implementation of this procedure, constructing additional infrastructure is necessary to ensure that the TaxiBots are at a safe distance from the movement area. Massive overhaul in infrastructure, particularly the construction of additional service roads for TaxiBots, is expected.

3.3. An intensive study regarding the impact of departure and arrival delays should also be considered. When the pilot run commenced in 2020, there were only a few aircraft flying in and out of the airport due to the COVID-19 travel restrictions. Ideally, this procedure works well for smaller airports, but for bigger airports with multiple runways and taxiways like Amsterdam's Schiphol Airport, delays would hamper operations and will have economic repercussions to both the city and the airlines serving Schiphol Airport.

4. DRAFT RECOMMENDATION

4.1. It is recommended that this working paper be accepted as information material.

5. REFERENCES

1. Air Transport Action Group, Waypoint 2050, 2021 [PDF] Retrieved from https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

2. Actieplan Slim én Duurzaam, 2022 [PDF] Retrieved from https://www.nlr.nl/wp-content/uploads/2022/06/Slim-en-duurzaam-update-2022.pdf

3. Luchtvaart Nederland. (2018). Slim én duurzaam. Retrieved July 9, 2024 from https://acn.nl/wp-content/uploads/2019/11/Actieplan-slim-en-duurzaam.pdf

4. Lukic, M., Hebala, A., Giangrande, P., Galea, M., & Nuzzo, S. (2019). Review, Challenges, and Future Developments of Electric Taxiing Systems. IEEE Transactions on Transportation Electrification, 5(4), 1441-1457.

5. Skybrary. (2019, June 23). Pushback. Retrieved July 9, 2024, from Skybrary: https://www.skybrary.aero/index.php/Pushback

6. Xu, H., Fu, Q., Yu, Y., Liu, Q., Pan, J., Cheng, J., Liu, L. (2020). Quantifying aircraft emissions of Shanghai Pudong International Airport with aircraft ground operational data. Environmental Pollution, 261, 114-115.

7. Winther, M., Kousgaard, U., Ellermann, T., Massling, A., Nøjgaard, J. K., & Ketzel, M. (2015). Emissions of NOx, particle mass and particle numbers from aircraft main engines, APU's and handling equipment at Copenhagen Airport. Atmospheric Environment, 100, 218-229.

8. Balakrishnan, H., & Deonandan, I. (2010). Evaluation of strategies for reducing taxi-out emissions at airports. 10th AIAA Aviation, Technology, Integrations, and Operations Conference. Fort Worth.

9. Kesgin, U. (2006). Aircraft emissions at Turkish Airports. Energy, 31(2-3), 372-384. Retrieved July 9, 2024

10. Ashok, A., Balakrishnan, H., & Barret, S. R. (2017). Reducing the air quality and CO2 climate impacts of taxi and takeoff operations at airports. Transportation Research Part D: Transport and Environment, 54, 287-303.

11. Postorino, M. N. (2010). Environmental effects of airport nodes: a methodological approach. International Journal of Sustainable Development and Planning, 5(2), 192-204.

12. Ibid.

13. Yang, X., Cheng, S., Lang, J., Xu, R., & Lv, Z. (2018). Characterization of aircraft emissions and air quality impacts of an international airport. Journal of Environmental Sciences, 72, 198-207.

14. Winther, M., Kousgaard, U., Ellermann, T., Massling, A., Nøjgaard, J. K., & Ketzel, M. (2015). Emissions of NOx, particle mass, and particle numbers from aircraft main engines, APU, and handling equipment at Copenhagen Airport. Atmospheric Environment, 100, 218-229.

15. ICAO. (2011). Airport Air Quality Manual. Retrieved July 11, 2024, from https://www.icao.int/publications/Documents/9889_cons_en.pdf

16. Guo, R., Zhang, Y., & Wang, Q. (2014). Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. Transportation Research Part C: Emerging Technologies, 44, 98-109.

17. Hospodka, Jakub. (2014). Electric taxiing – TaxiBot system. MAD - Magazine of Aviation Development. 2. 17. 10.14311/MAD.2014.10.03.

18. Ibid.

19. Australian Aviation (2014, February 6). Retrieved July 11, 2024, from https://australianaviation.com.au/2014/02/iai-TaxiBot-sets-new-tug-speed-mark/

20. Hospodka, Jakub. (2014). Electric taxiing – TaxiBot system. MAD - Magazine of Aviation Development. 2. 17. 10.14311/MAD.2014.10.03.

21. Smart Airport Systems. Schiphol Feasibility Study Confirms 'TaxiBot' as Integral to Sustainable Taxiing Program (2021). Retrieved July 12, 2024. https://www.smart-airport-systems.com/schiphol-feasibility-study-confirms-taxibot-as-integral-to-sustainable-taxiing-program/

22. Royal Schiphol Group. Traffic and transport figures. (2023). Retrieved July 11, 2024 from https://www.schiphol.nl/en/schiphol-group/page/transport-and-traffic-statistics/

23. Schiphol Newsroom. Why do I always fly from 'de Polderbaan'?. (2017). Retrieved July 12, 2024 from https://news.schiphol.com/why-do-i-always-fly-from-de-polderbaan/

24. Schiphol Newsroom. Aviation sector presents sustainable taxiing roadmap
d (2021). Retrieved July 12, 2024 from https://news.schiphol.com/aviation-sector-presents-sustainable-taxiing-roadmap/

25. Ibid.

26. SESAR Joint Undertaking. ALBATROSS - The most energy-efficient flying bird (2022). Retrieved July 12, 2024 from https://www.sesarju.eu/projects/ALBATROSS

27. AirMed & Rescue (2022). Sustainability in Aviation. Retrieved from https://www.airmedandrescue.com/latest/long-read/sustainability-aviation-engines-and-fuels

28. Guo, R., Zhang, Y., & Wang, Q. (2014). Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. Transportation Research Part C: Emerging Technologies, 44, 98-109.

29. Ibid.

30. Lukic, M., Hebala, A., Giangrande, P., Galea, M., & Nuzzo, S. (2019). Review, Challenges, and Future Developments of Electric Taxiing Systems. IEEE Transactions on Transportation Electrification, 5(4), 1441-1457.

31. Re, F. (2017). Model-based Optimization, Control, and Assessment of Electric Aircraft Taxi Systems. Retrieved July 9, 2024, from https://tuprints.ulb.tudarmstadt.de/6239/1/Dissertation%20-%20Fabrizio%20Re%20-%20Final.pdf

32. Hospodka, J. (2014). Electric taxiing - TaxiBot system. MAD - Magazine of Aviation Development

33.Soepnel, S., Roling, P., Haansta, J.-O., Busink, J., & de Wilde, W. (2017). Impact of Electric Taxi Systems on Airport Apron Operations and Gate Congestion. 17th AIAA Aviation Technology, Integration, and Operations Conference.

34. Schmidt, M., Plötner, K. O., Pornet, C., Isikveren, A. T., & Hornung, M. (2013). Contribution of Cabin Related and Ground Operation Technologies Towards Flightpath 2050. Deutscher Luft-und Raumfarhtkongress. Munich. Retrieved July 10, 2024, from https://www.researchgate.net/profile/Askin_Isikveren/publication/274704939_Contributions_of_Cabin_Related_and_Ground_Operation_Technologies_Towards_Flightpath_2050

6. APPENDIX

6.1. SUSTAINABILITY IN AVIATION – ENGINES AND FUELS

6.1.1. New technologies in the industry are already making positive impacts on reducing harmful emissions: high by-pass ratio (HBPR) turbofan engines like CFM International's LEAP use less fuel, while winglets (vertical extensions of wingtips) improve airflow around its wings, reducing fuel consumption and increasing the aircraft's range. Lighter materials such as carbon fibre composite materials lead to significant savings in fuel[27].

6.1.2. The global aerospace industry has acknowledged the necessity of reducing greenhouse gas emissions, marking the start of a significant shift towards greater sustainability. Continuous advancement of cutting-edge technologies is essential to achieve the goal of reduced net emissions by 2050. This effort includes engine design improvements, future technologies such as electrification, the use of sustainable fuels, and the incorporation of composite materials in airframes. Additionally, increasing consumer awareness about the environmental impact of air travel is helping to drive this change in focus.

6.2. PUSHBACK/TAXI CONCEPTS

6.2.1. The pushback/taxi concept or innovative Aircraft Ground Propulsion System (AGPS) was conceptualised to significantly reduce aircraft ground-movement-related fuel burn and emissions. The AGPS function is to perform a pushback, move the aircraft, and drive the aircraft along the taxi route to the active runway, and vice versa. There are two kinds of AGPS:

6.2.2. External: Move the aircraft by using a modified pushback/tow truck.

6.2.3. On-board systems: Move the aircraft by using electric motors installed in the wheels of the landing gear or main gears, whereby energy is produced by the APU[28].

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[27] AirMed & Rescue (2022). Sustainability in Aviation. Retrieved from https://www.airmedandrescue.com/latest/long-read/sustainability-aviation-engines-and-fuels

[28] Guo, R., Zhang, Y., & Wang, Q. (2014). Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. Transportation Research Part C: Emerging Technologies, 44, 98-109.

6.3. In choosing AGPS, there are trade-offs in fuel and emissions. The external emissions showed the least fuel burn while focusing on emission reduction, while the onboard system has the best performance[29]. However, choosing the AGPS depends on the cost, ease of implementation, kinematic performance, and fuel and time savings[30]. Only when the systems enter the market, it is possible to decide which is optimal for a particular situation.

6.4. Lukic et al. mentioned that wide-body aircraft will utilise external systems, while narrow-body aircraft will use on-board systems. However, the optimal selection of AGPS[31] can only be determined through a thorough analysis of the flight schedule for the specific type of aircraft. Furthermore, the primary interest in on-board systems is driven more by economic considerations than by environmental ones.

6.5. External systems are a more practical option for hub airports[32] with high fuel consumption and long taxi-out times. However, as innovations make onboard systems progressively lighter over the years, they become more competitive with external systems, especially for wide-body aircraft. This leads to a preference for on-board systems.

6.6. The electric pushback/taxi concept has positive and negative economic impacts, potential savings, and costs. It concluded that this concept brings more benefits than costs, making it appealing to most air operators. Using an onboard system reduces costs and environmental impact during apron operations while enhancing the safety, capacity, and efficiency of the airport apron environment[33].

6.7. Ultimately, the electric pushback/taxi concept has the potential to decrease taxi-out CO_2 emissions per passenger kilometre by 55.1% and shorten the time required to push back an aircraft. Compared to traditional taxiing where engines

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[29] Ibid.

[30] Lukic, M., Hebala, A., Giangrande, P., Galea, M., & Nuzzo, S. (2019). Review, Challenges, and Future Developments of Electric Taxiing Systems. IEEE Transactions on Transportation Electrification, 5(4), 1441-1457.

[31] Re, F. (2017). Model-based Optimization, Control, and Assessment of Electric Aircraft Taxi Systems. Retrieved July 9, 2024, from https://tuprints.ulb.tudarmstadt.de/6239/1/Dissertation%20-%20Fabrizio%20Re%20-%20Final.pdf

[32] Hospodka, J. (2014). Electric taxiing - TaxiBot system. MAD - Magazine of Aviation Development

[33] Soepnel, S., Roling, P., Haansta, J.-O., Busink, J., & de Wilde, W. (2017). Impact of Electric Taxi Systems on Airport Apron Operations and Gate Congestion. 17th AIAA Aviation Technology, Integration, and Operations Conference.

are running at idle, electric taxiing could save up to 3% in CO_2 emissions per passenger[34].

[34] Schmidt, M., Plötner, K. O., Pornet, C., Isikveren, A. T., & Hornung, M. (2013). Contribution of Cabin Related and Ground Operation Technologies Towards Flightpath 2050. Deutscher Luft-und Raumfarhtkongress. Munich. Retrieved July 10, 2024, from https://www.researchgate.net/profile/Askin_Isikveren/publication/274704939_Contributions_of_Cabin_Related_and_Ground_Operation_Technologies_Towards_Flightpath_2050