Improving Air Quality by Reducing Aircraft Fuel Use and Emissions with Semi-Autonomous Electric Tugs

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Abstract

In order to ensure healthy lives and promote well-being for all at all ages even as the demand for global air travel grows, reducing emissions from aircraft is increasingly important. Previous attempts to minimize the amount of time aircraft engines are turned on before take-off are examined and analyzed. The proposal to use electrically powered, semi-autonomous tugs to ferry aircraft on the ground and its ability to produce a significant reduction in fuel use and thus emissions is evaluated. Analysis is performed using the Federal Aviation Administration’s Aviation Environmental Design Tool analysis software to simulate the effects implementation would have at the busiest airport in the United States (Hartsfield-Jackson Atlanta International Airport). A design for such a tug and control and coordination system is proposed and described. It is shown that implementation of such a system would result in significant reductions in fuel use and emissions. Areas of future research are outlined.

Keywords: Air quality, Emissions, Electric vehicles, Autonomous, Fuel use, Aircraft, Airliner

Nomenclature

AEDT……………… Aviation Environmental Design Tool

APU……………… Auxiliary Power Unit

CNG……………… Compressed Natural Gas

ICE……………… Internal Combustion Engine

LIDAR……………… Light Detection and Ranging

LTO……………… Landing and Takeoff Cycle

SDG……………… Sustainable Development Goals

Background

Goals 3.9 and 11.6 of the United Nations’ Sustainable Development Goals (SDGs) and Targets for the 2030 Agenda articulate the great importance of reducing air pollution [1]. Even in developed countries, air pollution can have significant negative impacts on health and well-being. In Utah in the United States, research has found that approximately 5,000 people die prematurely annually because of poor air quality caused by pollution, reducing the average life expectancy of state residents by more than two years [2]. Globally the story is similar, especially as emerging economies develop a growing appetite for activities such as airline travel. In China, for example, between 1990 and 2017, air traffic increased 29-fold, with corresponding increases in pollutants, despite reductions in per passenger emissions during the same time period [3].

Civilian air travel accounts for about two percent of anthropogenic CO2 emissions, but air travel is predicted to increase 400 percent by 2050 [4]. Airlines, airports, and other stakeholders, including the general public, face multiple sources of exigent pressure to reduce airliner emissions, including increasing regulations [5], fluctuating fuel prices [6] and the need to reduce greenhouse gas emissions related to environmental concerns [4]. As well, air quality near major airports (commonly near cities) is usually worse than elsewhere [7, 8]. This is especially true of PM 2.5 emissions. Rangel-Alvarado et-al. summarized research from various sources and show that emissions from aircraft idling, taxiing, and taking off tend to have an out-sized correlation with PM 2.5 levels at the airport and surrounding areas [8]. For these reasons, reducing the fuel use of passenger aircraft during those stages will be essential to achieving SDGs 3.9 and 11.6 [9, 10].

The typical approach to reducing fuel use has been to find ways to increase fuel efficiency of airplanes themselves. This effort, while laudable, usually results in one of two scenarios: In the first scenario, a marginal increase in fuel efficiency is achieved by taking an evolutionary step forward such as adding winglets or increasing the use of carbon-fiber composite parts to lighten the aircraft [11, 12]. This route requires extensive engineering design and testing work and usually results in improvements in fuel efficiency in the range of 1-6 percent [13].

The second scenario involves the proposal of some revolutionary new airliner design, such as a flying wing or a blimp or an electrically powered aircraft [12, 14]. These design proposals, while likely to deliver step-change improvements in fuel efficiency and worthy of research and development, also demand orders of magnitude more in terms of design and testing than scenario 1. It is understandable then, why they are often considered to be ‘perpetually 10-20 years in the future’. Even if such a new airliner could be designed, tested, and ready to produce immediately, it would take years if not decades to replace the current fleet of jet airliners. Commercial jetliners tend to have long lives. For example, Boeing’s 737-200, which was first introduced in the late 1960’s, still had 60 aircraft being flown by airliners in the year 2020. One 737-200 in particular has been in active service since May of 1974 [15, 16].

Stettler et al estimated that as much as 36 percent of emissions for a typical airline flight are produced during the “LTO” or Landing and Take-off cycle [17]. LTO includes the portions of a flight that occur below 3,000 feet above ground level, including departure taxi-out and idle, taekoff roll, climbout to 3,000 feet above ground level, approach from 3,000 feet above ground level, and arrival taxi and idle [18]. Other sources put the maximum number for LTO emissions closer to 25 percent of the total[11]. Of those, taxi operations are often the largest source of emissions [11, 19]. The fact that such a significant portion of emissions are produced while the plane is still on the ground begs the question if there is a method of mitigating, if not eliminating, these emissions produced before the plane and its passengers are even in the air.

Some attempts have been made previously to address this “low-hanging fruit” opportunity. Deonandan and Balakrishnan evaluated strategies for reducing taxi-out emissions at airports and identified and evaluated three different options: using fewer engines to taxi, towing aircraft out to the runway before starting their engines, and reducing taxi times by optimizing taxi “traffic” flow at airports [20].

In all cases, they point out that all aircraft must warm their engines up before take-off, for a conservative estimate of five minutes. Thus, any taxi-out operation that requires less than five minutes would not benefit from an alternative taxiing strategy such as the ones proposed. Given this threshold, they calculate that at most major U.S. airports, a reduced engine taxi strategy would result in a reduction in taxi-related emissions of between 20 and 40 percent[20]. Similar conclusions were reached by British officials at Heathrow International Airport [21].

Additional benefits to this approach include minimal operational changes for pilots, crew, and airport staff [21] and, of course, no change to the airplanes themselves. Potential drawbacks to “single-engine” taxiing, as it is commonly called, include reduced maneuverability, especially for twin engine aircraft, as well as increased potential for damage due to jet blast as a result of increased thrust per engine still running [20]. The Auxiliary Power Unit, or APU on some aircraft may be required to run at a higher capacity during reduced engine taxiing, offsetting some of the reductions as well [21].

If instead, aircraft are towed out to the runway by traditional internal combustion engine (ICE) powered airport tugs, all the engines of the aircraft can remain off until the required 5-minute warm up pre-takeoff. However, now the emissions of the tugs must be considered. The authors analyzed diesel, gasoline, and CNG powered tugs and found that while fuel burned during taxiing was reduced on the order of 75 percent, net emissions of some pollutants, such as NOx or CO doubled or quadrupled and these calculations did not include the tugs’ return trips after delivering the aircraft close to the runway. They also noted that using traditional tugs would reduce taxing speeds significantly and reported that Heathrow airport experienced a 3x increase in taxiing times when they attempted to implement such a system [20]. Other cons for this approach include increased communications required between the pilot, control tower, and tug driver [22].

Others have attempted to take the tug tow-out concept further and address some of these issues. TaxiBot, a joint effort by Honeywell and Safran until 2016 used an 800 hp hybrid-electric drive-train tug that claimed to maintain normal taxi speeds while reducing all emissions. Pilots controlled the tug during taxiing and a tug driver controlled the tug at other times such as during return trips [23].

NASA Ames investigated the possibility of a fully autonomous, ICE powered tugs for towing out aircraft in 2015 and concluded that autonomous vehicle technology, deployed in a controlled space such as an airport tarmac, would be significantly more feasible than deploying self-driving vehicles on freeways or public roads. They calculated that a tug fleet of roughly 1/3 the number of aircraft to be serviced would result in a throughput rate that matched the scenario of aircraft taxiing on their own [24].

Wheeltug, one example of a so-called “EGTS” or Electric Green Taxiing System, mounts electric motors to the nose-wheels of an airplane and draws power from the plane’s Auxiliary Power Unit (APU) to allow the plane to taxi under its own power [25, 26]. While the system eliminates the need for tugs entirely and claims to reduce emissions compared to traditional taxiing (although no documentation of this could be found), the added weight of the motors and other hardware (nearly 700 pounds) negatively impacts any other reduction in emissions [26].

Finally, Deonandan et al. examined the potential effect of optimizing the flow of tarmac traffic at airports. Optimistically, this could result in as much as a 60 percent decrease in LTO fuel consumption [20]. Many other researchers have considered a variety of methods for optimizing ground traffic flow at airports over the years [27–29]. Their estimates for improvement vary. Rathinam et al, for example, estimated an average decrease in taxi time of about 6 minutes with their algorithm [27]. Li et al. used a genetic algorithm and found a 17 percent reduction in fuel consumption during taxiing [29].

Potential benefits of tarmac traffic optimization include requiring no change to the design of the planes and, it is assumed, minimal or no change to the hardware in use at airports. Their effectiveness depends on a variety of factors including how faithfully the mathematical models chosen represent the complex reality of airport traffic management, and how well they are implemented by individual airports. They tend to be highly dependent on controllers having real-time access to high-fidelity data and may lose effectiveness if the built-in assumptions, such as conditions on the tarmac related to weather or upkeep are not as assumed in the model [29]. Agent-Based Modeling is one proven modeling approach that allows system designers to extract emergent behavior from the integration of multiple agents, such as aircraft, within a world such as an airport, where external stimuli can be explored such as weather or between agents such as scheduling conflicts between arrivals and departures.

Proposed Design

Methodology

Deriving from the research cited in the Background section, the design of a device and/or strategy to reduce the emissions produced by aircraft on the ground at airports would need to be evaluated based on the following performance metrics:

1) Minimize *overall* fuel consumption during LTO operations, including jet engine, APU, tug, or other fuel consumption. Reducing overall fuel consumption will, in turn, reduce PM 2.5 and 10 in accordance with SDG 3.9 and 11.6 [1].

2) Maintain taxiing speeds equivalent to all engines-on

3) Maintain aircraft maneuverability while taxiing

4) Not increase the weight of the aircraft

5) Minimize changes to the aircraft themselves

6) Minimize changes to operational procedures

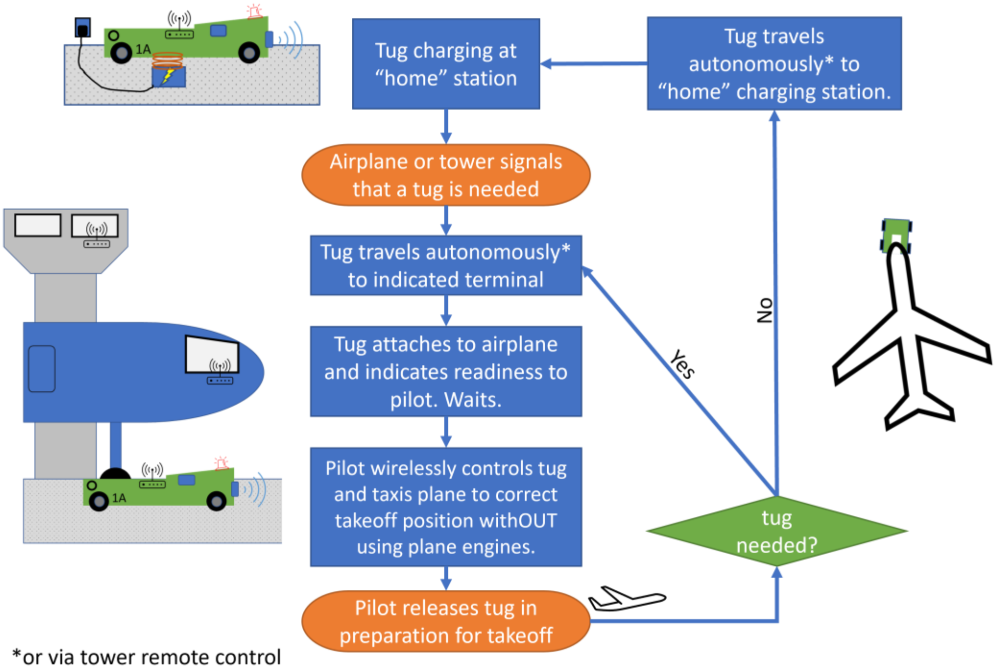
7) Maintain safety on the tarmac

8) Perform well in less than ideal or even anomalous situations

It is proposed that a fully-electric tug, capable of autonomous as well as remotely controlled functionality, can achieve these desired performance metrics, especially that of reducing fuel use and emissions during the LTO cycle.

Such a tug would use batteries and electric motors for propulsion and attach to aircraft in a manner similar to tugs already in use. An array of sensors, including cameras, GPS, LIDAR, radar, and other sensors connected to a computational system will allow the tug to autonomously navigate the highly controlled tarmac area safely and efficiently. Fully autonomous road vehicles have been under development for more than 15 years, with multiple teams successfully completing the 2004 and 2005 DARPA Grand Challenges [30, 31]. While full vehicle autonomy has been achieved for quite some time, autonomous vehicles still remain out of consumers' reach due to the highly variable environment cars may operate in, as well as privacy and ethical questions that arise[32, 33]. Unlike passenger vehicles, aircraft tugs operate in an environment that is, at at all times, highly controlled and maintained. Because the precise location of every moving entity on the airport tarmac is known, building a fully operational and safe autonomous tug can be achieved using existing technologies. Additionally, communications equipment to allow the tug to send data to and receive data from other sources (such as a pilot or other source) would be included to allow for remote control of the tug and act as a fail-safe in the event the autonomous controlled failed.

The autonomous functionality of the tug would allow it to arrive at an airplane ready to back away from the terminal and to leave a plane that had just been delivered to the end of the runway. Upon completing the taxi process for a plane, the tug would find another plane that needs to be tugged, or return to a designated recharge station. While the tug is attached to the plane and providing the needed thrust to propel it on the tarmac, it could act either autonomously, or be remotely controlled to varying degrees by either the pilot of the aircraft or by some other controller. This flexibility would allow different carriers, airports, or even individual pilots the degree of control they may desire. See figure 1.



*or via tower remote control

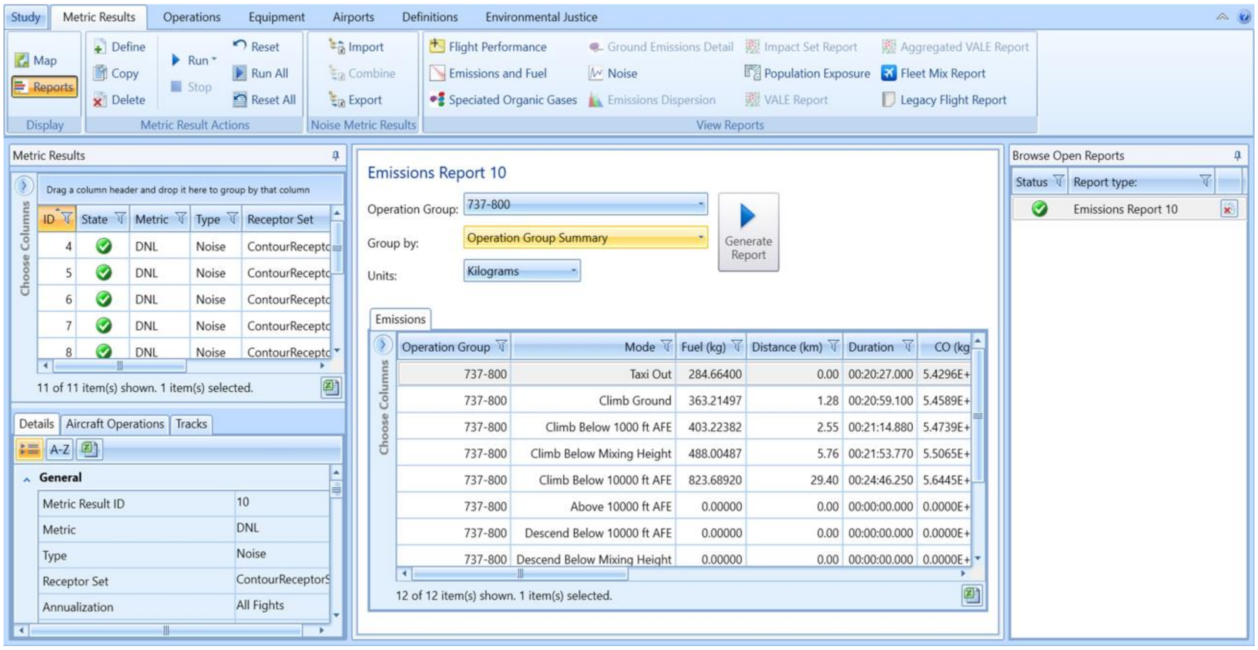
Fig. 1 Flow diagram for potential semi-autonomous electric tug activity

This design would allow the plane to taxi with all engines off and avoid emissions from the tug as well. While considered outside the scope of this paper, since the tug is electric, the power source to charge it could also be a renewable or green source of electricity, thus further improving the reduction in emissions and environmental impact of the flight. Regarding use of the APU, it is possible that an umbilical or other connection from the tug to the aircraft could be supplied along with the towing connection so that the aircraft's APU would not need to be used during taxiing either. This possibility will be considered in greater detail in future research.

As demonstrated by the Taxibot [23], normal taxiing speeds and maneuverability can be maintained with a tug tow-out as long as the tug is properly sized and powered. The weight of the aircraft will be unaffected by the proposed approach since no new hardware will need to be introduced on the aircraft themselves. And, given the fact that the tugs will return autonomously from towing out aircraft, sensing and avoiding obstacles along the way to their next destination, operational procedures at the airport should remain largely unchanged. In the event of a tug that malfunctions and is unable to complete a tow-out, the aircraft could simply be detached from the tug and complete its taxiing procedure attached to a different tug or under its own power.

Modeling

To further analyze the effectiveness of the idea, computer simulations modeling the impact of such a proposal in a real-world scenario were created. First, data for all 2019 flights to and from Hartsfield-Jackson Atlanta International Airport were downloaded from the U.S. Department of Transportation's Bureau of Transportation Statistics [34]. Then, using the Federal Aviation Administration's Aviation Environmental Design Tool (AEDT) [35], fuel and emissions reductions were calculated for 10 of the most common and impactful aircraft using Hartsfield-Jackson Atlanta International Airport. See figure 2. Hartsfield-Jackson is the busiest airport in the United States and one of the busiest in the world [35]. Despite the ongoing pandemic, in 2020 alone, the airport saw nearly 43 million passengers pass through its gates[35].



ID	State	Metric	Type	Receptor Set
4	✓	DNL	Noise	ContourRecepto
5	✓	DNL	Noise	ContourRecepto
6	✓	DNL	Noise	ContourRecepto
7	✓	DNL	Noise	ContourRecepto
8	✓	DNL	Noise	ContourRecepto

11 of 11 item(s) shown. 1 item(s) selected.

Metric Result ID	10
Metric	DNL
Type	Noise
Receptor Set	ContourReceptorS
Annualization	All Fights

Emissions Report 10

Operation Group: 737-800

Group by: Operation Group Summary

Units: Kilograms

Operation Group	Mode	Fuel (kg)	Distance (km)	Duration	CO (kg
737-800	Taxi Out	284.66400	0.00	00:20:27.000	5.4296E+
737-800	Climb Ground	363.21497	1.28	00:20:59.100	5.4589E+
737-800	Climb Below 1000 ft AFE	403.22382	2.55	00:21:14.880	5.4739E+
737-800	Climb Below Mixing Height	488.00487	5.76	00:21:53.770	5.5065E+
737-800	Climb Below 10000 ft AFE	823.68920	29.40	00:24:46.250	5.6445E+
737-800	Above 10000 ft AFE	0.00000	0.00	00:00:00.000	0.0000E+
737-800	Descend Below 10000 ft AFE	0.00000	0.00	00:00:00.000	0.0000E+
737-800	Descend Below Mixing Height	0.00000	0.00	00:00:00.000	0.0000E+

12 of 12 item(s) shown. 1 item(s) selected.

Status	Report type:
✓	Emissions Report 10

Fig. 2 Screenshot of AEDT software used to simulate conditions at Hartsfield-Jackson Atlanta International Airport (Georgia, U.S.A.)

Results

Using the AEDT software, simulations were developed for ten of the most impactful aircraft utilizing Hartsfield- Jackson during the year 2019: the three aircraft with the most flights (Boeing 737-800, Airbus A320-100/200, and the McDonnell Douglas DC9 Super80/MD81/82/83/88) and the seven aircraft at the airport using the most fuel per departure taxi-out (Airbus A380-800, variations of the Boeing 747, and variations of the Boeing 777).

Figure 3 shows the number of departures during 2019 of each type of aircraft considered. As can be seen, the Boeing 737-800 had the greatest number of departures from Hartsfield-Jackson with 1,281 or about 3.5 per day on average, with the smallest number of departures coming from the Airbus A380 at just 18, or one or two per month on average.

Figure 4 shows the calculated amount of fuel each of the considered aircraft consume per departure taxi-out. As can be seen, the A380 is by far the largest consumer of fuel per departure taxi-out at over 1,310 kg, or about 420 gallons. The Boeing 737-800 consumes the least fuel per departure taxi-out at just 285 kg, or about 94 gallons of fuel.

Figure 5 shows the calculated total amount of fuel of each considered aircraft consumed during all departure taxi-outs in 2019. As can be seen, although its per-aircraft footprint may be considerably smaller, the Boeing 737-800 uses considerably higher amounts of total fuel in a given year than other considered aircraft simply because of its high number of flights.

Figure 6 shows the calculated amounts of various types of emissions produced by each considered aircraft per departure taxi-out. As can be seen, emissions generally tend to follow fuel-use (first row) with some exceptions. PM 2.5 levels, specifically mentioned in the U.N. Sustainable Development Goals 3.9 and 11.6 [1, 9, 10], are positively impacted in some instances more than would be expected if simply observing fuel use reductions. The Boeing 747-400 and 777-200ER/200LR/233LR exhibit this characteristic. Other aircraft, such as the Airbus A380-800, seem to have a smaller reduction in PM 2.5 levels than would be expected based on reduction in fuel use.

Discussion

Based on the simulations run using the AEDT software, the amount by which fuel use could be reduced by implementing the proposed idea appear to be significant. As seen in figure 7, an average reduction of approximately 10-12 percent of LTO fuel use could be achieved only by implementing the proposed idea for departure taxi-out.

While prices for jet-fuel are prone to fluctuation, using the current average price for jet fuel, for just the Boeing 737-800s departing Hartsfield-Jackson, using the described proposal to taxi-out these airplanes could have reduced costs by about 450,000 U.S. dollars in 2019 [36, 37].

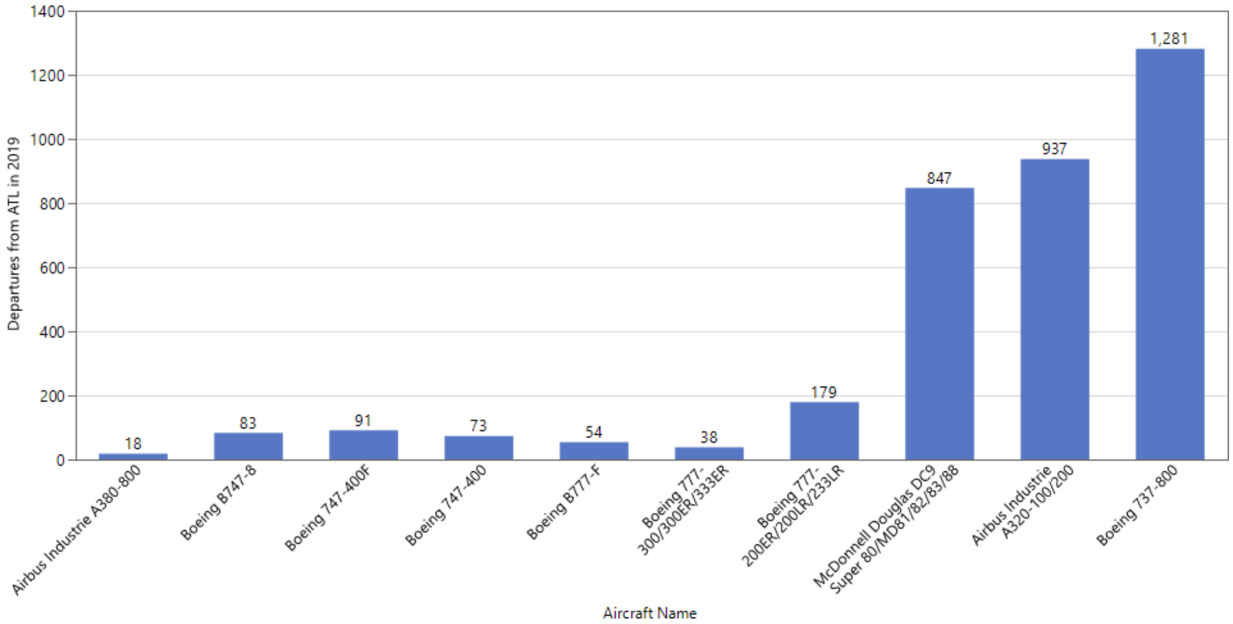


Fig. 3 Number of 2019 departures by aircraft type

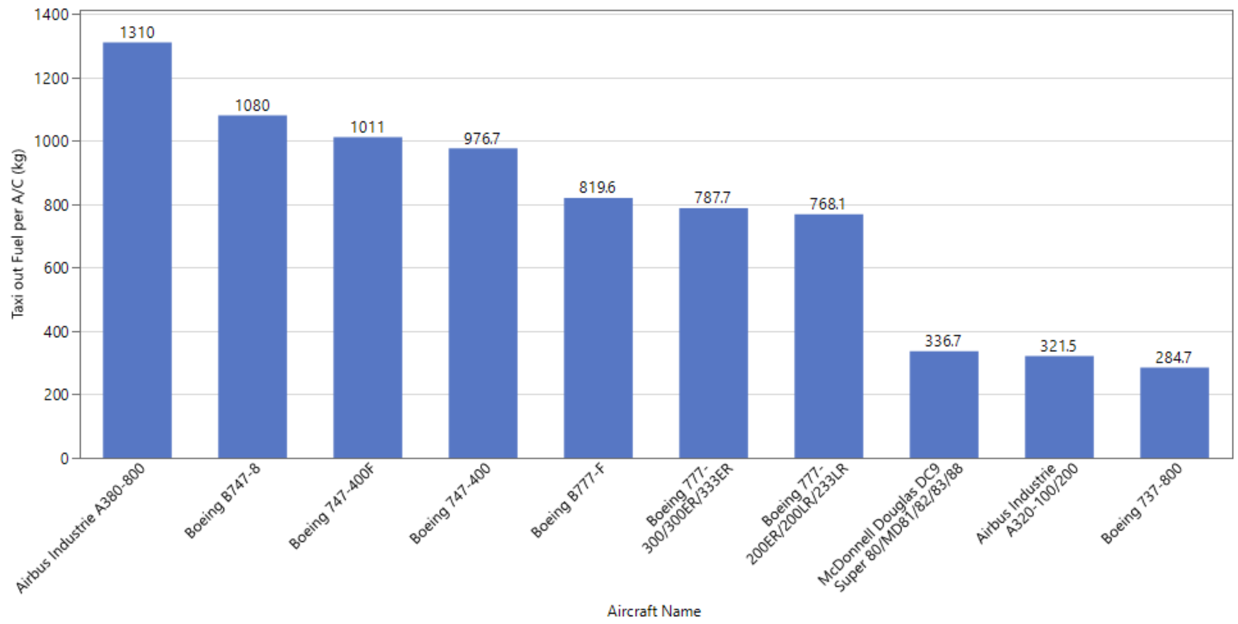


Fig. 4 Fuel used per aircraft for each departure taxi-out

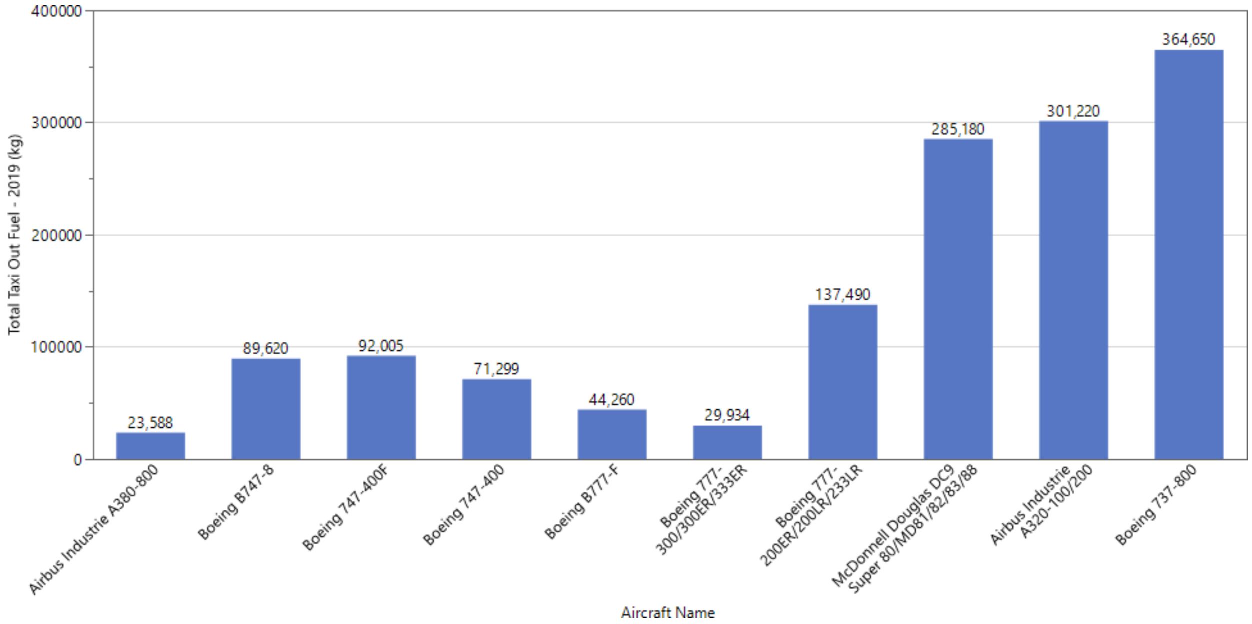


Fig. 5 Total amount of fuel used per aircraft during 2019 for departure taxi-outs

As shown in figure 6, emissions would also be significantly reduced. Taking CO2 emissions as an example, each Airbus A380 departing Hartsfield-Jackson is estimated to emit about 4,130 kg of CO2 just during the taxi-out phase of LTO. If all A380s departing Hartsfield-Jackson during 2019 were towed out using the described proposal, more than 74,000 kg of CO2 emissions would be eliminated, equivalent to removing more than 16 automobiles from the road for a full year [38]. If instead all Boeing 737-800s departing Hartsfield-Jackson during 2019 were towed out as proposed, the equivalent number of cars removed from the road for a full year would increase to more than

250. PM 2.5 emissions, or the emission of suspended fine particulate matter, also reduced significantly.

This matters not only because overall air quality is improved, but also because of the fact that these emissions would be reduced while the aircraft is on the ground, during the time when the aircraft is closest to people, including airport workers on the tarmac, travellers and staff in the airport, and residents in areas close to the airport [18].

It should be noted that the reductions in fuel and emissions calculated above are conservative. They do *not* include taxi-in, supplementing or replacing APU power, or tarmac traffic flow optimization. Including any or all of those would markedly increase the level of positive impact.

Limitations

The simulations described above are limited in some ways that are important to acknowledge. For example, the software uses an average value for the time required for an aircraft to taxi from the terminal to the end of the runway (taxi-out). A more nuanced analysis would consider exact flight numbers, which terminal/runway combination was used, and other details.

Other software limitations include the inability to calculate round trips, making total trip fuel consumption difficult to estimate. Weather conditions and mixing height are also generalized within the AEDT software meaning that accuracy of pollution data and fuel used in LTO is affected.

Future Research

Several important areas of future research related to the proposed idea exist and are described below.

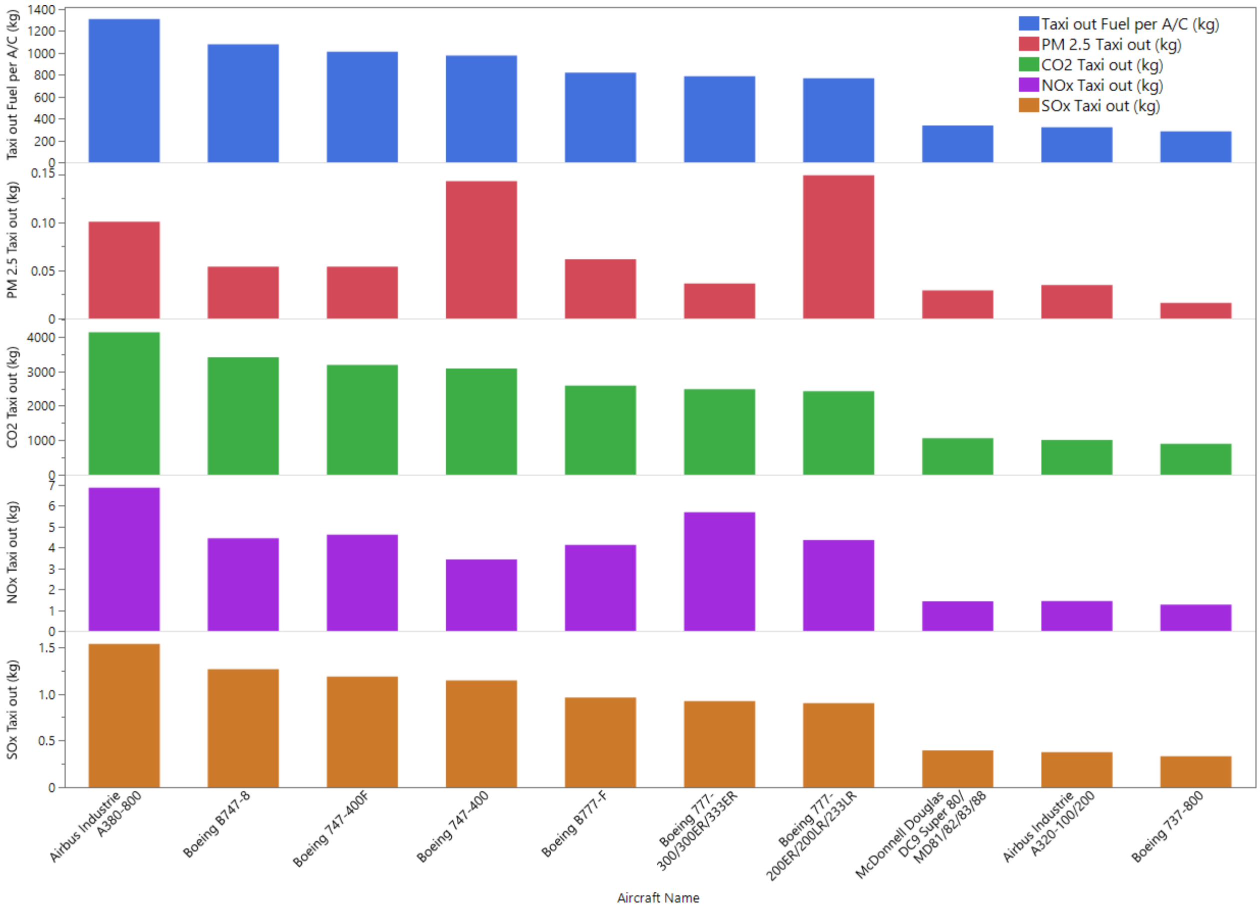


Fig. 6 Other Emissions. CO2 and SOx perfectly correlated with fuel mass. PM 2.5 and NOx were less correlated, but still showed significant improvement.

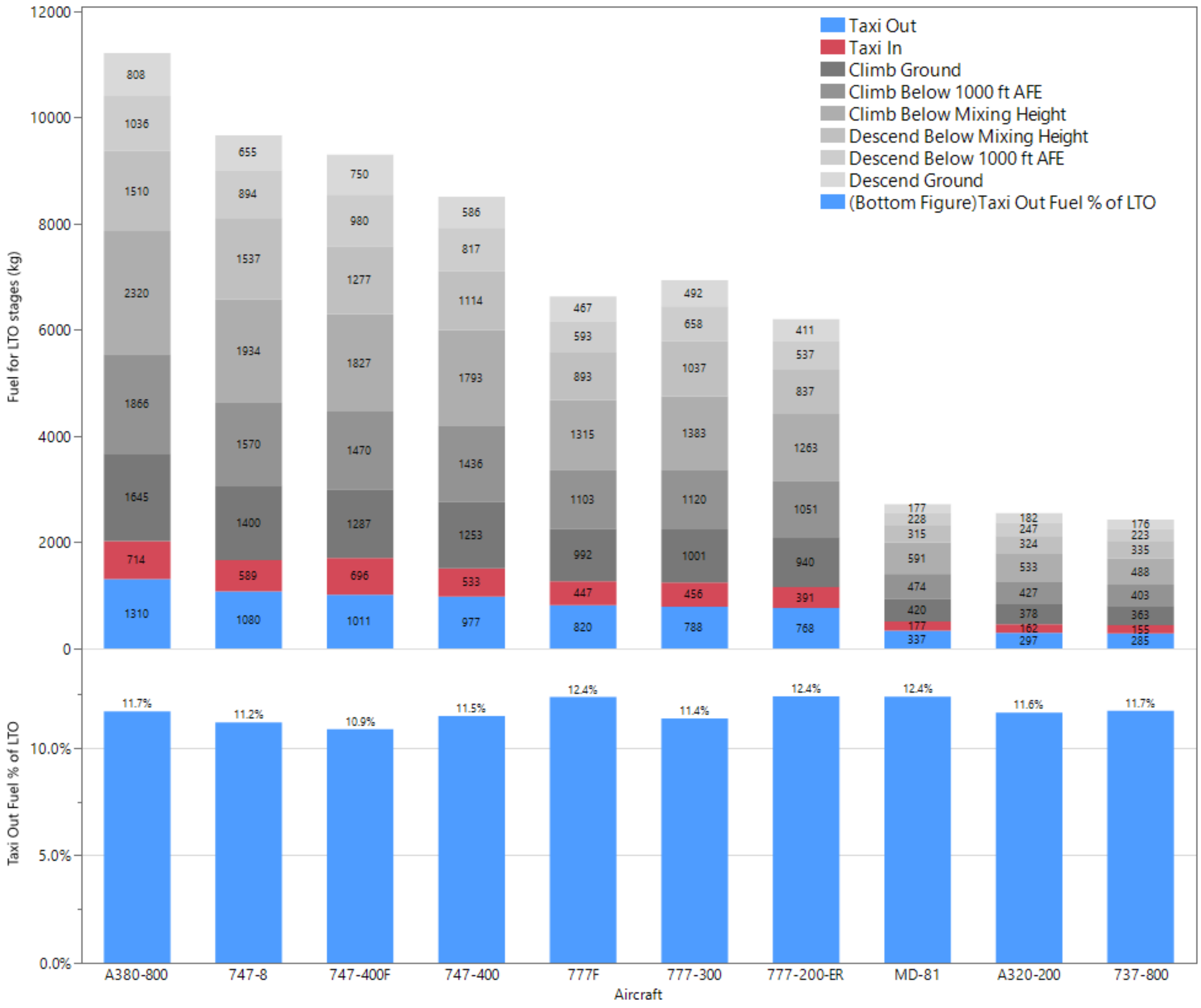


Fig. 7 (Top) Fuel usage for different phases of LTO. (Bottom) Percentage of LTO fuel use from the Taxi Out phase that could be reduced by implementing the proposed idea per aircraft considered. These percentages correspond to the proportion of the blue taxi-out phases of the aircraft in the top figure.

Taxi-In

It may be noted that the figures and analysis above only include the departure taxi-out portion of the LTO cycle. Since the tugs described could also be used to reduce the time aircraft engines are on during arrival, future research will include taxi-in data as well. This may present a more technically challenging proposition than taxi-out since traditionally aircraft do not come to a complete stop immediately after landing, but transition seamlessly to taxiing. That would indicate that either aircraft would need to come to a complete stop as soon as possible after landing to allow a tug to attach, *or* tugs would need to be able to attach to the aircraft while in motion. Each situation clearly has its own unique challenges that will need to be considered.

APU

The current analysis does not consider the possibility of supplementing or replacing power from aircraft APUs during taxi-in/out with an umbilical from the proposed tugs. Replacing APU power with power from the tugs would further reduce the amount of fuel and emissions produced by aircraft on the ground. Supplying electrical power from the tug to the aircraft would require some form of connection, preferably an automatic one, and would necessitate some modification of hardware on the aircraft itself. This possibility will be considered in future research.

Noise Reduction

Reduction of fuel use and emissions are only two potential benefits of using a tug system like the one proposed in this paper. Noise from aircraft has been shown to have significant detrimental corollaries on various aspects of human and environmental health, negatively affecting everything from cardiovascular health to the academic performance of children attending schools in the vicinity of airports [39]. Future research will investigate the potential benefits implementation of a tug system such as the one described in this paper could have in reducing the negative effects of aviation noise, including by using the AEDT software's ability to model sound and noise dispersion at and around various U.S. airports.

Tarmac Traffic Flow Optimization

Implementation of semi-autonomous electric tugs does not exclude also applying techniques such as tarmac traffic flow optimization. Implementation of both would save even more fuel, and may even enhance the effectiveness of optimization schemes.

By providing pilots and/or controllers with the choice to have pilots steer their aircraft over the tarmac (powered by the tugs) or allow tugs to direct the planes (either at some chosen level of autonomy or via remote control) more advanced traffic optimization could be experimented with and implemented as airports, pilots, and other stakeholders see best.

Other Potential Uses

Semi-autonomous electric tug type vehicles may be well suited to fill other roles on the ground at airports. Potential areas for future investigation could include tasks such as picking up and transporting baggage trains, providing quick response to fires or other emergency situations or other roles where a variable level of autonomy and/or remote control would be a useful supplement to human activity.

Prototyping and Testing

To provide concrete evidence of the effectiveness of the proposed idea, scaled and eventually full-scale prototypes of the tug and other necessary systems will be developed. These prototypes will enable validation and refinement of the proposed design. Input from industry, government, and other stakeholders will be sought in the process of determining details such as what size of aircraft initial tug prototypes should be sized for.

Conclusion

Previous efforts to reduce aircraft fuel use and emissions in order to support SDGs 3.9 and 11.6 by considering the LTO cycle were reviewed and analyzed. A set of performance metrics regarding characteristics of a successful device for reducing LTO cycle fuel use and emissions was developed based on that review, and a new idea for a device with the required characteristics was proposed and described.

Using the FAA's AEDT software, simulations were created to assess the potential impact a device such as the one proposed could have at the U.S.'s busiest airport (Hartsfield-Jackson Atlanta International Airport). The simulations show that, even with the scope of the analysis conservatively limited to only departure taxi-outs, fuel use and emissions, including especially impactful PM 2.5 emissions, could be significantly reduced, along with potential economic, environmental, and other benefits. Areas for future research and development, including analyzing impact on airport noise levels and development of prototypes were briefly described.

Reduction of PM 2.5 and other emissions at airports will significantly support SDG 3.9 and 11.6. This matters because the air quality and health of airport workers, passengers, and those living and working in areas surrounding airports will improve significantly. Generally, implementation of the proposed device would also help to achieve various environmental, economic and health goals that would improve the lives of people across the globe.

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