Environmental Impacts Analysis of Different Aircraft Ground Propulsion Systems at Airport

Rui Guo
Graduate Research Assistant*
Phone: 813-974-8906
rui@mail.usf.edu

Yu Zhang¹
Assistant Professor*
Phone: 813-974-5846
yuzhang@usf.edu

Qing Wang
Graduate Research Assistant*
Phone: 813-974-8906
qingwang@mail.usf.edu

¹Corresponding Author
*Department of Civil and Environmental Engineering
University of South Florida
4202 E. Fowler Ave, ENB 118
Tampa, FL 33620
Fax: 813-974-2957

Total Words = 5226 + 250*6(3 Figures + 3 Tables) = 6726
ABSTRACT

The continuing increase of global air travel makes the environmental impact of aviation a worldwide concern for sustainable development. To reduce fuel consumption and emissions during surface movement at airport, different technologies of engineless taxiing have been emerging in recent years. In this paper, we summarize the pros and cons of alternative aircraft ground propulsion systems (AGPS) at airports and estimate the impacts they may have on the environment. Given the operational data at the 10 busiest U.S. airports, a comparison of environmental impacts is performed for four kinds of AGPS: conventional, single engine-on, external, and on-board systems. The study quantifies the benefits of alternative AGPS at airports. This study also provides some insights of future trends about adequately modeling and quantifying environmental impacts of AGPS. In addition, this study provides stakeholders a decision support tool for whether to proceed with the emerging technologies.
1. INTRODUCTION

With the continuous growth of global air travel, the environmental impacts of aviation have become a worldwide concern for sustainable development. In particular, aircraft operation at the surface movement level contributes significantly to fuel consumption and emissions at airports. To reduce fuel consumption and emissions during surface movement at airports, different technologies of engineless taxiing have emerged in recent years. The consequent question is whether and how to proceed with these emerging technologies in the aviation community. Thus the ability to adequately measure and quantify fuel consumption and emissions of operational alternatives at the airport level as well as system wide is of high importance.

At airports, aircraft emission amounts vary by aircraft operation modes and depend on the time spent at each mode/phase during the Landing and Take Off cycle (LTO). LTO includes all activities near the airport that take place below the altitude of 3000 feet (1000 m), which consists of taxiing-out, taking-off and climbing out for departures, and descending, touching down, and taxiing-in for arrivals, as illustrated in Figure 1 (1). Pushback is a procedure during which an aircraft is pushed backwards away from an airport gate. Traditionally, pushbacks are carried out by special, low-profile vehicles called pushback tractors or tugs, or by the aircraft itself with engines on. Taxiing is the movement of an aircraft on the ground using taxiways between the terminal gate and runway. Currently, an aircraft moves under its own power during both taxi-out and taxi-in phases. The taxi-out time is defined as the time between the actual pushback and wheels-off, and the taxi-in time is the time between actual wheels-on and gate-in. After exiting from the taxiway, a departure aircraft sometimes stop at the end of the runway. Alternative AGPS aims to change the current operations of taxi-in and taxi-out. Thus in this study, we focus on the taxi-in and taxi-out phases during LTO at the surface movement level, without consideration of the aircraft climb-out and descent.

![FIGURE 1 Landing and Take-off Cycle at Airport (Source: ICAO).](image)

Taxiing times are not negligible compared to flight time, especially at large, busy airports. On average, a 21 percent taxi-out time increase has been reported from 1995 to 2007 (4). Table 1 shows the 10 airports with the largest taxi-out times in 2007 in the United States (4). At low power settings during the current taxiing mode, combustion aircraft engines operate at low
efficiency and generate a host of emissions at airports and adjacent areas. Due to congestion on the airport surface, elongated taxiing delays also contribute to excessive fuel burn and emissions. A recent study suggests that excessive taxiing delays account for nearly 50% of fuel burn and emission at airports (2). The emissions escape into the local environment and lead to public health concerns. There are two primary approaches to mitigating extra aircraft fuel usage and emissions at airports. One is to develop more efficient operational strategies on airport surface movement so as to optimize the operational performance and reduce the taxiing delay. The 2010 operational performance report (3) indicates that the average additional taxiing out time at major U.S. airports is estimated to be 5 minutes per flight. Compared with other flight phases, the excess fuel burn during taxing out is estimated to be 75 kg per flight, accounting for about 26% of fuel savings among the estimated benefit pool actionable by Air Navigation Service. Various airport surface management methods have been tested at several airports in the US. The second approach involves the development of aircraft technologies (such as, engineless taxiing, fuel efficient engine design, and alternative jet fuels). Such improvements require significant technology breakthroughs and capital investment, among which, engineless taxiing has shown the most promising progress and could be ready in the very near future. Hence, this study focuses on emerging engineless taxiing technologies and estimates their environmental benefits. Given the operational data at the top 10 busiest airports, this paper performs a comparison of the environmental impacts for four kinds of AGPS systems: conventional, single engine-on, external and on-board systems.

<table>
<thead>
<tr>
<th>Airport</th>
<th>Average Taxi-Out Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 New York, JFK, NY (JFK)</td>
<td>37.1</td>
</tr>
<tr>
<td>2 Newark, NJ (EWR)</td>
<td>29.6</td>
</tr>
<tr>
<td>3 New York, La Guardia, NY (LGA)</td>
<td>29.0</td>
</tr>
<tr>
<td>4 Philadelphia, PA (PHL)</td>
<td>25.5</td>
</tr>
<tr>
<td>5 Detroit, Metro Wayne County, MI (DTW)</td>
<td>20.8</td>
</tr>
<tr>
<td>6 Boston, Logan, MA (BOS)</td>
<td>20.6</td>
</tr>
<tr>
<td>7 Houston, George Bush, TX (IAH)</td>
<td>20.4</td>
</tr>
<tr>
<td>8 Minneapolis-St. Paul, MN (MSP)</td>
<td>20.3</td>
</tr>
<tr>
<td>9 Atlanta, Hartsfield-Jackson, GA (ATL)</td>
<td>19.9</td>
</tr>
<tr>
<td>10 Washington, Dulles, DC (IAD)</td>
<td>19.7</td>
</tr>
</tbody>
</table>

NOTE: Average taxi out time at Nantucket, MA was 19.8 minutes for 2007. However, service was provided only seasonally with an average of only two departures per day, and thus it is not included in this table.

The remainder of this paper is organized as follows. The next section reviews the literature relative to alternative AGPS including single-engine taxiing, external, and on-board AGPS systems. Afterwards, different scenarios are generated and the methodology to quantify fuel consumption and different emissions in each scenario is proposed. Meanwhile, the data sources of airport operations at top 10 airports and emission factors for each scenario are introduced. Next, the results are presented and discussed, along with a comparison of different scenarios.
based on a normalization procedure. Finally, the summary and future work of this research is discussed to provide insights of future trends about modeling and quantifying the environmental impacts of AGPS at airports. The study results provide a decision support tool for stakeholders that will be involved in deciding whether and how to proceed with the emerging technologies at airports.

2. LITERATURE REVIEW

As mentioned before, the aircraft engines during conventional taxiing are operating at a low speed, which results in very low efficiency and extensive emissions. In addition, landing gear brakes are used during this phase, resulting in a considerable waste of energy and high brake heating. Given the increasing concerns of climate change, energy saving and human health, eco-friendly operational strategies and alternative AGPS technologies have become an attractive perspective in recent years. According to Re (5), the required functions for AGPS include: a) performing gate pushback; b) moving the aircraft from standstill with a sufficient acceleration, and c) driving the aircraft along the assigned taxi route. In this section, the single-engine taxiing strategy, external AGPS that can be connected to the aircraft, and integrated on-board AGPS will be reviewed, followed by the discussion of the pros and cons of each system.

2.1 Single-engine Taxiing

Single-engine taxiing is one of the most straightforward operational strategies. Single-engine taxiing means taxiing with less than all engines, i.e. only using one engine for taxiing twin-engine aircrafts, or two engines for four-engine aircrafts (6). Studies have shown the benefits in fuel consumption and emission reduction of this operational strategy during taxiing (6, 7). Meanwhile, the use of a single engine during taxi-in and taxi-out phases can achieve a certain level of engine life economy.

However, there are some issues with single-engine taxiing, especially the responsibility of such a procedure to the airlines (5). Aircraft manufactures like Airbus pointed out that such procedures need to be considered carefully, and operators have to define their field of application. For example, this procedure is not recommended for uphill slopes or slippery surfaces, or when deicing operations are required (7, 8). Besides, pilots must consider which engine, inner or outer engine, to use for achieving the required operational performance. There are also safety concerns such as jet blast and Foreign Object Damage (FOD) risk, especially for large engine, heavy aircraft (e.g. A330, A380, B777 etc.) since they need more thrust for starting the aircraft and steering when maneuvering sharp turns with engines not operating (9).

Single-engine taxiing is rarely used now in aircraft operations. Besides the concerns described above, another reason that prevents pilots from using single-engine taxiing is the engine warm-up time (typically 2-5 mins) needed for other engines to be warmed for take-off (6, 7, and 8). The engine warm-up time adds to the complexity of handling aircraft during the taxiing phase. At busy airports where demand is close to and sometimes exceeds capacity, pilots cautiously keep their positions in the take-off queue and intend to eliminate any additional uncertainties.

2.2 External AGPS
External AGPS systems are tractors or vehicles that can be attached to aircrafts for towing between airport gates and runways. They are different from conventional pushback tugs, which are only used for backward movement from gates to hand-off points. The emerging automated systems are proposed to tow the aircraft for the entire ground movement. This procedure is also known as dispatch towing (5, 7). While aircraft engines can use limited alternative jet fuel, the tractors in external systems can be powered by many different kinds of renewable energy.

In the class of external systems, the TaxiBot system, developed by Israel Aerospace Industries, has been tested at France’s Chateauroux airport, with service entry scheduled for 2016 (10). TaxiBot system, a semi-robotic towbarless tractor, is featured with a diesel engine and electrically-driven wheels. It is connected to the aircraft by embracing the Nose Landing Gear (NLG) and loading it onto a platform instead of using a conventional towbar (5). The nose-wheel platform also allows for some lateral movement to absorb loads and avoid nose-gear damage (10). The potential benefits of the TaxiBot system include reduced fuel consumption, emissions, noise, and levels of FOD, which could result in substantial savings for airline operators and the commercial airline industry (11).

Aforementioned external systems, however, also have some disadvantages. It is suggested in Cleansky 2011 (12) that the TaxiBot system may need a grid of roads parallel to the taxiways that tractors would use for non-towing travels. Similarly, dedicated parking areas may be needed to provide a safe place near the runway for tractors waiting for a landing aircraft (5). Besides the construction costs, the maintenance of additional infrastructure and operating costs (e.g. additional drivers of tractors, advanced guidance systems) at airports would increase simultaneously. The airport, and eventually airport users, will have to bear the capital cost of infrastructure investment, the purchasing expenses of such systems, and additional operating cost. Furthermore, such external systems add tractor traffic on the ground and increase the complexities of airport operations. Although the complexity of additional traffic can be alleviated by the grid of roads dedicated to external systems, it requires the consolidation of the control of ramp operations and active movement area (taxiways and runways) operations, which are currently controlled by different entities.

2.3 On-board AGPS

The integrated on-board AGPS systems eliminate the use of airplane engines during taxi-in and until immediately prior to take-off during taxi-out, which is similar to external systems. The difference is that on-board systems are based on electric traction from additional electric motors installed in the wheels of the landing gear or main gears. They also have the great potential of reducing emissions, fuel usage, and foreign object engine damage from runway debris. Representatives of this class of systems are WheelTug and Electric Green Taxiing System (EGTS).

WheelTug, a subsidiary of Borealis Exploration Limited, is a fully integrated AGPS for aircraft, which is driven by a twin induction machine from Chorus Motors integrated within the NLG (13). The integration can be easier in NLG because of its simpler structure, in particular because of the absence of the brakes (5). In 2005, the feasibility of WheelTug has been successfully demonstrated in a proof-of-concept ground test using a Boeing 767 aircraft. In 2010, the WheelTug system was tested on a Boeing 737-800 under winter conditions at Prague airport.
Different from WheelTug, EGTS, developed in partnership by Honeywell and Safran, is featured with a direct-drive motor integrated within the main gears (14, 15). The feasibility and electromagnetic design of this direct drive wheel actuator for green taxiing is discussed in (15). As pointed out by Re (5), the challenges are the thermal behavior of the motor, the thermal influence of the neighboring brakes and dealing with the takeoff and landing phases as no mechanical clutch is foreseen.

WheelTug and EGTS systems use the onboard Auxiliary Power Unit (APU) to power motors in the aircraft wheels, which allows aircraft to taxi without turning on the main engines. They aim to improve the operational efficiency by reducing fuel and other taxi related costs, as well as providing environmental benefits by slashing the emissions created during engine-on taxiing operations. Nevertheless, besides the aforementioned challenges from the thermal behavior of the motor, a key issue of on-board AGPS is the additional weight added to the aircraft. The added weight includes, but is not limited to, the weights from the on-board generator, the motor controllers and the electric motors (5). Although engineless taxiing would potentially save fuel during the LTO mode, the additional weight from on-board AGPS would result in relatively lower fuel efficiency during cruise mode. Some studies conducted the analysis of global fuel saving from on-board AGPS, with the consideration of the trade-off of fuel burn between en-route phase and taxiing phase due to additional weight of the systems (16, 17). The comparison analysis showed global fuel reduction of up to 2.5% for mid-sized aircraft with a 500kg on-board AGPS in reference (16) and the global fuel savings between 1.1% and 3.9% based on US domestic flights in 2007 with a 1,000kg on-board AGPS in reference (17).

In summary, the recent emerging alternative AGPS systems are developed mainly to gain environmental benefits. Table 2 summarizes the features as well as the pros and cons of each AGPS. It is very likely that some or all of the systems will be implemented at airports in the near future. To help stakeholders make decisions on which system to implement, more quantitative analysis and comparison of the benefits of AGPS are needed. With the concern of sustainable development, this paper focuses on the environmental impact of these innovative systems.

**TABLE 2 Features, Pros and Cons for Different AGPS at Airport**

<table>
<thead>
<tr>
<th>Alternative AGPS</th>
<th>Main Features</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-engine</td>
<td>less than all engines operating</td>
<td>• Energy efficiency</td>
<td>Extra infrastructure costs, congestion and safety issues</td>
</tr>
<tr>
<td>External Systems</td>
<td>TaxiBot</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>• Emission reduction, • Less noise</td>
<td></td>
</tr>
<tr>
<td>On-board Systems</td>
<td>WheelTug</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EGTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TRB 2014 Annual Meeting

Original paper submittal - not revised by author
3. METHODOLOGY & DATA SOURCES

The environmental impact of air transportation can be categorized into global and local groups. The global environmental impact is mainly associated with greenhouse gas emission, which contributes to global warming and climate change. The local environmental impact is usually associated with air pollutant emissions, noise and water contamination. Air pollutant emissions have been attracting increasing concerns from the public, because they affect air quality and are detrimental to human health, especially in the local area. In this study, we focus on three pollutant species, namely, carbon monoxide (CO), Nitrogen oxides (NOx) and Hydrocarbon (HC). CO emission is a colorless, odorless, non-irritating but very poisonous gas. It is a product from incomplete combustion of fuel and vehicular exhaust is a major source of this type of pollutant. HC emissions result from fuel that does not burn completely in the engine. It reacts with nitrogen oxides and sunlight to form ozone, which is the major component of smog. NOx refers to nitric oxide (NO) and nitrogen dioxide (NO2), which lead to the formation of ozone and contribute to the formation of smog and acid rain (19). NOx also causes irritation to human mucus membranes, reduces lung function and increases risks of respiratory problems. All of these emissions have negative impacts on local air quality (e.g. smog and acid rain) and cause health problems to human beings at airports and its adjacent areas.

3.1 Methodology for Emissions Estimation

Four scenarios are generated for quantifying and comparing the environmental impacts of airport surface movement: 1) Baseline scenario-conventional taxiing; 2) The single-engine taxiing scenario; 3) External AGPS scenario: TaxiBot system; and 4) On-board AGPS scenario: WheelTug and EGTS. In these four scenarios, emissions at airports can be generated from the backward movement (pushback phase), forward movement (taxi-out and taxi-in phases) and engine start. Since the emissions from backward movement and engine start are usually fixed and almost the same in all scenarios, this study only conducts a comparison of emissions from forward movement based on taxi-out and taxi-in times of airport surface movement. Furthermore, single-engine operation and emerging systems all claim their taxiing speeds are no less than the speed of conventional taxiing (10, 11, 13 and 14), thus the potential environmental benefits of alternative AGPS are conservatively estimated based on the current operating time assuming the taxiing speeds with different AGPS are the same.

Scenario 1- Conventional taxiing

For conventional taxiing, the International Civil Aviation Organization (ICAO) suggests three approaches to quantify aircraft engine emissions: simple approach, advanced approach and sophisticated approach (1, 20). Note that the sophisticated approach still needs further development with the expectation of more accurate emission estimation (20). In our study, the advanced approach, which reflects an increased level of refinement regarding aircraft types, emission indices calculations and time-in-mode, is adopted. Compared with the simple approach, this approach represents a more accurate estimation of aircraft engine emissions.

Based on the ICAO fuel burn indices, the fuel burn during taxiing of flight i in kg, denoted $F_i$, could be estimated by

$$F_i = \sum (T_{im} \times 60) \times N_i \times FF_{im}$$  \hspace{1cm} (1)
Where $T_{im}$ is the time-in-mode for mode $m$ (e.g. taxi-in and taxi-out), in minutes, for flight $i$, $N_i$ is the number of engines on flight $i$ and $FF_{im}$ is the fuel flow index in mode $m$ (e.g. taxi-in and taxi-out), for each engine used on flight $i$ (in kg/sec).

The emissions from flight $i$ for each pollutant $j$ (e.g. NO$_x$, CO or HC), denoted $E_{ij}$, in grams, for taxiing, are calculated by

$$E_{ij} = \sum(T_{im} \times 60) \times N_i \times FF_{im} \times EI_{im}$$  \hspace{1cm} (2)

Where $EI_{im}$ is the emission index for pollutant $j$ (e.g. NO$_x$, CO or HC) from each engine on flight $i$, measured in grams of pollutant per kilogram of fuel consumed (g/kg of fuel), in mode $m$ (e.g. taxi-in and taxi-out). By summing the above quantities over all departures and arrivals in the system or at any particular airport, the total fuel consumption and emissions can be obtained.

**Scenario 2-Single-engine taxiing**

In the single-engine taxiing scenario, aircrafts taxi with less than all engines operating. Assuming the use of one engine for taxiing twin-engine aircrafts and two engines for four-engine aircrafts, the single-engine taxiing fuel consumption of flight $i$ in kg, denoted as $F_i^{\text{single}}$, can be estimated by

$$F_i^{\text{single}} = \sum(T_{im} \times 60) \times (N_i/2) \times FF_{im}$$  \hspace{1cm} (3)

The single-engine taxiing emissions from flight $i$ for each pollutant $j$ (denoted $E_{ij}$, in kg) is calculated by

$$E_{ij}^{\text{single}} = \sum(T_{im} \times 60) \times (N_i/2) \times FF_{im} \times EI_{im}$$  \hspace{1cm} (4)

**Scenario 3- External AGPS**

In Scenario 3, fuel consumption and emissions from engineless taxiing are generated from towing vehicles. For external AGPS, similar to push-back tugs, the emissions depend on the type of energy powering the towing vehicles as well as required engine horsepower. The following equations calculate the fuel consumption (in kg) and emissions $E_{ij}^t$ of pollutant $j$ from the towing vehicle type $t$ (in grams), for flight $i$ respectively.

$$F_i^t = \sum(T_{im} \times 60) \times BHP \times LF \times FF_{im}^t$$  \hspace{1cm} (5)

$$E_{ij}^t = \sum(T_{im} \times 60) \times BHP \times LF \times EI_{ij}^t$$  \hspace{1cm} (6)

Where $FF_{im}^t$ is the fuel flow index in mode $m$ (e.g. taxi-in and taxi-out), corresponding to the engine-fuel type of vehicle $t$ used to tow aircraft $i$ (in kg/BHP-sec), $BHP$ is the average rated brake horsepower (BHP) of the towing vehicle engine, $LF$ is the load factor utilized in the operation. And $EI_{ij}^t$ is the emission index for each pollutant $j$, in grams per BHP-sec, which is specific to a given engine-fuel type of vehicle $t$.

In this scenario, a particular case, TaxiBot system featured with hybrid diesel-electric vehicle is considered. The case study can be potentially extended to include other alternative energy for
powering the external system. To simplify the problem, the possible additional travel time and excess delays due to the increase of traffic from external systems are not considered in this study.

**Scenario 4 - On-board AGPS**

In Scenario 4, the on-board systems are driven by electric motors integrated with the wheels, with power supplied by the onboard APUs. According to Reid's study, only minor, if any, modifications of the APUs would be required for on-board AGPS. Instead, a change would be needed in the usage procedures of APU and the details can be found in reference (5). Thus, we assume the fuel flow and emission index for different APU models keep the same as those of conventional APUs. APUs burn a certain amount of jet fuel and create exhaust emissions like aircraft main engines. The methodology for calculating emissions from APUs is adapted from the U.S. EPA’s Procedures for Emissions Inventory Preparation (21). Equations (7) and (8) calculate the fuel consumption and pollutant emissions from an APU on flight \(i\) based on APU operating time, fuel flow, and the emission indices for the specific APU.

\[
F_{i,APU}^{APU} = \Sigma(T_{im} \times 60) \times FF_{im}^{APU}
\]

\[
E_{i,j,APU}^{APU} = \Sigma(T_{im} \times 60) \times FF_{im}^{APU} \times EI_{j}^{APU}
\]

Where \(FF_{im}^{APU}\) is the fuel flow index in mode \(m\), for specific APU used on flight \(i\) (in kg/sec), \(EI_{j}^{APU}\) is the emission index for pollutant \(j\), for each APU used on flight \(i\), measured in grams of pollutant per kilogram of fuel consumed (g/kg of fuel).

### 3.2 Data Sources

Based on the above methodology, we summarize the types of data needed for emission estimations: 1) aircraft type, number of engine, engine type or APU model; 2) operating time; 3) number of operations/flights; and 4) fuel and emission index for each scenario.

The first three types of data can be obtained from the Aviation System Performance Metrics (ASPM), which provides operational data of flights to and from the ASPM airports (22). The ASPM dataset provides individual flight data including each flight’s scheduled and actual gate departure time, runway wheel-off time, runway wheel-on time and gate arrival time, etc. Besides operational data, detailed data of aircraft is retrieved from airline-fleets reference book, which provides administrative information for all known commercial aircraft operators, plus technical information on every aircraft over 3,000 lbs. For instance, current registration, type, serial number, engine type and number, and maximum take-off weight can all be found in this reference book (23).

The last type of data is gathered from different resources for each scenario. For the first two scenarios, fuel and emission indices are obtained from ICAO Engine Emission Databank (24). For Scenario 3, the BHP values for each aircraft and vehicle engine type, the corresponding fuel consumption and emission coefficients are based on the data from FAA technical report (25). For Scenario 4, ACRP Report 64 (26) provides the latest data on fuel flow and emission index from onboard APUs for three distinct power settings: No-Load (lowest power setting used during the “APU Start” mode), Environmental Control System (normal running condition used to support the “Gate In” and “Gate Out” modes), and Main Engine Start (highest power setting used to...
support the start of the main engines). For Scenario 4, we use the highest power settings to estimate the APU emissions.

4. CASE STUDY AND RESULTS

In the case study, the departure and arrival data at the top 10 airports, which are listed in Table 1, are downloaded from ASPM for the year of 2012. To deal with the mass data, statistics software, SAS, is used to process the input data and compute the fuel usage and emissions of each scenario based on the methodology described in Section 3. Figure 1 presents the comparison results of quantitative assessment of fuel burn and each type of pollutants. In general, the alternative AGPS scenarios show significant reduction in fuel burn and emissions during taxiing compared with the conventional scenario. Especially, Scenario 4 (on-board AGPS) shows the most emission reduction, while Scenario 3 (external AGPS) consumes the least fuel. Specifically, Scenario 4, with the use of onboard APUs, results in a significant reduction of fuel burn and emissions when comparing with single-engine taxiing. It can be explained by the fact that one smaller reaction engine near its nominal working point is more efficient than two or more large ones (e.g. main engine) at idle. However, Scenario 3 reveals the increase of NOx emissions compared to single-engine scenario because the diesel engine in external AGPS generates more NOx than jet fuel.

a) Comparison of fuel consumption for 4 scenarios; b) Comparison of HC for 4 scenarios

![Comparison of Fuel Burn](image1)

![Comparison of CO](image2)

![Comparison of NOx](image3)

![Comparison of HC](image4)

![Comparison of CO](image5)

![Comparison of NOx](image6)

FIGURE 2 Results of quantitative assessment.
As mentioned above, Scenarios 3 and 4 show the best performance in different indicators (fuel consumption or emissions). To allow different scenarios to be compared with a general indicator, a normalization procedure is performed. The value of a normalized indicator of 1 is chosen to correspond to the best environmental performance among the scenarios considered. Therefore, normalized indicator, $(N_{\text{Ind}})_i$, for indicator $i$ (fuel and air pollution emissions) is proposed according to the following equation:

$$
(N_{\text{Ind}})_i = \frac{\left(\frac{1}{\text{Ind}}\right)_i}{\left(\frac{1}{\text{Ind}}\right)_{\text{max}}}
$$

(9)

Where $\left(\frac{1}{\text{Ind}}\right)_i$ are the reciprocal values of the indicator of fuel consumption and air pollution emissions. $\left(\frac{1}{\text{Ind}}\right)_{\text{max}}$ denotes the maximum of the reciprocal values of these indicators.

Figure 3 and Table 3 present the normalized indicators and normalized general indicator for four scenarios at 10 airports. The normalized general indicator is the normalization of general indicator, which is the product of all normalized indicators. This is a simple geometrical aggregation of criteria when the weighting coefficients are absent. The scenario with the best environmental performance is associated with a generalized indicator of 1; as such a scenario possesses all the advantages of the factors considered. Figure 3 shows the same trend of all the normalized indicators for the 10 study airports. The calculated values of normalized general indicators, in Table 3, indicate clearly that Scenario 4 (on-board AGPS) is the best in term of environmental performance for all airports in this study.

FIGURE 3 Normalized indicators for four scenarios.
TABLE 3   Normalized General Indicator for Four Scenarios at 10 Airports

<table>
<thead>
<tr>
<th>Airport Scenarios</th>
<th>ATL</th>
<th></th>
<th></th>
<th></th>
<th>BOS</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized general indicator</td>
<td>Sce 1</td>
<td>Sce 2</td>
<td>Sce 3</td>
<td>Sce 4</td>
<td>Sce 1</td>
<td>Sce 2</td>
<td>Sce 3</td>
<td>Sce 4</td>
</tr>
<tr>
<td>ATL</td>
<td>2.3E-05</td>
<td>3.7E-04</td>
<td>3.2E-02</td>
<td>1.00</td>
<td>1.6E-05</td>
<td>2.6E-04</td>
<td>2.2E-02</td>
<td>1.00</td>
</tr>
<tr>
<td>DTW</td>
<td>3.1E-05</td>
<td>4.9E-04</td>
<td>2.0E-02</td>
<td>1.00</td>
<td>2.0E-05</td>
<td>3.6E-04</td>
<td>1.1E-02</td>
<td>1.00</td>
</tr>
<tr>
<td>IAD</td>
<td>3.2E-05</td>
<td>5.4E-04</td>
<td>1.6E-02</td>
<td>1.00</td>
<td>2.8E-05</td>
<td>5.5E-04</td>
<td>1.3E-02</td>
<td>1.00</td>
</tr>
<tr>
<td>JFK</td>
<td>2.4E-05</td>
<td>4.0E-04</td>
<td>1.9E-02</td>
<td>1.00</td>
<td>1.4E-05</td>
<td>2.4E-04</td>
<td>1.1E-02</td>
<td>1.00</td>
</tr>
<tr>
<td>MSP</td>
<td>2.8E-05</td>
<td>4.6E-04</td>
<td>2.1E-02</td>
<td>1.00</td>
<td>2.2E-05</td>
<td>3.6E-04</td>
<td>3.0E-02</td>
<td>1.00</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS AND FUTURE WORK

In this study, local environmental impacts of different AGPS are evaluated by examining selected air pollution emissions at the 10 busiest airports in the U.S. The main features of alternative AGPS, as well as their pros and cons are discussed. Given the operational data at the 10 airports, a comparison of environmental impacts is performed for four kinds of AGPS: conventional, single engine-on, external and on-board systems. The study demonstrates that the alternative AGPS can significantly reduce fuel burn and emissions during taxing compared with the conventional scenario. On-board AGPS shows the best performance in the emission reduction, while external AGPS consumes the least fuel (diesel in the case study). When a general indicator is considered, on-board AGPS shows the best potential of reducing local environmental impacts. Although the manufactures provided benefit analysis during the testing of innovative AGPS, this study provides a comprehensive comparison of different AGPS and provides a decision support tool for stakeholders to determine whether and how to proceed with the emerging technologies.

One extension of this study could be generating more scenarios assuming some of the systems (e.g. external AGPS) can be powered by alternative energy, such as biodiesel, hydrogen, and electricity from wind or solar farms. In addition, noise, as one of the local environmental impacts should also be considered. With more data and technical specifications of alternative AGPS becoming available, the modeling and quantification of environmental impacts of alternative AGPS will be more promising. In the future when the technologies are more mature, the study can be extended to a more complete Environmental Impact Analysis (EIA) including economic aspects and Life Cycle Analysis (LCA).


1 REFERENCES


(4) U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, Airline On-Time Performance Database.


(18) German Aerospace Center DLR. *DLR Airbus A320 ATRA taxis using fuel cell-powered nose wheel for the first time.*


(22) Federal Aviation Administration (FAA). *ASPM System Overview.*


