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Comparison of emerging ground propulsion systems for electrified aircraft taxi operations

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A B S T R A C T

Aviation is a mode with high fuel consumption per passenger mile and has significant environmental impacts. It is important to seek ways to reduce fuel consumption by the aviation sector, but it is difficult to improve fuel efficiency during the en-route cruise phase of flight because of technology barriers, safety requirements, and the mode of operations of air transportation. Recent efforts have emphasized the development of innovative Aircraft Ground Propulsion Systems (AGPS) for electrified aircraft taxi operations. These new technologies are expected to significantly reduce aircraft ground-movement-related fuel burn and emissions. This study compares various emerging AGPS systems and presents a comprehensive review on the merits and demerits of each system, followed with the local environmental impacts assessment of these systems. Using operational data for 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 results show that there are tradeoffs in fuel and emissions among these emerging technologies. On-board system shows the best performance in the emission reduction, while external system shows the least fuel burn. Compared to single-engine scenario, external AGPS shows the reduction of HC and CO emissions but the increase of NO_x emission. When a general indicator is considered, on-board AGPS shows the best potential of reducing local environmental impacts. The benefit-cost analysis shows that both external and on-board systems are worth being implemented and the on-board system appeals to be more beneficial.

1. Introduction

Fuel cost represents about 32% of the airline industry's operations budget, the second highest expense after labor (Jordan, 2013). According to the statistics from the International Aviation Transport Association (IATA), the airline industry spent \$209 billion on fuel in 2012, which was \$33 billion higher than in 2011. The industry is expected to pay an additional \$7 billion in 2013 (IATA, 2013a). Despite the easing of fuel prices in recent weeks, the airline industry remains concerned with high and volatile fuel prices. IATA launched a Fuel Action Campaign to assist airlines with mitigating the impact of rising fuel prices. One way of doing that is to encourage airlines to improve their operating efficiencies, such as opening new and more direct routes, realigning inefficient routes, and improving ground traffic flows (IATA, 2013b). Another method that has been implemented to reduce fuel consumption and noise is Continuous Descent Approach (CDA) (Cao et al., 2011; Zhao et al., 2013). Instead of approaching an airport in a stair-step fashion, throttling down, and requesting permission to descend to

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each new (lower) altitude, CDA allows for a smooth, constant-angle descent to landing and consumes less fuel than conventional descent. Nevertheless, more innovative ways are needed to further alleviate the dependence of airlines on fuel prices.

Flight phases can be categorized into two major parts: en-route cruise and Landing and Take Off cycle (LTO). It is especially difficult to reduce jet fuels in en-route cruise because environmental and economic aspects must yield to safety rules. Safety regulations require aircraft to carry fuel beyond the minimum needed to fly from origin to destination to allow for unforeseen circumstances or for diversion to another airport if the planned destination turns unavailable. Furthermore, under the supervision of air traffic control, aircraft flying in controlled airspace must follow predetermined routes known as airways, even if such routes are not as economical as a more direct flight (Khurana, 2009). Since it is much harder to control fuel consumption in the en-route cruise of flight, researchers and practitioners are beginning to seek fuel-economic control strategies for aircraft ground movement during 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 Fig. 1. Besides the aforementioned CDA, which has been implemented at many U.S. airports, another innovative solution is to apply other power resources for aircraft taxiing on airport surface.

During LTO, aircraft fuel consumption and emission amounts vary by aircraft operation phases (e.g., taxi-in phase, taxi-out phase, take-off and landing phase) and depend on the time spent at each phase. Taxiing is the movement of an aircraft on the ground using taxiways between the terminal gate and runway. Conventional taxiing-out usually includes push-back and engine-on taxiing. 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. Currently, an aircraft moves under its own power during most of taxi-out phase and the entire taxi-in phase. At low power settings during the current taxiing mode, combustion aircraft engines operate at lower fuel efficiency than at cruise power settings and generate a host of emissions at airports and adjacent areas.

From the system operational point of view, the taxi-out time of a departure flight is measured as the time difference between its gate-out time and wheel-off time, which include unimpeded taxi-out time and additional taxi-out time (called taxi-out delay) (Zhang and Wang, 2011a). Literature has shown the trend of the taxiing delay in recent years (a 21% taxi-out time increase was reported from 1995 to 2007 in the U.S.) and ways of benchmarking airport taxiing performance (Glover and Ball, 2013; Kuhn, 2013; Zhang and Wang, 2011b; Zhang et al., 2012). Overall, after controlling for air traffic demand and other inputs, U.S. airports shows longer taxiing time compared to their counterparts in Europe. Year 2007 is known as a high delay year in the U.S. air industry. Table 1 shows the 10 airports with the longest average taxi-out times in 2007 in the U.S. (Goldberg and Chesser, 2008). Taxiing time is not negligible compared to overall flight time; aircraft are estimated to spend 10–30% of their flight time taxiing in Europe (Deonandan and Balakrishnan, 2010). Elongated taxiing times lead to excessive fuel burn and emissions, which not only worsen the financial situation of airlines, but also the emissions from aircraft taxiing that escapes into the local environment and leads to public health concerns. Compared with other flight phases, the excess fuel burn during taxiing out in the U.S is estimated to be 165 lbs. (75 kg) per flight, accounting for about 26% of fuel savings among the estimated benefit pool actionable by Air Navigation Service (USDOT, 2013).

To reduce fuel consumption and emissions of aircraft surface movement at airports, innovative control strategies and technologies of fuel-efficient taxiing have emerged in recent years. There are two primary approaches to mitigating aircraft fuel usage and emissions for taxiing at airport surface. One is to develop a more ecofriendly operational procedure, such as single-engine taxiing (Deonandan and Balakrishnan, 2010; Airbus Customer Services, 2004; Heathrow Airport, 2012 and Gubisch, 2013a), Pushback Rate Control (PRC) (Simaiakis et al., 2011), Collaborative Departure Queue Management (CDQM) (Brinton et al., 2011), Spot and Runway Departure Advisor (SARDA) (Hoang et al., 2011) and so on. The other involves the development of aircraft technologies such as engineless taxiing, fuel-efficient engine design, and alternative jet fuels (Re, 2012b). Such improvements require significant technology breakthroughs and capital investment, among which engineless taxiing with innovative Aircraft Ground Propulsion Systems (AGPS) has shown the most promising progress and could be ready in the very near future (Gubisch, 2013a,b; Cleansky, 2013; WSJ, 2013).

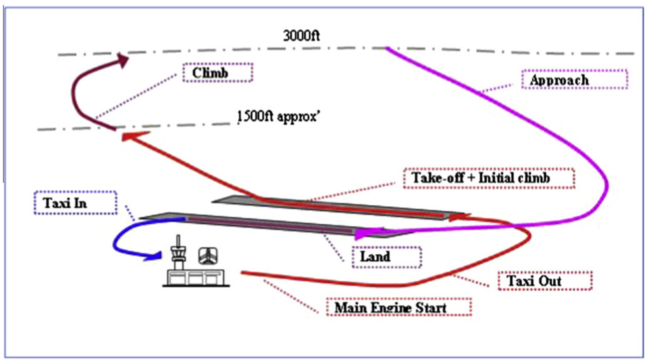

Fig. 1. Landing and take-off cycle at airport (*photo by Eurocontrol*).

Table 1
Top 10 Airports with Largest Taxi-Out Times in 2007. *Source:* Bruce Goldberg and David Chesser, BTS Special Report: Sitting on the Runway: Current Aircraft Taxi Times Now Exceed Pre-9/11 Experience.

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

Note: Average taxi out time at Nantucket, MA was 19.8 min 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 consequent question is whether and how to proceed with these emerging technologies in the aviation community. The ability to adequately measure and quantify fuel consumption and emissions of operational alternatives at airports is of high importance for decision makers. Although the manufactures of these innovative systems have done some cost-benefit analysis, their estimation focuses on one system only and is quite rough, not considering real airport operational conditions. To fill in this gap, this study reviews emerging engineless taxiing technologies and discuss their merits and demerits. In addition, this study estimates and compares the fuel consumption and environmental benefits of different AGPS using data from the 10 busiest airports (by annual average taxi-out time) in the U.S. The four AGPS systems analyzed in this study include conventional, single engine-on, external and on-board systems. Among the four AGPS systems, the on-board system requires the installation of additional components to aircraft, which increase the carrying weight of the aircraft. Nevertheless, existing literature shows that fuel savings during LTO requires less fuel to be carried, which offsets the additional weight of the on-board system and eliminates the negative impact of the added motors (Re, 2012b; Dzikus et al., 2011). In addition, this study focuses on the local environmental impacts of different systems. Hence, this study investigates the taxi-in and taxi-out phases during LTO at the surface movement level, assuming fuel consumption and emissions in other phases are the same.

The remainder of this paper is organized as follows. Section 2 reviews the literature relative to alternative AGPS and summarizes the features, pros, and cons for each system. Then, different scenarios are generated and the methodology to quantify fuel consumption and different types of emissions in each scenario is proposed. The data sources for airport operations at the top 10 busiest 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, a 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.

2. Overview of emerging AGPS

As mentioned, aircraft engines during conventional taxiing operate at a low speed, which results in low fuel 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 related to climate change, energy dependence, and human health, eco-friendly operational strategies and alternative AGPS technologies have become an attractive perspective for air transportation in recent years. According to Re (2012b), 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 are reviewed, followed by a 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., using only one engine for taxiing twin-engine aircraft or two engines for four-engine aircraft (Kumar et al., 2008). Studies have shown the benefits in fuel consumption and emission reduction of this operational strategy during taxiing (Kumar et al., 2008; Deonandan and Balakrishnan, 2010). Meanwhile, the use of a single engine during the taxi-in and taxi-out phases can achieve a high level of engine life economy.

Nevertheless, obstacles exist to prevent single-engine taxiing, especially the additional responsibility of such a procedure to the airlines and pilots (Re, 2012b). In addition, single-engine taxiing is not operable under special conditions of taxiing. For example, this procedure is not recommended for uphill slopes or slippery surfaces, or when deicing operations are required (Deonandan and Balakrishnan, 2010; Airbus Customer Services, 2004). Aircraft manufacturers such as Airbus point out that such a procedure needs to be considered carefully and operators have to define their field of application based on the understanding of specific airport conditions. 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 (Heathrow Airport, 2012).

Besides these concerns, another reason preventing pilots from using single-engine taxiing is time (typically 2–5 min) needed for other engines to be warmed for take-off (Kumar et al., 2008; Deonandan and Balakrishnan, 2010; Airbus Customer Services, 2004). 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 aircraft 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 (Re, 2012b; Deonandan and Balakrishnan, 2010). 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 (Gubisch, 2013a). The 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 (Re, 2012b). The nose-wheel platform also allows for some lateral movement to absorb loads and avoid nose-gear damage (Gubisch, 2013a).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 (Gubisch, 2013b).

Dispatch towing has been used at some airports in the U.S. (Quinn, 2012). However, these external systems also have some disadvantages that limit their widespread usage. First of all, the tugs for dispatch towing could impose heavy fatigue loads on the aircraft nose landing gear that shorten its lifespan (e.g., details can be found in the tests conducted by Virgin Atlantic and Boeing in recent TRB report by Quinn, 2012). Moreover, it is suggested in Cleansky (2013) that the TaxiBot system may need additional roads connecting the parking area of external AGPS systems and the end of runways for non-towing travels. Dedicated parking areas may also be needed to provide a safe place near the runway for tractors waiting for a landing aircraft (Re, 2012b). In addition to construction costs, the maintenance of additional infrastructure and operating costs (e.g., additional drivers of manually-controlled tractors, advanced guidance systems for autonomous/remotely-controlled tractors) at airports would increase simultaneously. The airport—and, eventually, airport users—would 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 roads dedicated to external systems for non-towing travel, the efficient movement of external system requires the consolidation of the control of ramp and active movement area (taxiways and runways) operations, which are currently controlled by different entities at most airports in the U.S.

2.3. On-board AGPS

Integrated on-board AGPS systems eliminate the use of airplane engines during taxi-in and 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. Such systems also have the great potential of reducing emissions, fuel usage, and FOD from runway debris. Representatives of this class of systems are WheelTug and the 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 (WSJ, 2013). The integration can be easier in NLG because of its simpler structure, in particular because of the absence of the brakes (Re, 2012b). In 2005, the feasibility of WheelTug was 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. On October 23, 2013, WheelTug plc. announced the execution of a Slot Option Purchase Agreement for Airbus A320 WheelTug Systems. With the new reservations the order book for WheelTug® aircraft drive systems grows to 731 delivery slots reserved by thirteen airlines from Europe, America, the Middle East and Asia. (WSJ, 2013).

Different from WheelTug, EGTS, developed in partnership by Honeywell and SAFRAN, features a direct-drive motor integrated within the main gears (SAFRAN, 2013; Raminosoa et al., 2011). The feasibility and electromagnetic design of this direct drive wheel actuator for green taxiing is discussed in Raminosoa et al. (2011). As pointed out by Re (2012b), the challenges of EGTS are the thermal behavior of the motor, the thermal influence of the neighboring brakes, and the needs of dealing with the takeoff and landing phases, as the motor is in the vicinity of the brakes, which could reach very high temperatures (Re, 2012b). Motor temperature can be reduced by either installing a fan at the front aspect of the wheel or placing the converter within a pressurized aircraft zone to increase the volt-ampere rating. However, if a mechanical clutch

Table 2
Features, Pros, and Cons for Different AGPS at Airports.

Alternative AGPS		Main features	Pros	Cons
Single-engine		Less than all engines operating	• Energy efficiency	Complexity of operation and safety issues
External systems	TaxiBot	Hybrid diesel-electric tractor	• Emission reduction	Extensive equipment investment, system development and operations, and congestion and safety concerns; diesel engine may generate more NOx than jet fuel
	Others	Potentially using alternative energy	• Less noise	
On-board systems	WheelTug	Additional motor at nose landing gear powered by onboard APU		Extra weight and fuel consumptions in en-route phase and APU modification needs
	EGTS	Additional motor at main wheels powered by onboard APU		
	Others	Powered by alternative energy, electricity, fuel cell, etc.		

is employed between the motor and the wheel rim, the motor requirements could be less onerous at the expense of the additional complexity of having a clutch (Raminosoa et al., 2011). EGTS targets entry into service on new aircraft and for retrofit on existing planes starting in 2016 (Gubisch, 2013b).

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 possible key issue concerned users 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 (Re, 2012b). Although engineless taxiing would potentially save fuel during the LTO mode, the additional weight from on-board AGPS may result in higher fuel consumption during the cruise mode. Some studies conducted an 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 (Re, 2012a; Dzikus et al., 2011). The comparison analysis showed global fuel reductions of up to 2.5% for mid-sized aircraft with a 500 kg on-board AGPS in reference (Re, 2012a) and global fuel savings between 1.1% and 3.9% based on U.S. domestic flights in 2007 with a 1000 kg on-board AGPS in reference (Dzikus et al., 2011). The global fuel savings are gained mainly from electrical taxiing on ground. As pointed out by WSJ (2013), electrical taxiing requires less fuel to be carried by aircraft, which offsets the additional weight of the on-board system. Thus, the cruise phase with very slight weight change is not considered in the comparison study of Section 3.

Table 2 lists a summary of the features of emerging alternative AGPS and the pros and cons of each system. It is very likely that some or all of the systems will be implemented in the near future (Gubisch, 2013a,b; WSJ, 2013). To help stakeholders make decisions on which system to implement, more quantitative analysis and comparison of the benefits of AGPS are needed. Related to sustainable development, the next section focuses on the energy consumption and environmental impacts of these innovative systems. In Section 3, the methodologies for fuel burn and emission estimation are discussed, and estimation methods are applied with actual operational data from the 10 busiest airports in the U.S.

3. Comparison of fuel consumption and local environmental impacts of different AGPS

Aviation is a mode with high fuel consumption per passenger mile and has significant environmental impacts. The environmental impacts of air transportation can be categorized into global and local groups. Global environmental impacts are associated primarily with greenhouse gas emissions, which contribute to global warming and climate change. Local environmental impacts are usually associated with air pollutant emissions, noise, and water contamination. Air pollutant emissions attract increasing concerns from the public because they affect local air quality and are detrimental to human health, especially for residents living in the vicinity of airports. In this study, we focus on three pollutant species, namely, carbon monoxide (CO), nitrogen oxides (NO_x) and hydrocarbon (HC). CO emission is a colorless, odorless, non-irritating but very poisonous gas and is a product of the incomplete combustion of fuel; vehicle 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. NO_x refers to nitric oxide (NO) and nitrogen dioxide (NO_2), which leads to the formation of ozone and contributes to the formation of smog and acid rain (EPA, 2012). NO_x 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 humans at airports and their adjacent areas.

3.1. Methodology for fuel burn and emissions estimation

Four scenarios were generated for quantifying and comparing the environmental impacts of airport surface movement: (1) baseline scenario—conventional taxiing, (2) single-engine taxiing, (3) external AGPS—TaxiBot system, and (4) on-board

AGPS—WheelTug and EGTS. In these four scenarios, emissions at airports can be generated from backward movement (push-back phase), forward movement (taxi-out and taxi-in phases), and engine start. Since backward movement time is included in the taxi-out time in the database (more details can be found in Section 3.2) and the emissions from engine start are usually fixed and almost the same in all scenarios, this study conducts only a comparison of fuel burn and emissions based on taxi-out and taxi-in times of airport surface movement. Furthermore, single-engine operation and emerging systems all claim that their taxiing speeds are no less than the speed of conventional taxiing (Gubisch, 2013a,b; WSJ, 2013; SAFRAN, 2013); 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 (ICAO, 2008; Kurniawan and Khardi, 2011). Note that the sophisticated approach still needs further development, with the expectation of more accurate emission estimation considering airport meteorological conditions, actual aircraft/engine configuration data, different load, etc. (Kurniawan and Khardi, 2011). Those interested in the details of the sophisticated approach can refer to the ICAO report (Secretariat, ICAO, 2010) that summarizes the results of the eighth meeting of ICAO's Committee on Aviation Environmental Protection (CAEP/8, February 2010). In our study, the advanced approach, which reflects an increased level of refinement regarding aircraft types, emission indices calculations, and time-in-mode, was adopted. Compared with the simple approach, the advanced 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 as F_i, is estimated by

$$F_i = \sum_m (T_{im} * 60) * N_i * FF_{im} \tag{1}$$

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 for each engine used on flight i (in kg/s).

The emissions from flight i for each pollutant j (e.g., NO_x, CO or HC), denoted as E_{ij}, in grams, for taxiing, are calculated by

$$E_{ij} = \sum_m (T_{im} * 60) * N_i * FF_{im} * EI_{ijm} \tag{2}$$

where E_{ijm} 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 at a particular airport, the total fuel consumption and emissions at that airport can be obtained

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- Scenario 2—Single-Engine Taxiing

In the single-engine taxiing scenario, aircrafts taxi with only a subset of their engines. 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^{single}, can be estimated by

$$F_i^{single} = \sum_m (T_{im} * 60) * (N_i/2) * FF_{im} \tag{3}$$

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

$$E_i^{single} = \sum_m (T_{im} * 60) * (N_i/2) * FF_{im} * EI_{ijm} \tag{4}$$

This is an acceptable rough estimate, but it should be noted that single-engine taxiing may not suit all aircraft types or airport conditions. Therefore, the estimation results from scenario 2 will be slightly higher than the 50% of the results from scenario 1.

- 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 F_i^t (in kg) and emissions E_{ij}^t of pollutant j from the towing vehicle type t (in grams), for flight i respectively.

$$F_i^t = \sum_m (T_{im} * 60) * BHP * LF * FF_{im}^t \tag{5}$$

$$E_{ij}^t = \sum_m (T_{im} * 60) * BHP * LF * EI_{ij}^t \tag{6}$$

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/BHP-sec), which is specific to a given engine-fuel type of vehicle t.

In this scenario, a particular case, the 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. Assume that auxiliary taxiways are provided for non-towing travel of the external system and the additional fuel consumption and emissions due to non-towing travel 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 Re (2012b), 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 the APU; details can be found in Re (2012b). 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 similar to aircraft main engines. The methodology for calculating emissions from APUs is adapted from the the U.S. Environmental Protection Agency's Procedures for Emissions Inventory Preparation (EPA, 1992). Eqs. (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.

$$F_{i}^{\mathrm{APU}} = \sum_{m}(T_{im} * 60) * FF_{im}^{\mathrm{APU}} \tag{7}$$

$$E_{ij}^{\mathrm{APU}} = \sum_{m}(T_{im} * 60) * FF_{im}^{\mathrm{APU}} * EI_{ij}^{\mathrm{APU}} \tag{8}$$

Where FF_{im}^{APU} is the fuel flow index in mode m for specific APU used on flight i (in kg/s), and EI_{ij}^{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

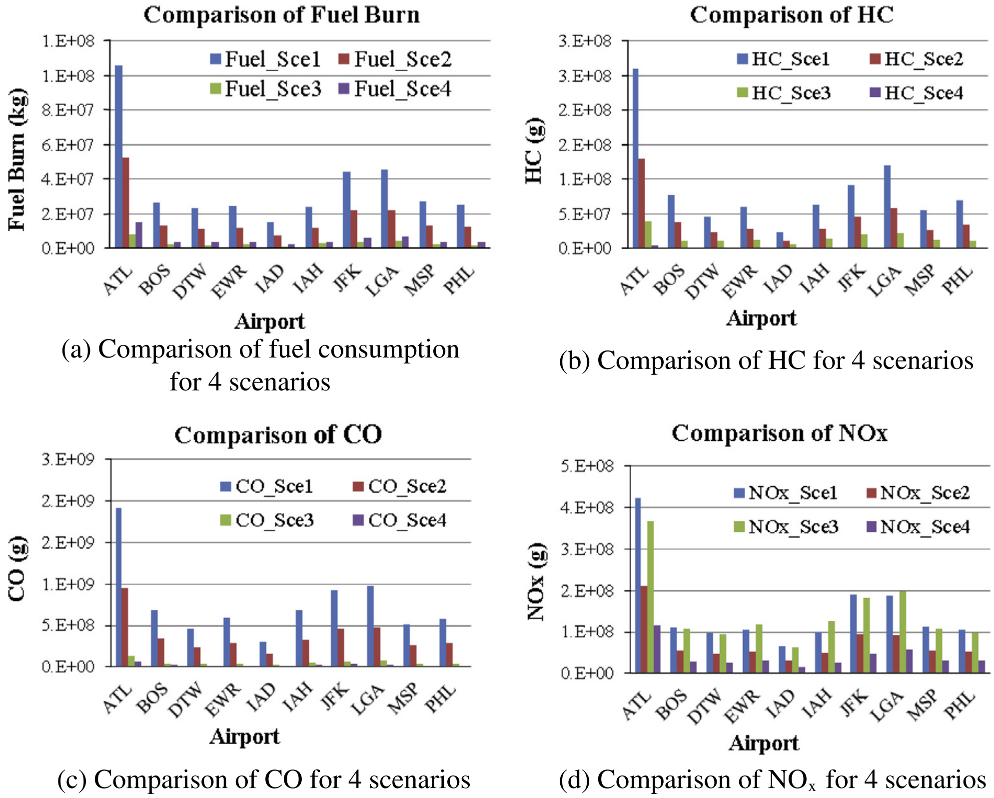
Based on the above methodology, we summarize the types of data needed for emission estimations: (1) aircraft type, number of engine, engine type or APU model; (2) operating time; (3) number of operations/flights; and (4) fuel and emission index for each scenario.

The first three types of data can be obtained from the Aviation System Performance Metrics (ASPM), which provides operational data for flights to and from the ASPM airports (FAA, 2013). 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, gate arrival time, etc. Besides operational data, detailed data of aircraft are retrieved from the airline-fleet reference book, which provides administrative information for all known commercial aircraft operators, plus technical information on every aircraft over 3000 lbs. Current registration, type, serial number, engine type and number, maximum take-off weight, etc., can be found in this reference (Buchair, 2010).

The last type of data were gathered from various resources for each scenario. For the first two scenarios, fuel and emission indices were obtained from the ICAO Engine Emission Databank (ICAO, 2007). For scenario 3, the BHP values for each aircraft and vehicle engine type and the corresponding fuel consumption and emission coefficients are based on the data from FAA technical report (EEA, 1995). For scenario 4, ACRP Report 64 (ESA, 2012) 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 used the highest power settings to estimate the APU emissions.

3.3. Case study and results

In the case study, the departure and arrival data at the top 10 U.S. airports (listed in Table 1), were obtained from ASPM for 2012. To deal with the mass data, the statistics software SAS was used to process the input data and compute the fuel usage and emissions for each scenario based on the methodology described in Section 3. In the fuel and emissions estimation for conventional and single-engine taxiing, an aggregate 7% of full thrust setting was assumed based on ICAO's databank in this study. Fig. 2 presents the comparison results of the quantitative assessment of fuel burn and each type of pollutant. In general, the alternative AGPS scenarios show a significant reduction in fuel burn and emissions during taxiing compared with the conventional scenario. In particular, scenario 4 (on-board AGPS) shows the most emissions reduction, and 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. This 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)



(a) Comparison of fuel consumption for 4 scenarios

(b) Comparison of HC for 4 scenarios

(c) Comparison of CO for 4 scenarios

(d) Comparison of NO_x for 4 scenarios

Fig. 2. Results of quantitative assessment.

at idle. However, scenario 3 reveals the increase of NO_x emissions compared to the single-engine scenario because the diesel engine in the external AGPS generates more NO_x than jet fuel.

As mentioned, 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 was performed. The value of a normalized indicator of 1 was chosen to correspond to the best environmental performance among the scenarios considered. Therefore, a normalized indicator, $(N\_Ind)_i$ for indicator i (fuel and air pollution emissions) was proposed according to the following equation:

$$(N\_Ind)_i = (1/Ind)_i/(1/Ind)_{max} \tag{9}$$

where $(1/Ind)_i$ are the reciprocal values of the indicator of fuel consumption and air pollution emissions, and $(1/Ind)_{max}$ denotes the maximum of the reciprocal values of these indicators.

Fig. 3 and Table 3 present the normalized indicators and normalized general indicator for the four scenarios at the 10 study 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. Fig. 3 shows the same trend of all the normalized indicators for the 10 study airports. The calculated values of the normalized general indicators, in Table 3, indicate clearly that scenario 4 (on-board AGPS) is the best in terms of environmental performance for all airports in this study.

When a normalized indicator is adopted, as shown in Fig. 3, on-board AGPS shows the most emission reduction, but external AGPS consumes the least fuel. Fuel consumption and emission are not consistent with each other because the two types of AGPS are powered by different energy sources (diesel for external tug vs. jet fuel for onboard systems). For external AGPS (Scenario 3), fuel burn and emissions are calculated with Eq. (5) and (6) and the flow/emission indexes are based on the data from FAA technical report (EEA, 1995). For on-board AGPS (Scenario 4), fuel burn and emissions are calculated with Eq. (7) and (8) and based on the latest index data from ACRP Report 64 (ESA, 2012) (the highest power setting was adopted in our estimation). When converting to the same unit, the fuel flow rate for APUs (using jet fuel) is higher than the rate for diesel (e.g., fuel rates are 0.047 kg/s and 0.064 kg/s for wide body aircrafts powered by diesel and APUs, respectively). In terms of emissions, diesel engines generate less CO and HC but much more NO_x than gasoline engines (e.g., for narrow body aircrafts towed by diesel-powered tugs, CO, HC and NO_x emission rates are 0.298, 0.090 and 0.819 g/s and for APU-powered narrow body aircraft, CO, HC and NO_x emission rates are 0.188, 0.011 and 0.290 g/s).

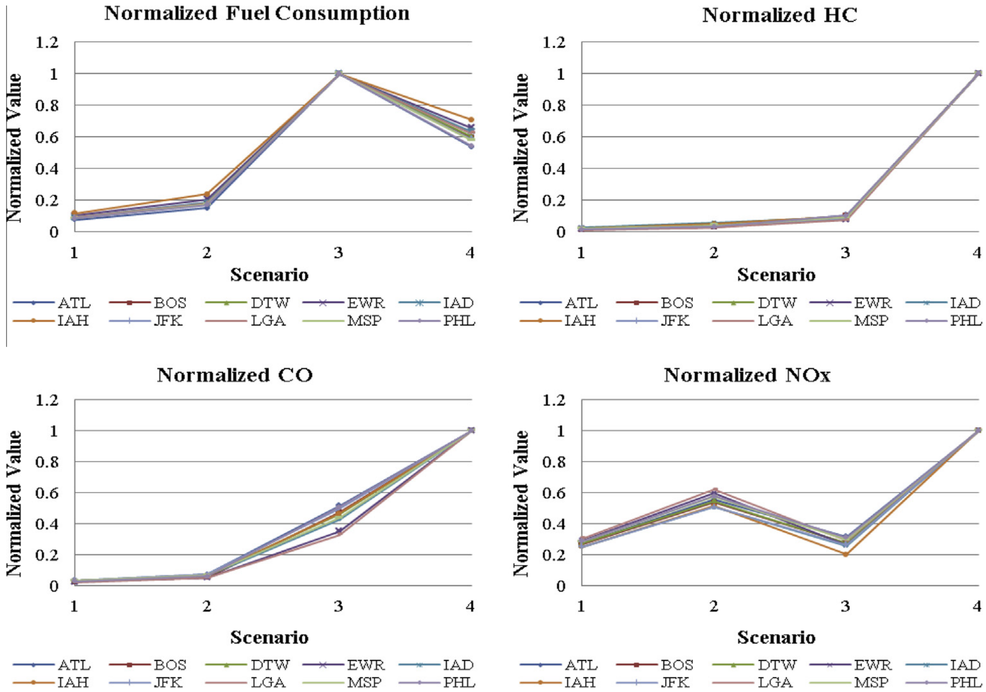


Fig. 3. Normalized indicators for four scenarios.

Table 3
Normalized general indicator for four scenarios at 10 study airports.

Airport	ATL				BOS			
Scenarios	*Sce 1*	*Sce 2*	*Sce 3*	*Sce 4*	*Sce 1*	*Sce 2*	*Sce 3*	*Sce 4*
Normalized general indicator	2.3E−05	3.7E−04	3.2E−02	**1.00**	1.6E−05	2.6E−04	2.2E−02	**1.00**
Airport	DTW				EWR			
Scenarios	*Sce 1*	*Sce 2*	*Sce 3*	*Sce 4*	*Sce 1*	*Sce 2*	*Sce 3*	*Sce 4*
Normalized general indicator	3.1E−05	4.9E−04	2.0E−02	**1.00**	2.0E−05	3.6E−04	1.1E−02	**1.00**
Airport	IAD				IAH			
Scenarios	Sce 1	Sce 2	Sce 3	Sce 4	Sce 1	Sce 2	Sce 3	Sce 4
Normalized general indicator	3.2E−05	5.4E−04	1.6E−02	**1.00**	2.8E−05	5.5E−04	1.3E−02	**1.00**
Airport	JFK				LGA			
Scenarios	Sce 1	Sce 2	Sce 3	Sce 4	Sce 1	Sce 2	Sce 3	Sce 4
Normalized general indicator	2.4E−05	4.0E−04	1.9E−02	**1.00**	1.4E−05	2.4E−04	1.1E−02	**1.00**
Airport	MSP				PHL			
Scenarios	Sce 1	Sce 2	Sce 3	Sce 4	Sce 1	Sce 2	Sce 3	Sce 4
Normalized general indicator	2.8E−05	4.6E−04	2.1E−02	**1.00**	2.2E−05	3.6E−04	3.0E−02	**1.00**

As mentioned in the introduction, operational procedure (e.g., PRC, CDQM and SARDA) could improve the efficiency of airport surface movement and reduce fuel burn and emissions. The estimated benefit from previous study of PRC is cited and compared with the estimated outcomes in this study. Simaiakis et al. (2011) tested PRC at Boston Logan Airport for eight four-hour operational periods from August to September 2010 (one month period). Their study showed that, with PRC, fuel usage was reduced by an estimated 1.05E+04∼1.30E+04 kg (3400–4300 US gallons), by holding 247 flights at their gates longerat an average of 4.4 min per flight. In our study, the fuel reduction for taxi-out phase at BOS with alternative AGPS implemented is about 5.58E+05∼9.90E+05 kg for the same operational periods tested in Simaiakis et al., which is about one order greater in magnitude than that of pushback rate control strategy.

3.4. Benefit-cost analysis

To provide stakeholders with the decision support of whether to proceed with the alternative taxiing systems, a preliminary benefit-cost analysis (BCA) is conducted by quantifying the benefits and costs, both in monetary units, associated with each alternative system over its lifetime. The benefit-cost ratio (B/C ratio), expressed as the benefits relative to the costs, is calculated to indicate the overall value of the alternative system.

Two types of benefits are considered in evaluating the alternative AGPS: user benefits/direct benefit (e.g., changes in the fuel cost) and non-user benefit/indirect benefit (e.g., changes in local environmental cost). In Section 3.3, the fuel burn for main engine taxiing and alternative AGPS for all flights at each airport has been calculated. To get the change in fuel cost for alternative aircraft taxiing, the change in energy consumption is multiplied by the price of each power source (i.e., jet fuel and diesel). The benefits associated with a reduction in the emissions of the pollutants are monetized using the marginal damage costs (MDCs) based on Yu's study (Yu et al., 2013), where an extensive literature review was performed to harvest a large sample for more reliable MDCs estimation. MDC is the cost of emitting an additional unit of air pollutant that general public needs to pay to offset the effects on environment. In our analysis mean values of MDCs from existing literature, both in the U.S. and European studies, were used to calculate the emission costs of CO and NO_x. In the future, when more MDCs data are readily available for each county in the U. S. for criteria pollutants, given the location of each airport, more detailed estimation could be performed. The fuel price and MDCs used in this study for benefits estimation are summarized in Table 4.

The results show that relative to Scenario 1, the total benefits of year 2012 for ten airports are in the range of [$2.42E+08, $1.56E+09] for Scenario 2, [$1.03E+08, $1.04E+09] for Scenario 3, and [$3.85E+08, $2.43E+09] for Scenario 4. In order to calculate the total lifetime benefit present value, it is assumed that the life of the project will be 10 years with year 2012 as the first year. Note that this study did not take air traffic volume increases in the future years into consideration. Assuming a discount rate of 7% (Vaishnav, 2014), the present values of annual benefits are summarized in Table 5.

The costs of alternative AGPS include purchase and maintenance costs. For external system, the capital cost of each tractor is $1.5 million, which was obtained from TaxiBot manufacturer (Vaishnav, 2014). For on-board system, the purchase cost is assumed to be $260,000 per narrow-body aircraft and $1,000,000 per wide-body aircraft based on Vaishnav's estimation (2014). The purchase costs for both systems are amortized over a 10-year period, assuming a discount rate of 7%. Similar to BCA for Ground Support Equipment (GSE) (Morrow et al., 2007), it is assumed that each tractor is manned 18 h per day and the personnel cost for external system is $50/h. The number of tugs needed for each airport and the average of flights per day are assumed based on Vaishnav's study (2014) as well. The GSE cost model v1.1 (Morrow et al., 2007) is used to estimate the costs for each alternative AGPS at 10 airports by combining user-defined data (e.g., purchase costs) with the default data (e.g., maintenance costs) over a 10-year estimation period. The cost results are presented in Table 5. Note that the estimation is rough with assumptions because detailed technical data and pricing information from manufacturers are not available yet.

Given the benefits and costs described above, the benefit-cost ratios for external and on-board systems at each airport are summarized in Table 5. Table 5 clearly show that the B/C ratios are about 30:1 for Scenario 3 and 80:1 for Scenario 4, which means both external and on-board systems are worth being implemented and the on-board system appeals to be more beneficial.

Table 4
Fuel Price and MDCs for Benefits Estimation of Alternative AGPS.

Alternative AGPS	Fuel consumption		MDCs of local environmental impacts		
	Type	Price	HC emission	CO emission	NO_x emission
External System (Scenario 3)	Diesel	$3.97/gallon[a]	N/A	$354/ton	$5511/ton
On-board Systems (Scenario 4)	APU-jet fuel	$3.056/gallon[b]			

[a] 12-month average diesel cost in 2012, EIA U.S Gasoline and Diesel Fuel Update: http://www.eia.gov/petroleum/gasdiesel/. (Diesel is 3.24 kg/gal).
[b] 12-month average jet fuel cost in 2012, EIA U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB: http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=eer_epjk_pf4_rgc_dpg&f=d (Jet fuel is 3.08 kg/gal).

Table 5
The Results of Benefit-Cost-Analysis.

Flight# (2012)[a]		ATL 464676	BOS 159192	DTW 134239	EWR 127738	IAD 105905	IAH 211085	JFK 177235	LGA 166159	MSP 159519	PHL 124898
Benefit ($)	Sce3	3.8E+09	2.0E+09	1.3E+09	1.1E+09	8.9E+08	7.6E+08	1.7E+09	1.7E+09	1.6E+09	1.5E+09
	Sce4	1.8E+10	6.4E+09	5.2E+09	4.7E+09	3.5E+09	6.1E+09	6.2E+09	7.0E+09	5.9E+09	4.7E+09
Cost ($)	Sce3	1.4E+10	5.2E+09	4.2E+09	3.8E+09	2.8E+09	4.9E+09	5.0E+09	5.6E+09	4.8E+09	3.7E+09
	Sce4	1.7E+08	5.8E+07	4.9E+07	4.5E+07	3.8E+07	7.7E+07	6.4E+07	6.0E+07	5.8E+07	4.5E+07
B/C Ratio	Sce3	39:1	38:1	28:1	25:1	25:1	17:1	33:1	33:1	38:1	39:1
	Sce4	86:1	90:1	86:1	84:1	76:1	65:1	79:1	94:1	82:1	83:1

[a] Note that the flight numbers here refer to the calculated data, which are around 50–70% of total fights (52.5% for ATL, 50.5% for BOS, 68% for DTW, 68% for EWR, 63.5% for IAD, 58% for IAH, 54.5% for JFK, 54% for LGA, 62% for MSP and 71% for PHL) since there are missing data about the aircraft/engines for those 30–50% 0f flights. The calculated flight numbers include both departure and arrival flights in 2012.

4. Conclusions and future work

To reduce fuel consumption and emissions during surface movement at airports, innovative control strategies and technologies of alternative taxiing systems have been developed in recent years. Besides the single-engine taxiing, engineless taxiing with innovative AGPS has shown the most promise and could be ready in the very near future. These engineless taxiing methods can be categorized into two groups: (1) external AGPS with tractors/vehicles attached to aircraft for towing and (2) on-board AGPS with motors installed in the wheels. In this study, a comprehensive review is conducted on the main features, merits and demerits for each AGPS, as summarized in Table 2.

Related to sustainable development, the fuel consumption and local environmental impacts of different AGPS were evaluated. Given the operational data at the 10 study airports, a comparison of environmental impacts was performed among four kinds of AGPS: conventional, single engine-on, external, and on-board systems. The study demonstrated that alternative AGPS can significantly reduce fuel burn and emissions during taxiing compared with conventional scenarios. On-board AGPS shows the best performance in emissions reduction, and 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 manufacturers provided benefit analysis during the testing of innovative AGPS, this study provides a comprehensive comparison of different AGPS and provides the decision support for stakeholders to determine whether and how to proceed with the emerging technologies. The BCA shows that both external and on-board systems (with 30:1 and 80:1 B/C ratios, respectively) are worth being implemented and the on-board system appeals to be more beneficial.

One extension of this study could be generating more scenarios assuming some of the systems (e.g., external AGPS) be powered by alternative energy, such as biodiesel, hydrogen, or electricity from wind or solar farms. In addition, the study can be extended to consider noise, another local environmental impact (Prats et al., 2010). When more sophisticated and accurate emission estimations for aircraft become available, more detailed flight operational data than ASPM (e.g., Airport Surface Detection Equipment, Model X, namely ASDE-X) can be used to improve the precision of the evaluation. If the ASDE-X data are adopted, sensitivity analysis would be helpful to test how the results would change if different thrust settings are considered during each taxiing state (e.g., ground idling, constant-speed taxiing, accelerating from stop and perpendicular turns at 4%, 5%, 9%, and 7% thrust settings, respectively) (Nikoleris et al., 2011). 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 and aLife Cycle Analysis (LCA) could be conducted for different AGPS.

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