



## Deriving Benefits from Alternative Aircraft-Taxi Systems

### DETAILS

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**AIRPORT COOPERATIVE RESEARCH PROGRAM**

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**ACRP REPORT 158**

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**Deriving Benefits  
from Alternative  
Aircraft-Taxi Systems**

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## AIRPORT COOPERATIVE RESEARCH PROGRAM

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## FOREWORD

By **Michael R. Salamone**  
Staff Officer  
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As demand for air travel continues to grow, airports are facing increased pressure to reduce their contributions to local air emissions and noise. Airport managers, environmental agencies, and other parties in the aviation industry are becoming increasingly aware of the contribution of airport-related activities to local air quality, greenhouse gas emissions, and noise. Moreover, as the price of fuel fluctuates, aircraft operators are driven to consider operational alternatives that reduce fuel consumption cost. Fuel is one of the key costs that airlines have to consider, and any fuel price volatility can adversely affect profit margins. The majority of aircraft fuel is consumed during the cruise phase of flight, and there is very little that an airport or airline can do to reduce these costs. However, airlines can reduce fuel use, emissions, and costs while aircraft are on the ground.

Alternative approaches to taxiing aircraft in movement areas may offer needed relief. By removing the need for using aircraft main engines during the majority of the taxi phase of operation in aircraft movement areas, there may be an overall net benefit for both the airport and aircraft operator. Recently, non-main-engine aircraft-taxiing (alternative aircraft-taxiing) systems have attracted the interest of industry and government research organizations. These systems include, among other alternative systems, an electric motor permanently fixed to the aircraft, or an electric tug. While many of these alternatives may provide energy and environmental benefits, their use may introduce potential challenges to aircraft operators and air traffic control, as well as place new demands on airport infrastructure. This report helps to address those challenges.

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Under ACRP Project 02-50, the research team, led by The Cadmus Group, Inc., developed a resource guide focused on alternative aircraft-taxiing systems at U.S. airports; however, a large body of research from Europe has been incorporated where relevant. For context, some estimates show that a typical short-to-medium-range aircraft in Europe spends between 10% and 30% of its total flight time taxiing, constituting about 10% of its fuel consumption. It is assumed that similar proportions would also apply in the United States.



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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at [www.trb.org](http://www.trb.org)) retains the color versions.

# Introduction

This resource guide was produced as part of ACRP Project 02-50. Full documentation of the research conducted and findings compiled are presented in a final report that, while not being published, is available to future researchers and other interested parties by contacting ACRP.

Airport managers, environmental agencies, and other parties in the aviation industry are becoming increasingly aware of the contribution of airport-related activities to local air quality, greenhouse gas emissions, and noise. Fuel is one of the key costs that airlines have to consider, and any fuel price volatility, such as that seen in 2008, can adversely affect profit margins. The majority of aircraft fuel is consumed during the cruise phase of flight, and there is very little that an airport or airline can do to reduce the costs of the fuel used during this phase. However, airlines can reduce fuel use, emissions, and costs during other phases of flights and while aircraft are on the ground through the following:

- Reduced takeoff and climb thrust, as highlighted in the recently completed research conducted under ACRP Project 02-41, “Estimating Takeoff Thrust Settings for Airport Emissions Inventories” (Horton et al., 2014).
- Increased efficiency during aircraft taxiing—for example, reducing the number of engines used during taxiing, although this approach may involve operating the remaining engines at a higher thrust setting.
- Improved operational efficiency through programs such as NextGen (United States) and Single European Sky ATM [air traffic management] Research (SESAR, European Union).
- Use of alternative fuels to reduce emissions of pollutants such as oxides of sulfur and particulate matter (PM) in compliance with future U.S. Environmental Protection Agency regulations.
- Replacing the use of the aircraft main engines for taxiing with alternative aircraft-taxiing systems such as onboard alternative aircraft-taxiing systems or equipment similar to aircraft pushback tractors.

This ACRP Project 02-50 resource guide is focused only on alternative aircraft-taxiing systems at U.S. airports; however, a large body of research from Europe has been incorporated where relevant. For context, Airbus (2013) estimates that a typical short-to-medium-range aircraft in Europe spends between 10% and 30% of its total flight time taxiing, constituting about 10% of its fuel consumption. It is assumed that similar proportions would also apply in the United States.

A number of alternative aircraft-taxiing systems that are at different stages of development have the potential to enable an aircraft to taxi without the use of its main engines. When these alternative aircraft-taxiing systems are used, there is no associated aircraft main engine fuel burn, emissions, or noise, but these will be partly replaced by those of the alternative aircraft-taxiing system. However, main engines must be warmed up approximately 5 minutes before takeoff, resulting in aircraft main engine fuel burn, emissions, and noise. The net reduction in fuel burn, emissions, and noise will be a result of the length of time spent taxiing and the types of equipment



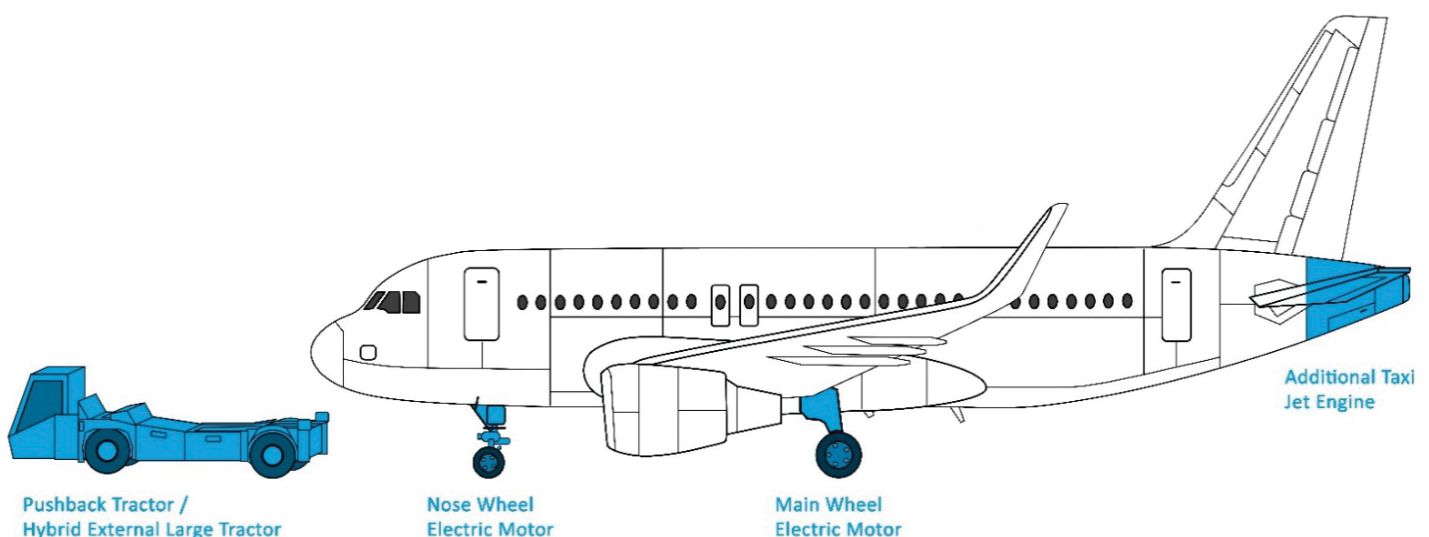
## 2 Deriving Benefits from Alternative Aircraft-Taxi Systems

and engines used for the aircraft and the alternative aircraft-taxiing system. In some cases, the overall benefits will be limited. The potential also exists for increased costs [for purchase (or lease) of the alternate system, maintenance, and fuel]. However, there are other issues that should be considered before any fuel, emissions, and noise benefits can be realized. Key considerations for airport operators, aircraft operators, and ground service providers implementing these systems include the following:

- Existing (and future) taxiing time. If the taxiing time is too short, then any benefit is likely to be minimal (i.e., up to approximately 5 minutes will be needed for main engine warm-up/cool-down).
- Existing (and future) aircraft fleet mix. Most alternative aircraft-taxiing systems are intended for the narrow-bodied market (e.g., Airbus A320 and Boeing 737), although there are external systems that can handle larger aircraft (i.e., as large as Airbus A380).
- Nose-wheel landing-gear fatigue loading if standard aircraft pushback tractors are considered.
- Aircraft main engines starting on the taxiways (or close to runway hold points) and the impact of a failed engine start (e.g., delays to other aircraft in the queue for takeoff).
- Additional staff and training requirements.
- Taxiing speed (including likely acceleration/traction needed for stop/start cycle at congested airports) and ability to cross active runways within a safe time period.
- Necessary modifications to aircraft, including any necessary certification from the FAA.
- Necessary modifications to airports, including infrastructure and land use.
- Whether the system is pilot-controlled.
- Likelihood of certification for noncertified alternative aircraft-taxiing systems.
- Safety and visibility.
- Communication with air traffic control (ATC) regarding engine starts.
- Potential time savings.
- Ownership of alternative aircraft-taxiing systems—airport, airline, or ground handler?

Five types of alternative aircraft-taxiing systems are considered in this resource guide (see Figure 1):

- Dispatch taxiing (e.g., using existing aircraft pushback tractor technology).
- Semi-robotic dispatch taxiing (i.e., similar to a pushback tractor but using a hybrid external large tractor developed specifically for taxiing).



**Figure 1.** Different types of alternative aircraft-taxiing systems (shaded).

- Nose-wheel–mounted alternative aircraft-taxiing systems.
- Main landing gear alternative aircraft-taxiing systems.
- Replacement of the auxiliary power unit (APU) with an additional onboard taxi jet engine capable of providing sufficient thrust for taxiing.

This resource guide has been developed for airport practitioners and other stakeholders. It provides information on potential cost, energy, and environmental benefits such as reductions in noise, emissions, and time, as well as potential challenges of implementing alternative aircraft-taxiing systems at U.S. airports. The resource guide includes the following:

- Chapter 1: Introduction
  - Introduces the concept of alternative aircraft-taxiing systems
  - Introduces the outline structure of this resource guide
- Chapter 2: Alternative Taxiing Assessment Matrix (ATAM)
  - Introduces and describes the ATAM tool, which is a spreadsheet-based tool that provides a useful compendium of benefits of and concerns associated with the different types of alternative aircraft-taxiing systems
- Chapter 3: Discussion
  - Additional discussion of alternative aircraft-taxiing systems
- Appendices
  - Appendix A: Detailed Description of Information in the ATAM: Provides detailed discussion of each of the benefits and concerns associated with alternative aircraft-taxiing systems included in the ATAM tool
  - Appendix B: Acronyms and Abbreviations
  - Appendix C: References



## CHAPTER 2

# Alternative Taxiing Assessment Matrix (ATAM)

This chapter introduces and describes the spreadsheet-based ATAM tool. The following bullet points provide an overview of each of the three sheets within the ATAM tool:

- **Instructions**—This sheet provides an outline of how to use the tool.
- **ATAM**—This sheet provides a traffic light matrix of the various benefits and issues associated with each of the five types of alternative aircraft-taxiing systems. In the tool, benefits are highlighted in green, neutral issues in amber, and concerns in red. The summary information is linked to a pop-up discussion of each of the benefits and issues associated with alternative aircraft-taxiing systems.
- **Fuel and Emissions**—This sheet provides an interactive tool that allows the user to enter different aircraft fleet mixes and taxiing times to assess potential overall fuel and emissions changes from ground-level fuel consumption for the three primary alternative aircraft-taxiing systems. Changes are based on use of aircraft main engines, APU, pushback tractors, and alternative aircraft-taxiing systems. The calculations use FAA’s Emissions and Dispersion Modeling System (EDMS) and an APU load factor from *ACRP Report 64: Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems*. (Environmental Science Associates, 2012).

### 2.1 Instructions

The ATAM tool can be found on the ACRP Project 02-50 web page (<http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3696>). Click on the ATAM.xlsx file to open the ATAM tool. When opened, the ATAM tool presents the Instructions sheet (see Figure 2), which contains details on how to use the tool. The hyperlinks (e.g., [Go to ATAM](#)) in the instructions allow the user to navigate between sheets, and the text next to each link provides an overview of each sheet.

### 2.2 ATAM

The ATAM sheet contains a table of issues, benefits, and summary information associated with each type of alternative aircraft-taxiing system. The ATAM sheet (see Figure 3 for example) is linked to a pop-up discussion of each of the benefits and concerns associated with alternative aircraft-taxiing systems, which are also included in Appendix A.

Within the ATAM, colors indicate whether a particular issue or benefit is considered a positive benefit (green), a negative impact (red), or neither (amber).

If a mouse pointer is used to hover over a cell within the ATAM, a more detailed description of the particular issue or benefit will pop up.


<b>Instructions</b>	
<u>Go to ATAM</u>	<p>The "ATAM" sheet contains a table of issues, benefits and summary information associated with each type of alternative aircraft-taxiing system. The "ATAM" sheet is linked to a pop-up discussion on each of the benefits and issues associated with alternative aircraft-taxiing systems, which are also included in Appendix A of the Resource Guide. Within the "ATAM" the colors indicate whether a particular issue or benefit is considered positive benefit (green), negative impact (red) or neither (amber).</p> <p>If a mouse pointer is used to hover over a cell within the "ATAM" a more detailed description of the particular issue or benefit will pop-up.</p>
<u>Go to Fuel and Emissions</u>	<p>The sheet "Fuel and Emissions" allows the user to enter an aircraft fleet mix and average or typical taxiing times, into the yellow cells, which could be for a specific airport.</p> <p>The fleet mix can be for any time period as it is only used to derive the relative proportions; the aircraft size designations are based on EDMS. Once the aircraft fleet mix and taxiing times have been entered, the results are shown graphically for both fuel and emissions based on the original ACRP 02-50 study (red) and those for the user entered data (blue), with the black lines representing the range of calculated values.</p>

Figure 2. Instruction sheet for the ATAM.







<b>ATAM</b>	<u>Go to Instructions</u>	<u>Go to Fuel and Emissions</u>				
<b>Description</b>	 Pushback Tractors	 Hybrid External Large Tractor	 Nose Wheel Electric Motor	 Main Wheel Electric Motor	 Additional Taxi Jet Engine	
<b>Typical taxi speed (i.e. around 20 knots)</b>	Increased engine capacity for towing large distances at a reasonable speed/acceleration (or towing at a slow speed with low acceleration)	Good taxiing speed (with appropriate engine size)	For lighter smaller motors slow taxiing speed (e.g. 7 to 10 knots) and acceleration/traction	Reasonable taxiing speed and acceleration more likely due to two electric motors (compared to nose wheel version)	Reasonable taxiing speed (depending on engine)	
<b>Pilot control</b>	Need for a driver	Need for a driver if tractor is not controlled by aircraft, driver needs to drive back to gate area	No additional driver needed (but ground crew needed during the pushback period)	No additional driver needed (but ground crew needed during the pushback period)	No additional driver needed (but ground crew needed during the pushback period)	
<b>APU load</b>	APU operated at low load	When an aircraft is on the ground not connected to gate power, its APU is used to run on-board systems and to start the aircraft main engines. The aircraft on-board systems that are powered by the APU typically include lighting, heating, ventilation and air-conditioning. During conventional taxiing, the APU is often not used and power is taken from the aircraft's main engines for the electrical systems. However, for any alternative aircraft-taxiing system, the APU will run whenever the engines are not running to produce power. Aircraft with on-board alternative aircraft-taxiing systems that rely on power from the APU (i.e., nose or main wheel electric motors) will need an APU that is able to accommodate these additional power needs.			APU replaced by small jet engine	
<b>Acceleration (e.g. to allow runway crossing from stop in 40 seconds)</b>	Increased engine capacity for towing large distances at a reasonable speed/acceleration (or towing at a slow speed)	When an aircraft is on the ground not connected to gate power, its APU is used to run on-board systems and to start the aircraft main engines. The aircraft on-board systems that are powered by the APU typically include lighting, heating, ventilation and air-conditioning. During conventional taxiing, the APU is often not used and power is taken from the aircraft's main engines for the electrical systems. However, for any alternative aircraft-taxiing system, the APU will run whenever the engines are not running to produce power. Aircraft with on-board alternative aircraft-taxiing systems that rely on power from the APU (i.e., nose or main wheel electric motors) will need an APU that is able to accommodate these additional power needs.			Reasonable acceleration	

Figure 3. Sample page from the ATAM.

### 2.3 Fuel and Emissions

The Fuel and Emissions sheet allows the user to enter an aircraft fleet mix and average or typical taxiing times (see Figure 4). The fleet mix can be for any time period as it is only used to derive the relative proportions; the aircraft size designations are based on EDMS.

Once the aircraft fleet mix and taxiing times have been entered, the tool graphs the estimated fuel use, NO<sub>x</sub> (nitrogen oxide), and PM<sub>10</sub> emissions impacts for that mix for the three primary alternative aircraft-taxiing systems (nose-wheel electric motor, main-wheel electric motor, and hybrid external large tractor; other systems could not be modeled due to lack of data). For comparison purposes, the original ACRP Project 02-50 results are shown (in red in the ATAM tool), and those for the user-entered data (in blue in the tool), with the lines representing the range of calculated values.

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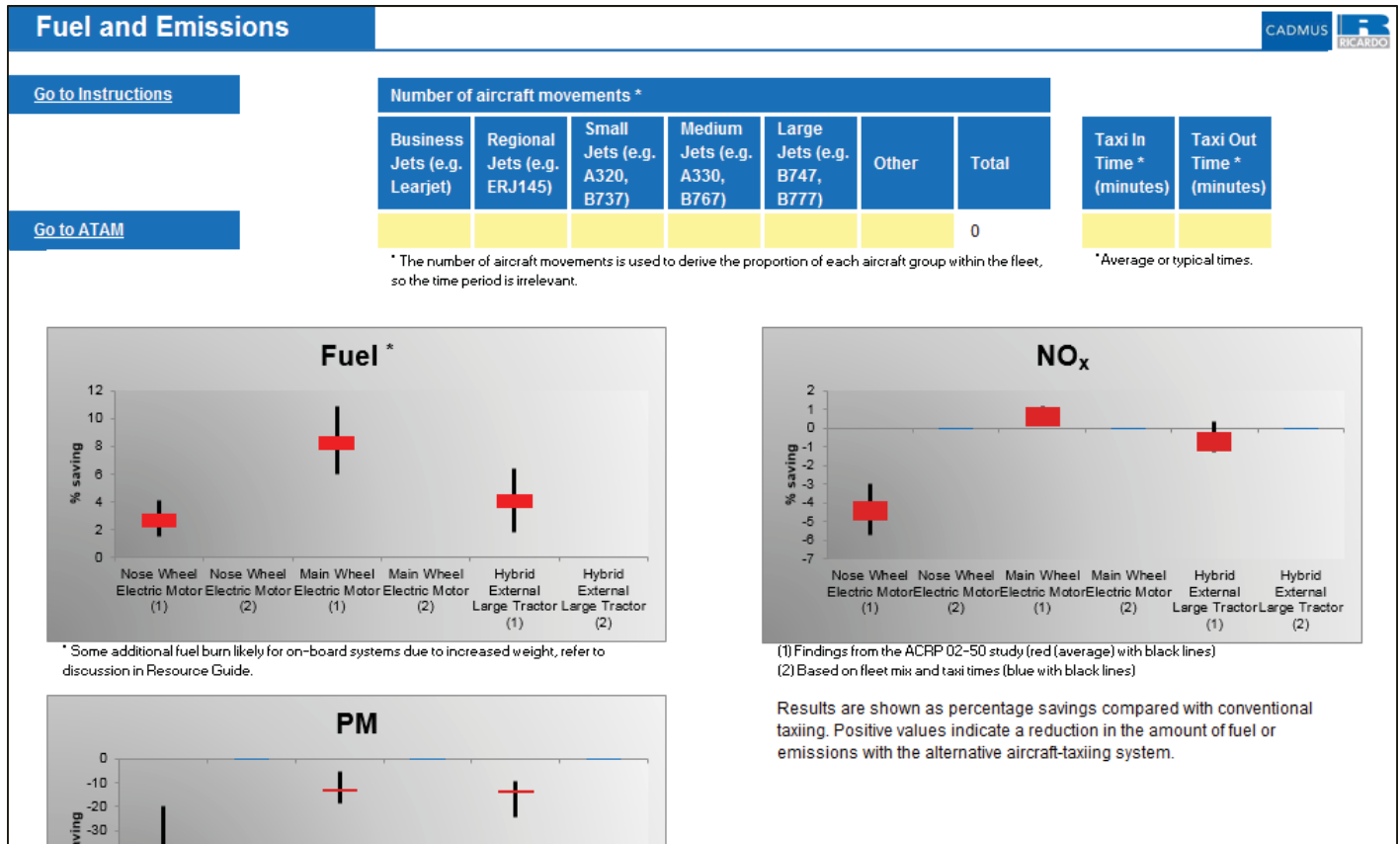


Figure 4. Fuel and Emissions sheet.

# Discussion

This resource guide has been developed for airport practitioners and other stakeholders. It provides information on the potential cost, energy, and environmental benefits (e.g., noise and emissions), as well as potential challenges of implementing alternative aircraft-taxiing systems at U.S. airports. Full documentation of the research conducted and findings compiled are presented in a final report. While the final report is not being published, it is available to future researchers and other interested parties by contacting ACRP.

This chapter provides a discussion of the broader issues related to alternative aircraft-taxiing systems as well as some of the assumptions underlying the modeled data used to develop the ATAM tool. Specific issues are addressed in the ATAM tool and are not reproduced here.

The modeling methodology used to underpin the calculations in the Fuel and Emissions sheet in the ATAM tool is broadly based on the FAA's EDMS. The alternative aircraft-taxiing system scenario calculations assumed that, for onboard systems, the power would be supplied by APUs operating at maximum load. APU load factor emissions were based on *ACRP Report 64: Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems* (Environmental Science Associates, 2012) for different APU operating modes. For each aircraft type, only average taxiing speeds (supplied by the airports being analyzed) were available for use in the fuel and emission analysis; these averages were used as a basis to develop the calculations underlying the Fuel and Emissions sheet in the ATAM tool. For nose-wheel-mounted systems, a slower taxiing speed (10 knots) was assumed. Changes in fuel use and emissions might have been more variable if more detailed black-box type data had been available regarding aircraft movement (i.e., to account for acceleration and deceleration). Black-box data might have also provided some estimation of the impact of additional aircraft weight (associated with onboard systems) on overall flight fuel burn. However, black-box data analysis is beyond the functionality of the FAA's EDMS model used in the ACRP Project 02-50 modeling. Similarly, the Hybrid External Large Tractor analysis in the ATAM tool used only average fuel and emissions data and followed the EDMS methodology used for ground support equipment (GSE), which did not account for the stop/start nature of taxiing. However, the fuel and emission analysis was based on the key differences expected for airports of different sizes, with their respective taxiing times and aircraft fleet mixes. Therefore, when presented in terms of percentage changes, the results can be considered broadly indicative.

Aircraft weight gain caused by the installation of an onboard alternative aircraft-taxiing system would result in increased fuel consumption during takeoff, climb, and cruise (if the number of passengers and/or cargo tonnage were assumed to remain the same). Any fuel weight savings associated with taxi-out does not affect the weight during takeoff, climb, and cruise because that fuel would have been burned prior to takeoff. Only the fuel saved during taxi-in (which, therefore, would not have been loaded onto the aircraft prior to departure) can be considered to

offset the weight gain of an onboard system for takeoff, climb, and cruise. The use of EDMS does not allow for the calculation of additional fuel burn and the resultant emissions due to changes in weight. However, a very broad approximation can be made if it is assumed that a typical Airbus A320 or Boeing 737 (the target aircraft for onboard systems) weighs, on average, 140,000 lbs (63,500 kg) during its flight. If the increase in weight (assuming the same passenger/cargo loading) is between 300 lb (136 kg) and 880 lbs (400 kg), and the percentage increase in weight is taken as a rough substitute for the percentage increase in fuel use (due to the extra weight), then the increase in fuel use is likely to be between 0.2% and 0.6% for takeoff, climb, and cruise. Therefore, there is likely to be a trade-off in terms of the increased fuel use during the flight compared with fuel savings accrued during taxiing. This trade-off will vary for each aircraft's flight.

All assessed alternative aircraft-taxiing systems typically reduce on-airport fuel use. However, airports with longer taxiing times have greater fuel savings than those with shorter times. Airports with a high proportion of narrow-bodied aircraft (e.g., Airbus A320 and Boeing 737) will have greater fuel savings with the onboard systems compared to other airports as these are designed for this type of aircraft. Aircraft that operate predominately on short-haul routes spend a greater proportion of their operating time taxiing; they might, therefore, be expected to benefit more from the onboard systems than aircraft that fly longer routes.

The variation in estimated emissions of different pollutants reflects the difference in emission factors for aircraft main engines, APUs, and GSE in EDMS. Emissions factors for particulate matter with a size of up to 10 microns ( $PM_{10}$ ) are considerably higher for APUs than those for aircraft main engines (based on EDMS). Therefore, using an APU-driven system operating at an assumed maximum load instead of using aircraft main engine leads to an increase in  $PM_{10}$  emissions, although there has been some evidence (e.g., Lobo et al., 2013) that more recent APUs can have significantly lower PM emissions than older technology examples. It should be noted that results for particulate matter with a size up to 2.5 microns ( $PM_{2.5}$ ) would be similar to those for  $PM_{10}$  because EDMS does not distinguish between  $PM_{10}$  and  $PM_{2.5}$  for aircraft. However, there would be slight differences due to diesel particulate size from the pushback-tractor-type equipment. Emission factors for oxides of nitrogen ( $NO_x$ ) from aircraft main engines vary considerably based on thrust setting. APUs may have similar or higher  $NO_x$  emission factors than aircraft using their main engines operating at low thrust for taxiing—the lower taxiing speeds of some alternative taxiing systems may then give increased  $NO_x$  emissions. In terms of the emissions savings, the use of alternative jet fuels could also further reduce emissions of PM and oxides of sulfur. However, these alternative fuels are unlikely to have an impact on the results for  $NO_x$ . Similarly, if an alternative taxiing system were powered by a low-polluting alternative (e.g., a hydrogen fuel cell), then  $NO_x$  and PM emissions from taxiing could become negligible.

Electric onboard aircraft-taxiing systems produce negligible noise and no local emissions. However, there would still be some noise produced by the APU used to generate the electricity. For an onboard alternative aircraft-taxiing system powered by the APU, Asensio et al. (2007) and Tam et al. (2005) compared APU noise to that of aircraft main engines. They suggested that the overall noise contribution of APUs is lower than that for a taxiing aircraft using its main engines. [Aircraft taxiing with main engines is estimated to be around 1.5 dB day-night average sound level (DNL) in Page et al., 2009.] The frequency (i.e., tonal) characteristics are also different. When an aircraft is taxiing, main engines peak at approximately 125 Hz, and APUs peak between 250 Hz and 350 Hz. Therefore, compared with main engines during taxiing, the noise from an APU is lower in level but slightly higher in frequency.

Similarly, the noise level from external systems such as tractors is likely to be lower than from aircraft main engines. For an alternative aircraft-taxiing system powered by an additional jet engine, however, the additional jet engine's noise would replace that of the main engines during taxiing. Studies undertaken by a number of alternative aircraft-taxiing system developers

(of both electric motor and external systems) indicate a noise reduction of between 10 dB and 12 dB close to taxiways. This level of noise reduction may be perceptible in communities close to airport taxiways. Many airports own and operate noise monitoring systems, which measure noise levels continuously. However, the monitors are typically located in communities surrounding airports and are designed to capture overflight noise levels. Even in the rare cases where a noise monitor is located near an airfield, it would be difficult to separate out noise levels from taxiing aircraft from those of takeoffs, arrivals, and reverse-thrust operations. Therefore, even if alternative aircraft-taxiing systems were in operation at a particular airport in the future, it is unlikely that alternative aircraft-taxiing systems would make significant differences to monitored noise levels.

Vaishnav (2014) estimates that external alternative aircraft-taxiing systems would cost about U.S.\$1.5 million for a small system (for use with narrow-bodied aircraft such as an Airbus A320 or Boeing 737) and U.S.\$3 million for a system for use with wide-bodied aircraft. Vaishnav also estimates that onboard systems are likely to cost approximately U.S.\$0.26 million for narrow-bodied aircraft and U.S.\$1 million for wide-bodied aircraft. One of the onboard system manufacturers will have a lease arrangement under which the airline pays half of the savings achieved by using the system. Purchasers should consider the fact that external systems can be used for several different aircraft (and can be used for a wider range/number of aircraft than modeled), whereas the onboard systems assessed are installed in one particular aircraft. Any onboard system is also likely to incur aircraft modification costs, whereas external systems will have very low, if any, aircraft modification costs. In addition, airlines should consider revenue lost during the installation of onboard alternative aircraft-taxiing systems.

Construction costs may be incurred for additional aircraft main engine start-up areas (needed if an airport or airline does not allow main engine start during taxi-out) and vehicle service roads for return of any external system to the gate area. Many larger airports already contain hold or deicing areas near the runway ends and relevant existing service roads, so these airports are unlikely to need additional infrastructure. For those airports that need additional holding areas and roadways, concrete taxiways cost approximately U.S.\$200 per square yard (U.S.\$240 per square meter) (Pers. comm., 2015). Concrete roadways cost approximately U.S.\$75 per square yard (U.S.\$90 per square meter) (Pers. comm., 2015). However, costs may vary depending on geographical region. Asphalt is about 20% cheaper than concrete (Pers. comm., 2015).

Additional operational, maintenance, installation downtime (onboard systems only), and staff costs may be incurred by airlines for onboard and external systems and by ground handlers for external systems. These costs are likely to be offset by cost savings. One cost consideration for external systems relates to drivers operating the equipment for longer periods than they would for conventional pushback (at a cost of around U.S.\$29.60 per hour). Cost savings, on the other hand, include not needing to use pushback tractors (approximately U.S.\$50 per cycle), reduced delays and taxi times (between U.S.\$66 and U.S.\$150 per minute per turnaround), and reduced fuel use. There may be additional taxi-queue management costs for alternative aircraft-taxiing systems with low speeds. Data on costs for alternative aircraft-taxiing systems were difficult to obtain for ACRP Project 02-50; in the future, more information on real-world active alternative taxiing systems and their associated costs is likely to be available. Airports, ground handlers, or airlines that are actively considering purchasing alternative aircraft-taxiing systems should undertake a full cost analysis.

To avoid congestion at airports where slow alternative aircraft-taxiing systems (i.e., those with speeds of less than 20 knots) are used in a situation where some aircraft use the alternative aircraft-taxiing systems and some do not, taxiing speeds may need to be managed, or aircraft fitted with the slow systems could potentially use different taxiing routes. However, air traffic control operations managers and frontline controllers at a large North American hub airport commented that alternative aircraft-taxiing systems should not have a significant effect on



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departure queues at larger airports (Pers. comm., 2015). Their opinion was based on the number of aircraft generally found in the queue and the fact that departure spacing results in low taxiing speeds for all aircraft in the queue. Aircraft under engine power are only able to attain maximum taxiing speed when they are at the head of the departure queue. The controllers believed that slower taxiing speeds at smaller airports would be a concern for airlines and not for air traffic controllers. However, air traffic controllers did have concerns with acceleration and taxi speed during a runway crossing. Controllers at this airport indicated that a general guideline is that an aircraft should be able to cross a runway surface and clear the safety area within 40 seconds. These controllers thought delays would occur if aircraft equipped with alternative aircraft-taxiing systems were unable to meet that performance standard. Controllers further suggested that if the crossing standard could not be met, alternative power should be abandoned in favor of main engine taxiing if an assigned taxi route included a runway crossing. Individual airports or airlines that are actively considering purchasing alternative aircraft-taxiing systems should consider whether taxiing speed is an issue at particular airports based on average taxiing speeds and any runway crossings.



## APPENDIX A

# Detailed Description of Information in the ATAM

This appendix provides a copy of the detailed discussion of each of the benefits and issues associated with alternative aircraft-taxiing systems included within the ATAM. It repeats some of the information presented in the main discussion, and some of the information repeats across each of the items that follow, but each discussion item from the ATAM has been included here in its entirety for completeness.

## Noise

Electric onboard aircraft-taxiing systems produce negligible noise and no local emissions. However, there would still be some noise produced by the aircraft's APU, which would be used to generate the electricity. For an onboard alternative aircraft-taxiing system powered by an APU, Asensio et al. (2007) and Tam et al. (2005) compare APU noise to that of aircraft main engines. This information suggests that the overall noise contribution of APUs is lower than that for an aircraft taxiing using its main engines (estimated to be around 1.5 dB DNL in Page et al., 2009). The frequency (i.e., tonal) characteristics are also different. When an aircraft is taxiing, main engines peak at approximately 125 Hz, and APUs peak at between 250 Hz and 350 Hz. Therefore, compared with main engines during taxiing, the noise from an APU is lower in level, but slightly higher in frequency. Similarly, the noise from external systems, such as a tractor, is likely to be lower than that from aircraft main engines. For an alternative aircraft-taxiing system powered by an additional jet engine, the additional jet engine's noise would replace that of the main engines during taxiing. Studies undertaken by a number of alternative aircraft-taxiing system developers (electric motor and external systems) into noise levels with and without the alternative aircraft-taxiing system close to taxiways indicates a noise reduction of between 10 dB and 12 dB.

## Cost for Alternative Aircraft-Taxiing System

Vaishnav (2014) estimates that external alternative aircraft-taxiing systems would cost about U.S.\$1.5 million for small systems (for use with narrow-bodied aircraft) and U.S.\$3 million for a system for use with wide-bodied aircraft. Vaishnav also estimates that onboard systems are likely to cost approximately U.S.\$0.26 million for narrow-bodied aircraft and U.S.\$1 million for wide-bodied aircraft. One of the onboard system manufacturers will offer a lease arrangement in which the airline pays half of the savings achieved by using the system. Purchasers should consider the fact that external systems can be used for several different aircraft (and can be used for a wider range/number of aircraft than modeled), whereas the onboard systems assessed are installed in one particular aircraft. Any onboard system is also likely to incur aircraft modification costs, whereas external systems will have very low, if any, aircraft modification costs. In addition, airlines should consider the revenue lost during installation for onboard systems.

## Construction Costs

Construction costs may be incurred for additional aircraft main engine start-up areas (needed if an airport or airline does not allow main engine start during taxi-out) and vehicle service roads for return of any external system to the gate area. Many larger airports already contain hold or deicing areas near the runway ends and relevant existing service roads, so these airports are unlikely to need additional infrastructure. For those airports that need additional holding areas and roadways, concrete taxiways cost approximately U.S.\$200 per square yard (U.S.\$240 per square meter) (Pers. comm., 2015). Concrete roadways cost approximately U.S.\$75 per square yard (U.S.\$90 per square meter) (Pers. comm., 2015). However, costs may vary by region. Asphalt is about 20% cheaper than concrete (Pers. comm., 2015).

## Other Costs (e.g., fuel, staff, installation downtime)

Additional fuel, maintenance, installation downtime (onboard systems only), and staff costs are likely to be related to use by airlines and ground handlers. These costs are likely to be minimal and offset by cost savings. Potential cost savings include the following:

- Not needing to use pushback tractors [approximately U.S.\$50 per cycle (Morrow et al., 2007)].
- Reduced delays and taxi times (at around U.S.\$66 to U.S.\$150 per minute per turnaround) due to, for example, eliminating the need to attach or detach aircraft pushback tractors for onboard systems (i.e., nose- or main-wheel electric motors).
- Being able to use two gates for passenger loading rather one gate, by having the aircraft taxi in parallel to the two gates (i.e., turning the aircraft around by 90 degrees), subject to the airport/gate layout.
- Reduced fuel use.

Other costs for airports are associated with additional taxi-queue management needed for systems with low speeds. For external systems, labor costs may increase since drivers will be needed to operate the equipment for longer than for conventional pushback [at a cost of around U.S.\$29.60 per hour (Pers. comm., 2014)].

## Safety

In the event of any alternative aircraft-taxiing system failure, the aircraft must still be able to taxi using its main engines. None of the systems reviewed prevent the use of main engines for taxiing. There were also safety concerns regarding alternative aircraft-taxiing systems that pilots do not directly control. Other safety issues include concerns regarding the visibility of aircraft pushback tractor equipment on taxiways, the possibility of jackknifing and braking failure (where braking did not use the aircraft's brakes), and visibility and identification of aircraft with onboard systems to allow for slower speed when crossing runways.

## Nose Fatigue Issues

Webster (2008) highlighted a major concern identified by Virgin Atlantic and Boeing with regard to the stress to the aircraft nose wheel caused by dispatch towing and subsequent reduction in the wheel's fatigue life. It is assumed that the Virgin Atlantic dispatch trial used a towbarless aircraft pushback tractor (TBLT) based on information in *ACRP Research Results Digest 15* (2012). In "Towbarless Towing Vehicle Assessment Criteria," Boeing (2003) describes the test criteria and procedure for evaluating the impact of TBLT used for pushback and maintenance towing on Boeing aircraft. The loads introduced by the TBLT should not exceed the aircraft nose-wheel

design loads, and tests are required to prove that the tow vehicle and aircraft maintain good stability at all times. While the document is not specifically written for dispatch towing, it can be used to assess the potential for nose-wheel fatigue. Therefore, potential fatigue to the aircraft nose wheel should be considered for any external tractor-type system, depending on how the tractor connects to the nose wheel.

## **Airframe Modifications Required**

Any onboard system will require aircraft modification. The level of modification needed will depend on the individual aircraft and onboard system but could include larger/new power cables due to increased power needs from the APU, APU modification if the APU is not powerful enough, replacement of the APU, changes to control cables and fuel pipes, and reinforcement of the rear of the aircraft for any additional jet engines.

## **Aircraft Brake Implications**

Aircraft brakes are attached to the main wheels of the aircraft. Therefore, main-wheel onboard systems may have an impact on aircraft brake cooling or could be affected by brake temperature, depending on the design.

## **APU Modifications Required**

Any onboard system will require aircraft modification. The level of modification needed will depend on the individual aircraft and onboard system but could include larger/new power cables due to increased power needs from the APU, APU modification if the APU is not powerful enough, replacement of the APU, changes to control cables and fuel pipes, and reinforcement of the rear of the aircraft for any additional jet engines.

## **System Weight**

For aircraft onboard systems (i.e., nose- or main-wheel electric motors or additional jet engines), Saia (2013) raises concerns about the impact of the additional weight when retrofitted to aircraft. Aircraft carrying extra weight will burn more fuel during cruise, but manufacturers of some onboard systems claim their equipment is weight-neutral because less fuel needs to be carried. However, the main issue with weight gain associated with the installation of an onboard alternative aircraft-taxiing system is the increased fuel consumption during takeoff, climb, and cruise (assuming the number of passengers and/or cargo tonnage remain the same).

Any fuel weight savings associated with taxi-out does not affect weight during takeoff, climb, and cruise because that fuel would have been burned prior to takeoff. Only the fuel saved during taxi-in (which, therefore, would not have been loaded onto the aircraft prior to departure) can be considered to offset the weight gain of an onboard system for takeoff, climb, and cruise. If an aircraft is operating close to its regulated takeoff weight (RTOW), then the impact of the additional weight may require an airline to remove cargo or passengers so the aircraft can operate within its RTOW.

Airline operators calculate takeoff weight by taking into account the operational empty weight of the aircraft with the weight of passengers, cargo, and fuel (FAA, 2005). The Joint Aviation Authorities (2007) describes the standard passenger weight for a passenger including 6 kg (13.2 lb) of carry-on (hand) luggage and takes into account passengers carrying infants. For an aircraft

with over 30 seats, the prescribed standard passenger weight for an average adult is 84 kg (185 lb) on scheduled flights and 76 kg (168 lb) on holiday charter flights. The Joint Aviation Authorities (2007) estimates the standard passenger weight for a child to be 35 kg (77 lb) for charter and schedule flights. The Joint Aviation Authority is a European agency, and the reference is used to illustrate weights only. The FAA similarly prescribes a standard adult passenger weight of 169 lbs, plus 5 lb of clothes (10 lb in winter) and 16 lb for carry-on items.

Thus, assuming no reduction in fuel allowance, if an aircraft typically operates at its RTOW, then the increase in weight due to the addition of an onboard system (weighing around 300 to 800 lbs) would be offset by a reduction of two or more passengers. For onboard systems attached to the nose wheel, the additional weight would slightly offset the center of gravity. Similarly, if a jet engine were used to replace an APU at the back of an aircraft, with any necessary strengthening of the airframe around the area, the center of gravity would be offset. However, the actual weight gain of any onboard alternative aircraft-taxiing systems is likely to be relatively small and so would have limited impact on the center of gravity.

### Center of Gravity Implications

For aircraft onboard systems (i.e., nose- or main-wheel electric motors or additional jet engines), Saia (2013) raises concerns about the impact of the additional weight when retrofitted to aircraft. Aircraft carrying extra weight will burn more fuel during cruise, but manufacturers of some onboard systems claim their equipment is weight-neutral because less fuel needs to be carried. However, the main issue with weight gain associated with the installation of an onboard alternative aircraft-taxiing system is the increased fuel consumption during takeoff, climb, and cruise (assuming the number of passengers and/or cargo tonnage remain the same).

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Airline operators calculate takeoff weight by taking into account the operational empty weight of the aircraft with the weight of passengers, cargo, and fuel (FAA, 2005). The Joint Aviation Authorities (2007) describes the standard passenger weight for a passenger including 6 kg (13.2 lb) of carry-on (hand) luggage and takes into account passengers carrying infants. For an aircraft with over 30 seats, the prescribed standard passenger weight for an average adult is 84 kg (185 lb) on scheduled flights and 76 kg (168 lb) on holiday charter flights. The Joint Aviation Authorities (2007) estimates the standard passenger weight for a child to be 35 kg (77 lb) for charter and schedule flights. The Joint Aviation Authorities is a European agency, and the reference is used to illustrate weights only. The FAA similarly prescribes a standard adult passenger weight of 169 lbs, plus 5 lb of clothes (10 lb in winter) and 16 lb for carry-on items.

Thus, assuming no reduction in fuel allowance, if an aircraft typically operates at its RTOW, then the increase in weight due to the addition of an onboard system (weighing around 300 to 800 lbs) would be offset by a reduction of two or more passengers. For onboard systems attached to the nose wheel, the additional weight would slightly offset the center of gravity. Similarly, if a jet engine were used to replace an APU at the back of an aircraft, with any necessary strengthening of the airframe around the area, the center of gravity would be offset. However, the actual weight gain of any onboard alternative aircraft-taxiing systems is likely to be relatively small and so would have limited impact on the center of gravity.

## **Typical Taxi Speed (i.e., around 20 knots)**

To achieve reasonable taxiing speeds (and acceleration), aircraft pushback tractors with greater horsepower may be needed. Airbus (2013) states that an alternative aircraft-taxiing system should be able to reach speeds of 20 knots. Similarly, Boeing stresses the need for aircraft to be able to reach reasonable taxiing speeds in a short time period (Paisley, 2015). A system fitted to the aircraft nose wheel (or main wheels) may be limited in speed due to motor size. Slower taxiing speeds at smaller airports could be an airline concern in terms of taxiing delay. At larger airports, with existing delays, slow taxiing speeds may be less of an issue, although all airports are striving to reduce such delays. A general guideline, according to air traffic controllers interviewed, is that an aircraft should be able to cross a runway surface and clear the safety area within 40 seconds (Pers. comm., 2015). If this requirement cannot be met for an alternative aircraft-taxiing system, then delays will occur unless main engines are used instead.

## **Pilot Control**

Any alternative aircraft-taxiing system that is directly pilot-controlled is likely to be considered safer by airlines and pilots than a system where the pilot has to work with a driver of an external system.

## **APU Load**

When an aircraft is on the ground not connected to gate power, its APU is used to run onboard systems and to start the aircraft main engines. The aircraft onboard systems that are powered by the APU typically include lighting, heating, ventilation, and air conditioning. During conventional taxiing, the APU is often not used, and power is taken from the aircraft's main engines for the electrical systems. However, for any alternative aircraft-taxiing system, the APU will run whenever the engines are not running to produce power. Aircraft with onboard alternative aircraft-taxiing systems that rely on power from the APU (i.e., nose- or main-wheel electric motors) will need an APU that is able to accommodate these additional power needs.

## **Acceleration (e.g., to allow runway crossing from stop in 40 seconds)**

To achieve reasonable taxiing speeds (and acceleration), aircraft pushback tractors with greater horsepower may be needed. Airbus (2013) states that an alternative aircraft-taxiing system should be able to reach speeds of 20 knots. Similarly, Boeing stresses the need for aircraft to be able to reach reasonable taxiing speeds in a short time period (Paisley, 2015). A system fitted to the aircraft nose wheel (or main wheels) may be limited in speed due to motor size. Slower taxiing speeds at smaller airports could be an airline concern in terms of taxiing delay. At larger airports, with existing delays, slow taxiing speeds may be less of an issue, although all airports are striving to reduce such delays. A general guideline, according to air traffic controllers interviewed, is that an aircraft should be able to cross a runway surface and clear the safety area within 40 seconds (Pers. comm., 2015). If this requirement cannot be met for an alternative aircraft-taxiing system, then delays will occur unless main engines are used instead.

## **Taxi-In and -Out**

It is less likely that external systems will be used for taxiing in as this would require a number of them to be positioned at runway exits and then be attached to an aircraft before taxiing it to the gate. However, there is no reason that onboard systems (i.e., nose- or main-wheel electric

motors or additional jet engines) cannot be used for taxiing in as they do not need to be attached to or detached from the aircraft, and there are no associated delays.

## **Attaching and Detaching**

In most cases, the alternative aircraft-taxiing system negates the need for the use of a pushback tractor, with the possible exception of the replacement of the APU with a certified jet engine. Larger jet engines cannot be started close to the gates due to engine blast. Therefore, a large jet-engine-based system would need to use a conventional pushback tractor before the extra jet engine was started to provide powering for taxiing and onboard systems. For external systems, the attaching and detaching needs to occur in a manner similar to that for conventional pushback, but near the runway. Potential time savings for onboard systems (i.e., nose- or main-wheel electric motors) are estimated at around 1.75 minutes, which is the time needed to attach or detach aircraft pushback tractors for onboard systems.

## **Start-up/Disconnection Area**

During conventional taxiing operations, the aircraft main engines are started at the gate, where the ground crew is present to observe any issues, and the aircraft taxi serves as the main engine warm-up period. The time needed to warm up most commercial aircraft main engines is considered by Deonandan and Balakrishnan (2010) and Airbus (2013) to be up to approximately 5 minutes. When alternative aircraft-taxiing systems are used, the aircraft main engines are started away from the gate. Virgin Atlantic (2006) found that dispatch taxiing required either aircraft main engines to be started during taxiing or the addition of designated areas for engine start-ups to allow for aircraft main engine warm-up. For external systems, there is the possible need for a designated detaching area near the runway to allow the external system to be removed from the aircraft. The cost for additional start-up/disconnection areas is likely to be similar to the cost for concrete pavements, which are approximately U.S.\$200 per square yard (U.S.\$240 per square meter) (Pers. comm., 2015). Asphalt is about 20% cheaper than concrete (Pers. comm., 2015), although it is standard practice to use concrete for engine run-up areas for safety reasons. Costs may vary by geographical region.

## **Additional Roadways**

Once external systems have taxied an aircraft to the runway, they will return to the gate area. Depending on the airport layout, additional roadways may be required to support this. Concrete roadways cost approximately U.S.\$75 per square yard (U.S.\$90 per square meter) (Pers. comm., 2015). However, costs may vary depending on geographical region. Asphalt is about 20% cheaper than concrete (Pers. comm., 2015).

## **Pushback Tractors**

In most cases, the alternative aircraft-taxiing system negates the need for the use of a pushback tractor, with the possible exception of the replacement of the APU with a certified jet engine. Larger jet engines cannot be started close to the gates due to engine blast. Therefore, a large jet-engine-based system would need to use a conventional pushback tractor before the extra jet engine was started to provide powering for taxiing and onboard systems. For external systems, the attaching and detaching needs to occur in a manner similar to that for conventional pushback, but near the runway. Potential time savings for onboard systems (i.e., nose- or main-wheel

electric motors) are estimated at around 1.75 minutes, which is the time needed to attach or detach aircraft pushback tractors for onboard systems.

## **Loading of Passengers**

Additional fuel, maintenance, installation downtime (onboard systems only), and staff costs are likely to be related to use by airlines and ground handlers. These costs are likely to be minimal and offset by other cost savings. Potential cost savings include the following:

- Not needing to use pushback tractors [approximately U.S.\$50 per cycle (Morrow et al., 2007)].
- Reduced delays and taxi times (at around U.S.\$66 to U.S.\$150 per minute per turnaround) due to, for example, eliminating the need to attach or detach aircraft pushback tractors for onboard systems (i.e., nose- or main-wheel electric motors).
- Being able to use two gates for passenger loading rather than one gate, by having the aircraft taxi in parallel to the two gates (i.e., turning the aircraft around by 90 degrees), subject to the airport/gate layout.
- Reduced fuel use.

Other costs for airports are associated with additional taxi-queue management needed for systems with low speeds. For external systems, labor costs may increase since drivers will be needed to operate the equipment for longer than for conventional pushback [at a cost of around U.S.\$29.60 per hour (Pers. comm., 2014)].

## **Engine Warm-Up**

The time needed to warm up the aircraft main engines is considered by Deonandan and Balakrishnan (2010) and Airbus (2013) to be up to approximately 5 minutes. Therefore, the use of alternative aircraft-taxiing systems at small airports with relatively short taxiing times of 5 minutes or less might not be beneficial.

## **Foreign Object Debris (FOD) Damage Issues**

A reduction in FOD damage is cited by Airbus (2013) as one result of the use of alternative aircraft-taxiing systems. This is because the aircraft main engines are not in use during taxiing, and the likelihood of engines sucking in FOD is reduced.





## APPENDIX B

# Acronyms and Abbreviations

APU	Auxiliary power unit
ATAM	Alternative Taxiing Assessment Matrix
ATC	Air traffic control
dB	Decibels
DNL	Day–night average sound level
EDMS	Emissions and Dispersion Modeling System
FOD	Foreign object debris
GSE	Ground support equipment
Hz	Hertz (one cycle per second, a measurement of frequency)
NextGen	Next Generation Air Transportation System
NO <sub>x</sub>	Oxides of nitrogen
PM	Particulate matter
PM <sub>2.5</sub>	Particulate matter with a size of up to 2.5 microns
PM <sub>10</sub>	Particulate matter with a size of up to 10 microns
RTOW	Regulated takeoff weight
SESAR	Single European Sky ATM [air traffic management] Research
TBLT	Towbarless aircraft pushback tractor

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*Abbreviations and acronyms used without definitions in TRB publications:*

A4A	Airlines for America
AAAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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