Low-hanging fruit? The costs and benefits of reducing fuel burn and emissions from taxiing aircraft

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Aviation is responsible for 3.5% of anthropogenic radiative forcing, but its share is expected to grow. At the same time, as energy prices have risen, airlines have struggled to maintain profitability. In this context, it is important to understand the costs associated with different measures to reduce the industry's environmental footprint. Aircraft are usually powered by their main engines while taxiing between the gate and the runway. This paper estimates the cost and emissions reductions associated with using electric, diesel or gasoline tugs to tow aircraft on the tarmac. It is found that, in the best case, emissions could be cut at a cost of *negative* \$140 per tonne of CO_2. The use of tugs could reduce the CO_2 emissions from domestic flights in the US by about 2 million tonnes each year, or about 1.4% of the total emissions in 2006. For aircraft that already taxi both in and out with only one engine, additional emissions reductions from using a tug come at a high cost: over \$100 per tonne of emissions abated. This suggests that caution needs to be exercised when savings from different approaches are combined: savings are often not independent of each other and cannot simply be added.

I. Greenhouse gas emissions from aviation

IN 2005 aviation was responsible for 3.5% of total anthropogenic radiative forcing. By 2050, its share is expected to rise to 4.0-4.7%. Both numbers exclude the impact of aviation-induced cirrus (AIC), which is highly uncertain. With AIC included, aviation's contribution to total radiative forcing was between 1.3-10% in 2005, and is expected to rise to between 2-14% by 2050.[1]

The growth of emissions from aviation is the consequence of two opposing phenomena. First, aviation has become consistently more efficient. The fuel efficiency of the domestic operations of certified US air carriers rose by 2.6% annually between 1990 and 2010, while that of their international operations rose by 1.3% each year during that period.[2]Analysts (e.g., Winchester et al.[3]) have assumed that aircraft fuel efficiency will continue to improve at about 1% per year. Second, passenger numbers are projected to grow at 5% per year up to 2030. At 7.6% per year, the growth is forecast to be most rapid in China. However, even in North America, where annual growth of 2.8% is forecast,[4] the rise in traffic is likely to outpace gains in efficiency, causing total emissions to grow.

In 2008, the European Parliament and Council issued a directive to include aviation in its emissions trading scheme (EU-ETS) from 2012. The text of the directive makes it clear that it is a response to expectations of rapid growth in greenhouse gas emissions from aviation.

> If the climate change impact of the aviation sector continues to grow at the current rate, it would significantly undermine reductions made by other sectors to combat climate change.[5]

The directive has been controversial and may yet be circumscribed.[6] Nonetheless, airlines have a strong incentive to reduce fuel consumption.

In 2010, fuel costs constituted 30% of US airlines' expenses,[7] and consumed 29% of passenger revenue.[8] The US airline industry has been profitable in only four of the eleven years from 2000 to 2010.[9] At the same time, the pressure on airlines to reduce their environmental footprint is likely to continue to grow. Indeed, public resistance to the expansion of aviation infrastructure might constrain the growth in passenger numbers.[10]

In this context, it is important for airlines and policymakers to understand the magnitude of emissions reductions that could be achieved by different measures, as well as what it would cost to achieve such reductions.

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II. Emission reductions from taxiing with minimal main engine use

A. Prior work

Deonandan & Balakrishnan[11] estimate reductions in fuel burn (and therefore CO_2 emissions), as well as hydrocarbon (HC) and carbon monoxide (CO) emission reductions, that accrue from using only one engine while taxiing out. They consider domestic commercial flights departing from the fifty busiest airports in the United States, and conclude that reductions of between 25% and 40% can be achieved in the emissions of each of the three pollutants considered.

McKinsey & Company[12]estimates that, in the global aviation industry, "measures costing less than €60 per tonne of CO_2 have an abatement potential of 0.36GtCO_2 per year in 2030, or 24 per cent [of total emissions]…"

Schäfer et al.[13] estimate the emissions reductions and associated costs of three technological improvements (1) A more advanced narrow-body aircraft: 17gCO_2[†] of savings per passenger kilometer (pkm) at zero marginal cost per tonne of emissions avoided, (2) Fast open-rotor aircraft: 27.2gCO_2 per pkm at a cost of €171 per tCO2, and (3) Reduced-speed open-rotor aircraft: 34gCO_2 per pkm at a cost of €158 per tCO_2.

Morris et al.[14] posit that 0.6 million tonnes, or 23% of the UK's total emissions from domestic aviation in 2020, could be cut in ways that reduce costs. Projected savings ranged from £187[‡] per tCO_2 emissions avoided through the better use of capacity to £20 per tonne of emissions avoided by more efficient air traffic management. Of the measures with a positive cost, the least expensive was the fitting of winglets wherever possible, at a cost of £20 per tCO_2. The most expensive measures included the replacement of old engines with the newest ones (£206 per tCO_2) and the early retirement of aircraft (£497 per tCO_2). The full range of measures considered would result in emissions reductions of 1.4 million tCO_2, or about 54% of the total.

B. Methods and data

The UN's International Civil Aviation Organization (ICAO) maintains a database of specific fuel consumption and emission indices for a large number of aircraft jet engines. The data are provided for four levels of thrust, the lowest of which is 'idle' or 7% of maximum. Throughout this paper, I assume that, when in operation during taxi, main engines are set to this level of thrust. Nikoleris et al.[15] have pointed out that the actual thrust setting during taxi may vary between 4% and 9%. However, a study of flight recorder data by Khadilkar and Balakrishnan[16] suggests that – with the exception of large Airbus aircraft such as the A330 and A340, which do not feature in my dataset - assuming a constant thrust level of 7% during taxi fits actual fuel burn, as measured by the flight data recorder, well.

This paper estimates the reduction in emissions of fuel burn and CO_2 that could be achieved if aircraft were to taxi without the use of their main engines, as well as the costs of the alternatives. The analysis is based on 2011 data on domestic passenger flights: 6 million flights are included.

Clewow et al.[17]report that over half the commercial pilots they surveyed taxied in (after landing) with only one engine running more than 75% of the time. However, the majority of pilots reported that they taxied out (before take-off) with both engines running over 90% of the time. As such, I assume in the Baseline scenario that all aircraft taxi out with all main engines operating, but operate both main engines for the smallest possible duration while

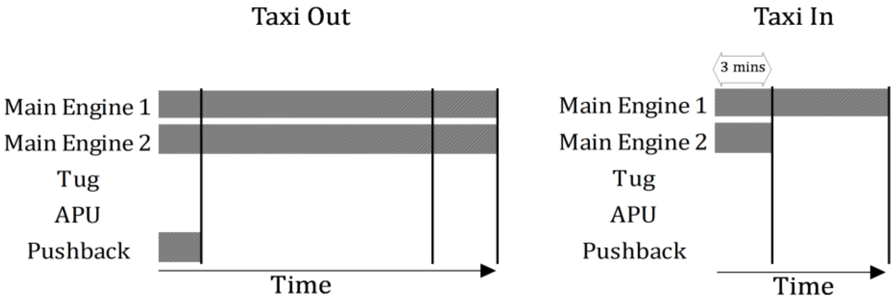

Figure 1. Schematic of Baseline scenario. Both engines are operated when the aircraft taxies out. However, both engines are run only for three minutes when the aircraft taxies in, after which the second engine is switched off.

[†] Baseline emissions are 76gCO_2 per passenger kilometer

[‡] Morris et al. assume an exchange rate of \$1.86 to £1. The current (Aug. 2012) exchange rate is approximately \$1.57 to £1.

taxiing in. In particular, I assume that all engines must be run for a minimum of three minutes after landing to allow them to cool down, [17] after which only one engine is run until the aircraft reaches the gate. A schematic of the Baseline scenario is shown in Fig. 1.

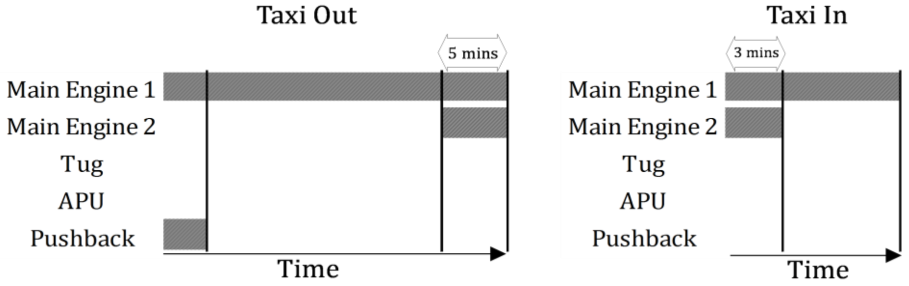

Figure 2. Schematic of the Single-engine taxi scenario. One of the main engines is used only for five minutes before take-off (to allow it to warm up) and for three minutes after landing (to allow it to cool down).

While the practice is rare, I also consider a variant (Fig. 2) of the Baseline scenario in which pilots taxi out with one engine. Tedrow[18] indicates that airlines instruct pilots to taxi with one engine as often as possible, and it is likely that the practice will become more prevalent. As such, it is appropriate that any alternatives to taxiing with main engines be compared to both two-engine and single-engine taxi out.

In the Tug scenario (Fig. 3), it is assumed that aircraft are towed from the gate to the runway by a tug powered by diesel, gasoline or an electric battery. This process is called dispatch towing. It is also assumed that the aircraft's APU, which is typically turned off during taxi if either of the main engines is on, is operated. With the main engines turned off, the APU supplies the bleed air necessary to run the aircraft's air cycle machine and to power its electrical systems. Emissions from the APU and tugs are taken into account, as are capital, maintenance, fuel and labor costs associated with their use.

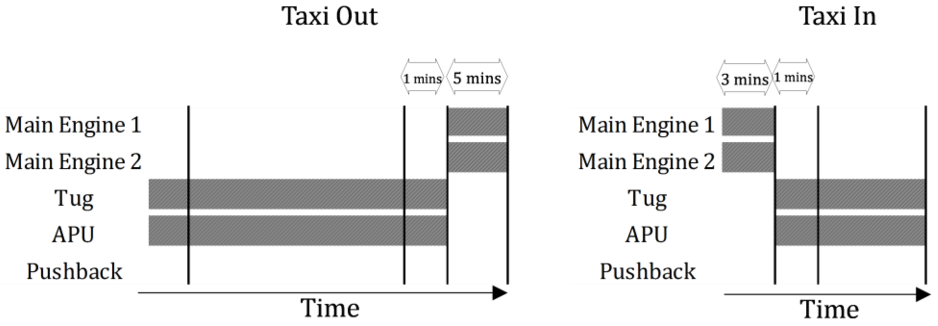

Figure 3. Schematic of Tug scenario. The main engines are used only for five minutes before take-off and for three minutes after landing. The actual taxi time may be longer than in the Baseline scenario, depending on what we assume about the relative taxiing speeds of the aircraft under main engine power and the tug. It is assumed that one minute is needed to detach the tug during taxi out, and another minute is needed to attach it after taxi in.

The Tug scenario is compared to both the Baseline and Single-engine Taxi scenarios. Combining emissions reductions and cost data makes it possible to arrive at an estimate of the cost (or savings) associated with each tonne of emissions avoided. The Appendix outlines in detail the sources of data used and assumptions made in comparing the scenarios above. Comparisons are made for all flights, as well as for flights departing from and arriving at the ten airports with the longest taxi times.

A number of firms (e.g., Honeywell-Safran,[19] Crane Aerospace,[20] WheelTug, Inc. [21]) are working on an electric-taxi (e-taxi) system. Such a system would use an electric motor, embedded in the landing gear and powered by the APU, to propel the aircraft on the ground. I estimate the fuel and cost savings that would be achieved by such a system, whose operation is described by the schematic in Fig. 4.

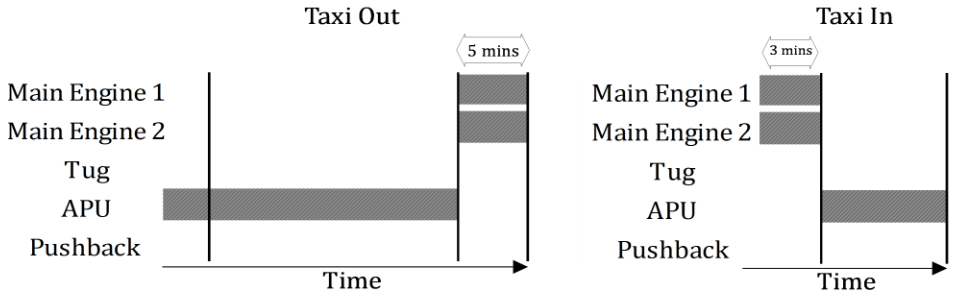

Figure 4. Schematic of e-taxi scenario. The main engines are used only for five minutes before take-off and for three minutes after landing.

The capital expense associated with retrofitting the system to existing aircraft, or incorporating it into new ones, is not known. Therefore, I calculate the cost per tonne of CO_2 emissions avoided for a range of assumptions about capital expenditure.

III. Results

Table 1 shows the savings in costs and emissions that could be attained if aircraft were towed to the runway using tugs. Emissions reductions are about 1.8 million tonnes of CO_2, 1.4% of the total 144 million tonnes of CO_2 equivalent that were emitted by US domestic commercial aircraft in 2006.[22] If we assume that the tugs tow the aircraft at the same speed as it would taxi under its own power, each type of tug would reduce emissions at negative cost.

Table 1. Fuel, cost and emissions savings resulting from the use of Tugs, relative to the Baseline scenario. The reduction in emissions is about 1.4% of the total CO_2 emissions from domestic civil aviation in the US. Assuming tugs tow aircraft as fast as they currently taxi; the use of tugs saves up to $140 per tonne of CO_2 emissions prevented.

Parameters				
Fuel for tug	Emission-free electricity	US grid electricity	Gasoline	Diesel
Cost of electricity ($ per kWh)	0.08	0.08		
Emission reductions and costs (annual)				
Reductions in				
Costs (million $)	$160	$180	$240	$260
CO_2 emissions (million kg)	2100	1800	1800	1800
Cost per tonne of reduction in the emissions of				
CO_2	-$80	-$100	-$140	-$140

In an environmental assessment for a new runway at Atlanta's Hartsfield-Jackson airport, it was assumed that taxiing speeds were, on average, 17 miles per hour (mph).[23] Deonandan & Balakrishnan[11] suggest that tugs can propel the aircraft at only 40% of the speed at which it would normally taxi. In an interview I conducted, one airline engineer suggested that towing speeds of 13-16 mph were feasible.[§]

As such, the speed at which aircraft may be towed is uncertain. Fig. 5 shows that tugs would have to tow aircraft approximately at the same speed as they currently taxi for dispatch towing to be an economical way of cutting emissions. Fig. 6 summarizes the economics of towing aircraft using tugs, at 70% of the current taxiing speeds, at ten US airports with the longest average taxi times. While the practice would not be economical if adopted system-wide, it would still be a cost-effective way of cutting emissions from domestic flights at some US airports. Though it

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[§] Pennock, S. Phone interview with Shawn Pennock, American Airlines. (9 March 2012) is not modeled here, slowing down taxiing could contribute to airport congestion, and could therefore be unacceptable, especially at busy airports.

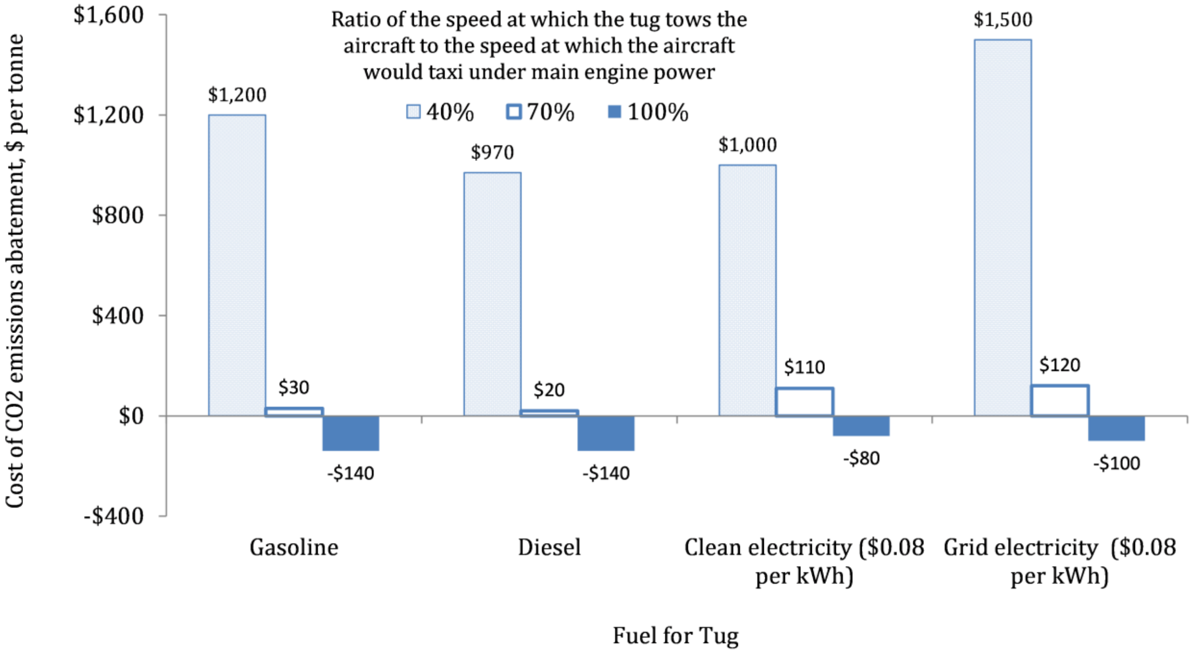

Figure 5. Regardless of fuel, tugs can reduce emissions at negative costs only if they can tow an aircraft approximately as quickly as an aircraft taxies under main engine power.

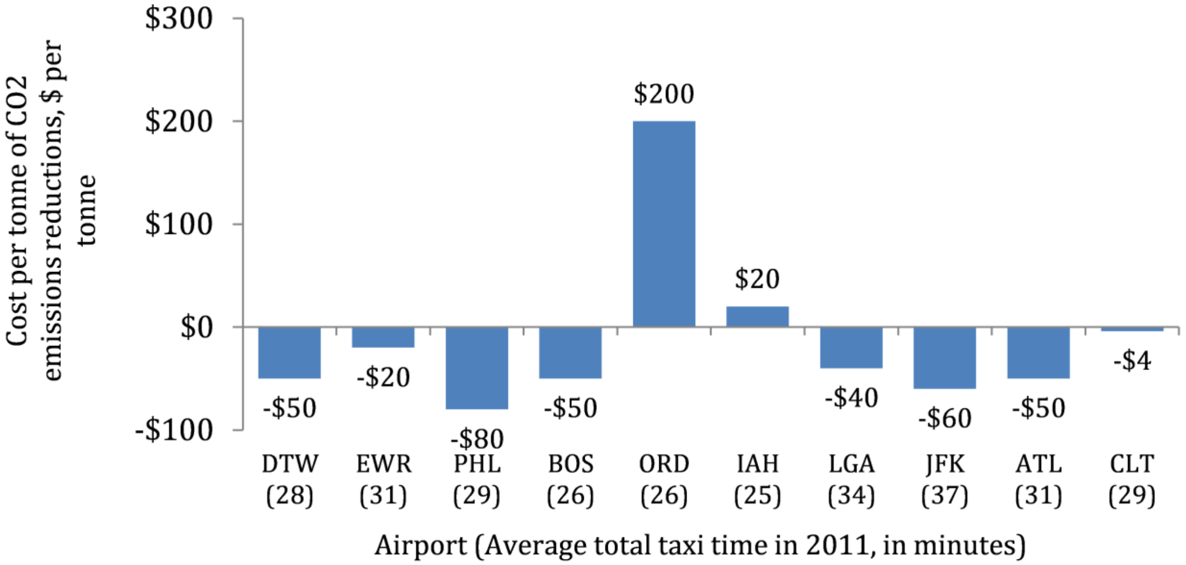

Figure 6. If diesel tugs could tow aircraft at 70% of the speed at which they would taxi under main engine power, they could be utilised to economically reduce emissions at some of the busiest airports in the US

The results summarized in Table 2 show that, if all aircraft taxied in and out with only one main engine running, additional emissions reductions from the use of tugs – though substantial – would come at a high price ($100-$200 per tonne of CO_2 emissions abated), even if it were assumed that dispatch towing was as fast as the current mode of taxi.

Table 2. Fuel, cost and emissions savings resulting from the use of Tugs, relative to the Single engine taxi scenario, when the aircraft taxies in and out – for as long as possible – on one engine. While incremental savings are significant, they come at a relatively high cost.

Scenario parameters				
Fuel for taxiing tug	Zero-emissions electricity	Grid Electricity	Gasoline	Diesel
Cost of electricity	0.08	0.08		
Emission reductions and costs (annual)				
Reductions in				
Costs (million $)	-$180	-$160	-$100	-$80
CO_2 emissions (million kg)	970	720	670	760
Cost per tonne of reduction in the emissions of				
CO_2	$190	$220	$140	$100

The data in Table 3 show that, if an e-taxi system could be attached to all aircraft on domestic service in the US, airlines would reduce costs, fuel burn and emissions in all but the most extreme scenario. A crucial caveat is that such a system would increase aircraft weight. As such, fuel savings during taxi could be partially (or fully) offset by additional fuel burn during cruise. I neglect this weight penalty, which could be significant and even exceed the savings realized during taxi.

Table 3. If an e-taxi system could be fitted to all planes on domestic service, substantial savings in emissions could be achieved at a negative cost

Scenario Parameters						
Savings compared to	Baseline scenario			Single-engine taxi scenario		
Capital cost of fitting e-taxi system ($)	250,000	500,000	1,000,000	250,000	500,000	1,000,000
Emission reductions (annual)						
Reductions in						
Costs (million $)	$530	$420	$220	$190	$90	-$120
CO_2 emissions (million kg)	2000	2000	2000	880	880	880
Cost per tonne of reduction in the emissions of						
CO_2	-$270	-$220	-$110	-$220	-$100	$140

IV. Discussion

A. Problems associated with the use of tugs for taxiing

In 2006, the Dutch Ministry of Infrastructure and Environment worked with BAA (which operates London's Heathrow and Gatwick airports) and Virgin Atlantic Airlines to evaluate the use of tugs while taxiing. The tests – which involved Boeing 747 aircraft – were discontinued due to "operational difficulties." A number of these difficulties were discussed in a report to the Ministry.[24] The operators were told that aircraft nose gear assemblies were not built to withstand the lateral forces associated with being tugged for long periods of time. It is also not clear that all airports and all runways have routes that allow tugs to safely return after they have detached from the aircraft (see, for example, Aviation Week & Space Technology).[25] If dispatch towing were considerably slower than current taxi speeds, an aircraft would need to be told precisely when and from which runway it is scheduled to take off sooner than it currently needs to be.[11] At busy airports, this might be difficult to do. Finally, in planning their schedules to ensure robust on-time performance airlines would need to account for the fact that a larger proportion of each gate-to-gate journey is likely to be spent on the ground.

B. Problems associated with e-taxi

A key determinant of the economics of an e-taxi system is its weight, and the cost of retrofitting it to the aircraft. Supplying an e-taxi system with enough power to propel the aircraft at sufficient speed might increase both cost and weight.

Consider an aircraft with mass 75 metric tonnes (e.g., the Airbus A320 family[26]), rolling on a runway– with coefficient of friction 0.03[27] – at 20mph, or 9 meters per second. This would require about 200kW[**] of power, which exceeds the capacity of APUs typically fitted to single-aisle aircraft, which are typically rated at less than 200 horsepower, or 150kW.[28]

Providing sufficient energy to propel aircraft at the required speeds, and run other electrical systems, might require larger - potentially heavier – APUs, or other technologies (e.g., a battery that charges while the aircraft is at the gate or during flight, and powers the e-taxi system on the ground).

V. Conclusions and implications for practice

Two measures to curtail the use of main engines while taxiing – the use of tugs and embedding an electric motor in the nose wheel of the aircraft – were considered, and the cost per tonne of CO_2 abated estimated.

If we assume that aircraft currently taxi out with both engines running, and taxi in with only one engine running, the use of tugs during taxiing could *save* airlines at most $140 per tonne of CO_2 abated. If we assume that aircraft typically taxi out with only one engine running, the use of tugs would reduce CO_2 emissions further. However, these incremental reductions would come at a *cost* of over $100 per tonne CO_2 abated. The use of tugs becomes uneconomical if we assume that dispatch towing would be significantly slower than current taxiing speeds.

The use of an electric motor – embedded in the landing gear, and powered by the aircraft's APU – would be an attractive way of cutting both emissions and costs, provided the costs of incorporating such a system and its weight could be kept low.

Importantly, the analysis demonstrates the dangers of aggregating savings from different sources. For instance, the results make it apparent that single-engine taxiing and the use of tugs are both attractive ways of reducing emissions when considered in isolation, and when compared to taxiing with both engines running. However, even though an airline that is successful in exploiting savings from single-engine taxiing could further reduce its emissions by using a tug, that reduction would remain unrealized because the incremental cost associated with it would be too big. Clearly, the wide range of costs obtained with different assumptions suggests that sweeping statements about the potential and cost of emissions reduction may be unreliable guides to decision-making, and might even be misleading.

While the study has focused on emissions of CO_2, a significant proportion of the flight's emissions of HC and CO are likely to be emitted during taxiing.[29] The approaches discussed might also be cost- effective ways of reducing the emissions of pollutants that are relevant to local air quality (HC, CO and NO_X).

The range of logistical challenges associated with the use of tugs and single-engine taxiing suggests that the efficacy of any measure depends strongly on the operating environment. This may well be different for each combination of location, aircraft type and airline. For instance, 2011 taxi data shows that the average taxi out time for Boeing 737 aircraft operated by SouthWest airlines is, on average, just over 10 minutes. Boeing 737 aircraft operated by all other airlines taxi out for much longer: on average, 17 minutes. Clearly, SouthWest would have a much smaller incentive to adopt the measures discussed above than would other airlines.

A clear implication for policymakers seeking to reduce greenhouse gas emissions from aviation is that putting a price on emissions but leaving airlines to decide where and how to achieve reductions is likely to be both more effective and more efficient than prescribing – or trying to build a consensus for the adoption of – specific measures.

Appendix

Data	**Source**	**Remarks**
Fuel consumption and emissions indices for HC, CO, NO_X, and SO_2 during taxiing	International Civil Aviation Organisation[30]	This was calculated for each flight, based on the taxi time and type of aircraft. BTS On-time Performance data state the tail number of the aircraft that was used on each flight. FAA[31] data was used to identify which aircraft type each tail number corresponded to.

[**] The power requirement is calculated as force times velocity, where the force is given by the weight of the aircraft times co-efficient of friction. As such, Power required = 75,000 kg × 9.81 m/s^2 × 0.03 × 9 m/s = 198kW

<table>
<tr><th>Data</th><th>Source</th><th>Remarks</th></tr>
<tr><td>Taxiing-out and taxiing-in times</td><td>BTS On-time Performance Data[32]</td><td>This information was used to calculate emissions from main engines in the Baseline scenario, and from the APU in alternate scenarios. After considering the marginal impact of stops and turns, Khadilkar and Balakrishnan [16] conclude that fuel burn is determined almost entirely by taxi time.
Calculations are based on the 6 million domestic flights that were operated by major airlines in 2011.
For each flight, the amount of time a tug (and APU) would be needed for taxi out was calculated by checking if the reported taxi time was greater than 5 minutes, which is the warm-up time for which both engines must run. If yes, the amount of time the tug and APU would need to operate was calculated as the reported taxi time, less 5 minutes. If no, then it was assumed that tugs could not be used to dispatch that particular flight. The same analysis was repeated for taxi in, with a threshold of 3 minutes, which is the cool-down time for main engines.</td></tr>
<tr><td>CO_2 emission index of jet fuel, gasoline and diesel</td><td>Intergovernmental Panel on Climate Change[33]</td><td>Used to calculate CO_2 emissions from main engines, APUs, and tugs, after fuel burn is estimated.</td></tr>
<tr><td>Emissions from electricity</td><td>EPA eGrid[34]</td><td>Overall US grid data are used for system-wide calculations.</td></tr>
<tr><td>Horsepower, fuel consumption, load factor, maintenance cost of gasoline, diesel and electric tugs.</td><td>Energy and Environmental Analysis, Inc. for Environmental Protection Agency[28]</td><td>For electric pushback trucks, power consumption is calculated by assuming that they have the same power output as diesel tugs, are 85% efficient, and charge with 85% efficiency. To estimate the additional amount of electricity that needs to be generated, transmission losses of 10% are also assumed. All costs are inflated at 2% per year to 2011 dollars. All capital costs are amortized at 7%.</td></tr>
<tr><td>Labour costs</td><td>BTS Average Annual Wages and Salaries[35]</td><td>Each tug is assumed to require one operator. It is assumed that operators work in two eight-hour shifts (effectively, each piece of equipment requires two full-time operators). Each operator is assumed to cost $40,000 per year.</td></tr>
<tr><td>Pushback tug time of operation per flight</td><td>Assumption</td><td>It is assumed that a pushback tug operates for 2 minutes per flight.</td></tr>
<tr><td>Unit cost of fuel</td><td>For gasoline and diesel: US EIA Gasoline and Diesel Fuel Update[36]</td><td>Electricity is assumed to cost $0.08 per kWh. A sensitivity analysis was performed by varying this number, but it was found not to have a significant bearing on the economics, as the capital costs associated with tugs in general – and electric tugs in particular -</td></tr>
<tr><td>Capital costs associated with a taxiing tug</td><td>Based on interviews with airline and airport managers, tugs that can propel narrow-body aircraft are assumed to cost $800,000</td><td>The cost estimates provided by the experts interviewed are as below.
<table>
<tr><th></th><th>Type of tug</th><th>Cost ($'000s)</th></tr>
<tr><td>Source 1[††]</td><td>For regional jet only</td><td>400-450</td></tr>
<tr><td></td><td>For narrow-body and some wide-body</td><td>700-900</td></tr>
<tr><td></td><td>For wide-body</td><td>900-1400</td></tr>
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[††] Phone interview with Scott Branderhorst, Delta Airlines. (21 March 2012)

		Source 2[‡‡] 700 Source 3[§§] For Boeing 767 and below 750-900 Source 4[***] 700-800 The cost per tonne of CO_2 emissions abated is not very sensitive to the cost of the tug: halving the capital cost would only reduce the per-tonne cost of abatement by 30% For electric tugs, the size of battery needed was calculated assuming that the tug would need to carry 16 hours (two shifts) of charge. The additional cost of the battery was estimated at $300 per kWh.[37]
Number of tugs needed at each airport	Calculation	The total number of minutes for which tugs would be needed to tow aircraft at each airport was calculated, based on data about taxi times, and assumptions about the speed of dispatch towing relative to current taxi speeds. The time needed to attach and detach tugs was accounted for. In addition, it was assumed that 50% of the time, tugs would have to roll back empty (without an incoming aircraft in tow) after dispatching an aircraft; and that 50% of the time, tugs would have to roll out empty (without a departing aircraft in tow) to pick up an incoming aircraft. It was assumed that each tug would be available for 80% of the 16 hours (960 minutes) that each airport operated daily.
Model of APU used in each aircraft type; and estimates of fuel burn rate	Fleuti and Hofmann for Zürich Airport,[38] Energy and Environmental Analysis, Inc. for Environmental Protection Agency[28]	The aircraft type was identified using tail numbers from BTS data, and the FAA aircraft registry. APU type was identified once aircraft type was known.
Number of e-taxi systems needed	BTS On-time Performance Data[32]	It was assumed that every aircraft on domestic service would have an e-taxi system installed on it. The number of aircraft is identified from Bureau of Transportation Statistics (BTS) delay data: this data lists every domestic flight undertaken by a major US airline, and includes the tail number of the aircraft used for it. I estimated the number of aircraft on domestic service in the US by calculating the number of unique tail numbers in the dataset for 2011.

Acknowledgments

This work was supported by the center for Climate and Energy Decision Making (SES-0949710), through a cooperative agreement between the National Science Foundation and Carnegie Mellon University and by Academic Funds through the Department of Engineering and Public Policy from the CIT Dean's Office.

References

[1]Lee, D. S. *et al.* "Aviation and global climate change in the 21st century," *Atmospheric Environment* **43**, 3520–3537 (2009).

[‡‡] Phone interview with Michael Pulaski, US Airways. (29 March 2012)

[§§§§] Phone interview with Shawn Pennock, American Airlines. (9 March 2012).

[***] Phone interview with Paul Martinez, Dallas-Fort Worth Airport. (6 March 2012).

[2] BTS “National Transportation Statistics: Energy Intensity of Certificated Air Carriers,” (2011) URL: http://www.bts.gov/publications/national_transportation_statistics/excel/table_04_21.xls

[3] Winchester, N. *et al. The Impact of Climate Policy on U.S. Aviation*. (MIT Joint Program on the Science and Policy of Global Change: 2011) URL: http://web.mit.edu/aeroastro/partner/reports/proj31/proj31-captraderpt.pdf

[4] Boeing “Current Market Outlook 2011-2030,” (2011) URL: http://active.boeing.com/commercial/forecast_data/index.cfm

[5] The European Parliament and Council *Directive 2008/101/EC of the European Parliament*. (2008) URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0101:EN:NOT

[6] Clark, P. “Air carbon permit fight escalates,” *Financial Times* (2011) URL: http://www.ft.com/intl/cms/s/0/d3c934f0-0186-11e1-8e59-00144feabdc0.html#axzz1eCIg4INn

[7] BTS *Fuel Expense as Percentage of Total Expense*. (2011) URL: http://web.mit.edu/airlinedata/www/2010%2012%20Month%20Documents/Expense%20Related/Fuel/Fuel%20Expense%20as%20Percentage%20of%20Total%20Expense%20%28Excluding%20Transport%20Related%20Expense%29.htm

[8] BTS *Fuel Expense as Percentage of Total Revenue*. (2011) URL: http://web.mit.edu/airlinedata/www/2011%2012%20Month%20Documents/Expense%20Related/Fuel/Fuel%20Expense%20as%20Percentage%20of%20Total%20Revenue%20(Excluding%20Transport%20Related%20Revenue).htm

[9] Airline Data Project “Net Income (Loss),” (2011) URL: http://web.mit.edu/airlinedata/www/2010%2012%20Month%20Documents/Probability,%20Balance%20Sheet%20&%20Cash%20Flow/Income%20Statement/Net%20Income%20%28Loss%29.htm

[10] Pickard, J. & Jacobs, R. “Labour drops support for third Heathrow runway,” *Financial Times* (2011) URL: http://www.ft.com/intl/cms/s/0/59410a1e-03d4-11e1-bbc5-00144feabdc0.html#axzz1eCXkBcR4

[11] Deonandan, I. & Balakrishnan, H. “Evaluation of Strategies for Reducing Taxi-out Emissions at Airports,” *Proceedings of the AIAA Aviation Technology, Integration, and Operations (ATIO) Conference* (2010) URL: http://www.mit.edu/~hamsa/pubs/DeonandanBalakrishnanATIO2010.pdf

[12] McKinsey & Company *Pathways to a Low-Carbon Economy*. (2009) URL: https://solutions.mckinsey.com/ClimateDesk/default.aspx

[13] Schäfer, A. *et al. TOSCA Project Final Report: Description of the Main S&T Results/Foregrounds*. (TOSCA Project: 2011) URL: http://www.toscaproject.org/FinalReports/TOSCA_FinalReport.pdf

[14] Morris, J., Rowbotham, A., Angus, A., Mann , M. & Poll, I. *A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector* (Omega - Aviation in a Sustainable World: 2009) URL: http://www.omega.mmu.ac.uk/Downloads/Events/omega%2014%20final%20draft%20v2%20020309.pdf

[15] Nikoleris, T., Gupta, G. & Kistler, M. “Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas/Fort Worth International Airport,” *Transportation Research Part D: Transport and Environment* **16**, 302–308 (2011)

[16] Khadilkar, H. & Balakrishnan, H. “Estimation of Aircraft Taxi-out Fuel Burn using Flight Data Recorder Archives,” *Proceedings of the AIAA Guidance, Navigation, and Control Conference* (2011) URL: http://www.mit.edu/~hamsa/pubs/KhadilkarBalakrishnanGNC2011.pdf

[17] Clewow, R., Balakrishnan, H. & Reynolds, T. G. “A Survey of Airline Pilots Regarding Fuel Conservation Procedures for Taxi Operations,” *International Airport Review* **14**, (2010).

[18] Tedrow, S. “Continental Airlines eco-skies Commitment to the Environment,” (2008) URL: http://www.trbav030.org/pdf2008/TRB08_S_Tedrow_Continental.pdf

[19] Honeywell *Safran and Honeywell Commence Electric Green Taxiing System Testing*. (Dubai, 2011) URL: http://honeywell.com/News/Pages/Safran-and-Honeywell-Commence-Electric-Green-Taxiing-System-Testing.aspx

[20] Crane Aerospace *GreenTaxi Electric Drive Taxi System*. (2012) URL: http://newsroom.craneae.com/2012/07/greentaxi-electric-drive-taxi-system/

[21] WheelTug plc “Components of WheelTug,” (2011) URL: http://www.wheeltug.gi/components.shtml

[22] US Department of Transport *Transportation’s role in reducing US greenhouse gas emissions*. (2010) URL: http://ntl.bts.gov/lib/32000/32700/32779/DOT_Climate_Change_Report_-_April_2010_-_Volume_1_and_2.pdf

[23] Hartsfield-Jackson Atlanta International Airport *Appendix E of the Fuel Consumption with Additional Taxi Distance Due to Construction Component*. (2009) URL: http://www.atlanta-airport.com/docs/airport/environmental/appendices/Appendix%20E%20-%20Fuel%20Consumption_Taxi-Stage%20Length.pdf

[24] de Wolf, A. *Het slepen van vliegtuigen*. (ministerie van Verkeer en Waterstaat: 2007) URL: http://www.rijksoverheid.nl/bestanden/documenten-en-publicaties/kamerstukken/2007/10/29/200711036-bijlage-kamervragen-over-het-slepen-van-vliegtuigen/200711036-bijlage.pdf

[25] Aviation Week & Space Technology “Tugs’ Return Trips in Doubt,” *Aviation Week & Space Technology* 4 (2007)

[26] Airbus “Airbus A320 Product Brochure,” (2012) URL: http://www.airbus.com/fileadmin/media_gallery/files/brochures_publications/aircraft_families/A320_Family_market_leader-leaflet.pdf

[27] Nicolai, L. M. “Estimating R/C Model Aerodynamics and Performance,” (2009) URL: http://students.sae.org/competitions/aerodesign/rules/aero_nicolai.doc

[28] Energy and Environmental Analysis, Inc. *Technical Data to Support FAA’s Advisory Circular on Reducing Emissions from Commercial Aviation*. (U.S. Environmental Protection Agency: 1995) URL: http://www.epa.gov/otaq/regs/nonroad/aviation/faa-ac.pdf

[29] European Environment Agency *EMEP/EEA air pollutant emission inventory guidebook — 2009*. (2009) URL: http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-a-aviation_annex.zip

[30] International Civil Aviation Organisation “ICAO Engine Emissions Databank,” (2010) URL: http://www.caa.co.uk/default.aspx?catid=702&pagetype=68

[31] FAA “Aircraft Registry,” (2012) URL: http://www.faa.gov/licenses_certificates/aircraft_certification/aircraft_registry/releasable_aircraft_download/

[32] BTS “Airline On-Time Performance Data,” (2011) URL: http://www.transtats.bts.gov/Fields.asp?Table_ID=236

[33] Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J. & McFarland, M. *Aviation and the Global Atmosphere*. (Intergovernmental Panel on Climate Change: 1999) URL: http://www.ipcc.ch/ipccreports/sres/aviation/index.php?idp=22

[34] EPA *eGRID2010 Version 1.1: Year 2007 Summary Tables*. (2011) URL: http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2010V1_1_year07_SummaryTables.pdf

[35] Bureau of Transportation Statistics *Average Annual Wages and Salaries*. (2011) URL: http://web.mit.edu/airlinedata/www/2010%2012%20Month%20Documents/Employees%20and%20Compensation/Ground/Average%20Annual%20Wages%20and%20Salaries%20-%20INHOUSE%20PASSENGER,%20CARGO%20AND%20AIRCRAFT%20HANDLING%20PERSONNEL.htm

[36] U.S. Energy Information Administration “Gasoline and Diesel Fuel Update,” (2011) URL: http://38.96.246.204/oog/info/gdu/gasdiesel.asp

[37] Patel, P. “New Battery Could Be Just What the Grid Ordered - Technology Review,” (2011) URL: http://www.technologyreview.com/energy/38689/

[38] Fleuti, E. & Hofmann, P. *Aircraft APU Emissions at Zurich Airport*. (Unique (Flughafen Zürich AG): 2005) URL: http://www.zurich-airport.com/Portaldata/2/Resources/documents_unternehmen/umwelt_und_laerm/Technical_Report_APU_Emission_Calculation_Methodology_2005.pdf