Costs and Benefits of Reducing Fuel Burn and Emissions from Taxiing Aircraft

Low-Hanging Fruit?

Parth Vaishnav

While taxiing, aircraft are powered by their main engines. This paper estimates the potential reductions in costs and emissions that could be achieved with tugs or an electric motor embedded in the landing gear to propel aircraft on the ground. The use of tugs would result in the avoidance of $20/ton of carbon dioxide (CO_2) emissions if the measure were adopted for all domestic flights. Estimates of average net savings for airlines vary from $100 per flight at John F. Kennedy International Airport in New York City to a loss of $160 per flight in Honolulu, Hawaii. Electric taxiing would save between $30 and $240/ton of CO_2 emissions avoided. Either approach could reduce CO_2 emissions from domestic flights in the United States by about 1.5 million tons each year, or about 1.1% of the total emissions in 2006. If the switch were limited to large narrow-body aircraft on domestic service at the busiest airports in the United States, the total reduction in emissions would be 0.5 million tons of CO_2 annually, accompanied by savings of $100/ton. Air quality benefits associated with lower main engine use were monetized by using the air pollution emission experiments and policy model and ranged from more than $500 per flight in the New York City area to just more than $20 per flight in the Dallas–Fort Worth, Texas, area. The analysis also demonstrates that emissions reductions from different interventions (e.g., single-engine taxiing and the use of tugs) are often not independent of each other and therefore cannot be combined in a simple way.

In 2005, aviation was responsible for 3.5% of total anthropogenic contributions to increased radiative forcing. By 2050, aviation's share is expected to rise to between 4.0% and 4.7%. Both numbers exclude aviation-induced cirrus, whose impact is highly uncertain. Including aviation-induced cirrus, aviation's contribution to the increase in anthropogenic radiative forcing was between 1.3% and 10% in 2005 and is expected to rise to between 2% and 14% by 2050 (*1*).

The energy intensity (energy use per passenger mile) of the domestic operations of certified U.S. air carriers fell by 46% between 1990 and 2011 (2.9% annually), while that of their international operations fell by 16% (0.8% annually) during that period (*2*). Analysts [e.g., Winchester et al. (*3*)] have assumed that aircraft fuel efficiency will continue to improve by about 1% annually. Passenger miles globally are projected to grow more rapidly, 5% annually until 2030, with forecast growth in China to be most rapid, at 7.6% per year. However, even in North America, where annual growth of 2.8% is forecast, the rise in traffic is likely to outpace gains in efficiency and cause total emissions to grow (*4*).

In 2008, the European Union Council issued a directive to include aviation in its emissions trading scheme from 2012 onward, though the inclusion of international airlines in the scheme is currently on hold. The council said that it had decided to regulate greenhouse gas emissions from aviation because "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*).

Airlines also have a strong economic incentive to reduce fuel consumption. In 2010, fuel costs constituted 30% of U.S. airlines' expenses and consumed 29% of passenger revenue (*6*). The pressure on airlines to reduce their environmental footprint is likely to continue to grow. In this context, airlines and policymakers need to understand the magnitude of emissions reductions that could be achieved by different measures as well as the costs required to achieve such reductions.

PRIOR WORK

McKinsey & Company estimates that, in the global aviation industry, "measures costing less than €60 per ton of CO_2 [carbon dioxide] have an abatement potential of 0.36GtCO_2 per year in 2030, or 24 per cent [of total emissions]" (*7*).

Schäfer et al. estimate the emissions reductions and associated costs of three technological improvements (*8*): (*a*) a more advanced narrow-body aircraft, 17 g CO_2 of savings per passenger kilometer (pkm) at zero marginal cost per ton of emissions avoided (baseline emissions are 76 g of CO_2 pkm), (*b*) fast open-rotor aircraft: 27.2 g of CO_2 per pkm at a cost of €171/ton of CO_2, and (*c*) reduced-speed open-rotor aircraft: 34 g CO_2 per pkm at €158/ton of CO_2.

Morris et al. calculate that 0.6 million tons, or 23%, of the United Kingdom's total emissions from domestic aviation in 2020 could be cut in ways that reduce costs (*9*). Projected savings ranged from £187/ton of CO_2 emissions avoided through the better use of capacity to £20/ton of emissions avoided by more efficient air traffic management [Morris et al. assumed an exchange rate of $1.86 to £1 (*9*)]. Of the measures with a positive cost, the least expensive was the fitting of winglets wherever possible, at a cost of £20/ton of CO_2. The most expensive measures included the replacement of old engines with the newest ones (£206/ton of CO_2) and the early retirement of aircraft (£497/ton of CO_2). The full range of measures considered would result in emissions reductions of 1.4 million tons of CO_2, or about 54% of the total.

Department of Engineering and Public Policy, Carnegie Mellon University, Baker Hall 129, 5000 Forbes Avenue, Pittsburgh PA 15213-3890. parth.vaishnav@gmail.com.

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This paper estimates the reduction in fuel burn and CO_2 emissions that could be achieved if aircraft were to taxi without the use of their main engines as well as the costs of two alternatives: the first is the use of a tug to tow aircraft from the gate to the start of the runway; the second is an electric taxi (e-taxi) system, which uses an electric motor—embedded in the aircraft's landing gear and powered by its auxiliary power unit (APU)—to propel the aircraft on the ground. The alternatives are compared by considering domestic flights operated by major airlines in the United States in 2011.

Deonandan and Balakrishnan estimate reductions in fuel burn that accrue from using only one engine while taxiing for departure (*10*). They consider domestic commercial flights departing from the 50 busiest airports in the United States and conclude that fuel use and emissions from ground operations could be cut by between 25% and 40% by taxiing for departure with only one engine running. They also calculate that towing aircraft to the runway before takeoff would reduce jet fuel burn by about 75% during that period. Fuchte et al. estimate that an e-taxi system installed on a Boeing 737 or Airbus A320 aircraft on domestic service would reduce fuel burn by between 1.1% and 3.9% (*11*).

METHODS AND DATA

The scenarios compared in this paper are described below.

Baseline Scenario

More than half the commercial pilots surveyed by Clewlow et al. said that, more than 75% of the time, they taxied (after landing) with only one engine running (*12*). However, a majority of pilots reported that, more than 90% of the time, they taxied (before takeoff) with both engines running. (In the data set used in this analysis, all aircraft on domestic service had two engines.) Clewlow et al. also found that pilots ran both engines for an average of 3 min after landing, to allow them to cool down. Therefore, the baseline scenario (Figure 1*a*) assumes that aircraft taxied for departure with both main engines operating but that, while taxiing upon landing and after the cool-down period, only one engine was run until the aircraft reached the gate. The baseline scenario also assumes that the aircraft was pushed from the gate by a tractor, a process that took 2 min.

Single-Engine Taxiing Scenario

While single-engine taxiing is currently rare, a variant of the baseline scenario (Figure 1*b*) in which pilots taxied for departure with one engine was also considered. [In addition to the work of Clewlow et al. (*12*), research by Page et al. suggests that single-engine taxiing for departure is relatively rare (*13*).]. Tedrow indicates that airlines instruct pilots to taxi with one engine as often as possible, and it is likely that the approach will become more widely adopted (*14*). For this scenario, the current work assumed that both engines were run an average of 5 min before takeoff, a duration called "spool-up time" (*12*).

Furthermore, the author calculated the time for which the main engines must be run for each flight. For example, if an aircraft taxied for precisely 3 min on its way to the gate, both its engines were assumed to be operated throughout the duration of taxiing. Fuel burn and emissions were calculated for 6 min (three times two engines) of main engine operation. If it taxied for longer—say 5 min—it was assumed that one engine was run for the entire 5 min, while the other was run for only 3 min. Therefore, fuel burn and emissions were calculated for 8 min of engine run time. The scenarios for the baseline and for single-engine taxiing assumed that both engines were or one engine was, respectively, operating at the moment the aircraft backed from the gate.

Tug Scenario

The tug scenario (Figure 1*c*) assumed that aircraft were towed from the gate to the runway by a tug powered by diesel. This process is called "dispatch towing." [Aircraft taxi-in times are significantly shorter than taxi-out times, and the use of single-engine taxiing is much more common during taxiing for arrival than taxiing for departure (*12*). Therefore, fuel savings from using tugs for taxi-in are small. Furthermore, ensuring that a tug is available to meet an aircraft a few minutes after it lands is operationally complex. So tugs were assumed to be used only to tow aircraft to the runway before departure and not back to the gate after landing.] Another assumption was that the aircraft's APU, which is typically turned off during taxiing if either of the main engines is on, was operated. APU supplies bleed air to run the aircraft's air cycle machine and powers its electrical systems.

Two variants of the tug scenario were considered. The first assumed that tugs would be used to tow every domestic flight. But the use of tugs would likely be curtailed by two factors. First, as described later in the section on operational issues, only one manufacturer produces a tug designed to be used for operational dispatch towing. This tug is engineered to operate only with aircraft that are at least as large as the Airbus A318. Second, its cost is $1.5 million, and it is expensive to maintain. Therefore, for flights with short taxi times (e.g., those departing from uncongested airports), the capital and maintenance costs of the tug are likely to exceed the fuel savings its use generates.

The second variant of the tug scenario, then, considered the use of tugs to tow aircraft only at least as large as the Airbus A318, and these tugs were deployed only at the 50 busiest airports in the United States (Table S5), where it was economical to do so. (All tables and figures coded S are available online as supplementary materials at https://db.tt/WsadebxZ.)

E-Taxi Scenario

A number of firms are working on an e-taxi system (*15–18*). This analysis estimated the fuel and cost savings that would be achieved by such a system, whose operation is described by the schematic in Figure 1*d:* both main engines would be run for a minimum of 5 min during departure and 3 min during arrival. APU would be run the rest of the time. No push-back tractor would be needed, as the electric motor would be able to propel the aircraft both backward and forward. (Doing so might initially require wing walkers to guide the pilot and prevent tail strikes. Eventually, the aircraft may be able to reverse autonomously, perhaps with the help of a rear-facing camera mounted on the aircraft to assist the pilot.) The author assumed that all aircraft on domestic service are equipped with an e-taxi system for both scenarios: baseline and single-engine taxiing.

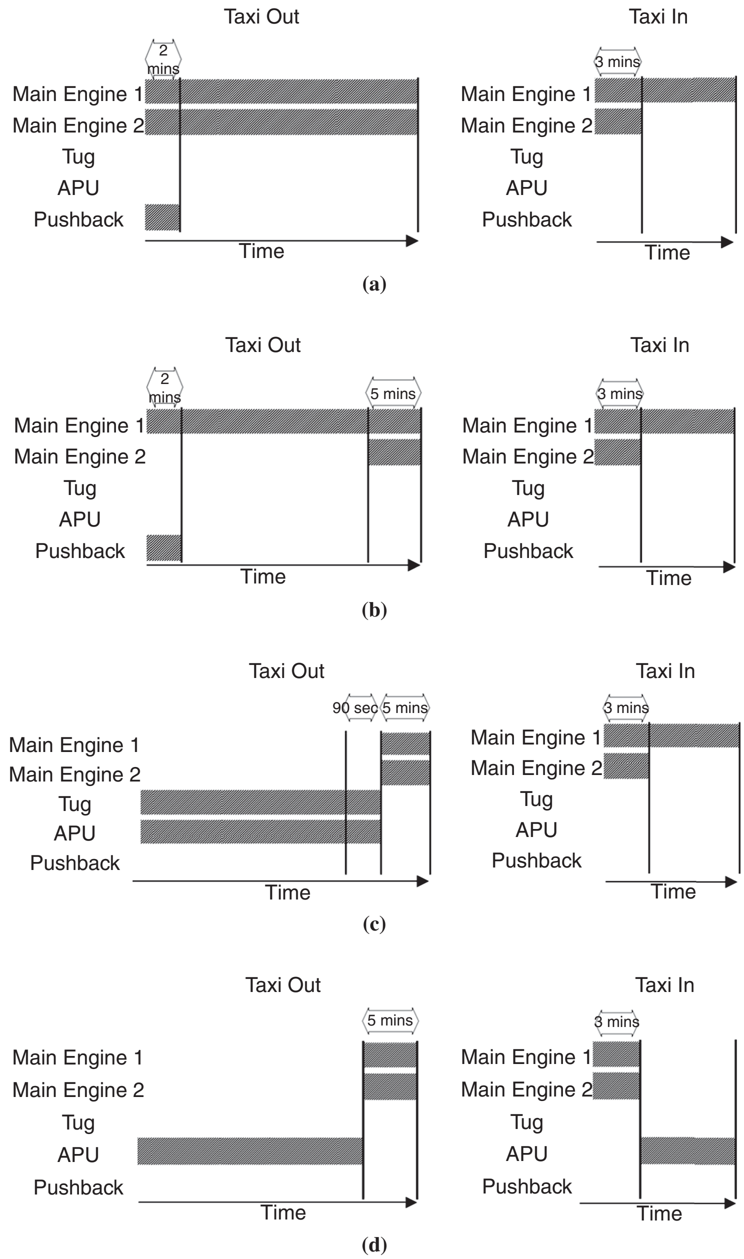


FIGURE 1 Schematics of scenarios: (*a*) baseline, (*b*) single-engine taxi, (*c*) tug, and (*d*) e-taxi.

In practice, an e-taxi system would be gradually adopted and restricted to aircraft that are operated on routes for which the aircraft spends a significant fraction of the total flight time on the ground.

Costs and Benefits

The reduction in main engine fuel burn for each flight was calculated by assuming that the plane went from being propelled by its main engines during taxi to using either a tug or an e-taxi. This change in fuel use was multiplied by the price of jet fuel to arrive at the change in jet fuel cost attributed to use of the main engines.

Any potential saving from decreased fuel use was offset by an increase in the cost of jet fuel for the APU in both the tug and e-taxi scenarios. The analysis accounted for the capital cost associated with purchasing the tugs or e-taxi systems and their operating costs. These operating costs included the cost of fuel and maintenance. In the case of the tugs, the cost of the personnel required to operate the tug was taken into account. In the case of e-taxi systems, the cost of additional fuel burn associated with carrying the extra weight of the system during cruising was also estimated.

These costs were subtracted from the saving in main engine fuel burn costs to calculate a net saving.

In most cases, a net reduction in fuel burn resulted, even when the additional fuel burn for the APU and tug were taken into account.

This reduction resulted in lower emissions of CO_2, nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM).

The cost per ton of CO_2 emissions avoided was calculated as the negative of the net saving divided by the quantity of CO_2 emissions avoided in tons. This method of quantifying the benefits (or costs) associated with a reduction in CO_2 emissions was used because it facilitates comparison with other ways of reducing greenhouse gas emissions, in both aviation and other sectors.

The benefits associated with a reduction in the emissions of the other pollutants were monetized by using the air pollution emission experiments and policy (APEEP) analysis model (*19*). This model gives the marginal cost of emitting an additional ton of NO_x, volatile organic compounds or—for the purposes of this analysis—HCs, and PM in each county in the United States. (The APEEP model also gives the marginal cost of sulfur dioxide and ammonia emissions, but these are taken into account in this analysis.) The counties in which each of the 50 busiest airports in the United States is situated were identified, and the benefit in improved air quality was calculated on the basis of the APEEP model and the previously described estimate of the reduction in emissions.

Taxiing Times

The U.S. Bureau of Transportation Statistics defines "taxi-out time" as "the time elapsed between departure from the origin airport gate and wheels off," and "taxi-in time" as that "between wheels down and arrival at the destination airport gate" (*20*).

The taxi times of all domestic flights operated by "major airlines"—defined as those "that account for at least one percent of domestic scheduled passenger revenues"—are published by the Bureau of Transportation Statistics (*21*). For 2011, data are available for six million of the nine million domestic flights (*22*). The latter number includes flights operated by minor airlines.

Fuel Burn and Emissions of Main Engines

The data from the Bureau of Transportation Statistics include the tail numbers of the aircraft that undertook each flight (*21*). (For 14% of the flights, the tail number was not available. For such flights, a "typical" aircraft was assumed. The fuel burn rate for this hypothetical aircraft was calculated by weighting the burn rate for all other aircraft by the number of flights performed by them and then averaging. Characteristics of all aircraft, including the typical aircraft, are given in Table S4.) An FAA database was used to identify the aircraft type on the basis of tail number (*23*). The engine most commonly associated with a particular aircraft type was identified in a study done by Energy and Environmental Analysis, Inc., for the U.S. Environmental Protection Agency as well as by referring to airframe manufacturers' websites (*24*).

The International Civil Aviation Organization maintains a database of specific fuel consumption and emission indices for a large number of aircraft jet engines (*25*). The data are provided for four levels of thrust, the lowest of which is "idle" or 7% of maximum. The analysis assumed that, when in operation during taxiing, main engines were set to this level of thrust. [Nikoleris et al. have noted that the actual thrust setting during taxi may vary between 4% and 9% (*26*). However, a study of flight recorder data by Khadilkar and Balakrishnan suggests that—with the exception of large Airbus models such as the A330 and the A340, which are not included in the data set for this paper—an assumption of a constant thrust level of 7% during taxi yields a good estimate of actual fuel burn (*27*).]

After considering the marginal impact of stops and turns, Khadilkar and Balakrishnan conclude that fuel burn is determined almost entirely by total taxi time (*27*). The emissions of CO_2 are determined by the quantity of fuel burned. The CO_2 emission index of jet fuel is obtained from a study by the Intergovernmental Panel on Climate Change (*28*). Therefore, this entire analysis assumed that main engine fuel burn and emissions are determined by the time for which the engines are run. The emissions indexes for other pollutants (NO_x, HC, and PM) were obtained from Wade (*29*).

Operation Times for APUs and Tugs

The APU and tug operation times are a function of taxi time and engine spool-up and cool-down times, as shown in Figure 1, *c* and *d.* They are calculated separately for each flight.

Fuel Consumption and Emissions of APUs

The models of APUs most commonly associated with particular aircraft types were identified by using the study by Energy and Environmental Analysis, Inc. (*24*) as well as a more recent study done for the Zurich, Switzerland, airport (*30*). The rate of fuel burn of the APUs was obtained from these studies, whereas the emissions index was obtained from Wade (*29*). These data were combined with the estimated run times of the APU in each of the scenarios to calculate fuel burn and emissions.

Fuel Burn and Emissions of Tugs

As discussed in the section on operational issues, only one manufacturer currently produces a tug designed for operational dispatch towing. This tug is powered by diesel. Statistics on fuel burn and emissions for the tug were obtained from the manufacturer. CO_2 emissions were calculated directly on the basis of fuel burn (*28*).

Fuel Prices

For jet fuel and diesel, price data were obtained from the U.S. Energy Information Administration (*31, 32*).

Capital Costs of Tugs

Each tug costs $1.5 million. This estimate was obtained from the manufacturer and was amortized over 10 years at an assumed discount rate of 7%. [This is the coupon rate of a US Airways bond that matures in 2020 (*33*).]

Capital Costs of E-Taxi System

The capital expense associated with retrofitting the e-taxi system to existing aircraft, or incorporating it into new ones, is not publicly available. Therefore, this value was parameterized and the cost per ton of CO_2 emissions avoided was calculated under the assumption that the system costs between $250,000 and $1,000,000 per aircraft.

It was assumed that the system's capital cost was amortized over 20 years at a discount rate of 7%, as noted earlier. Finally, it was assumed that each aircraft performs an average of 3.5 flights per day, 365 days a year (*34, 35*).

Operating and Maintenance Costs of Tugs

Discussions with the tug manufacturer led to the assumption that during its operational life the tug would undergo two major overhauls: one in the 5th year after purchase and another in the 10th year. At the assumed discount rate of 7%, the cost of each overhaul was amortized over 5 years to arrive at an annual cost. Additional assumptions were that the tug incurs an annual routine maintenance cost of 7.5% of the price of a new tug, that each tug is manned 18 h/day, and that the tug operator is paid $40/h. (The analysis is not sensitive to this assumption: halving the hourly rate increases the average per-flight saving by about 30%.)

Operating and Maintenance Costs of E-Taxi Systems

Maintenance costs were assumed to be 20% of annualized capital expense. A further assumption was that the e-taxi system would draw on APU power; therefore, the fuel costs associated with using the system were included in APU fuel burn.

Number of Tugs Needed

Two versions of the tug scenario were evaluated. The first assumed that tugs would be deployed at 300 airports and that virtually every domestic flight would be towed from the gate to the runway. The second version assumed that tugs would be deployed only at those of the 50 busiest airports in the United States where they saved money. This second version of the tug scenario also assumed that tugs would be used only to tow aircraft larger than the Airbus A318.

The following procedure was used to evaluate the number of tugs needed in the first version of the tug scenario.

All domestic flights that departed from each of the 31 busiest airports in July were arranged in chronological order. (July was chosen because aircraft taxied the longest in July for virtually all the airports considered. Then, the assumption was made that analysis of July data would yield a conservative estimate.) The tug assigned to the first flight was assumed to be unavailable for the time required for it to tow the aircraft to some point close to the edge of the runway, to detach from the aircraft, and then to return to a gate. [This point of detachment was assumed to be 5-min taxiing time from the runway, as the engines would need to be run for this period before departure, in any case. Therefore, if a flight in the data set had taxied for 10 min, the assumption was that the use of a tug to tow the aircraft to the edge of the runway would require 11.5 min: 5 min (10 – 5 min) to tow the aircraft, 1.5 min to detach from it, and 5 min to return to the gate. In practice, the drive back to the gate should not take long, as the tug would likely not have to spend any time waiting in the departure queue, as it would while towing the aircraft to the runway. In that way, this is a conservative assumption.] Each flight that started taxiing between the time that the first tug left from and then returned to the gate would have to be towed by other tugs. The number of such flights would be an estimate of the number of tugs needed at for time. Such estimates were obtained for every flight and analyzed to arrive at the number of tugs that would have been sufficient to meet demand in 95% cases.

Once this number was obtained for the 31 busiest airports, an ordinary least squares regression model was built to express the number of tugs needed at an airport as a function of the number of departures and the average taxi time there. The model was used to arrive at an estimate of the number of tugs needed at the remaining 270 airports in the data set. (When the model estimated that a noninteger number of tugs were needed, that number was rounded to the nearest higher integer.)

For the second version of the tug scenario, the calculation outlined earlier for each of the 50 busiest airports was repeated. Only domestic flights that were operated on aircraft larger than the Airbus A318 were considered. Initial calculations that assumed a 95% service level were performed. However, the service level was then adjusted to ensure that the net saving was maximized. This calculation did not account for the social benefit produced by the reduction in pollution: the assumption was that whoever operated the tugs would operate them to maximize the financial benefit to themselves.

Weight Penalty of E-Taxi System

Boeing published estimates of the percentage change in fuel burn associated with a 1,000-lb change in the zero-fuel take-off weight of each of its major aircraft types (*36*). A strong correlation is shown between these percentage reductions and the zero-fuel take-off weights of the aircraft (see supplemental material at https://db.tt/WsadebxZ).

This correlation was applied to other aircraft types to estimate the amount of change in their fuel burn with an increase in weight. Baseline fuel burn associated with each flight is based on the European Environment Agency's air emissions inventory, which provides typical fuel burn for various aircraft and mission lengths (*37*). Additional fuel burn attributable to the weight of the e-taxi equipment was calculated on the basis of baseline fuel burn and the percentage increase estimated from the Boeing data. Two assumptions were made here: a practical e-taxi system would weigh 1,000 lb, and the percentage change in fuel burn would vary linearly with weight.

To validate the model, its predictions were checked against estimates Airbus published of additional fuel burn associated with a given increase in weight for a number of its aircraft (*38*). Meaningful comparisons could be made for only three aircraft types, but the agreement between the model and Airbus's estimates was good (see supplemental material at https://db.tt/WsadebxZ).

RESULTS

Switching from Baseline Scenario to Tug Scenario for All Domestic Flights

If one assumes that all six million domestic flights in the United States in the data set taxied for departure powered by both engines, the use of tugs to tow virtually all of them from the gate to the runway would reduce fuel burn by 0.5 million tons each year and CO_2 emissions by 1.7 million tons. [The reasons for "virtually all" flights being towed is that tugs would not be used for the extremely small number of flights (<1% of the total) that have a taxi-out time of less than 5 min and that this scenario assumes only enough tugs to provide a service level of 95%.] Use of this alternative would be accompanied by a net saving of $36 million each year. Cutting CO_2 emissions in this way would save $20/ton. This saving varies considerably from airport to airport: a cost would be incurred of more than $1,000/ton of CO_2 abated at Guam, but the use of tugs would save $100 per ton at Philadelphia (Pennsylvania) International Airport.

Switching from Single-Engine Taxi-Out Scenario to Tug Scenario for All Domestic Flights

If all domestic flights analyzed were assumed to have taxied for departure with only one engine save for the final 5 min before taxiing for departure, a switch to dispatch towing would reduce fuel use by 0.2 million tons/year and CO_2 emissions by 0.6 million tons. However, because of the costs of buying and operating the tugs, net costs would increase by $300 million annually and result in a cost of $500/ton of CO_2 abated. Clearly, where single-engine taxiing for departure is the current practice, a switch to using tugs may not be economical.

Switching from Baseline Scenario to Tug Scenario for Large, Narrow-Body Aircraft at Select Airports

An overview of the results of this analysis is given in Table S2. The results for Newark (New Jersey) Liberty International Airport are discussed in detail here.

In 2011, about 60,000 flights on large narrow-body aircraft departed from Newark. Under the assumption that these aircraft taxied by using two engines, this analysis concludes that total net savings would have been maximized if 65%, or 39,000, of these flights had been towed with a tug. To provide this level of service, seven tugs would have been needed, and their use would have resulted in a net cost saving of, on average, $80 per flight, which translates to a saving of $3 million annually at Newark. [Modifications might be required to airport layout and procedures to enable the use of tugs (see the later section on operational issues); this analysis has not accounted for these costs.] Because taxiing times vary considerably between flights, so would the savings. Figure 2 illustrates these variations and shows that—even at a 65% service level—about 30% of the flights that are towed would lose money. This calculation assumes that cherry-picking of flights with long taxiing times is not possible. Such an assumption is reasonable because flights with the longest taxiing times are likely to occur during times of congestion. Selectively towing all these flights would result in a larger saving in fuel costs but also require the purchase of a large number of tugs that would sit idle at other times and thereby reduce net savings. A tug could most likely be used to push back aircraft from the gate, though this function would depend on whether space between the aircraft and the gate was sufficient for a tug to maneuver. Another determining factor would be the maneuverability of the tug itself: for example, a tug with four-wheel steering would be able to "crawl" sideways under the jet bridges and position itself to push back aircraft as needed. Airlines may currently pay as much as $90 per flight for push-back services; eliminating the need for a separate push-back service could yield a significant saving.

The analysis indicated that the switch to using tugs would reduce emissions of PM by an average of 0.5 kg per flight. The APEEP model described earlier estimates that the mean cost of a marginal ton of PM emissions in Union County, New Jersey, is $360,000.

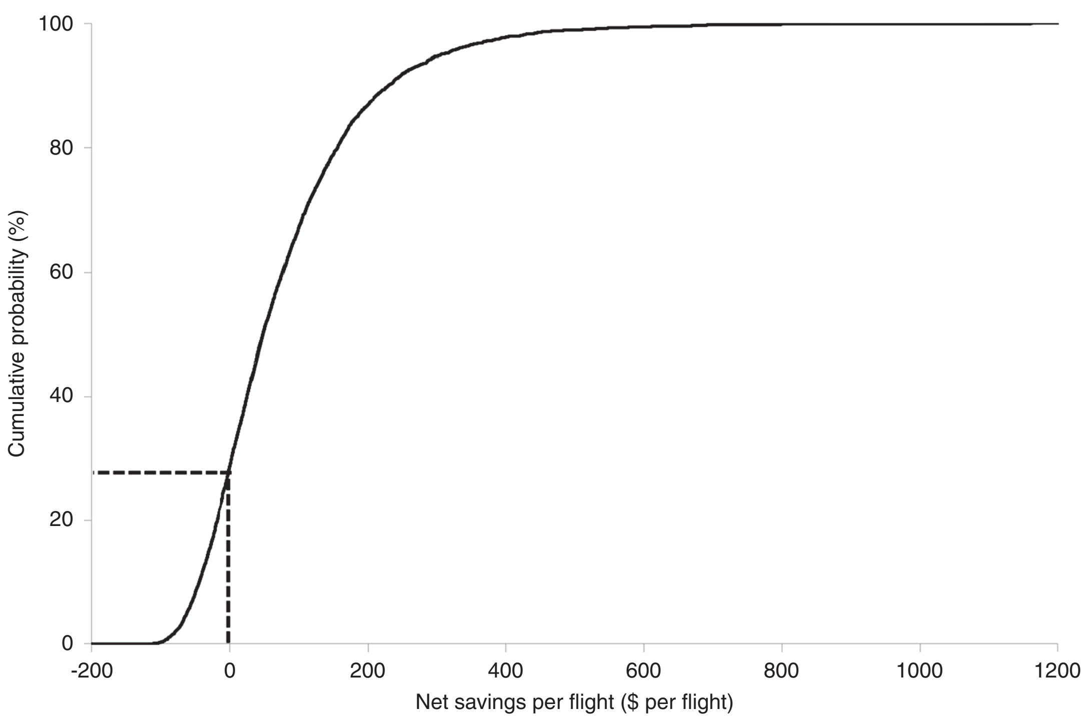


FIGURE 2 Even at service level of 65%, about 30% of flights departing from Newark would lose money if towed by tugs. Towing flights that do not taxi for long would reduce savings, whereas towing flights with long taxi times would increase savings.

In contrast, the switch to using tugs would generate, on average, a benefit of $180 per flight from reduced PM emissions. Similarly, reducing NO_x emissions is associated with a cost of $1,500 per ton, and switching to dispatch towing would reduce them by 0.7 kg per flight. In this case, the average damage done by using tugs instead of main engines would be $1.10 per flight. Damage from hydrocarbon emissions is valued at $32,000 per marginal ton and would be reduced by, on average, 0.5 kg per flight; using tugs would produce a mean benefit of $16 per flight. Overall, the average air quality benefit at Newark of using tugs would be about $200 per flight. In fact, the marginal cost of emitting a pollutant is highly uncertain, and the APEEP model provides the 5th- and 95th-percentile estimates of this cost for each pollutant. To quantify the impact of this uncertainty, this information was used with the mean, and the marginal cost was assumed to follow a triangular distribution. The air quality benefits per flight also depend on the duration of taxiing for departure. A lognormal distribution was fitted to the taxiing times observed for large narrow-body aircraft at Newark in 2011. In a 10,000-run Monte Carlo simulation, the marginal cost of each pollutant and the duration of taxiing for departure were varied with each run. The results are shown in Figure 3.

Using tugs reduces CO_2 emissions from each flight by an average of 0.6 ton. This reduction translates to savings of $130/ton of CO_2 emissions. The 90% confidence interval for the emissions reduction is 0.15 to 1.33 tons of CO_2 per flight, while that for the net cost ranges from savings of $230 to costs of $400 per flight. Apart from the marginal benefits of reducing pollutants and taxi-out times, the values of other parameters are either uncertain or liable to fluctuate (e.g., the price of jet fuel). A sensitivity analysis was performed to determine the impact that each of these parameters has on the average net savings. The results for Newark are shown in Figure 4. Savings are most sensitive to the taxi-out time, the price of jet fuel, and the fuel burn rate of the main engine. A 30% reduction in any of these would reduce average net savings to zero. Future attempts to reduce taxi-out times—by, for example, holding aircraft at the gate when congestion is likely to decrease taxi-out times—would be detrimental to the economics of tugs, as would the introduction of increasingly efficient engines. The economic savings would also fall dramatically if the cost of the tug could be amortized over only 3 years or fewer. Furthermore, changes in the price of the tug and the price of diesel do not have dramatic impacts on the net savings.

Finally, if the switch from two-engine taxiing for departure to dispatch towing were made for large narrow-body aircraft on domestic service at all 41 of the 50 busiest airports in the United States, the total net savings would amount to $50 million annually. CO_2 emissions would fall by 0.5 million tons each year. This reduction in emissions would be accompanied by a savings of $100 per ton. In addition producing a net savings from reduced fuel burn, the switch would result in $150 million in annual air quality benefits from reduced PM, HC, and NO_x emissions. More than 85% of these air quality benefits ($130 million annually) would come from reduced PM emissions.

Switching from Single-Engine Taxiing to Tug Scenario for Large, Narrow-Body Aircraft at Select Airports

If single-engine taxiing for departure is assumed to be the baseline, the use of tugs is not economical anywhere (Table S3), unless a $90 per flight saving is realized from avoiding push back. Under the assumption of the same levels of service (and, therefore, number of tugs) as in the previous scenario, such a switch made at all 50 of the busiest airports in the United States would increase costs by $60 million annually. However, a reduction of 0.2 million tons in CO_2 emissions would still occur, albeit at a cost of $300/ton of CO_2 abated. The total increase in HC emissions would produce a loss of $2 million annually, but it would be offset by $1 million in benefits from reduced NO_x emissions and $60 million in benefits

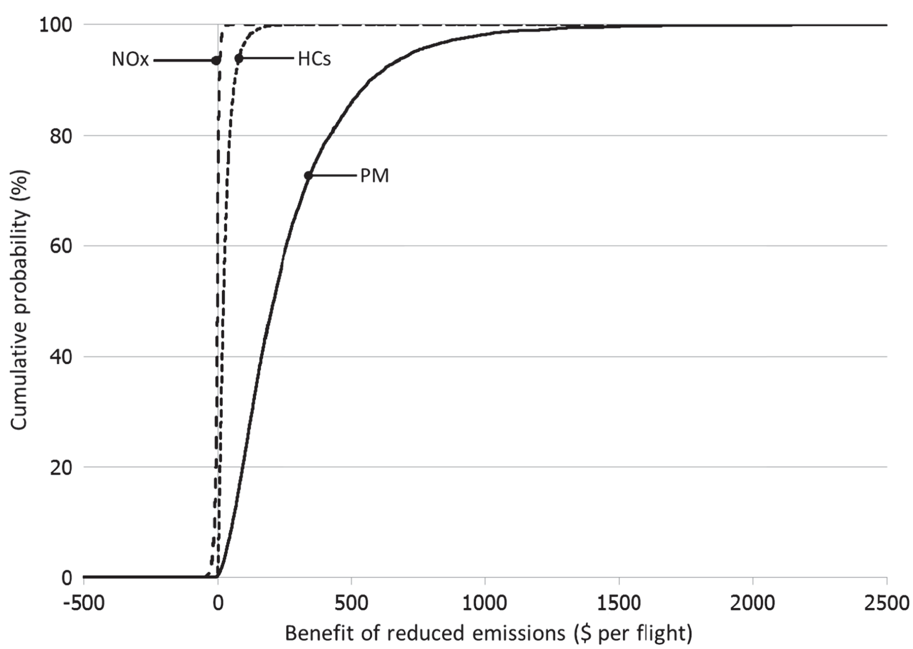


FIGURE 3 Benefits of reduced emissions of particulate matter dominate. For about 80% of flights, these benefits exceed $100.

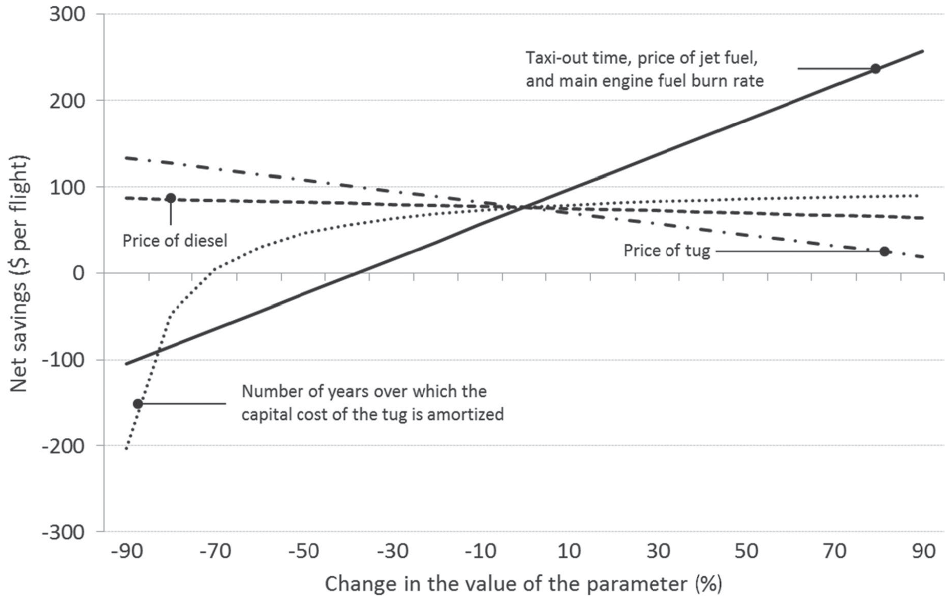


FIGURE 4 Sensitivity analysis showing impact of various parameters on average net savings.

from reduced PM emissions; if air quality benefits were taken into account, the total impact of a switch from single engine taxiing to using tugs would still be a small positive number (<$1 million annually). If the switch were made only at airports where the sum of the net savings and the air quality benefits was positive, the total reduction in CO_2 emissions would be 60,000 tons and would be accompanied by a monetary loss of $11 million. Total benefit, including that from improvement in air quality, would be $24 million annually. These calculations assume that each main engine consumes the same amount of fuel regardless of whether the aircraft is powered by one or two engines. Actually, during single-engine taxiing, the one engine powering the aircraft would likely need to be operated at elevated levels of thrust. Measurements by Presto et al. suggest that increasing engine load from 4% to 7% raises fuel burn by about 10% (*39*). The assumption that, during single-engine taxiing, the main engine burns 10% more fuel does not qualitatively change the results: shifting from single-engine taxiing to tug use would not be economical unless savings from avoiding push back were taken into account.

Switching from Main Engine Taxiing to E-Taxiing

Table 1 shows the economics of shifting all flights to e-taxiing relative to the baseline and single-engine taxiing scenarios. For a random sample of 500,000 domestic flights, the fuel and cost savings

TABLE 1 Economics of Shifting All Flights to E-Taxiing Relative to Baseline and Single-Engine Taxiing Scenarios

	Cost of Installing System per Aircraft		
Variable	$1,000,000	$500,000	$250,000
Relative to 2-Engine Taxi-Out and 1-Engine Taxi-In			
Total CO_2 emissions reductions (tons of CO_2)	1,900,000	1,900,000	1,900,000
Per flight CO_2 emissions reductions (tons of CO_2)	0.31	0.31	0.31
Total annual savings	$50,000,000	$320,000,000	$454,000,000
Average savings per flight	$10	$50	$70
Cost per ton of emissions reductions ($ per ton of CO_2)	–$30	–$170	–$240
Proportion of flights that would lose money	70%	40%	30%
Relative to 1-Engine Taxi-Out and 1-Engine Taxi-In			
Total CO_2 emissions reductions (tons of CO_2)	700,000	700,000	700,000
Per flight CO_2 emissions reductions (tons of CO_2)	0.11	0.11	0.11
Total annual savings	–$329,000,000	–$59,000,000	$75,000,000
Average savings per flight	$50	–$10	$10
Cost per ton of emissions reductions ($ per ton of CO_2)	$490	$90	–$110
Proportion of flights that would lose money	90%	80%	60%

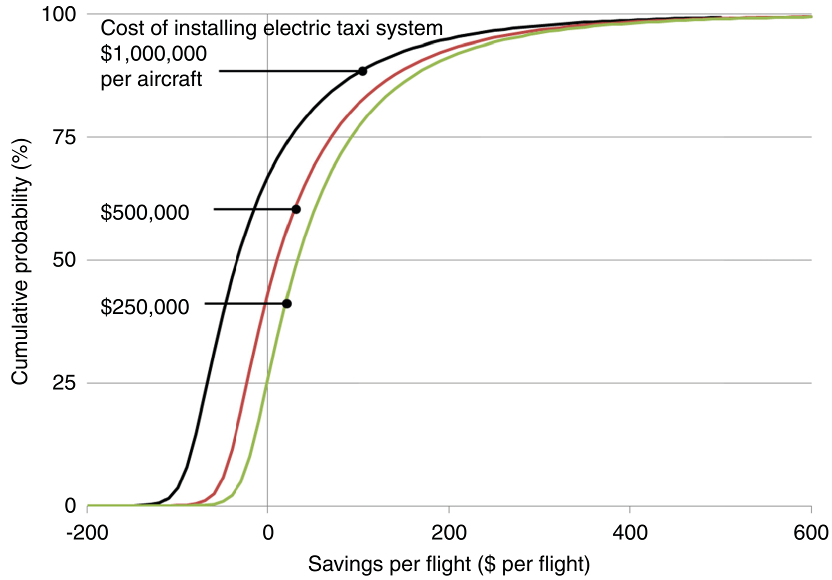


FIGURE 5 Distribution of per flight cost savings associated with various assumptions about capital costs.

that would accrue from using e-taxiing were calculated. The distribution of per-flight cost savings associated with different assumptions about capital costs is shown in Figure 5. An e-taxi system would likely eliminate the need for a separate push-back tractor, saving up to $90 per flight. If (*a*) the e-taxi system cost $1 million per aircraft to put in place, (*b*) this cost was amortized over 20 years at 7%/year, and (*c*) the aircraft performed 3.5 departures per day, then the capital cost per flight would be $75. If one assumed that maintenance was 20% of capital cost, the total fixed cost of the system would be $90 per flight, which would be fully paid by the elimination of push-back services.

For the A320 family of aircraft, an ordinary least squares model estimated the total reduction in fuel burn as a function of total flight distance (in miles) and total taxiing time (in minutes). Compared with the baseline scenario of two-engine taxi for departure and one-engine taxi for arrival, the model was as follows:

$$\text{reduction in fuel burn} = 8.92 \times \text{total taxi time} - 0.03 \times \text{total flight distance} - 83.85$$

All coefficients are highly significant ($p < 2 \times 10^{-16}$), and the model has an R^2 of .94. These results are unsurprising because this regression essentially involved running the model used to estimate fuel savings in reverse.

By using this relationship, the net average saving per flight was calculated for different assumptions about both the capital expense associated with equipping an aircraft with the e-taxi system and the total taxiing time.

Figure 6 shows the results of this calculation. The average taxiing time and average flight distance for the A320 family aircraft in the data set here are 24.5 min and 990 mi, respectively. The analysis suggests that, for the average 25-min taxiing time, the e-taxi system—even if expensive to install—would reduce fuel costs for flights of up to 2,000 mi. Flights that taxi less than 10 min apparently would lose money regardless of how inexpensive the e-taxi system is to install.

OPERATIONAL ISSUES

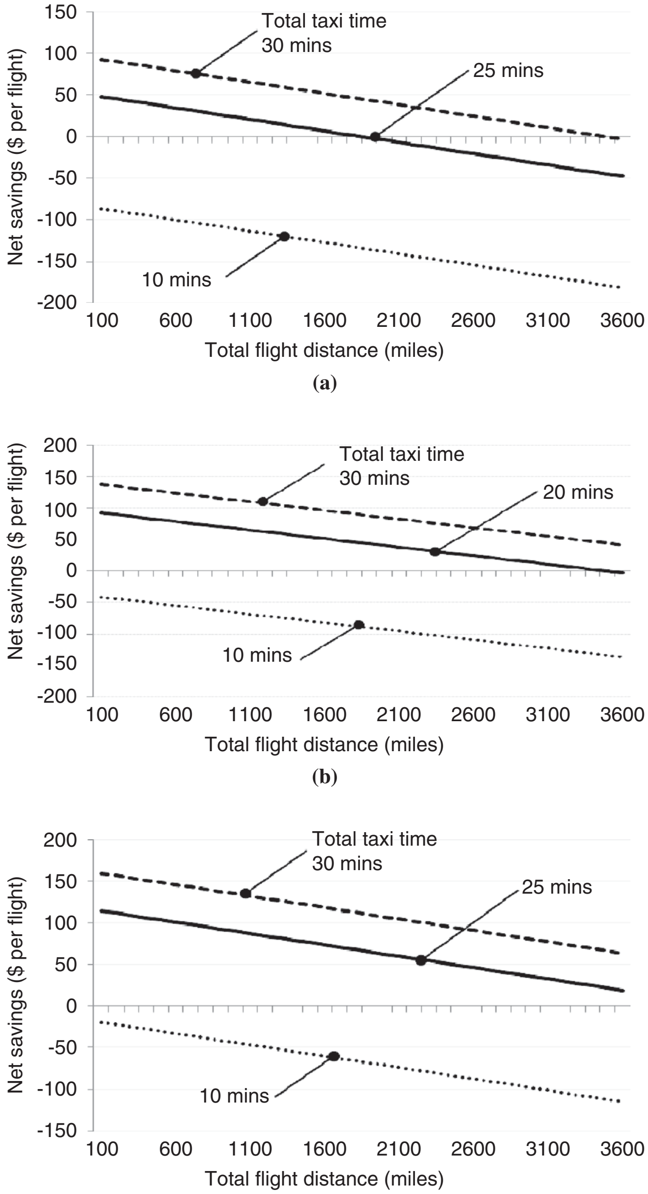
Tugs

A recent TRB report briefly discussed the issues associated with dispatch towing:

> Dispatch towing has been used at some airports in the U.S. However, a number of issues related to dispatch towing have been identified that limit widespread use. First, TBLT [towbarless tractor] towing places heavy stress loads on the nose gear. Tests conducted by Virgin Atlantic and Boeing found that dispatch towing with TBLTs resulted in a reduced operational life of aircraft nose gear because of the additional stress. Additionally, the TBLT must disconnect from the aircraft near the end of the runway and return to the terminal. This return trip represents an additional vehicle on the airfield with which ATC [air traffic control] must maintain contact until such a point that the TBLT exits the movement area or can use a vehicle service road. (*40,* pp. 9–10)

These issues and possible solutions are discussed in detail next.

First, using currently available tugs for dispatch taxiing imposes on the aircraft's nose wheel a fatigue load that reduces its life. This load is greater than that experienced by the aircraft during maintenance towing. Aircraft are virtually empty when towed between hangars and are typically full of fuel and passengers when taxiing for departure. An empty A320 weighs about 40 tons, whereas the maximum ramp weight of the same aircraft is 78 tons. Aircraft also need to brake more often when they are in a queue before departure, especially if they have to cross active runways and taxiways and therefore wait for other aircraft to pass. Because current TBLTs use their own brakes to stop the aircraft, they have to transmit through the nose landing gear a braking force large enough to arrest the momentum of the fully laden aircraft within a reasonable distance. The braking distances are likely to be shorter—and the required forces correspondingly larger—if the aircraft is being towed on and across active taxiways than if it is being towed on maintenance roads. Finally, small narrow-body aircraft perform nearly five departures per day, whereas large narrow-bodies perform



(c)

FIGURE 6 Net savings versus total flight distance for various total taxiing time and capital costs per A320 aircraft of (*a*) $1 million, (*b*) $500,000, and (*c*) $250,000.

more than three. An aircraft might need to be towed from a maintenance area to a gate (or between maintenance areas) less frequently than that. So, compared with maintenance towing, dispatch towing is more frequent, involves heavier aircraft, and is likely to involve more braking; in addition, the fatigue loads imposed on the nose gear are greater for dispatch towing.

This issue has been addressed by the development of an advanced tug that limits fatigue loads on the nose gear in two ways (*41, 42*). First, this tug allows the aircraft to brake by using the aircraft's own brakes. Therefore, if power to the tug was cut when it detected that the aircraft was braking, the nose gear would need to transmit only enough force to stop the tug. Because the tug is considerably lighter (~25 tons) than a fully laden aircraft (~75 tons), this difference alone would significantly reduce the load on the landing gear. In fact, the tug is designed to reduce the load further by braking in tandem with the aircraft. It is also designed to apply a load that compensates for braking forces to ensure that—even if the load on the nose gear fluctuates—no reversal in the direction of the load occurs and that the amplitude of the fluctuations is minimized.

Second, airport rules may prohibit the operation of vehicles in movement areas. For example, those rules for the Port Authority of New York and New Jersey state, "Non-Port Authority vehicles are prohibited from operating on any runway, taxiway and safety area unless under escort by the Port Authority or FAA maintenance. All vehicles shall obtain permission from the Control Tower before entering or operating on the movement areas" (*43,* p. 85).

If airlines want to use tugs for dispatch taxiing, they will have to negotiate exemptions from such rules in a way to ensure that safety and operational efficiency are not compromised. For example, aircraft would need to be towed to a location near the edge of the departure runway. They would have to stop there for a few moments, while the tug decoupled from them. Such a location would have to be positioned so that the aircraft could leave and rejoin the departure queue safely: aircraft could not be permitted to stop and decouple while in the queue, as doing so would delay the aircraft behind them. Such locations would need to be identified on a case-by-case basis, and permission would need to be sought to use them in this manner. For example, a deicing pad near the edge of a runway at Philadelphia International Airport could be used for decoupling (Figure 7). In this case, the tug could complete its journey without entering movement areas. [Quinn defines "movement areas" as "[t]he airport runways, taxiways, and safety areas. The movement area does not include loading ramps or aircraft parking areas. Specific approval for entry onto the movement area must be obtained from ATC" (*40*).]

While the tugs and the aircraft could be treated as a single entity while they are joined, the tug would become an additional object for ramp or active area controllers to manage after decoupling. Then the use of tugs would require (*a*) these controllers to agree to take on the additional workload and (*b*) the development of procedures that permit safe operations. (If the tug stayed on the ramp at all times, its movements would have to be managed by ramp controllers, who are often airline employees and potentially more amenable to adopting a procedure that benefits the airline economically.) The tug must be equipped with appropriate transponders so that controllers could "see" and communicate with them, and tug operators would have to be trained to be able to communicate with the air traffic control tower.

For other airports, both an area for decoupling the aircraft and a service road to return the tug might need to be constructed. Tug operations would lower fuel costs and reduce pollution and noise. Therefore, airlines and airport operators (the latter of which, in the United States, are invariably public bodies) stand to benefit from their use. They would have to establish a way of sharing the costs of any new infrastructure that might need to be built to enable such operation. One potential source of funding could be the FAA's Voluntary Airport Low Emissions program.

E-Taxi

Here a narrow-body aircraft with mass 75 tons [e.g., the Airbus A320 family (*44*)], rolling on a flat taxiway—with coefficient of friction 0.03 (*45*)—at a typical taxiing speed of 20 mph, is consid-

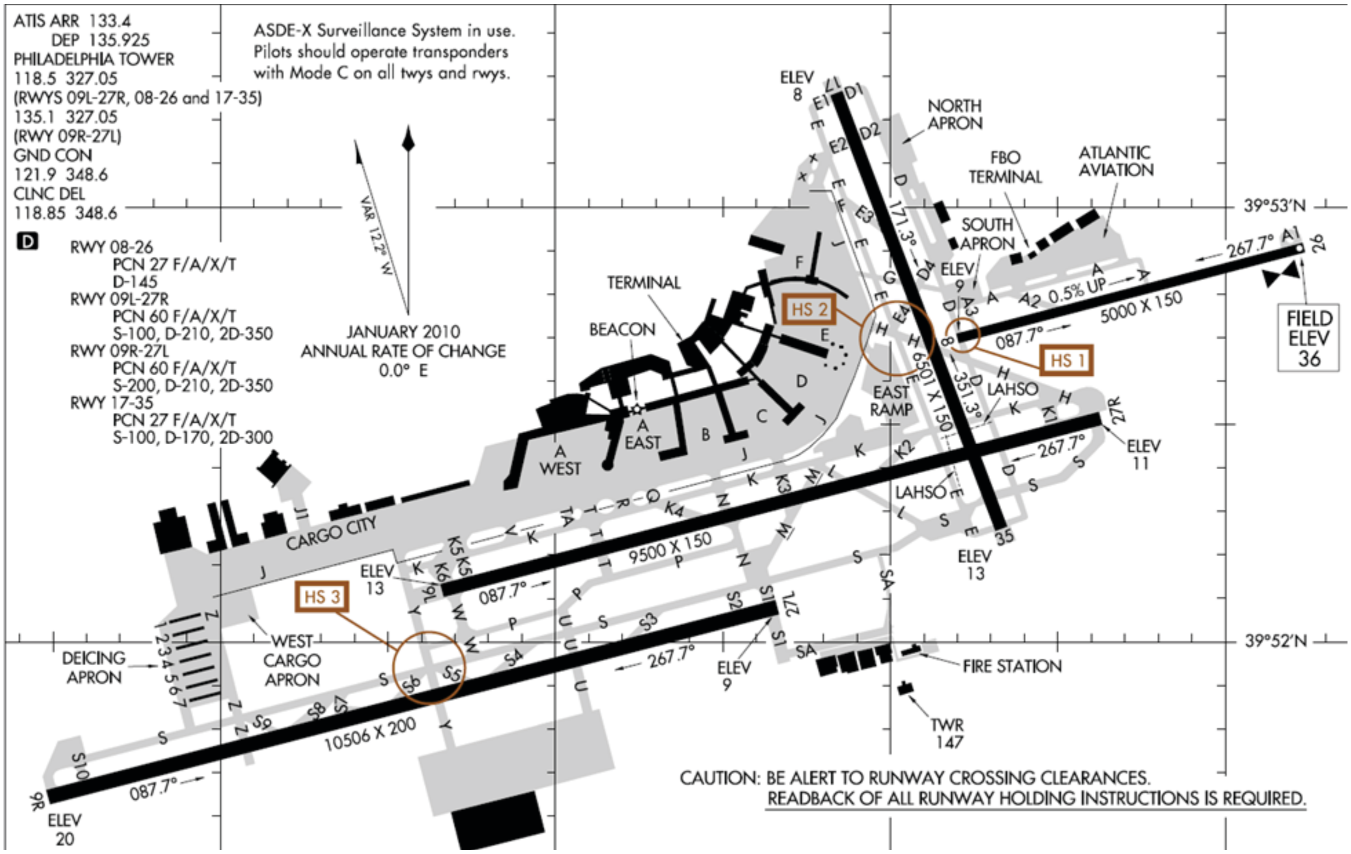


FIGURE 7 Layout of Philadelphia International Airport allows aircraft departing eastward from Runway 9R to exit departure queue and decouple from tug at deicing apron (circled at lower left).

ered. These conditions would require about 200 kW, or 270 hp, of power. (The power requirement is calculated as force times velocity, where the force is given by the weight of the aircraft times the coefficient of friction. Then, power required = 75,000 kg × 9.81 m/s^2 × 0.03 × 9 m/s = 198 kW.) To climb slopes and to accelerate the aircraft sufficiently quickly, the APU would need to provide even more power, or another source of power would need to be found. Any such modification is likely to incur both cost and weight penalties. The calculations above are therefore a best-case estimate of the economics of e-taxiing.

CONCLUSIONS AND IMPLICATIONS FOR PRACTICE

Estimates were made of the costs and benefits of two measures to curtail the use of main engines, and therefore fuel burn and emissions, while taxiing: (*a*) the use of tugs and (*b*) embedding an electric motor in the aircraft landing gear.

If the switch from two-engine taxiing for departure to dispatch towing were made for large narrow-body aircraft on domestic service at the 41 of the 50 busiest airports in the United States where doing so would be economically beneficial, the total net savings would amount to \$51 million annually. CO_2 emissions would fall by 0.5 million tons annually, or about 0.3% of the 144 million tons of CO_2 equivalent emitted annually by domestic civil aviation (*46*). Though relatively small, this reduction would be accompanied by a saving of \$100/ton of CO_2 through technology that is already available. In addition to the savings from reduced fuel burn, the switch would produce \$150 million in annual air quality benefits from reduced PM, HC, and NO_x emissions.

Even under the assumption that aircraft typically taxi for departure with only one engine running, a switch to the use of tugs would result in a reduction in CO_2 emissions; however, these incremental reductions would come at a cost of more than \$300/ton of CO_2 abated. If air quality benefits were taken into account, the total impact of a switch from single-engine taxi to the use of tugs would still be a small positive number (<\$1 million annually).

Electric taxiing could be an attractive way of cutting both emissions and costs, provided the cost of incorporating such a system into airplanes and its weight were kept low.

This analysis also demonstrates the dangers of aggregating emissions reductions obtained in different ways. For instance, the results make apparent that single-engine taxiing and the use of tugs are both attractive ways of reducing emissions when considered in isolation and when compared with 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 likely remain unrealized because the incremental cost associated with making the change would negate any savings. Clearly, the wide range of costs obtained under different assumptions suggests that sweeping statements about the potential benefits and cost of emissions reduction may be unreliable guides to decision making and might even be misleading.

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, which may well be different for each combination of location, aircraft type, and airline. For instance, 2011 taxi data show that the average taxi-out time for Boeing 737 aircraft operated by SouthWest airlines was slightly more than 10 min. Boeing 737 aircraft operated by all other airlines taxi for departure for much longer: 17 min on average. Clearly, SouthWest would have a smaller incentive to adopt the measures discussed here than would other airlines.

A potential 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 could be both more effective and more efficient than prescribing—or trying to build a consensus for the adoption of—specific measures.

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