Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)

Fuel Burn Impacts of Taxi-out Delay and their Implications for Gate-hold Benefits

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***Abstract*— Reducing fuel consumption is a unifying goal across the aviation industry. As such the aviation community is considering many initiatives in the form of policy, operational changes and technology deployment. One fuel-saving initiative for the air transportation system is the possibility of holding aircraft at the gate, or the spot, until the point at which they can taxi unimpeded to the departure runway. The extent to which gate holding strategies have financial and environmental benefits hinges on the quantity of fuel that is consumed during surface operations. Aircraft may execute the taxi procedure on a single engine or utilize different engine thrust rates; in addition an aircraft might change their fuel consumption rate during the taxi phase because of a delay. In the following study, we utilize airline fuel consumption data to distill the taxi fuel consumption rate both in nominal taxi time and in delayed taxi time for different aircraft types towards understanding the fuel consumption rate in taxi, both during nominal and delayed times. We find that the fuel consumption attributed to a minute of taxi out delay is less than the impact of a minute of nominal taxi time; for some aircraft types, the fuel consumption rate for a minute of taxi delay is half of that for nominal taxi. It is therefore not appropriate, even for rough calculations, to apply the nominal rates to convert delayed taxi out time into fuel burn. On average we find that eliminating taxi delay would reduce overall flight fuel consumption by about 1%. When we consider the savings on an airport-by-airport basis, we find that some airports could help the flights that operate at their airport reduce up to 2% of fuel consumption if delay were eliminated on their airfields.**

Keywords-Aviation; Fuel consumption; Taxi Delay Impact; Surface Operations

I. INTRODUCTION

Reducing fuel consumption is a unifying goal across the aviation industry, offering a way to reduce costs, mitigate environmental impact, and manage the risks related to fuel price fluctuations and uncertainty surrounding future environmental policy. As such the aviation community is considering many initiatives in the form of policy, operational changes, and technology deployment. One fuel-saving initiative for the air transportation system is the possibility of holding aircraft at the gate, or the spot, until the point at which they can taxi virtually unimpeded to the departure runway. The extent to which gate holding strategies have financial and environmental benefits hinges on the quantity of fuel that is consumed during surface operations. Estimating the possible fuel savings from gate holding is, however, a challenging task as the rate at which aircraft consume fuel in taxi is not well understood. Aircraft may execute the taxi procedure on a single engine or utilize different engine thrust rates; an aircraft might change their taxi fuel consumption rate during the taxi phase because of a delay. In the following study, we utilize airline fuel consumption data to estimate the taxi fuel consumption rate for both nominal taxi time and taxi delay for different aircraft types. This enables us to estimate the reduction in fuel consumption from adopting gate holding at airports throughout the National Airspace System (NAS).

Delays on the ground are growing as a function of rising airport demands and airline mergers [1, 2]; as a result, fuel consumed from aircraft surface operations is growing. Saving fuel can improve the financial health of airlines, as fuel costs grew from 14% of operating costs to 33% percent of operating costs from 2003 to 2012 [3]. Reducing fuel consumption also provides predictability and financial stability, as airlines are better able to plan for the future when their dependency on a resource with a wildly fluctuating price is reduced [4]. Finally, reducing fuel consumption has significant environmental benefits, as ground-based environmental emissions can be particularly harmful. While Greenhouse Gas emissions at altitude can be particularly harmful in terms of an increased warming effect, local pollutants such as CO, NOx, and PM have their strongest impact on human health when emitted on the ground [5, 6]. In fact, in some metropolitan areas, airports are responsible for 10% of NOx emissions in the region [7].

There is a growing body of research on procedures and technologies to reduce the time aircraft spend in surface operations and to reduce the fuel consumed during this time. Reference [8] investigates the potential of a surface management strategy which provide times and sequences for flights regarding their release into the aircraft movement area. The study finds that, during periods of high traffic, taxi fuel consumption from decreased movement and time was reduced up to 38 percent. Reference [9] investigates the potential of a rate to meter pushbacks from gate to prevent aircraft from queuing on the taxiways. In a field test at Boston Logan International Airport, the authors found that they were able to reduce fuel consumption from surface operations significantly. In estimating the fuel benefit, both studies utilize the ICAO Emissions Databank, a database capturing fuel flow rates for all engine types at different thrust settings, to calculate the taxi fuel consumption and savings. Reference [9] assumes two engines at a constant thrust to calculate fuel consumption during taxi. Reference [8], utilizing a model built by [10], assumes two engines at a thrust setting that varies with aircraft movement states (stopping, turning, accelerating, moving forward at a constant speed, or braking).

Complimenting this research on surface management strategies is a growing movement among aviation stakeholders to promote the practice of single engine taxi. A report from the International Civil Aviation Organization (ICAO) [11] noted that the single engine taxi procedure should be the normal departure procedure unless it is precluded by conditions, because of a stated large potential for fuel savings [12]. The American Airlines (AA) FUEL SMART program suggests a company guideline of using one engine during taxi when safe and operationally feasible. American Airlines claims that the procedure saves more than 2 million gallons of jet fuel and eliminates about 42 million pounds of CO_2 emissions annually [13]. Similar results are found in a study by Spanair which quantified the effects of single engine taxi on carbon dioxide (CO_2) emissions by comparing it with two-engine taxi [14].

Despite the fuel savings potential of taxiing on a single engine, such a procedure cannot always be executed as it is sensitive to numerous factors. Larger aircraft types, and aircraft with greater take-off weights, may have more difficulties taxiing on one engine because additional thrust may be necessary to propel the aircraft. The blast from turning on an engine can also be significant, and a larger aircraft must take care for the trailing aircraft when starting up an engine on the taxiway [15]. Because the incidence of single engine taxi is unknown, benefit pools from gate holding are not completely understood. In the absence of understanding the incidence of single engine taxi, researchers have considered the incidence of single engine taxi parametrically or avoided the topic all together. For example, reference [16] compares single engine taxi procedures to procedures with all engines running at two case study airports towards estimating the emissions savings due to delay reduction. Due to the uncertainty around single engine taxi procedures and the absence of airline data regarding such taxi procedures, reference [17] does not include ground-based externalities in a study of the environmental impact of an airport closure.

Uncertainty regarding taxi fuel consumption rates could lead to inaccurate fuel savings benefit pool estimates for ground-based initiatives, causing airports, governments, and ANSPs to make suboptimal investments. To address this problem, we utilize airline fuel consumption data to estimate the taxi fuel consumption rate both in nominal taxi time and in delayed taxi time for different aircraft types. We develop statistical models of fuel consumption based on actual airline data to isolate the taxi fuel consumption rate during nominal taxi time and taxi delay for specific aircraft. We find that the taxi fuel consumption rate during taxi delay is smaller – sometimes significantly smaller – than the rate for nominal taxi. We then employ our model to estimate a benefit pool for the reductions taxi delay that would result from implementing gate holding, on a per flight and a per airport basis.

Drs. Ryerson and Hansen would like to thank the Federal Aviation Administration for partial funding support.

II. Establishing a Generalized Taxi Fuel Consumption Model

In the following section, we estimate a general (non-airport specific) taxi fuel consumption rate by aircraft type. This analysis will reveal the rate of fuel consumption during the taxi phase, both during nominal taxi time and delay taxi time.

A. Data Collected

Data were collected from two sources: the fuel and flight statistics data from a major United States-based air carrier, and the flight level performance data from the Federal Aviation Administration (FAA) Aviation system Performance Metrics (ASPM) database.

A major U.S.-based airline provided data for this study. This carrier operates an extensive domestic network. The dataset provided from the airline includes all U.S. domestic flights between April 2012 and May 2013, inclusive. There are altogether 810,227 flights during the 14 months for which data is collected. The airline dataset contains flight-by-flight data on planned and actual fuel consumption from gate-to-gate, planned and actual flight times (including out-off-on-in times), takeoff weight, airport origin and destination, distance flown, equipment used, and delay information.

The FAA ASPM flight level database includes individual flight data for the 77 large airports in US. It contains the unimpeded taxi-out and taxi-in time, as well as the taxi-out and taxi-in delay, which is the positive difference between actual and unimpeded times. For airborne phase of the flight, the dataset provides the difference between the estimated enroute time and the actual airborne time, in minutes.

We merged the ASPM dataset with our carrier dataset by flight number, origin airport and destination airport, and year, month, and day of the flight. As a result, the final merged dataset has, for each individual flight, the unimpeded time and delay for the taxi-out and taxi-in phase of flight.

As we will use the dataset to model fuel consumption and the fuel burn rate of a flight varies greatly among aircraft types, we estimate separate models for different equipment specified in the dataset. The aircraft with sufficient observations in our dataset include the A319 (40762), A320 (71245), B757-200 (104212), B757-300 (15724), DC-9(20929), MD-88(109729), and MD-90(50373) (with the number of observations for each aircraft type during the 13-month time period in parenthesis). These aircraft are commonly used by airlines in the US and abroad.

B. Model Formulation and Estimation

We seek to statistically estimate the contribution of different components of flight time to flight fuel burn. The dependent variable $F(n, ac)$ is the actual fuel burn in lbs for a realized individual flight n operated with equipment ac. Each individual flight is operated between a unique origin (o) and destination (d) airport, on a given year (y), month (m), and day (d).

The independent variables will capture taxi times (nominal times and delayed times) and airborne times (nominal times and delayed times). We note that while there may be other possible determinants of taxi fuel consumption beyond time, including the number of turns and acceleration patterns, these are confirmed to be either small or insignificant [18].

Our independent variables begin with a decomposition of taxi time. We seek the impact of different flight times and delays on actual flight fuel burn. Using the flight-level ASPM data which was merged with the airline data, we define variable $nom\_to(n)$ which is the nominal (unimpeded) taxi-out time of the fight. This variable indicates the minimum taxi-out time for this flight, without any surface disruptions. The nominal time is based on analysis of taxi times under low traffic conditions [19]. Variable $delay\_to(n)$ indicates taxi-out delay, calculated as the positive difference between unimpeded and actual taxi-out time of the flight. Similarly, variables $nom\_in(n)$ and $delay\_in(n)$ denote the unimpeded taxi-in time and taxi-in delay. Also include the squares of these delay variables in our models, since it is likely that very long delays will result in different fuel burn regimes than shorter delays.

The airborne time and delay information in the ASPM dataset is also considered in our model. We calculate the unimpeded airborne time for the flight using the flight performance dataset. The calculated unimpeded airborne time captures the minimum time needed to complete the airborne phase of the flight without disruptions, similar to the concept of the nominal (unimpeded) taxi times in the ASPM dataset. To do this, flights are aggregated by month, OD pair and equipment type. The airborne times of the flights in the same month, between the same OD pair, and using the same aircraft type form a distribution. The 25th percentile of the distribution is defined as the unimpeded airborne time, denoted as $nom\_air(n)$. The unimpeded airborne time is merged to individual flights by month, OD pair and equipment type. This variable represents the airborne time for the flight without any disturbance. The positive difference between the actual airborne time of the flight and the sum of unimpeded airborne time and the difference between the estimated enroute time and the actual airborne time captures any en route delay. It is also included in our model and is denoted as $nonholding\_air(n,ac)$. Also, the positive difference between the actual airborne time and the estimated enroute time , denoted as $delay\_air(n,ac)$ is included in the model as well.

Lastly, the distance of an individual flight, $dist(n)$ is an independent variable in our model. For a given flight time, the distance captures the variation in ground speed, which in turn is a reflection of airspeed, which is directly related to fuel burn rate. The distance was obtained from the airline dataset, and as such is the distance from the final filed flight plan.

As there exists substantial variation in fuel burn activity across airports, fixed effects for individual origin and destination airports are included in the model. Each flight has a specific origin airport *ori*, and destination airport *dest*, with the fixed effects captured in variables ρ_{ori} and γ_{dest} .

Using the variables defined above, we assume a linear specification for modeling the variables $F(\cdot)$ and estimate fuel consumption using a fixed effects model. By defining the model in this way, the taxi fuel consumption rates will be the marginal fuel consumption rate, such that engine start-up will be captured by the constant term. We choose a linear form as the linear model can be viewed as a first order approximation of a more general model around the mean values in the data; since we are looking to compare the taxi fuel burn rate observed in practice to others used in research, the mean values are what we seek to estimate. As mentioned above, the model is estimated for different equipment types separately. The general model formulation is as below. In addition to parameter estimation, we also applied robust covariance estimator suggested by [20] to address potential heteroskedasticity, which might be expected given the diversity of operating environments among airports and in the en route airspace.

$$\begin{aligned} F(n,ac) &= \alpha_1(ac)\times nom\_to(n) + \alpha_2(ac)\times delay\_to(n) \\ &+ \alpha_3(ac)\times delay\_to^2(n) + \beta_1(ac)\times nom\_air(n) \\ &+ \beta_2(ac)\times delay\_air(n) + \beta_3(ac)\times nonholding\_air(n) \\ &+ \chi_1(ac)\times nom\_ti(n) + \chi_2(ac)\times delay\_ti(f) \\ &+ \chi_3(ac)\times delay\_ti^2(n) + \lambda(ac)\times dist(n) + \rho(ac)_{ori(n)} + \gamma(ac)_{dest(n)} \end{aligned} \quad (1)$$

C. Estimation Results

Estimation results regarding seven major aircraft types are presented in Table 1. The nominal taxi fuel consumption rates range from roughly 30 to 70 lbs/minute. These represent marginal fuel consumption rates, since effects such as engine start-up are captured by the constant term. We also see that taxi fuel consumption rates for taxi-out delay are consistently lower than the rates of fuel consumption during nominal taxi-out time. This reflects that taxi-out delays are associated with single engine operation or lower engine thrust, saving fuel.

Table 1 also shows the fuel flow assuming 7% engine power for each (a common assumption for engine settings during the taxi phase as discussed by [18] assuming two engines are operating, as reported by ICAO [11]. We see that in general our nominal taxi fuel consumption rates reflect these ICAO rates. The rates estimated for taxi fuel consumption during delayed periods, however, are 10%-50% less than the ICAO two-engine rates. In short, a flight that experiences delay during taxi is expected to have a lower average taxi fuel consumption rate but a higher overall fuel consumption total compared to a similar, non-delayed flight.

Table 1 also shows that the square of the taxi-out delay is negative and significant. Combined with the linear-taxi out delay term, this implies that the fuel burn caused by taxi-out delays is concave in delay-duration. This is probably because longer delays involve more extended periods of single engine operation.

TABLE 1 ESTIMATION RESULTS OF 8 AIRCRAFT TYPES' FIXED EFFECTS MODELS (DEPENDENT VARIABLE: ACTUAL FUEL BURN IN LBS)

	AC Type	**DC9**	**757-300**	**757-200**	**A320**	**A319**	**MD88**	**MD90**
	ICAO 2-engine taxi fuel consumption rate (lbs./minute)	**38.5**	**50.3**	**50.3**	**33.9**	**33.9**	**36.24**	**32.8**
Parameter Notation	**Variable Description**	**Parameter estimates (P-value)**						
α_1	Nominal Taxi Out Time (in Minutes)	38.40 (<0.0001)	46.76 (0.0008)	68.32 (<0.0001)	38.62 (<0.0001)	36.42 (<0.0001)	32.33 (<0.0001)	29.58 (0.0002)
α_2	Taxi Out Delay (in Minutes)	34.23 (<0.0001)	27.49 (<0.0001)	29.50 (<0.0001)	27.76 (<0.0001)	25.53 (<0.0001)	32.22 (<0.0001)	28.35 (<0.0001)
α_3	Taxi Out Delay Squared (in Minutes Squared)	-0.19 (<0.0001)	-0.08 (0.0100)	-0.11 (<0.0001)	-0.13 (<0.0001)	-0.12 (<0.0001)	-0.16 (<0.0001)	-0.19 (<0.0001)
β_1	25th Percentile of Actual Airborne Time (the 25th percentile of actual airborne time for flights in the same month, between same OD pair and with the same aircraft type, in Minutes)	96.89 (<0.0001)	131.62 (<0.0001)	119.12 (<0.0001)	89.20 (<0.0001)	84.11 (<0.0001)	102.34 (<0.0001)	94.76 (<0.0001)
β_2	Airborne Delay (the holding time portion of the actual airborne time, in Minutes)	88.98 (<0.0001)	100.92 (<0.0001)	93.53 (<0.0001)	75.97 (<0.0001)	69.98 (<0.0001)	98.19 (<0.0001)	82.73 (<0.0001)
β_3	Non-holding Airborne Time(the positive difference between actual airborne time minus airborne delay (holding time), and the 25th percentile of actual airborne time, in Minutes)	139.99 (<0.0001)	164.35 (<0.0001)	136.65 (<0.0001)	120.46 (<0.0001)	117.47 (<0.0001)	138.48 (<0.0001)	145.59 (<0.0001)
λ	Travel Distance (in Nautical Miles)	3.17 (<0.0001)	1.29 (<0.0001)	0.68(<0.0001)	1.52 (<0.0001)	0.89 (<0.0001)	1.81 (<0.0001)	2.04 (<0.0001)
χ_1	Nominal Taxi In Time (in Minutes)	81.24 (<0.0001)	98.66 (<0.0001)	174.51 (<0.0001)	175.87 (<0.0001)	133.07 (<0.0001)	155.45 (<0.0001)	200.73 (<0.0001)
χ_2	Taxi In Delay (in Minutes)	37.06 (<0.0001)	14.88 (<0.0001)	31.77 (<0.0001)	16.32 (<0.0001)	16.91 (<0.0001)	24.09 (<0.0001)	27.91 (<0.0001)
χ_3	Taxi In Delay Squared (in Minutes Squared)	-0.35 (<0.0001)	0.27 (<0.0001)	-0.24 (<0.0001)	-0.02 (0.7050)	0.08 (0.1286)	-0.10 (0.0721)	-0.28 (0.0003)
	Number of observations	20,929	15,724	104,212	71,245	40,762	109,729	50,373
	Adjusted R-squared	0.958	0.983	0.985	0.981	0.975	0.965	0.965

Note:
1. To save space, origin and destination airports fixed effects estimates are not presented in this table.
2. Breusch-Pagan test suggests rejecting the homoscedasticity assumption. Thus, robust standard error estimator is used to correct heteroskedasticity among error terms.

III. INDIVUDAL FLIGHT AND SYSTEM WIDE BENEFITS ASSESSMENT

The results of the previous section yield estimates of the relationship between taxi out delay, among other factors, and fuel consumption. In this section, we use those results to estimate the reduction in fuel consumption that could be obtained from gate holding. It follows that the taxi out delay should be zero in the ideal scenario. As a result, fuel consumption before and after gate holding would vary by a factor of the taxi out delay term (α_2) and squared taxi out delay term (α_3) from Eq. 1. For each of the 412,974 realized flights in our 13-month airline dataset, we calculate $\alpha_2(ac)\times delay\_to(\cdot)+\alpha_3(ac)\times delay\_to^2(\cdot)$ as the reduction in fuel consumption that would result from gate holding. This represents the maximum saving that can be gained from reduced delay that could result from gate holding. We calculate this value at the individual flight level and then aggregate and extrapolate to obtain airline and national level estimates. The results are shown in Table 2. For the aircraft types included in our dataset, in a scenario where taxi out delay does not exist, the fuel consumption would be reduced by around 80-160 pounds per flight, ranging across different aircraft types. As a percentage of total flight fuel consumption, this savings ranges from 0.7% to 1.6% of total flight fuel consumption. It is notable that these values are comparable to the savings estimated from use a continuous decent approach as compared to a conventional step-down approach. Another way to interpret the fuel saving is in the form of savings in CO_2 emissions. The last column in Table 2 shows the saving of fuel translated into CO_2 emissions in the unit of kg. To convert excess fuel consumption into kgs of CO_2, we utilize the U.S. Environmental Protection Agency conversion factor for Jet Fuel [21]. The per flight saving of CO_2 emission ranges from 120 to 230 kg.

The annual total savings in fuel consumption across our study airline is shown in the second to last row of Table 2. The airline-wide total saving weighted by aircraft type is 50 million pounds of fuel, translating into 7.4 million gallons of fuel (applying a conversion rate of 6.79 lbs/gallon for jet fuel).

And on average the saving accounts for 0.89% of the total flight fuel consumption.

In an effort to see the impact of reduced taxi out delay on the entire domestic aviation system, we expand our results from the aircraft types and the specific airline we studied to all aircraft types and all domestic airline flights in the national aviation system. This assumes that the flights considered in our models represent a reasonably representative sample of the larger domestic airline flight population. In the last row, these savings are presented. In total, the annual saving of fuel burn is 959 million pounds of fuel, translating into 141.2 million gallons. At $2 per gallon fuel price and $0.05/kg for the social cost of carbon emissions [22] this translates into a potential benefit pool of about $350 million per year.

TABLE 2 BENEFIT ANALYSIS RESULTS

Aircraft Type	No. of Flights	Fuel Saving per Flight (lbs)	Total Fuel Consumption per Flight (lbs)	Percentage of Fuel Saving	CO_2 Emissions Saving per Flight (kg)
A319	40,762	81.72	10185.51	0.80%	117.35
A320	71,245	90.13	12274.86	0.73%	129.43
B757-300	15,724	131.02	18856.71	0.69%	188.14
B757-200	104,212	129.47	15962.20	0.81%	185.92
DC9	20,929	161.93	10104.89	1.60%	232.53
MD88	109,729	134.65	13400.29	1.00%	193.36
MD90	50,373	127.82	13246.10	0.96%	183.55
Annual Total Flights	No. of Flights	Total Fuel Savings (lbs)	Fuel Consumption	Percentage Fuel Saving	Total CO_2 Emissions Saving
Study Airline (Selected Aircraft Types)	412,974	49,907,145	5,599,000,000	0.89%	71,666,661
National Aviation System (All Aircraft Type)	7,935,194	958,953,536	107,583,000,000	0.89%	1,377,057,293

IV. AIRPORTS BENEFITS ASSESSMENT

In the final section, we consider the possible fuel savings from reducing taxi out delay on a per airport basis. There is high policy relevance for looking at this issue on an airport-by-airport basis. The U.S. Federal Aviation Administration is currently investing in and implementing a large-scale airspace modernization initiative titled the Next Generation Air Transportation System (NextGen). NextGen has both air and ground components. Improved surface operations, enabled by enhanced communication, improved situational awareness, and technologies to optimize traffic flow are a major component of NextGen [23]. Airports are taking part in NextGen in a highly contextual way; as the FAA seeks to maximize their investments, each airport is evaluated for the possible benefits from different NextGen procedures and technologies. For example, a recent airport-specific project includes the continuous descent approach procedures coupled with precise navigation and other new procedures at Seattle-Tacoma International Airport, which are estimated to save Alaska Airlines 2.1 million gallons of jet fuel annually [24]. As airports individually will be the focus of NextGen technologies and procedures, understanding the value of reducing taxi delay from a fuel perspective on an airport-by-airport basis produces a value input into NextGen benefits assessment.

To understand the airport-by-airport benefit we study the potential flight fuel consumptions savings on an individual airport basis. To do so, we cluster flights in our dataset by origin airport. Then, for each flight, we again calculate the fuel saving from reduced delay per flight: $\alpha_2(ac) \times delay\_to(\cdot) + \alpha_3(ac) \times delay\_to^2(\cdot)$. We then average the values for each airport across the total number of operations for that airport in our dataset. Fig. 1 presents the average per-flight taxi out delay fuel savings (in lbs) for the top 20 airports with the largest possible taxi out delay fuel savings and the top 20 airports with the smallest possible taxi out delay fuel savings. (Note that the axes are on different scales.) These are airports for which our study airline had at least 1,000 operations over the 13 month period.

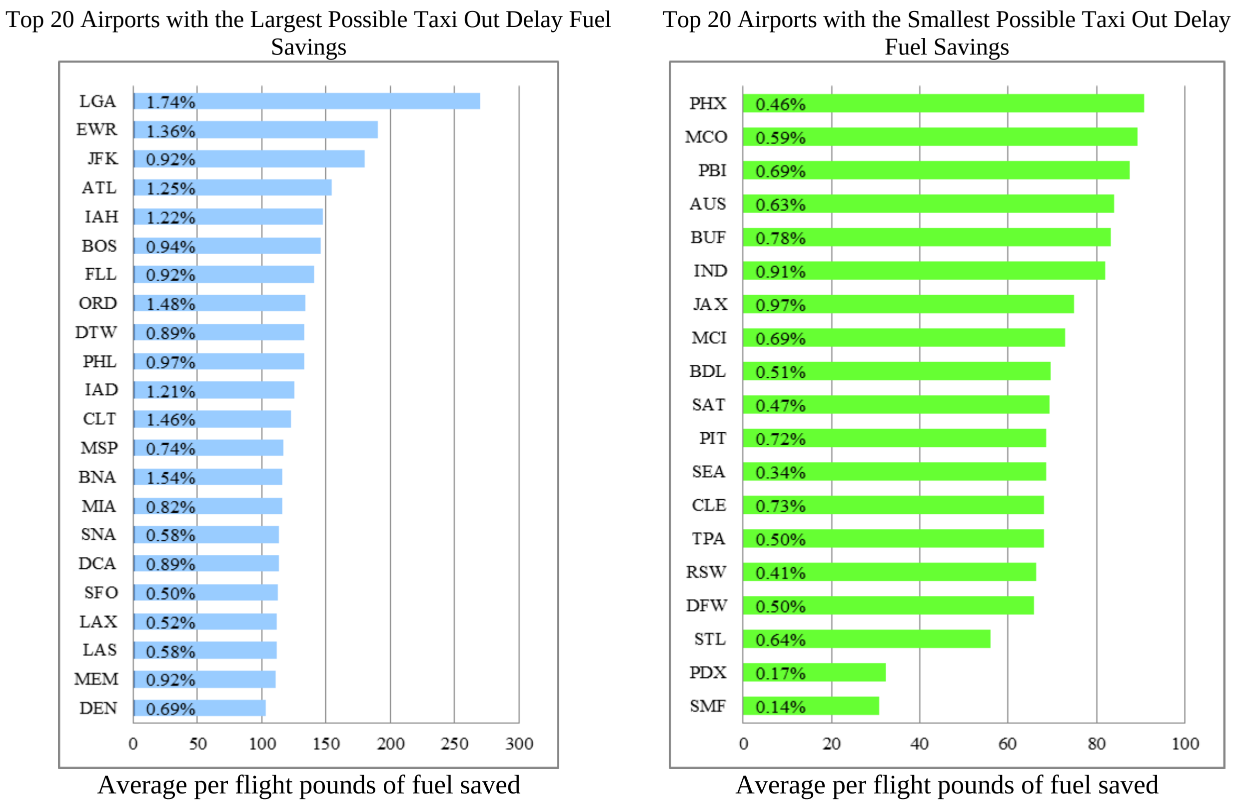

Figure 1 Airport-by-Airport Taxi Out Fuel Savings

We can see from Fig. 1 that the highest possible savings from reducing taxi out delay are from the airports known for high levels of surface congestion: the New York Metropolitan Area Airports (LaGuardia (LGA), Newark (EWR), and Kennedy (JFK)), and the major hub airports such as Atlanta (ATL), Houston (IAH), Chicago (O'Hare, ORD), Philadelphia (PHL), Washington Dulles (IAD), Minneapolis-St. Paul (MSP), and Washington National (DCA). At these airports, an average flight could save 100-150 lbs of fuel, and up to 270 lbs at LGA.

For the 20 airports with the smallest possible fuel savings from reducing taxi out delay, the savings are on the order of 60-80 lbs of fuel per flight, with some airports such as Portland OR (PDX) and Sacramento (SMF) in the 20-40 lbs range.

Fig. 1 also shows the percentage fuel consumption due to taxi delay at each airport. We find that, for about the 10 airports with the highest overall savings from reducing taxi delay, the average flight consumes about 1% of its fuel in taxi delay, with LGA and EWR having percentages greater than 1%. While some airports in the "bottom 20" are close to 1% possible savings, most are around 0.5-0.6%. These percentages show us that, at the airports with high levels of surface congestion, initiatives that greatly reduce taxi delay are commensurate with other existing NextGen initiatives.

V. Conclusions

This analysis shows the possibility to reduce fuel consumption through taxi delay reductions from gate holding strategies. We find the average potential fuel consumption reduction from eliminating taxi delay to be about 1% of total fuel consumption. When we consider the savings on an airport-by-airport basis, we find that some airports could help the flights that operate at their airport reduce up to 2% of fuel consumption if delay were eliminated on their airfields.

In performing this analysis, we decomposed surface operations into nominal and delayed taxi time to establish the relationship of both quantities of time on fuel burn. Notably, we find that the fuel consumption attributed to a minute of taxi out delay is less than the impact of a minute of nominal taxi time; for some aircraft types, this effect is up to one-half as great. It is therefore not appropriate, even for rough calculations, to apply the nominal rates to convert delayed taxi out time into fuel burn. As taxi delays grow, the rate of fuel consumption for a minute spent in taxi decreases even further, and the likelihood that an aircraft is employing fuel saving measures during taxi such as taxiing on a single engine is greatly increased.

This study demonstrates the power of an airline data set in improving and deepening our understanding of how fuel is consumed in practice. From this conclusion, we propose that a publicly available repository of airline fuel consumption data could greatly enhance fuel consumption research and modeling. There is strong precedent for such a database. The Bureau of Transportation Statistics collects vast amounts of aviation data through numerous databases including the Airline Origin and Destination Survey (DB1B) Market database which collects a 10% sample of all tickets purchased on reporting US carriers; Form 41, which contains monthly data on costs and operating statistics on an airline-aircraft basis; the Airline On-Time Performance Data, which includes operational statistics for individual flights; and many others. There is significant experience with this data in the research and government community, and, in the absence of individual flight fuel consumption data, researchers have worked to model fuel consumption in an aggregate manner with this data (there are numerous examples, such as [25] and [26]. A database that captures a 10% sample of airline fuel consumption data without capturing identifying flight characteristics (as in flight number) could greatly contribute to the ability to model operational fuel consumption and provide tools to government decision-making teams towards improving and refining their modeling capabilities.

ACKNOWLEDGMENT

The authors would like to thank the U.S. carrier for providing data and numerous pilots for providing their insight into taxi operations. The authors would like to thank Xiaowei Wu of the University of California, Berkeley and Amber Woodburn of the University of Pennsylvania for data analysis support. The authors would also like to thank Joe Post of the FAA and Frank Ketcham of the University of California, Berkeley for helpful comments on a previous version.

REFERENCES

[1] P. Balakrishna, R. Ganesan, L. Sherry, "Airport Taxi-Out Prediction Using Approximate Dynamic Programming (Intelligence-Based Paradigm)". Transportation Research Record: Journal of the Transportation Research Board, No. 2052, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 54–61.

[2] M.S. Ryerson, and H. Kim. "Integrating airline operational practices into passenger airline hub definition". Journal of Transport Geography, 2013, Vol. 13, pp. 84–93.

[3] International Air Transport Association. IATA Economics, Industry Financial Forecast Table. Fact Sheet: Fuel, Jun 2012. http://www.iata.org/pressroom/facts_figures/fact_sheets/pages/fuel.aspx Accessed Jul, 2013.

[4] M.S. Ryerson, M. Hansen. "Assessing the role of operating, passenger, and infrastructure costs in fleet planning under fuel price uncertainty". Proceedings of the Eight Annual FAA/EUROCONTROL Air Traffic Management Research and Development Seminar, Napa, CA, June 29-July 2, 2009. Available at http://www.atmseminar.org/seminarContent/seminar8/presentations/pr_155_FP.pdf [Accessed 23 January 2015].

[5] M.V. Chester, and A. Horvath. "Environmental assessment of passenger transportation should include infrastructure and supply chains". Environmental Research Letters, 2009, Vol. 4.

[6] V. Williams, R.B. Noland, R. Toumi. "Reducing the climate change impacts of aviation by restricting cruise altitudes". Transportation Research Part D: Transport and Environment, 2002, Vol. 7, pp. 451–464.

[7] C. Rice. "Restricting use of reverse thrust as an emissions reduction strategy". Transportation Research Record: Journal of the Transportation Research Board, No. 1788, 2002, pp. 124-131.

[8] Y. Jung, T. Hoang, J. Montoya, G. Gupta, W. Malik, L. Tobias, H. Wang. "Performance evaluation of a surface traffic management tool for Dallas/Fort Worth International Airport". Ninth USA/Europe Air Traffic Management Research and Development Seminar, 2011.

[9] I. Simaiakis, H. Khadilkar, H. Balakrishnan, T. G. Reynolds, R. J. Hansman, B. Reilly, S. Urlass. Demonstration of Reduced Airport Congestion Through Pushback Rate Control. Ninth USA/Europe Air Traffic Management Research and Development Seminar, 2011.

[10] T. Nikoleris, G. Gupta, Kistler M. "Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas/Fort Worth International Airport". Transportation Research Par D: Transport and Environment, Vol. 16, 2011, pp. 302-308.

[11] International Civil Aviation Organization (ICAO). Aircraft Engine Emissions Databank, Jan 2012. http://easa.europa.eu/environment/edb/aircraft-engine-emissions.php Accessed Jul 14, 2013.

[12] R. Sowden. "Alternate airport selection during flight planning to enhance fuel efficiency". International Civil Aviation Organization: Aviation operational measures for fuel and emissions reduction workshop, Madrid 2002. http://www.icao.int/Meetings/AMC/MA/2002/workshop/sowden.ppt Accessed Jun 20, 2013.

[13] Fuel Smart program. American Airlines News Room. http://hub.aa.com/en/nr/media-kit/operations/fuelsmart Accessed May 12, 2013.

[14] Enviro.aero. "Case Studies: Airlines. Spanair and Single-Engine Taxi", 2008. http://www.enviro.aero/spanairandsingleenginetaxi.aspx Accessed May 12, 2013.

[15] R. Guo, Y. Zhang, Q. Wang. "Comparison of emerging ground propulsion systems for electrified aircraft taxi operations." Transportation Research Part C: Emerging Technologies 44 (July), 2014, pp. 98–109.

[16] V. Kumar, L. Sherry, T. Thompson. "Analysis of emissions inventory for "single-engine taxi-out" operations". Proceedings of the Third Conference of International Conferences on Research in Air Transportation (ICRAT), 2008, Virginia, USA.

[17] T. Pejovic, R.B. Noland, V. Williams, R. Toumi. "A tentative analysis of the impacts of an airport closure". Journal of Air Transport Management, Vol. 15, 2009, pp. 241–248.

[18] H. Khadilkar, and H. Balakrishnan. "Estimation of aircraft taxi fuel burn using flight data recorder archives". Transportation Research Part D: Transport and Environment, Vol. 17, 2012, pp. 532-537.

[19] ASPM, 2012. ASPM: Estimation Techniques. http://aspmhelp.faa.gov/index.php/ASPM:_Estimation_Techniques. Last accessed: January 2015.

[20] H. White. Heteroskedasticity-Consistent Covariance Matrix and a Direct Test for Heteroskedasticity. Econometrica 48, 1980, pp. 817-838.

[21] EPA, 2013a. Emission Factors for Greenhouse Gas Inventories, US Environmental Protection Agency. http://www.epa.gov/climateleadership/documents/emission-factors.pdf. Last accessed: January 2015.

[22] Interagency Working Group on the Social Costs of Carbon, United States Government, Technical Support Documents, Technical Update on the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf

[23] NextGen Implementation Plan. August 2014. Available at: http://www.faa.gov/nextgen/library/media/NextGen_Implementation_Plan_2014.pdf

[24] FAA NextGen Website, 2012. Available at: https://www.faa.gov/nextgen/snapshots/stories/?slide=6

[25] M.S. Ryerson, and M. Hansen. "Capturing the impact of fuel price on jet aircraft operating costs with engineering and econometric models." Transport. Res. Part C: Emerging Technologies 33, 2011, pp. 282–296.

[26] B. Zou, M. Hansen, M. Elke. Evaluating air carrier fuel efficiency and CO_2 emissions in the U.S. airline industry. Proceedings of the Tenth Annual FAA/EUROCONTROL Air Traffic Management Research and Development Seminar, Chicago, Il, June 10-13, 2013. Available at http://www.atmseminar.org/papers.cfm?seminar_ID=10 [Accessed 23 January 2015].

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APPENDIX: AIRPORT ABBREVIATIONS
LGA -- LaGuardia Airport
EWR -- Newark Liberty International Airport
JFK -- John F. Kennedy International Airport
ATL -- Hartsfield-Jackson Atlanta International Airport
IAH -- George Bush Intercontinental Airport
BOS -- Gen. Edward Lawrence Logan International Airport
FLL -- Fort Lauderdale–Hollywood International Airport
ORD -- Chicago O'Hare International Airport
DTW -- Detroit Metropolitan Wayne County Airport
PHL -- Philadelphia International Airport
IAD -- Washington Dulles International Airport
CLT -- Charlotte/Douglas International Airport
MSP -- Minneapolis–St. Paul International Airport
BNA -- Nashville International Airport
MIA -- Miami International Airport
SNA -- John Wayne Airport
DCA -- Ronald Reagan Washington National Airport
SFO -- San Francisco International Airport
LAX -- Los Angeles International Airport
LAS -- McCarran International Airport
MEM -- Memphis International Airport
DEN -- Denver International Airport
PHX -- Phoenix Sky Harbor International Airport
MCO -- Orlando International Airport
PBI -- Palm Beach International Airport
AUS -- Austin-Bergstrom International Airport
BUF -- Buffalo Niagara International Airport
IND -- Indianapolis International Airport
JAX -- Jacksonville International Airport
MCI -- Kansas City International Airport
BDL -- Bradley International Airport
SAT -- San Antonio International Airport
PIT -- Pittsburgh International Airport
SEA -- Seattle–Tacoma International Airport
CLE -- Cleveland-Hopkins International Airport
TPA -- Tampa International Airport
RSW -- Southwest Florida International Airport
DFW -- Dallas/Fort Worth International Airport
STL -- Lambert-St. Louis International Airport
PDX -- Portland International Airport
SMF -- Sacramento International Airport