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LETTER

Landing on empty: estimating the benefits from reducing fuel uplift in US Civil Aviation

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Abstract

Airlines and Air Navigation Service Providers are united in their goal to reduce fuel consumption. While changes to flight operations and technology investments are the focus of a number of studies, our study is among the first to investigate an untapped source of aviation fuel consumption: excess contingency fuel loading. Given the downside risk of fuel exhaustion of diverting to an alternate airport, airline dispatchers may load excess fuel onto an aircraft. Such conservatism comes at a cost of consuming excess fuel, as fuel consumed is a function of, among other factors, aircraft weight. The aim of this paper is to quantify, on a per-flight basis, the fuel burned due to carrying fuel beyond what is needed for foreseeable contingencies, and thereby motivate research, federal guidance, and investments that allow airline dispatchers to reduce fuel uplift while maintaining near zero risks of fuel exhaustion. We merge large publicly available aviation and weather databases with a detailed dataset from a major US airline. Upon estimating factors that capture the quantity fuel consumed due to carrying a pound of weight for a range of aircraft types, we calculate the cost and greenhouse gas emissions from carrying unused fuel on arrival and additional contingency fuel above a conservative buffer for foreseeable contingencies. We establish that the major US carrier does indeed load fuel conservatively. We find that 4.48% of the fuel consumed by an average flight is due to carrying unused fuel and 1.04% of the fuel consumed by an average flight is due to carrying additional contingency fuel above a reasonable buffer. We find that simple changes in flight dispatching that maintain a statistically minimal risk of fuel exhaustion could result in yearly savings of 338 million lbs of CO_2, the equivalent to the fuel consumed from 4760 flights on midsized commercial aircraft. Moreover, policy changes regarding maximum fuel loads or investments that reduce uncertainty or increase the ability to plan flights under uncertainty could yield far greater benefits.

1. Introduction

1.1. Background

Air transportation contributes 8% of transportation greenhouse gas emissions (GHG) in the US and 10.6% of transportation emissions globally (Environmental Protection Agency 2012, Sims *et al* 2014). The US domestic and international shares are both expected to increase as incomes rise and the US recovers from the 2008 recession (Federal Aviation Administration 2012a). In addition, aviation's contribution to US and global GHG emissions is also expected to rise due to the technical, institutional, and financial challenges of reducing aviation fuel consumption. While the Air Navigation Service Providers (ANSPs) (such as Federal Aviation

Administration (FAA) and European Organisation for the Safety of Air Navigation (Eurocontrol)) are investing in systems and technologies to modernize their airspaces, these programs are both behind schedule and rely on the air carriers investing in expensive avionics equipment (Lee 2010, Office of the Inspector General 2014). Initiatives to support aviation alternative fuels are active yet their timeline is highly uncertain (Sims *et al* 2014). Much of the fuel savings in the aviation industry stems from airlines upgrading their aircraft as well as seeking to improve profitability with low-cost methods to reduce fuel consumption, including encouraging fuel-saving flight procedures such as taxiing on a single engine to reducing aircraft weight from eliminating non-essential items on board a flight (Abeyratne 2009, Lee *et al* 2009, Swan and Adler 2006, American Airlines 2014, Hao *et al* 2015).

The airline practice of eliminating aircraft weight to save fuel is a well-established method of reducing fuel consumption. There is, however, little discussion of reducing fuel on board, which is the largest component of added weight to the aircraft (Sadraey 2012). Beyond fuel required to complete a flight, or 'mission fuel', the FAA and other ANSPs regulate the amount of reserve fuel that must be added for contingencies; for example, a flight may have to hold above an airport before landing because of congestion, thus requiring extra fuel. It is, however, possible for airlines to add fuel beyond the mandated reserve fuel. In fact, it is common for airlines to load discretionary fuel for contingencies guided by the amount of extra fuel, compared to the planned mission fuel, that was needed in the past year (Karisch *et al* 2012). Airlines load this discretionary fuel to reduce the probability that a flight will need to divert to an alternate airport, which costs approximately $25 000 in direct operating costs (Ayra *et al* 2014), as a result of low fuel. Airlines must make the complex trade-off between the probability of diverting and the absolute cost of carrying discretionary fuel.

Airlines appear to have varying approaches to determining the amount of discretionary fuel load. In one of the few US existing studies of airline fueling practices, Trujillo (1996) finds airline pilots and dispatchers tend to load large quantities of discretionary fuel. The findings of Trujillo stand in stark contrast to the recent actions of E.U.-based carrier Ryanair. After five Ryanair flights required emergency landings due to low fuel, the Spanish Civil Aviation Accident and Incident Investigation Commission (CIAIAC) (2010) found that Ryanair aircraft 'generally land with the minimum required fuel'. The Ryanair study is one of the few recent looks at the fueling practices of airlines; yet, given the nature of Ryanair and the European airspace, it is ill-advised to generalize these results. US network airlines of Delta, American, and United Airlines, which comprise approximately 40% percent of the US domestic flights (Bureau of Transportation Statistics 2015) are traditionally less fuel efficient than the 'low cost' carriers (Zou *et al* 2014); one reason being that the network airlines routinely trade fuel for time by operating a late flight at a faster speed if it is bound for a hub (Sherali *et al* 2002, Cook *et al* 2009). Network carriers protect their often lucrative hub operations, as propagated delay can impede hub operations and connections (Churchill *et al* 2010, Bilotkach and Pai 2014). The US airspace is also considerably less predictable than European airspace given the weather environment and unpredictability can lead to scheduling more time and adding more fuel to a flight (Federal Aviation Administration and Eurocontrol 2013, Hao and Hansen 2014, Ryerson *et al* 2014). Finally, airlines operating within the E.U. may file long, circuitous flight plans to avoid overflying countries with relatively expensive airspace charges with the hope their flight is routed directly to its destination (as the airspace charge is based on the last filed flight plan rather than the actual route of flight) (EUROCONTROL, n.d.). If an airline believes, based on historical information, that the flight will be routed directly to the destination, adding fuel for the circuitous route may be thought of as a form of contingency fueling (Button and Neiva 2013, Castelli *et al* 2013, Jovanović *et al* 2014, Reynolds 2014).

In the following study we investigate the state of fuel loading for one major US-based network airline. Our primary aim is to quantify the fuel burned and the greenhouse gas emissions released from fuel that is loaded but not consumed on a flight. We make this calculation based on detailed flight level fuel data for the study airline and estimated cost-to-carry factors for different aircraft types, the calculation of which is also a contribution of this paper. The cost to carry factors are used to estimate the fuel burned due to carrying (1) all fuel unused in flight and (2) additional *discretionary* fuel (excess beyond a conservative *discretionary* fuel buffer) loaded onto a flight. The results of these calculations enable us to assess the potential of fuel loading reform to reduce the environmental impact of aviation. Such reforms may either target rules that determine minimum fuel loads, behaviors that determine discretionary fuel loads above the minimum, or factors in the operating environment that shape behaviors or how the rules are applied. The results show that for the major US carrier 0.7%–4.48% of total flight fuel consumption derives from extra fuel being loaded, with the former estimate based on fuel above the discretionary fuel buffer and the latter based on all unused fuel. These results motivate consideration of reducing excess fuel as part of the broader program to reduce the environmental impact of aviation.

1.2. Domestic flight planning basics

Flight dispatchers make tactical and strategic flight planning decisions to ensure the safe operation of a flight from its origin to destination (see Karisch *et al* (2012) for a comprehensive review of flight planning and the supplementary information for a more detailed explanation of flight planning). Flight planning involves checking weather forecasts, projected payloads, and operating conditions, selecting routes and flight levels, and determining certain quantities of fuel to be loaded (or *uplifted*). As our study will focus on flights within the continental US (CONUS) only (due to data availability and the vast differences between US domestic and international flight dispatch) the following sections explores the decisions behind the discretionary fuel quantities for CONUS flights.

US Federal Aviation Regulations (14 C.F.R. section 91, *E-CFR* 2014) (FARs) require a domestic commercial flight to uplift enough fuel to complete the flight to the intended destination airport (*mission fuel*), as well as fly from the destination airport to the alternate airport (if required based on the weather forecast at the scheduled time of arrival) and hold in the air for 45 min at normal cruising speed (*reserve fuel*) (Federal Aviation Administration 2008). These quantities are automatically calculated by the airline's flight planning system after the dispatcher chooses a route of flight among several possible routes. Even if it is not required by the FARs, a dispatcher may uplift additional fuel for a flight to travel from the destination airport to an alternate airport. *Contingency fuel* is discretionary fuel uplifted onto a flight which reflects the airline dispatcher's assessment of the 'downside' risks that may lead to additional fuel burn beyond what is projected by the flight plan. Fuel uplifted for alternates that are not required can serve much the same purpose as contingency fuel if the alternate is dropped from the flight plan during the course of the flight.

2. Methodology

2.1. Data collection

A major US network airline provided an individual flight dataset for most of their flown flights within the CONUS (roughly 570 000 after removing spurious observations) between 1 June, 2012 and 31 May, 2013. The dataset contains data on planned and actual fuel consumption, fuel uplift in all categories including mission, reserve for 45 min hold, tanker (the process of carrying fuel on a flight segment for the purposes of using it on subsequent flight segments, reflecting a business decision of the airline), contingency, 1st alternate, and 2nd alternate, and flight information such as equipment, origin and destination, flight planned and actual times, and delay information. It also provides actual gate-to-gate fuel burn and the weight of the aircraft before and after the flight operation. It should be noted that the fuel uplift values are provided in both pounds of fuel and minutes of fuel calculated using pounds per minute conversion rates that are specific to the aircraft type. Dispatchers specify fuel uplift values in terms of minutes to avoid unnecessary conversions related to the fuel burn characteristics of different aircraft types.

The dataset also includes a variable termed 'Statistical Contingency Fuel (SCF)' which is a metric to guide contingency fuel loading on a flight-by-flight basis. By definition SCFX for a flight *f* is the Xth percentile of the difference between the planned and actual fuel burn, measured in minutes, based on a set of flights considered comparable to flight *f* (Karisch *et al* 2012). In the case of the study airline, the set of comparable flights consists of those that took place over the previous year and have the same origin, destination, and hour of departure. The SCF95 and the SCF99 presented to the dispatcher during the flight planning phase are included in our dataset. The SCF95 and SCF99 are conservative fueling benchmarks. Loading the quantity of contingency fuel specified by SCF95 (SCF99) would result in a flight being able to land without dipping into any reserve fuel 95% (99%) of the time for flights without an alternate airport. For flights with an alternate landing at the primary destination, the odds are even more favorable, since the alternate fuel is also available.

Our analysis required that we distinguish between FAR-required alternates and alternates included at the discretion of the dispatcher. As the airline did not provide forecast or actual weather data (and thus, it is unknown if uplifting fuel for possible travel to a 1st alternate is actually required), we collected weather data for the 77 busiest airports by flight traffic in US from the National Oceanic and Atmospheric Administration database. We then designated as required a 1st alternate added to a flight scheduled to land during a time when the weather was inclement under the specified FAR threshold (see the supplementary information for more details). Second alternates are never required.

2.2. Cost to carry factor estimation

The airline dataset includes the quantities of fuel loaded and burned; we seek cost to carry factors for each aircraft capturing the fuel consumed to carry a unit of fuel one unit of distance (in lb/lb-mile or kg/kg-km). Cost to carry factors will allow us to convert fuel loaded into fuel burned. While the airline maintains their own values, they cannot be made publicly available. The cost to carry factors could be estimated from the airline dataset; however, we do not want to include confounding effects of delay, engine use, and other factors that would be present if we were to use the airline data. We therefore simulate gate-to-gate (often termed block) fuel consumption (*b*) with Piano-5, a state-of-the-practice aircraft performance analysis software by Lissys (Pham *et al* 2010, Skowron *et al* 2013). Piano is frequently used in both research and practice for aviation fuel modeling to predict fuel

Table 1. Cost-to-carry factor estimates.

Aircraft type	Variable	Coefficient estimate	t—value	Aircraft type	Variable	Coefficient estimate	t—value
	Mass	0.020	108.44		Mass	0.018	104.01
A319	Mass × Distance	4.604×10^{-5}	83.35	B757-300	Mass × Distance	4.720×10^{-5}	160.8
	Distance	2.529	32.18		Distance	2.659	38.22
	Mass	0.019	112.73		Mass	0.020	102.71
A320	Mass × Distance	4.644×10^{-5}	105.1	B767-300	Mass × Distance	4.463×10^{-5}	106.01
	Distance	3.146	47.95		Distance	3.922	28.6
	Mass	0.025	59.11		Mass	0.024	74.99
A330-200	Mass × Distance	2.878×10^{-5}	86.9	B767-300ER	Mass × Distance	3.650×10^{-5}	100.13
	Distance	6.237	35.73		Distance	4.198	31.23
	Mass	0.023	100.6		Mass	0.023	95.62
A330-300	Mass × Distance	3.467×10^{-5}	148.62	B767-400	Mass × Distance	4.013×10^{-5}	155.73
	Distance	4.542	40.46		Distance	3.054	28.21
	Mass	0.021	124.9		Mass	0.028	58.12
B737-800	Mass × Distance	5.476×10^{-5}	153.86	B777	Mass × Distance	3.032×10^{-5}	105.13
	Distance	1.851	34.04		Distance	6.679	35.03
	Mass	0.020	143.2		Mass	0.027	164.63
B737-800	Mass × Distance	4.852×10^{-5}	141.64	DC9	Mass × Distance	7.429×10^{-5}	84.74
Winglets	Distance	2.265	42.94		Distance	3.519	37.77
	Mass	0.027	64.05		Mass	0.022	222.96
B747-400	Mass × Distance	3.327×10^{-5}	106.97	MD88	Mass × Distance	5.744×10^{-5}	172.12
	Distance	9.138	36.86		Distance	3.713	82.88
	Mass	0.019	89.81		Mass	0.016	151.36
B757-200	Mass × Distance	4.397×10^{-5}	94.82	MD90	Mass × Distance	5.564×10^{-5}	158.95
	Distance	3.104	30.81		Distance	2.704	54.09
	Mass	0.019	96.66				
B757-200	Mass × Distance	4.072×10^{-5}	98.29				
Winglets	Distance	3.255	35.98				

consumed as a function of aircraft dynamics and flight mission characteristics (Svensson *et al* 2004, Owen *et al* 2010, Krammer *et al* 2013, Dray 2014). While other fuel consumption models, such as Eurocontrol's Base of Aircraft Data model, can predict fuel consumption of a flight while airborne, Piano estimates are known to be higher fidelity as they are based on more detailed aerodynamic characteristics (Senzig *et al* 2009, Vera-Morales and Hall 2010). We model fuel consumption for a range of take-off weight, m, values that capture different amounts of fuel uplift and distances (d), for a range of aircraft types. (See the supplementary information for a validation of the Piano estimates.)

For each aircraft type a we estimate $b_{i,a}$, the block fuel consumed for flight i on aircraft a, as a function of weight ($m_{i,a}$) and distance flown d_i. The variables m and d enter into the equation as separate effects and also interacted to capture the effect on fuel consumption of carrying mass over distance

$$b_{i,a} = \beta_{1,a} m_{i,a} + \beta_{2,a} m_{i,a} d_i + \beta_{3,a} d_i. \quad (1)$$

From the estimated coefficients we can estimate the cost to carry factors, $\gamma_{i,a}$, in unit weight per weight-distance for each aircraft type a, as a function of the distance of flight i

$$\gamma_{i,a} = \frac{\beta_{1,a}}{d_i} + \beta_{2,a}. \quad (2)$$

Table 1 contains the estimates in US customary units, with weight measured in pounds and distance measured in miles. The estimation results for equation (1) estimated with International System of Units (SI) units with weight in kilograms and distance in kilometers, are found in table 1 in the supplementary information.

To illustrate the interpretation of these results we present the following calculation for an Airbus A320. For every 10 pounds of fuel (4.5 kg) uplifted on to an Airbus A320 for a 2000 mile flight (3200 km), an additional $0.019 \times 10 + 4.655 \times 10^{-5} \times 2000 \times 10 = 1.12$ pounds (0.50 kg) must be burned to carry those 10 lbs.

2.3. Cost to carry equations

In this section we adopt the following notation. For flight i we define (in units of weight unless noted otherwise):

D_i fuel onboard at the time of gate departure,

L_i fuel onboard at the time of gate arrival,

T_i fuel uplifted for tankering,

C_i contingency fuel uplifted,

R_i fuel uplifted for the 45 min *required* reserve holding fuel,

A_i^1 fuel uplifted for the first alternate airport,

A_i^2 fuel uplifted for the second alternate airport,

$SCF99_i$ SCF99 presented to the dispatcher during flight planning,

d_i distance traveled (in miles or km),

$\gamma_{i,a}$ cost to carry factor (lbs/lb-mile or kg/kg-km),

$I(i)$ an indicator function, $I(i) = 1$ if the first alternate is required by FARs, 0 otherwise.

Using these values we can specify equations to calculate the cost to carry total unused fuel for a given flight or some part of that fuel that is determined to be unnecessary for safe and reliable operation. Calculating the cost—in terms of additional fuel burned—to carry such fuel allows for a discussion of how this cost can be reduced. Clearly, the cost to carry all remaining fuel on board at the time of arrival represents a theoretical upper bound on the gains from eliminating excess fuel uplift. This upper limit could be attained only if the fuel required for a given flight could be precisely determined prior to departure. On the other hand, the cost to carry unnecessary extra fuel (defined in the subsequent paragraph) represents savings that are attainable without changes in the levels of uncertainty in today's flight operations. It can therefore be considered a lower bound on the possible fuel savings from reducing discretionary fueling.

While the upper bound is unambiguous, the lower bound is more subjective. For purposes of this research, we estimate the latter as any contingency fuel above the SCF99 value plus fuel uplifted for non-required alternates. Ignoring the alternate component, flights with contingency fuel equal to SCF99 would be able to land at their primary destination 99% of the time without using any reserve fuel. The odds are even more favorable for flights with alternates—even required ones—since diverting to an alternate is very rare. This means that in the vast majority of cases alternate fuel is also available, further reducing the chances that any reserve fuel will be burned. Conversely, for there to be no alternate fuel, forecast weather at the destination must be favorable. Since the flights on the far right tail with respect to the difference between planned and required mission fuel are likely to be flights that encounter adverse weather, the probability that a flight without an alternate and contingency fuel equal to SCF99 will be able to land without using all its contingency fuel is well above 99%.

Thus we calculate the cost to carry two quantities of fuel: (1) the total fuel on arrival for flight *i*, $FA(i) = L_i$ and (2) the total fuel on arrival with tankering, reserve-hold, and required 1st alternate fuel removed, $FATR(i) = (L_i - T_i - R_i - A_i^1 I(i))$. Let $Y \in (FA, FATR)$. Then the fuel burned to carry $Y(i)$ is $CtC_{Y(i)} = Y(i) \times \gamma_{i,a} \times d_i$. The quantity of CO_2 emissions from burning this fuel is found by applying the jet fuel to CO_2 conversion factor, 20.89 lbs CO_2/gallon of jet fuel or 9.50 kg CO_2/gallon (Environmental Protection Agency 2013). (Note that this conversion factor neglects any secondary warming effects of aviation fuel burn (Williams *et al* 2002, Williams and Noland 2006)). The percent of total fuel consumed due to carrying $Y(i)$ is calculated by dividing $CtC_{Y(i)}$ by the total actual fuel burn, $D_i - L_i$: $\%CtC_{Y(i)} = 100 \times \frac{CtC_{Y(i)}}{D_i - L_i}$. As the airline dataset does not include every domestic operation for the study airline, the data are annualized using publicly available aviation operations data from the Bureau of Transportation Statistics. The annualized values are found by multiplying the median values of $\%CtC_{Y(i)}$ with the total fuel consumed in a year by our study airline and the entire US domestic aviation system.

As noted above, we are also interested in additional contingency fuel beyond what is necessary to mitigate risks from needing to burn more fuel than is projected by the flight plan. For reasons explained previously, we consider SCF99 to be a suitable benchmark for determining unnecessary contingency fuel. We therefore calculate two additional metrics for unnecessary fuel: (1) the additional contingency fuel only for flight *i*, $ACF(i) = |C_i - SCF99_i|$ and (2) the additional contingency fuel, the fuel for 2nd alternates, and the fuel for non-required 1st alternates, $ACAF(i) = |C_i - SCF99_i| + A_i^1(1 - I(i)) + A_i^2$. The fuel burned in carrying $ACF(i)$ and $ACAF(i)$, the resulting CO_2 emissions, the percent of total fuel consumed due to carrying these quantities of fuel, and the annual fuel burned to carry them, are obtained in the same manner as discussed previously in the context of the fuel on arrival analysis.

3. Cost to carry results

In the following section we calculate the fuel consumed due to carrying fuel on arrival (*FA* and *FATR*) and additional contingency fuel (*ACF* and *ACAF*) on a per-flight basis. We then generalize the cost—in terms of fuel burned—from carrying unused and contingency fuel for our study airline and for the entire US domestic airline industry. We compare the potential fuel savings from reducing fuel uplift to existing fuel saving initiatives in the aviation and transportation sectors.

Table 2. Fuel on arrival and additional contingency fuel uplifted and the cost to carry this fuel.

		1st Qu.	Median	Mean	3rd Qu.
FA	Fuel on arrival (minutes)	84.4	105.3	111.9	132.3
	Fuel on arrival (lbs)	7500.0	9300.0	9970.0	11800.0
	Cost to Carry Fuel on arrival (lbs)	400.7	560.6	671.4	834.9
	Percent of total per-flight fuel consumed	3.65%	4.48%	4.86%	5.73%
FATR	Fuel on arrival (minutes)	34.9	51.6	59.7	79.5
	Fuel on arrival (lbs)	3165.0	4400.0	5328.0	7171.0
	Cost to Carry Fuel on arrival (lbs)	164.4	281.0	373.0	472.3
	Percent of total per-flight fuel consumed	1.55%	2.21%	2.56%	3.39%
ACAF	Fuel uplift (minutes)	13.0	23.0	40.2	59.8
	Fuel uplift (lbs)	1149.0	2027.0	3578.0	5312.0
	Cost to Carry (lbs)	58.48	131.50	225.20	316.00
	Percent of total per-flight fuel consumed	0.57%	1.04%	1.74%	2.54%
ACF	Fuel uplift (minutes)	10.0	16.0	17.5	23.0
	Fuel uplift (lbs)	922.1	1431.0	1564.0	2025.0
	Cost to Carry (lbs)	47.24	77.39	97.58	127.10
	Percent of total per-flight fuel consumed	0.44%	0.70%	0.77%	1.02%

3.1. Per-flight cost to carry results

The quartiles of fuel on board at arrival and contingency fuel boarded in minutes, in pounds, and the cost to carry this fuel in both pounds and in the percent of total flight fuel consumption are shown in table 2. (See the supplementary information for table 2 in SI units.)

Before analyzing the cost to carry fuel we consider fuel on board at arrival and contingency fuel boarded in both minutes of fuel and pounds of fuel. Investigating the minimum value of fuel on arrival in minutes shows that virtually all flights land with the 45 min of required reserve fuel for holding. As a rough rule of thumb, about 50% of the fuel on arrival is unnecessary in the sense that it is not mandated by the FARs. Specifically, the average flight lands with 112 min of fuel on arrival total, 60 min of which are not required to be loaded onto the flight. Regarding contingency fuel uplift, the first quartile of *ACF* across the entire dataset is 10 min, indicating that 75% of the flights have at least 10 min of *additional* contingency fuel (contingency fuel above a reasonable buffer); this value is 13 min when non-required alternate airports are considered as well.

The distributions of all four fuel metrics are skewed to the right. For example, while 50% of the flights depart with at least 25 min of extra discretionary fuel as measured by *ACAF*, 25% depart with between 23 and 60 min and the remaining 25% depart with more than 60 min. For all four categories of fuel on arrival and contingency fuel, the mean values are larger than the median values indicating that there are extreme values at the right tail of the distribution influencing the mean. This result showcases the impact of adverse flying conditions, and the degree of caution that dispatchers take under such conditions in their fuel loading decisions.

Table 2 also includes the fuel consumed due to carrying fuel on arrival and additional contingency fuel, which we term cost to carry. The median values of fuel burned due to carrying unused fuel per flight, in both lbs per flight and the percent a flight's fuel consumption are: *FA*: 560.6 lbs and 4.48%; *FATR*: 281.0 lbs and 2.21%; *ACAF*: 131.5 lbs and 1.04% and *ACF*: 77.4 lbs and 0.70%. The implication is that on a typical flight 4.48% of the fuel consumed is due to carrying fuel that is unused, while 1.04% of the fuel consumed is due to carrying additional contingency fuel above a reasonable buffer combined with loading fuel for unnecessary alternates.

3.2. Cross-airline and cross-industry fuel and CO_2 implications of carrying additional fuel

We ultimately would like to put the cost to carry results in the context of total aviation and transportation fuel consumption. We collect the total fuel consumed by both our study airline (1.56 billion gallons) and by all US airlines (10.15 billion gallons) during our one-year study period for all domestic flights from the Bureau of Transportation Statistics (BTS). Note that we use the BTS figure for our study airline rather than estimate it from our airline dataset because not every flight is represented in the data due to data entry errors reported by the airline.

Table 3 contains estimates of the annual cost to carry *FA*, *FATR*, *ACF*, and *ACAF* based on the median values of $\%CtC_{FA(i)}$, $\%CtC_{FATR(i)}$, $\%CtC_{ACF(i)}$, and $\%CtC_{ACAF(i)}$. The total fuel consumed per year in units of weight is converted to both monetary cost (using \$3.20/gallon, the average fuel price of our study airline and \$3.12/gallon, the average fuel price faced by all airlines in our study period as reported by BTS) and to CO_2 emissions using the jet fuel to CO_2 conversion factor.

Table 3. Annual cost to carry in terms of fuel consumed, cost of fuel consumed, and emitted CO_2.

		FA	*FATR*	*ACF*	*ACAF*
	Percent of Total Fuel Consumption	4.48%	2.21%	0.70%	1.04%
All Flights for Study Airline	Estimated Total Fuel Consumption (lb)	4.67×10^8	2.30×10^8	7.29×10^7	1.08×10^8
	Estimated Total Fuel Consumption (kg)	2.12×10^8	1.05×10^8	3.31×10^7	4.92×10^7
	Cost of Excess Fuel Burned @ \$3.20/ gallon	\$2.23 $\times 10^8$	\$1.10 $\times 10^8$	\$3.48 $\times 10^7$	\$5.17 $\times 10^7$
	Excess CO_2 Generated (lb)	1.46×10^9	7.18×10^8	2.27×10^8	3.38×10^8
	Excess CO_2 Generated (kg)	6.61×10^8	3.26×10^8	1.03×10^8	1.54×10^8
All Scheduled US Domestic Flights	Estimated Total Fuel Consumption (lb)	3.05×10^9	1.50×10^9	4.76×10^8	7.07×10^8
	Estimated Total Fuel Consumption (kg)	1.38×10^9	6.83×10^8	2.16×10^8	3.21×10^8
	Cost of Excess Fuel Burned @ \$3.12/ gallon	\$1.42 $\times 10^9$	\$7.00 $\times 10^8$	\$2.22 $\times 10^8$	\$3.29 $\times 10^8$
	Excess CO_2 Generated (lb)	9.49×10^9	4.68×10^9	1.48×10^9	2.20×10^9
	Excess CO_2 Generated (kg)	4.32×10^9	2.13×10^9	6.74×10^8	1.00×10^9
	Percent of Total Transportation CO_2 Emissions	0.247%	0.121%	0.039%	0.057%

Finally we calculate the percent of total *transportation* CO_2 emissions that are attributed to carrying unused fuel by dividing the total CO_2 produced attributed to carrying *FA, FATR, ACF,* and *ACAF* to the total quantity of CO_2 emissions from transportation in 2012 as reported by the Environmental Protection Agency (2012) (3.88×10^{12} lbs or 1.758×10^{12} kg).

Throughout the course of the year, our study airline burns 467 million lbs of fuel and emits 1.46 billion lbs of CO_2 to carry *all* fuel it does not burn in flight. This airline burns 108 million lbs of fuel and emits 338 million lbs of CO_2 to carry additional contingency fuel (relative to SCF99) and non-required alternate fuel throughout the course of the year. The monetary cost of carrying unused fuel is \$223 million (based on *FA*) while the cost to carry unnecessary extra fuel is \$51.7 million (*ACAF*) for our study year. If all airlines operating in the US domestic aviation system fuel their aircraft in a similar manner to our study airline, the total fuel consumed due to carrying all fuel unused in flight for our study year would be 3.05 billion lbs resulting in 9.49 billion lbs of CO_2; for additional contingency fuel and non-required alternate fuel these figures would be 707 million lbs of fuel and 2.20 billion lbs of CO_2. Considering the total of transportation CO_2 emissions, the contributions from airlines carrying extra fuel vary from .04% to .25%, depending on the metric considered. These percentages are small; however, in the context of broader transportation fuel consumption reduction goals it is well understood that CO_2 reduction goals will be met with a suite of small reductions rather than a few large-scale reductions (Lutsey and Sperling 2009, McCollum *et al* 2012).

3.3. Comparison of savings from reducing fuel uplift to existing fuel saving initiatives

To put the values of per-flight fuel consumed due to carrying fuel (table 2) and the annualized fuel consumed, CO_2 emitted, and cost incurred from carrying fuel (table 3) into context, we compare these values to current aviation and transportation fuel-saving initiatives.

First we consider per-flight fuel savings initiatives. Consider the FAA estimates that precise navigation and continuous approach procedures at Seattle-Tacoma International Airport, implemented in 2014, will save Alaska Airlines 14 million lbs of jet fuel annually (about 130 lbs per flight or 60 kg per flight) (Federal Aviation Administration 2014). The savings value from this specific, localized investment on a per-flight basis is very close to that from reducing additional contingency fuel and non-required alternative fuel uplift (with a median value of 146 lbs per flight).

Regarding ground-based initiatives, consider that there are numerous studies and federal initiatives focused on reducing fuel consumed by an aircraft during taxi out (from the gate to the runway) (Daniel 2002, Balakrishna *et al* 2008, Nikoleris *et al* 2011, Khadilkar and Balakrishnan 2012, Hao *et al* 2015). Simaiakis *et al* (2014) find that managing the rate of aircraft pushback from the gate a busy airport could reduce per-flight fuel consumption by about 110–130 lbs of fuel, a value slightly less than the median value of fuel savings from reducing *ACAF* from a flight. Hao *et al* (2015) find that eliminating taxi delay reduces per-flight fuel consumption by an average of 1% and up to 2% at the busiest airports; these percentages are directly in line with the savings from reducing fuel uplift seen in table 2.

To compare the savings from reducing fuel uplift to savings from reducing taxi out fuel consumption (for example by increasing use of single-engine taxi procedures), we calculate the average taxi fuel consumed by a flight in our dataset. Consistent with Chester and Horvath (2009) we select three representative aircraft sizes from our data (large, midsize, and small)

Table 4. Comparison between taxi out fuel consumption and the cost to carry contingency fuel.

Aircraft category	Median cost to carry:		Average fuel consumed in taxi out (lbs) (Standard deviation)	Percent taxi out fuel reduction equivalent to 100% reduction of:	
	ACAF	*ACF*		*ACAF*	*ACF*
Large aircraft	316.7	170.60	1115.00 (446.08)	28.4%	15.3%
Midsized aircraft	196.50	109.9	531.60 (224.59)	37.0%	20.7%
Small aircraft	116.0	67.61	428.80 (238.54)	27.6%	16.1%

and estimate the average fuel consumed during taxi out and the median value of per-flight fuel consumption from carrying *ACAF* and *ACF* (further details are provided in the supplementary information). A comparison of the cost to carry unnecessary contingency fuel and the fuel consumed in taxi out can be found in table 4. We see that eliminating unnecessary uplift for contingency fuel and alternates is equivalent to reducing taxi out fuel consumption by about 27–37%.

Finally, consider that Dray (2014) estimates that fuel savings from replacing aging aircraft with best-in-class aircraft technology on US domestic routes would reduce per-flight fuel consumption by up to 10%. The benefit pool then for aircraft and engine upgrades is high; however, there are barriers to fleet turnover. Investing in best-in-class aircraft technology is both expensive and risky for an airline. Ownership cost can dominate the cost function for owning and operating an aircraft, encouraging airlines to lease or purchase used, older aircraft rather than invest in those which are new (Swan and Adler 2006). Brugnoli *et al* (2015) finds that the current rate of endogenous technical progress leads to fuel and CO_2 reductions in the global aviation system of 1.34% per year, which is commensurate to the fuel savings we find from reducing fuel uplift.

Regarding system-wide benefits, the Federal Aviation Administration (2014) published estimates of the fuel savings benefits from NextGen amounting to 38.7 billion gallons of fuel through 2030 or 2.4 billion gallons per year. If we assume all carriers fuel their domestic aircraft in a similar manner, our overall benefit pool for eliminating *ACAF* is 707 million lbs of fuel (and 2.20 billion lbs of CO_2), or 29.5% of the entire annual fuel benefit from NextGen. Moreover, if it were possible to create a system in which aircraft could land with their fuel tanks containing only 45 min of reserve fuel and any required alternate reserve (*FATR*), the benefit across the industry alone would be 1.50 billion gallons of fuel per year, 62.5% of the estimated value for NextGen. Given that the benefit pool from reducing *ACAF* is achievable (as *ACAF* represents fuel that is above a reasonable buffer), the implication is that it is possible to achieve 29.5% of the benefit of NextGen (which is estimated to cost $29 billion through 2030) by changing fuel loading practices rather than investing in technology and changing operational procedures of airports, airlines, and the airspace.

Consistent with US Environmental Protection Agency recommendations that transportation emissions can be reduced by eliminating trips, we convert the figures in table 3 to the equivalent number of flights that would have to be removed from the system to achieve the same savings from reducing fuel uplift. Using the three categories of aircraft defined in table 4 (large, midsize, and small), we calculate the average per-flight fuel consumed by those aircraft using the Piano model (details are provided in the supplementary information). The values of annualized $CtC_{FATR(i)}$ and $CtC_{ACAF(i)}$ in table 3 for both the study airline and all US airlines are divided by the estimated per-flight fuel consumed for each aircraft type; the result is the equivalent number of flights that would have to be removed from the system per year to achieve the same savings (figure 1). Considering that our airline operates about 720 000 flights per year and assuming all of these are on midsized aircraft, these values are the equivalent to canceling all their domestic flights for 2.4 days (*ACAF*) to 5.13 days (*FATR*).

Finally, we compare the savings from reducing fuel uplift to the savings possible from reducing vehicle miles traveled on the highway system. Consider that a current (~20 mi/gal or 8.5 km/liter) vehicle emits about one pound of CO_2 per vehicle-mile traveled (VMT) (or 0.28 kg of CO_2 per vehicle-kilometer traveled). Using VMT figures cited in Chester and Horvath (2012), the savings from reducing fuel uplift (*FATR*) from our study airline is the equivalent of removing 718 million VMT per year or the equivalent of removing 0.32% of the VMT in the state of California. If we consider eliminating *ACAF* from the study airline, the savings are 338 million VMT per year or the equivalent of removing 0.15% of the VMT in the state of California (Chester and Horvath 2012). If we generalize the equivalent VMT savings from reducing fuel uplift across the entire US domestic aviation industry, we find that eliminating *FATR* from all US domestic flights is equivalent to removing 4.68 billion VMT and 1.99% of California VMT, while reducing

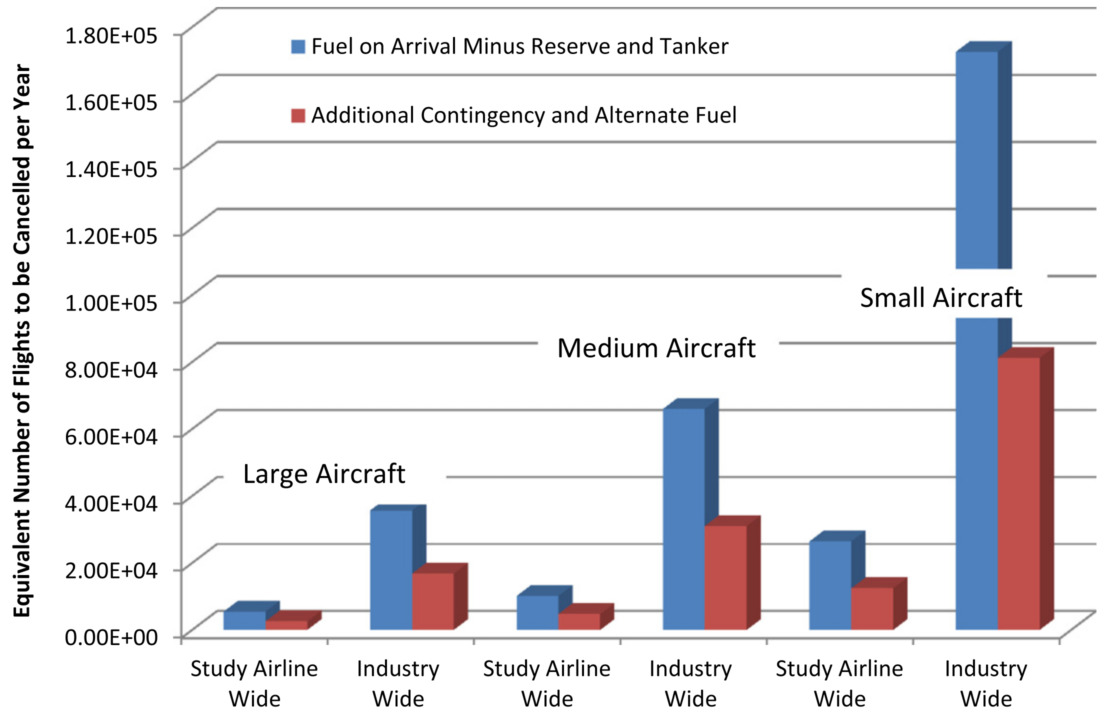

Figure 1. The number of flights that would have to be removed from the system per year to achieve the same savings from reducing fuel uplift.

ACAF is equivalent to removing 2.20 billion VMT and 0.93% of California's VMT.

4. Towards safely reducing discretionary fueling

In the previous sections, we established that a major US carrier is conservative in determining fuel uplift on its CONUS flights, resulting in large potential savings in fuel, cost, and CO_2 emissions from reducing fuel uplift. To estimate the monetary and environmental cost of fuel loading practices we estimate and report cost to carry factors, which capture, for each aircraft type operated by our major US carrier, the pounds of fuel burned to carry unit of fuel one unit of distance. We find that, depending on the aircraft type and distance flown, an aircraft burns between 0.05 and 0.25 lbs per pound of fuel carried. Using the cost to carry factors we establish the fuel burned to carry unused fuel on arrival and additional contingency fuel. We find that, at the median, 2.21%–4.48% of aircraft fuel consumption is attributed to carrying fuel that is unused in flight, and 0.70%–1.04% of aircraft fuel consumption is attributed to carrying unnecessary contingency and alternate fuel. When we convert this to monetary costs per year, we find that the costs incurred by our study airline during the study year for carrying all fuel unused in flight is $223 million and the cost for carrying excess contingency and non-required alternate fuel is $52 million. Extrapolated over all flights in the entire US domestic air transportation system, the costs are $1.42 billion and $329 million respectively. If fuel prices were to rise from the values from our study period—about $3 per gallon—to their 2007 levels of close to $4.00, these costs would increase proportionately (US Energy Information Agency 2015). The results indicate that conservative fuel loading persists despite heightened concerns regarding fuel costs and environmental impact in contemporary aviation.

To put the fuel burned due to carrying unused fuel on board and contingency fuel in context we compare the magnitude of fuel consumed due to carrying unused and unnecessary fuel to established efforts to reduce fuel consumption. These comparisons to NextGen and other initiatives are not intended to denigrate other efforts to improve the aviation system, but instead to suggest that the opportunity to achieve substantial savings through reducing fuel uplift is underappreciated.

Reduced fuel uplift is also a mechanism through which ongoing efforts in to modernize the aviation system generate benefit. The technologies of NextGen are intended to increase flight predictability, measured by factors that include the variance, standard deviation, mean absolute deviation, and inter-quartile range of flight time. NextGen technologies that allow for precise navigation enhance predictability by making the terminal area more efficient and less prone to delay. Our results show a long right tail of the contingency fueling distribution, indicating dispatchers responding to uncertain conditions. As more NextGen deployments are rolled out—particularly at the most inefficient and unpredictable terminals areas—we can expect that dispatchers will responds to this predictability with reduced contingency fuel loads (Ryerson *et al* 2014).

The comparison of fuel burned due to contingency uplift to other savings showcase how simple changes in dispatcher behavior—resulting from airline or federal guidance encouraging dispatchers to add contingency fuel at the SCF99 level—could result in significant fuel savings. Reducing contingency fuel uplift to the SCF99 level would not require rule changes and would still maintain a large safety margin. While saving fuel from reducing uplift could come in the absence of federal guidance, federal intervention could help. The FAA could consider revising the role of federally-mandated reserve fuel. It is at the discretion of the airline if the reserve fuel is considered useable fuel for contingencies or if instead it is to be treated as protected and not to be used (Federal Aviation Administration 2012b). Towards empowering airlines to reduce contingency fuel uplift beyond SCF99, the FAA could release guidance explicitly outlining how a portion of reserve fuel could be used for contingencies. Considering that fuel beyond SCF99 should (statistically) rarely be necessary, explicitly outlining how airlines could use the reserve fuel in these very unlikely situations could help reduce uplift.

By quantifying the cost of fuel uplift for contingencies and highlighting the existing fuel benefit pool from reducing fuel uplift, we estimate the 'benefit' side of a benefit-cost analysis of reducing fuel uplift. The cost side would be any possible increase in the number of diversions that the airline might experience (as an aircraft would not simply run out of fuel midair, but instead divert safely to another airport). Diversions can come with a significant cost as they are disruptive to hubbing operations. However, in our study we found large fuel benefits pools even for the most conservative fuel loading practices, indicating that there are benefits to be mined with minimal impacts on operations. The results of this study motivate further research on diversions and fuel loads as well as the development of specific planning methods or operational concepts that can tap the benefit pools that we have estimated.

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