

# Evaluating Air Carrier Fuel Efficiency in the U.S. Airline Industry

Bo Zou

Department of Civil and Materials Engineering  
University of Illinois  
Chicago, USA  
[bzou@uic.edu](mailto:bzou@uic.edu)

Matthew Elke, Mark Hansen

Department of Civil and Environmental Engineering  
University of California  
Berkeley, USA  
[matthew.elke@berkeley.edu](mailto:matthew.elke@berkeley.edu), [mhansen@ce.berkeley.edu](mailto:mhansen@ce.berkeley.edu)

**Abstract**—We employ ratio-based, deterministic, and stochastic frontier approaches to investigate fuel efficiency among 15 large jet operators (mainline airlines) in the U.S. Given the hub-and-spoke routing structure and the consequent affiliation between mainline and regional carriers, we consider not only fuel efficiency of individual mainline airlines, but also the joint efficiency of each mainline and its regional subsidiaries, as well as efficiency in transporting passengers from their origins to destinations. We find that: 1) airline fuel consumption is highly correlated with, and largely explained by, the amount of revenue passenger miles and flight departures it produces; 2) depending on the methodology applied, average airline fuel efficiency for the year 2010 is 9-20% less than that of the most efficient carrier, while the least efficient carriers are 25-42% less efficient than the industry leaders; 3) regional carriers have two opposing effects on fuel efficiency of mainline airlines: higher fuel per revenue passenger mile but improved accessibility provision; 4) the net effect of routing circuitry on fuel efficiency is small.

**Keywords**- *airline fuel efficiency; mainline airline; regional carrier; routing circuitry; frontier model*

## I. INTRODUCTION

Airlines are more intent nowadays than ever to improve fuel efficiency in their flight operations. With rising fuel prices, airlines are grounding and retiring older, less fuel-efficient aircraft, upgrading their fleet by introducing more fuel efficient models, and adjusting operating practices, for example, single-engine taxi procedures, to reduce fuel consumption and ease financial burden. Concern about anthropogenic climate change has added another layer of potential financial strain for airlines. Aviation induced carbon dioxide (CO<sub>2</sub>), one of the most important greenhouse gases, and regulated under the European Emissions Trading Scheme (ETS), is directly tied to the amount of fuel consumed in flight operations. Any monetization of CO<sub>2</sub>, therefore, spurs airlines further to improve their fuel efficiency by increasing the effective price of fuel. On the demand side, passengers are also becoming more environmentally conscious. Passengers worldwide have voluntarily participated in carbon offsetting programs in their air travel [1]. Travel management companies (TMCs), responsible for airline and airfare selection in business travel, have growing interests in incorporating fuel efficiency in their

decision making process. A track record of good fuel efficiency, and the consequent lower carbon foot-print, will improve the public image of an airline, which in turn contributes to maintaining, or even attracting, new, environmentally conscious demand. As the public's environmental awareness will only become stronger, airlines may devote more resources to increasing their fuel efficiency in the future.

Facing rising fuel price and mounting environmental concerns, the capability to evaluate fuel efficiency of airlines is critical to inform industry stakeholders, policy makers, and the public about the status quo of the industry fuel usage, and help shape future strategies to improve fuel efficiency. In this paper, we attempt to enhance such capabilities by employing ratio, deterministic and stochastic frontier methods to measure airline fuel efficiency. These methods provide different depictions of the relationships between airline fuel consumption, output, and production efficiency. Comparison of results yields useful insights about the differences between these methodologies and how they affect fuel efficiency rankings. We recognize—to our knowledge for the first time—that affiliations between large jet operators and regional carriers must be taken into account when assessing the fuel efficiency of the mainline airlines. We also measure airline fuel efficiency with respect to passenger trips, by using a passenger origin-destination (O-D) based airline output metric as an alternative to the standard passenger-mile metric, which ignores the effect of circuitous routings. In addition to creating a comprehensive assessment of airline efficiency and its sensitivity to assessment methodology, an equally important goal of the present study is to provide a simple and transparent airline fuel efficiency assessment scheme that is generic and can be extended to other airlines around the globe as long as equivalent data are available.

The remainder of the paper is organized as follows. Section 2 provides a brief overview of the organization of the U.S. airline industry. Three methodologies for airline fuel efficiency measurement are presented in Section 3. We apply these methodologies in Section 4 to 15 U.S. large jet operators (which later on are referred to as mainline airlines), and present detailed analysis and comparison of results under different approaches, with and without considering mainline-regional

carrier affiliations, and routing circuitry. Conclusions are presented in Section 5.

## II. AIRLINE INDUSTRY ORGANIZATION IN THE U.S.

The U.S. air transportation system is characterized by the coexistence of hub-and-spoke and point-to-point network structures. Large, legacy carriers, such as United, Delta, American, and US Airways, provide air services by relying extensively upon a relatively small number of hub airports. For these airlines, 30-50% of passengers completed their trips by connecting at least once at an intermediate hub airport. The advent of hubbing since industry deregulation in the late 1970s has allowed the legacy carriers to consolidate passengers for many Origin-Destination (O-D) pairs on one segment, resulting in increased load factors and flight frequencies. The benefits, widely recognized in the literature as the economies of density, help the legacy carriers reduce unit operating expense and offer low airfares to passengers. At the same time, hubbing enables the legacy carriers to establish dominant competitive positions at their hub airports, and exploit market power by charging higher fares in O-D markets involving these hubs.

On the other hand, deregulation has spurred the growth of low cost airlines, which constitute the second important group among U.S. large jet operators. The services provided by these low cost carriers are predominantly point-to-point, although substantial heterogeneity exists in terms of network structures and business models. For instance, there are major differences between Southwest, the first low-cost carrier which provides services with a wide range of stage length on multi-stop routes, and Virgin America, a newly established airline focusing on long-haul coast-to-coast travel. Compared to the legacy carriers, low cost carriers are relatively young; thus their fleets generally consist of newer aircraft with better fuel economies. By targeting specific markets, these low cost carriers have strengthened competition in the industry, and shaped the U.S. air transportation system into a more complex and diverse mixture of operating structures.

In addition to legacy and low-cost airlines, regional carriers represent another integral components of the system. Regional carriers support, and are sustained by, the hub-and-spoke network structure. Under many circumstances, a one-stop passenger itinerary consists of a short flight on a regional jet or a turboprop, and a longer haul flight on a larger jet aircraft, both connected to a hub. The shorter leg is often operated by a regional carrier, which serves as a sub-carrier of the mainline airline flying the longer leg. The regional carrier's services are important as they provide passengers living in non-metropolitan regions and smaller cities, where demand is thin, with access to the hub, through which they can reach further destinations. Regional and mainline carriers are mutually dependent in the U.S., with regional aircraft liveries based on their mainline partners, who are responsible for the ticketing, marketing, and often the scheduling of the regional carriers' flight operations [2]. This is also reflected in the airline ticket reporting process to the U.S. Department of Transportation. In the Bureau of Transportation Statistics (BTS) Airline Origin and Destination Survey (DB1B) database, the portions of itineraries flown by regional carriers are included under the name of the affiliated mainline carriers.

The use of regional subsidiaries and hub-and-spoke operations by the mainline carriers give rise to two issues that have not been considered in existing airline fuel efficiency literature. First, since operations of regional carriers and mainline airlines are closely intertwined, it is important to account for the impact of regional carriers' affiliations when evaluating the mainline airlines' efficiency. The results from incorporating regional carriers, however, can be confounding: on the one hand, regional carriers are in general less efficient on a fuel per passenger mile basis; on the other hand, regional carriers usually provide higher levels of accessibility than their mainline counterparts, a dimension of output mostly left unattended in previous studies. Second, hub-and-spoke operations introduce excess travel distance as compared to point-to-point systems carrying non-stop passengers. Airline output may be more appropriately measured by origin-to-destination distance than total distance traveled. Both of these two issues will be explicitly addressed in the remainder of the paper.

## III. AIRLINE RANKING METHODOLOGIES

The term efficiency refers to the comparison between the observed values of output(s) and input(s) with the optimal values of output(s) and input(s) used in a production process [3]. Specific to airline fuel usage, efficiency pertains to the amount of fuel consumed by airlines in order to produce a fixed amount of output. To assess airline fuel efficiency, ratio, deterministic and stochastic frontier methods are presented in this section, reflecting different views of airline production process. The ratio-based method has the virtue of simplicity and transparency; whereas the frontier approaches recognize that output is multi-dimensional, including both mobility and accessibility provided by airlines. The stochastic frontier approach further distinguishes between efficiency and random shocks, and accounts for inter-carrier differences in output characteristics that may significantly affect fuel requirements. The latter methods involve additional statistical assumptions and are more reliant on analyst judgment. By using a range of methods to assess airline fuel efficiency, we can identify conclusions that hold regardless of method, and are thus more definitive, as well as findings that are more contingent on methodology.

### A. Ratio Approach

Ideally, a ratio-based fuel efficiency metric should be one that measures the amount of fuel usage to produce a unit output, or inversely, the amount of output produced with the consumption of one unit of fuel (which is essentially equivalent to fuel-based partial productivity). Either way, a measure of output must be chosen. Well-established metrics include available seat miles (ASM), available ton miles (ATM), revenue passenger miles (RPM), or revenue ton miles (RTM). It is important to select one that is representative of the total production output. ASM and ATM measure what is available, whereas RPM and RTM capture what is actually used. The use of the former, production-oriented, metrics has odd implications: a carrier could improve its fuel efficiency by flying more empty seats and using the same amount of fuel [4]. As a consequence, RPM and RTM are preferred output

measures. Using RPM and RTM rewards carriers not only for efficient production, but also for efficiently matching the capacity they produce with the needs and wants of the traveling public.

Between RPM and RTM, an advantage of using RTM is that it considers the full range of transportation services of passengers, freight and mail in airline production and converts them into a single aggregate measure. However, this advantage needs to be weighed against several factors that favor the use of RPM. First, the U.S. airlines considered in the present study are all passenger service focused, with only a small portion of their traffic taking the form of cargo, mail and other types of business. Any difference resulting from the choice between RTM and RPM should be relatively insubstantial. Second, air cargo is far less energy efficient than other freight modes. In this sense, non-passenger RTMs are inherently inefficient, and it seems counter-intuitive to give airlines the same credit for freight output as for passenger output. A third reason involves assigning regional carriers' operations to the affiliated mainline airlines. As will be detailed later, the data sources available for performing this task are all passenger based. Using RPM will preserve consistency in the efficiency computation.

If we use Fuel/RPM as the ratio-based fuel performance metric, this metric needs to be adjusted if regional subsidiaries are to be considered. Recall that in supporting the mainline airlines' hub-and-spoke systems, regional carriers contribute both additional RPMs and fuel burn to the operation of the corresponding mainline airlines. We propose the following adjusted Fuel/RPM metric (for mainline airline  $i$ ),  $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}}$ :

$$\left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}} = \frac{\text{Fuel}_i + \text{Fuel}_{j_1}^i + \text{Fuel}_{j_2}^i + \dots + \text{Fuel}_{j_n}^i}{\text{RPM}_i + \text{RPM}_{j_1}^i + \text{RPM}_{j_2}^i + \dots + \text{RPM}_{j_n}^i} \quad (1)$$

where  $\left(\text{Fuel}\right)_{j_k}^i$  and  $\left(\text{RPM}\right)_{j_k}^i$  denote, respectively, the fuel consumed by regional carrier  $j_k$  ( $k = 1, \dots, n$ ) that is attributable to mainline airline  $i$ 's operations, and the RPMs from  $j_k$  that should be assigned to  $i$ . Therefore,  $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}}$  is calculated as the ratio between the sum of fuel consumption from the mainline airline plus the regional carriers that are attributable to the mainline airline's operation, and the sum of RPMs across the mainline and the regional carriers. The exact estimation of  $\left(\text{Fuel}\right)_{j_k}^i$  and  $\left(\text{RPM}\right)_{j_k}^i$  will be discussed in Section 4.

If the measurement of fuel efficiency is set on the basis of moving passengers from their origins to destinations, the previous metric needs to be further adjusted. We multiply  $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}}$  by mainline airline  $i$ 's routing circuitry, which is defined as the ratio between total RPMs and total revenue passenger O-D miles (RPODM) from the mainline airline as well as the appropriate portions of its regional affiliates:

$$\left(\frac{\text{Fuel}}{\text{RPODM}}\right)_i = \left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}} \times (\text{circuitry})_i = \left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}} \times \left(\frac{\text{RPM}}{\text{RPODM}}\right)_i \quad (2)$$

Circuitry always takes values no less than one. Airlines with high circuitry will be penalized compared to those flying direct routes.

The preceding discussion can be synthesized in a four-level hierarchical structure in Fig. 1, where the arrows indicate that one metric at the higher level is comprised of lower-level metrics. At the top level,  $\left(\frac{\text{Fuel}}{\text{RPODM}}\right)_i$  measures how efficient an airline (indexed by  $i$ ) is in transporting passengers between their O-Ds. At the second level, we decompose  $\left(\frac{\text{Fuel}}{\text{RPODM}}\right)_i$  into the product of  $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}}$  and  $\left(\frac{\text{RPM}}{\text{RPODM}}\right)_i$ , the latter penalizing airlines operating with circuitous routing structures.  $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^{\text{adjusted}}$  is expressed as a function of a set of (Fuel/RPM)'s, which are the level 3 metrics, for mainline  $i$  and the part of regional carrier  $j_k$ 's that is attributable to mainline  $i$ . The "\*" operator realizes the computation in (1). At the bottom level,  $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_i^i$  is further decomposed into the product of  $\left(\frac{\text{Fuel}}{\text{ASM}}\right)_i$  and  $\left(\frac{\text{ASM}}{\text{RPM}}\right)_i$ , the latter of which is the reciprocal of airline  $i$ 's average load factor. This suggests that if the amount of output produced (i.e. ASM) were to be used as the denominator in the efficiency ratio, the ratio (Fuel/ASM) would need to be corrected for the actual utilization of the output.

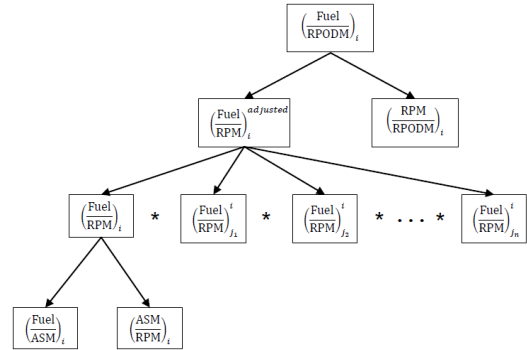


Figure 1. Four-level hierarchical structure of fuel efficiency metrics

## B. Frontier Approaches

RPMs used in the ratio-based approach measure essentially the level of mobility airlines provide for passengers. Another important aspect of transportation system performance is the provision of accessibility, or the ability to reach desired goods, services, and activities [5]. In the context of airline production, accessibility can be measured by the number of aircraft trips, or flight departures (dep). This is because each departure, like the stop of a bus or a train, affords an opportunity for passengers to embark or disembark. To the extent that an airline reduces fuel use by flying non-stop for long distances, and thus limiting the ability of customers to board and alight from its vehicles, the conventional ratio metrics based on RPMs will yield a distorted measure of the airline's fuel efficiency. To correct for this distortion, it is necessary to include both mobility and accessibility aspects in characterizing airline production output.

The frontier approaches meet this need. The rationale behind the frontier approaches is that airlines consume no less

than the amount of fuel under "best practice" on the fuel consumption frontier. The "best practice" frontier is constructed using observed fuel consumption and airline output, and indicates the minimum possible fuel burn in order to produce a given level of output. A general fuel consumption model can be specified as:

$$\text{fuel}_{it} = f(\text{RPM}_{it}, \text{dep}_{it}) \exp(u_{it}) \quad (3)$$

where subscript  $i$  denotes a specific airline, and  $t$  identifies the time period;  $f(\text{RPM}_{it}, \text{dep}_{it})$  specifies the fuel consumption frontier;  $u_{it}$  is a non-negative deviation term. The inefficiency of airline  $i$  at time  $t$  is measured as  $\exp(u_{it})$ .<sup>1</sup> Because  $u_{it} \geq 0$ , the inefficiency  $\exp(u_{it})$  is always no less than one. Various forms of frontier models can be derived, and categorized as either deterministic or stochastic, depending upon the assumptions about  $f(\text{RPM}_{it}, \text{dep}_{it})$ .

#### 1) Deterministic frontier

The deterministic frontier model assumes that the frontier part of the fuel consumption model,  $f(\text{RPM}_{it}, \text{dep}_{it})$ , can be deterministically characterized. In the present study, we specify the fuel consumption model which follows a log-linear functional form:

$$\ln(\text{fuel})_{it} = \beta_0 + \beta_1 \ln(\text{RPM})_{it} + \beta_2 \ln(\text{dep})_{it} + u_{it} \quad (4)$$

The frontier model can be estimated using the Corrected Ordinary Least Square (COLS) method, in two steps [6]. In the first step, we apply OLS to obtain consistent and unbiased estimates of the two slopes  $\hat{\beta}_1$  and  $\hat{\beta}_2$ , and an initial intercept  $\hat{\beta}_0'$ , which is consistent but biased. OLS residuals  $\hat{\eta}_{it}$  for each observation are calculated. In the second step, we correct  $\hat{\beta}_0'$  by shifting it downwards until it becomes  $\hat{\beta}_0$ , in which case no residual in the sample is negative, and at least one is zero. Therefore,  $\hat{\beta}_0 = \hat{\beta}_0' + \min_{i,t} \{\hat{\eta}_{it}\}$ . The estimated inefficiency for airline  $i$  at time  $t$  is  $\exp(\hat{u}_{it}) = \exp[\hat{\eta}_{it} - \min_{i,t} \{\hat{\eta}_{it}\}]$ .

According to (4),  $\exp(u_{it})$  can be alternatively expressed as  $\frac{1}{\exp(\beta_0)} \cdot \frac{(\text{fuel})_{it}}{\text{RPM}_{it}^{\beta_1} \text{dep}_{it}^{\beta_2}}$ , where  $\frac{1}{\exp(\beta_0)}$  is a constant across observations. Because of this equivalence, the deterministic frontier approach can also be viewed as a ratio, with the denominator involving both mobility and accessibility outputs, each raised to a certain power. In contrast to the ratio-based approach, the denominator is based upon an empirically estimated relationship between fuel consumption and output, rather than any *a priori* assumption.

When considering the joint fuel efficiency of mainline airlines and the regional affiliates, fuel, RPM, and dep in the deterministic frontier model will be their respective sums from the mainline airline and the assigned amounts from the affiliated regional carriers. The composite values will yield a new fuel consumption frontier. When routing circuitry is further considered, we substitute the corresponding RPODM values for the composite RPMs, and estimate another new frontier.

<sup>1</sup> In this study, we use both "fuel efficiency" and "fuel inefficiency" terms. While the former expression is the more natural one, from a technical point we consider the latter more appropriate.

The procedure for assessing efficiency remains unchanged once the appropriate frontier is obtained.

#### 2) Stochastic frontier

The deterministic frontier model has the advantages of being easy to estimate. On the other hand, in the deterministic frontier model all fuel burn variations not associated with variations in RPM and dep are attributed to fuel inefficiency, making no allowance for the effect of random shocks, such as vagaries of weather and plain luck, and measurement error. In addition, the estimated fuel consumption frontier will be parallel (in logarithmic values) to the OLS regression curve, implying that the structure of the "best practice" is the same as the structure of the "average practice", which is an overly restrictive property. To address these concerns, we also consider stochastic frontier models that are capable of separating shocks from the true variation in fuel efficiency. Specifically, an idiosyncratic error term  $v_{it}$  is introduced to the frontier part of (4). The fuel consumption model becomes:

$$\ln(\text{fuel})_{it} = \beta_0 + \beta_1 \ln(\text{RPM})_{it} + \beta_2 \ln(\text{dep})_{it} + v_{it} + u_{it} \quad (5)$$

Because of the idiosyncratic error term  $v_{it}$ , the associated fuel consumption frontier,  $\exp(\beta_0) \text{RPM}_{it}^{\beta_1} \text{dep}_{it}^{\beta_2} \exp(v_{it})$ , is now stochastic.

Under the assumptions that 1)  $v_{it}$ 's have identically and independently normal distributions, i.e.  $v_{it} \sim \text{iid } N(0, \sigma_v^2)$ ; 2)  $u_{it}$ 's follow some non-negative identically and independent distributions; 3)  $u_{it}$  and  $v_{it}$  are distributed independently of each other, and of the regressors in (5), the parameters  $\beta$ 's and those characterizing the distribution of  $u_{it}$  and  $v_{it}$  can be estimated jointly using the maximum likelihood method [7] [8]. In the subsequent analysis, we first assume  $u_{it}$  to follow a half-normal distribution, one of the most widely used distributions in the efficiency literature. Since  $u_{it} \sim \text{iid } N^+(0, \sigma_u^2)$ ,  $\sigma_u^2$  is the only distribution parameter to be estimated associated with  $u_{it}$ 's.

The assumption that all  $u_{it}$ 's have the same half-normal distribution can be restrictive for two reasons. First, the mode of the efficiency distribution may be non-zero. Second, one would expect heterogeneity across the efficiency terms, in particular the centrality of their distributions, given the different operational environment airlines may experience. To provide a more flexible pattern of the airline fuel efficiency, we relax the previous identical distribution assumptions, and assume that  $u_{it}$ 's are independently but not identically distributed as the non-negative truncations of a general normal distribution:

$$u_{it} \sim N^+ \left( \sum_{j=1}^M \delta_j z_{j,it}, \sigma_u^2 \right) \quad (6)$$

where  $\delta$ 's and  $\sigma_u^2$  are the parameters to be estimated, and  $z$ 's represent environmental variables. Through the mean of the efficiency distribution, the environmental variables  $z$ 's will have an influence on the "distance" between airlines' actual fuel burn and the frontier.

Due to the coexistence of  $u_{it}$  and  $v_{it}$ , the estimated residual for each observation is a realization of  $\varepsilon_{it} = v_{it} + u_{it}$  (termed

as  $\hat{\epsilon}_{it}$ ); whereas  $u_{it}$  is not directly observable. We use conditional expectation  $E[\exp(u_{it})|\hat{\epsilon}_{it}]$  as the point estimator of the fuel inefficiency for each observation. Further details about computing the point estimator for half-normal and truncated normal efficiency distributions can be found in [9] [10].

Stochastic frontier models can be applied to assess the joint fuel efficiency of mainline airlines and their regional affiliates, in the same fashion as in the deterministic frontier case. The only addition is that the environmental variables also need to be composite measures when heterogeneity is considered in the efficiency terms. Similarly, when the fuel efficiency assessment corrects for the circuitry of passenger itineraries, RPODM replaces RPM as the mobility output metric in the stochastic frontier models.

#### IV. APPLICATION TO US MAINLINE CARRIERS

##### A. Data

We focus on the domestic U.S. airline operations in 2010, the eve before two significant mergers in the industry (United with Continental; Southwest with AirTran), and assess the fuel efficiency of 15 large jet operators. The selection of the 15 operators is based on average aircraft size. Fig. 2 illustrates the sorted average aircraft sizes among the 37 U.S. carriers that had at least 500,000 enplaned passengers in 2010. We observe a clear demarcation between Republic Airlines and AirTran Airways, where average aircraft size leaps from 85 to 125 seats per flight. On the right hand side of this demarcation line are the 15 selected mainline airlines, which are large jet operators flying their own branded planes. The 15 carriers use similar technologies in their production, because their fleets consist primarily of narrow and wide body jets. Carriers on the left hand side of the line are unexceptionally regional airlines, operating as affiliates of the 15 mainline airlines.

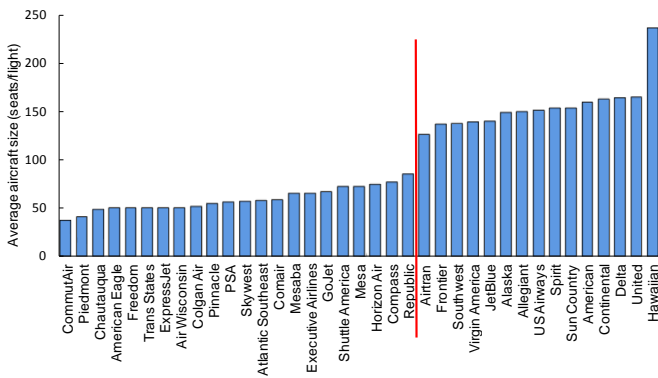


Figure 2. Average aircraft size of U.S. carriers (source: BTS).

In 2010, the 15 mainline airlines account for 80.7% of fuel consumption, and 86.5% RPMs provided in the U.S. domestic passenger air transportation system. Adding the 22 regional carriers, the 37 carriers together represent more than 99% in the system totals in terms of fuel, RPMs, departures, and enplaned passengers. Analyzing the 37 carriers, therefore, will give an almost complete picture of fuel efficiency in the U.S. domestic passenger air transportation system.

##### B. Mainline-only Fuel Efficiency

Airline fuel efficiencies are estimated following the three approaches described in Section 3. The records reported in the BTS Form 41 database are by airline-quarter. Under the ratio-based approach, we aggregate fuel burn and RPM across quarters to obtain annual numbers and calculate the ratio for each airline. When frontier methods are used, we first use airline-quarter observations to estimate the frontiers, based on which to calculate the fuel inefficiency for each observation. These inefficiencies are then averaged to generate the airline-level inefficiency estimates. Two data points (Spirit-Q3 and Frontier-Q4) are removed, because fuel burns depart substantially from those of their respective remaining quarters, while RPM outputs stay similar (the removal is also confirmed by plotting the residuals from preliminary OLS regression under the deterministic frontier approach, in which the two observations are clear outliers). Inefficiency and the associated ranking results are presented in Table I. The Fuel/RPM values in column 1 are standardized and converted to fuel inefficiency scores  $FI_{ratio}$  (column 2), in which value 1 is taken by the carrier with the lowest Fuel/RPM. The frontier estimation results are presented in Table II, with D1 denoting the deterministic frontier, and S1-S4 indicating different versions of stochastic frontiers. The 4th and 6th columns in Table I are the calculated inefficiencies based on D1 ( $FI_{DF}$ ) and S4 ( $FI_{SF}$ ).

TABLE I. FUEL/RPM, INEFFICIENCY SCORES, AND RANKINGS OF THE 15 MAINLINE AIRLINES

Carrier	Fuel/RPM (10 <sup>-2</sup> gallon/RPM)	$FI_{ratio}$	Ratio rank	$FI_{DF}$	DF rank	$FI_{SF}$	SF rank
Spirit	1.563	1.000	1	1.026	1	1.025	3
Continental	1.575	1.007	2	1.044	4	1.053	6
Alaska	1.589	1.016	3	1.030	3	1.028	4
Hawaiian	1.593	1.019	4	1.027	2	1.022	2
Virgin America	1.627	1.041	5	1.126	8	1.145	12
Frontier	1.664	1.065	6	1.061	6	1.051	5
Sun Country	1.714	1.097	7	1.161	11	1.169	13
Jet Blue	1.724	1.103	8	1.061	7	1.093	7
United	1.729	1.106	9	1.133	9	1.138	8
Delta	1.841	1.178	10	1.151	10	1.139	9
Southwest	1.841	1.178	11	1.056	5	1.015	1
US Airways	1.878	1.202	12	1.162	12	1.144	11
Allegiant	1.953	1.250	13	1.282	15	1.283	15
American	1.956	1.252	14	1.247	14	1.242	14
AirTran	1.959	1.253	15	1.173	13	1.140	10

Under the ratio-based approach,  $FI_{ratio}$  for a given airline indicates the percentage of extra fuel consumed to produce one unit of RPM compared to the "best practice", which occurs to Spirit and followed closely by Continental, Alaska, and Hawaiian. The three least fuel efficient carriers are Allegiant,

American and AirTran, approximately 25% less efficient than Spirit. In general, large, legacy carriers are less fuel efficient than their low-cost and smaller rivals.

TABLE II. ESTIMATION RESULTS OF FRONTIER MODELS (MAINLINE ONLY)

	D1	S1	S2	S3	S4
Ln(RPM)	0.869*** (0.040)	0.824*** (5.1e-05)	0.824*** (7.6e-06)	0.824*** (8.0e-06)	0.824*** (7.7e-06)
Ln(dep)	0.150*** (0.038)	0.200*** (3.5e-05)	0.200*** (6.7e-06)	0.200*** (6.9e-06)	0.200*** (6.2e-06)
Constant	-2.726*** (0.494)	-2.344*** (7.6e-04)	-2.344*** (1.0e-04)	-2.344*** (1.1e-04)	-2.344*** (1.1e-04)
Ln(Stage length)			0.008 (0.006)		0.147** (0.070)
Ln(Aircraft size)				0.008 (0.009)	-0.189* (0.100)
R <sup>2</sup>	0.997				
$\sigma_v$		1.7e-09	8.5e-09	8.2e-09	9.4e-09
$\sigma_u$		0.130	0.105	0.112	0.099
Log-likelihood		76.391	76.875	76.606	79.589

\*\*\* significant at 1% level; \*\* significant at 5% level; \* significant at 10% level.

Turning to the deterministic frontier model, we observe a very high R<sup>2</sup> in the frontier estimates, suggesting that the two outputs satisfactorily explain how airlines consume fuel. The estimates imply that: 1) controlling for dep, a 10% increase in RPM would lead to 8.7% more fuel consumption; 2) if one instead increases flight departures by 10% while preserving the total RPM, fuel consumption would rise by 1.5%. Clearly, mobility increase is the stronger driver of fuel requirements than accessibility increase.

As in the ratio-based results, Spirit remain the fuel efficiency champion under the deterministic frontier approach. Because FI<sub>DF</sub>'s are the averages by airline and it is unlikely that all observations for an airline fall on the frontier, the FI<sub>DF</sub> value for the most efficient airline will still be greater than one. The maximum range of relative inefficiency is almost identical (1.282/1.026=1.25) to that under the ratio-based approach. The overall picture that large, legacy carriers are in general less efficient remains valid. Most of the rankings either stay or change only a couple of places, while more drastic changes occur to Southwest, AirTran, Virgin America, and Sun Country.

The more substantial changes are mainly due to the introduction of dep as part of the airline production outputs. Given the frontier estimates, the inefficiency measure is equivalent to  $\frac{\text{Fuel}}{(\text{RPM})^{0.869}(\text{dep})^{0.150}}$  or  $\frac{\text{Fuel}}{\text{RPM}} \cdot \frac{1}{(\frac{\text{dep}}{\text{RPM}})^{0.150}} \cdot \frac{1}{\text{RPM}^{0.019}}$  in which the last two terms explain the departure from the ratio-based results. As shown in Fig. 3, airlines with higher

dep/RPM ratios, such as Southwest and AirTran, will be rewarded. Those having lower dep/RPM will slip in the ranking, as in the case of Virgin America. Closer inspection of the data reveals that the major source contributing to the difference in dep/RPM is stage length.<sup>2</sup> For example, the average stage length of Virgin America is more than double that of Hawaiian and Southwest (however, the effect of shorter stage length for Hawaiian is compromised by its significantly larger average aircraft size). In addition, the second term  $\frac{1}{\text{RPM}^{0.019}}$  suggests that deterministic frontier would slightly penalize airlines with smaller operation scales, such as Sun Country and Allegiant.

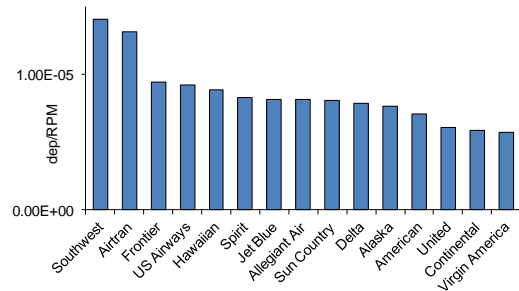


Figure 3. Dep/RPM ratio among the 15 mainline carriers.

The four stochastic frontier models in Table II correspond to four different specifications about  $u_{it}$ . S1 presents the basic version in which  $u_{it}$  is assumed half-normally distributed. S2-S4 consider the heterogeneity of airline operations by incorporating output characteristics in the mean of  $u_{it}$ , which is assumed to have truncated normal shapes. In S2 and S3, we include stage length and aircraft size, respectively, as the only explanatory variable for the mean of the efficiency term. S4 includes both. We have also experimented with a specification that further includes load factor in the mean inefficiency term. However, the coefficient for load factor appears highly insignificant. We do not include a constant in specifying the mean of  $u_{it}$  in S2-S4, as such models fail to converge based on our computational experiences. Somewhat surprisingly, all the four models support essentially the same conclusions concerning the structure of the fuel consumption technology. Compared to the deterministic frontier, the relative importance of RPM in frontier determination is reduced (from 0.869 to 0.824); whereas the coefficient of dep increased from 0.150 to 0.200.

Focusing on the coefficients for the environmental variables, stage length and aircraft size have the expected positive sign in S2 and S3, as flying longer and larger aircraft will consume more fuel. However, neither of the coefficients is statistically significant. When stage length and aircraft size are included in S4, both turn out to be statistically significant. The still positive but much larger coefficient for stage length is consistent with what we would expect at the flight level: controlling for RPM, departures, and aircraft size, flying longer

<sup>2</sup> It can be easily seen that  $\text{RPM} = \text{dep} * (\text{Average stage length}) * (\text{Average aircraft size}) * (\text{Average load factor})$ . For the 15 mainline airlines, average aircraft size and load factor are fairly close, except for Hawaiian in aircraft size.

distance means not only more fuel burn but a lower load factor, resulting in lower fuel efficiency. On the other hand, the negative sign appearing on aircraft size, significant at the 10% level, seems counter-intuitive. It implies that, keeping RPM, departures, and stage length constant, flying larger, and thereby emptier, planes increases fuel efficiency, or at least does not decrease it. While this seems implausible at the flight level, it must be remembered that this analysis is performed at the airline level. It is not unusual to obtain results at a given level of analysis that are counterintuitive at a different level of analysis, a phenomenon known as the "ecological fallacy". In this instance, the correct interpretation is that, all else equal, airlines with larger average aircraft sizes operate closer to the fuel consumption frontier.

We choose S4 as the preferred model, given the significance of both the stage length and aircraft size coefficients. The choice is further supported by the Likelihood Ratio (LR) test results in Table III. To facilitate exposition, we express the general form of the mean efficiency term as  $E(u_{it}) = \delta_1(\text{Stage length})_{it} + \delta_2(\text{Aircraft size})_{it}$ . Table III shows that we reject  $H_0$  in all three tests.

TABLE III. LIKELIHOOD RATIO TESTS ACROSS MODELS S1-S4

Null Hypothesis	$\chi^2$ -statistic	Prob $> \chi^2$	Decision
$H_0: \delta_1 = \delta_2 = 0$	6.39	0.0409	Reject $H_0$
$H_0: \delta_1 = 0$	5.97	0.0146	Reject $H_0$
$H_0: \delta_2 = 0$	5.43	0.0198	Reject $H_0$

Before turning to the inefficiency score values, it will be helpful to understand how estimates of inefficiency are obtained. Given the much smaller  $\sigma_v$  than  $\sigma_u$ , the stochastic frontier essentially collapses to a deterministic frontier. This can be shown through the calculation of  $FI_{SF,it}$ , for which  $\exp(\hat{\epsilon}_{it})$  is a very good approximation in our case [11]. As a consequence, difference in inefficiency from those using the deterministic frontier should be attributed to the difference in parameter estimates for RPM and dep. In the stochastic frontier models, further weight is given to departures. Therefore, airlines offering greater accessibility (i.e. with a higher dep/RPM ratio) will move up further in the rankings.

The actual inefficiency estimates confirm this. Most drastic inefficiency change and ranking movements occur to airlines with the highest or lowest dep/RPM values. Southwest leaps forward to the top ranking; AirTran also improves significantly, from the 13th to the 10th. By contrast, Virgin America falls from the 8th to the 12th. Continental drops by two places. The other airlines have less glaring inefficiency and ranking changes. Compared to Southwest, the least efficient Allegiant burns on average 26.3% more fuel, still comparable to the fuel efficiency differences found using the ratio and deterministic frontier approaches. The inefficiency estimates maintain the general impression that large, legacy carriers occupy the lower rungs of the efficiency ladder.

### C. Mainline-sub Affiliations

#### 1) Assigning regional airlines' operation to mainline carriers

While the previous analysis considers mainline airlines only, we argue that, since many mainline airlines depend on regional affiliates for much of their service, fuel efficiency assessment should incorporate fuel consumption and output from both mainline airlines and their regional partners. Towards this end, the first step is to accurately assign regional carriers' operations (in RPMs) to mainline airlines. We consider the 22 regional carriers that are introduced in the beginning of this section. Their subcontracted code share agreements with the mainline airlines usually belong to one of the following three types [12]:

- A regional carrier is a wholly owned subsidiary of the parent mainline airline company, or completely controlled by the mainline airline;
- A regional carrier is an independent company but contracts out all its operations to one mainline carrier;
- A regional carrier is an independent company and has code share agreements with multiple mainline airlines, depending upon geographic regions and hub airports.

For the first two types, 100% of the regional carriers' RPMs are assigned to the corresponding mainline airline. Assignment under the third type can be difficult, especially in situations where the regional carrier services more than one mainline airline on a flight segment. For the last type, we look at the relationship between the regional and mainline carriers on a segment-by-segment basis. We track the segment-level affiliation information through the regional and mainline airlines' websites based on their route maps, and other on-line resources such as Wikipedia and Airlines.net as back-up confirmation. To avoid unnecessary time spending on those very thin segments while ensuring the credibility of the assignment process, we focus on flights in and out of the Operational Evolution Partnership 35 airports ([http://aspm.help.faa.gov/index.php/OEP\\_35](http://aspm.help.faa.gov/index.php/OEP_35)) in the U.S., using the BTS T100 Domestic Segment Traffic database. These flights account for the vast majority of RPMs in the regional carrier's total—over 90% for all but one regional carrier (Chautauqua) of this type.

One particular situation for the type 3 regional carriers is when one regional carrier serves more than one mainline airline on the same flight segment. We assign the regional carrier's total RPMs on that segment to different mainline airlines based on the proportion of passengers that purchased tickets under each mainline carrier's name, using the BTS DB1B database. As already pointed out, passengers on these segments are likely to be transported by regional carriers, while the tickets reported to BTS show the names of the affiliated mainline airlines. This "polygamous" situation occurs quite rarely—on a total of about 50 segments. Therefore, any potential error due to the lack of knowledge should be rather small. The assigned RPMs on each segment are then aggregated across one regional carrier's entire network to obtain the RPMs and the percentages attributable to the incumbent mainline carriers. The RPMs are then adjusted by the ratio between the total RPMs reported from Form 41 and

T100 databases, to maintain the consistency with aggregate fuel and departure reporting. In 2010, American, Delta, United, US Airways, Alaska, and Frontier were using regional carriers in their operations.

## 2) Adjusted fuel efficiency

Besides RPMs, the efficiency estimation also requires the assignment of fuel and departures. In the stochastic frontier models, we need to compute further the composite average aircraft size and stage length. Absent relevant information, we assume that the assignment of fuel, departures, ASM, and revenue aircraft miles are proportional to RPM assignment.<sup>3</sup>

Similar to the mainline-only case, we report in Table IV the composite Fuel/RPM values, adjusted inefficiency scores under the three approaches ( $FI_{ratio}^c$ ,  $FI_{DF}^c$ ,  $FI_{SF}^c$ ), together with the ranking changes with respect to results in Table I. Airlines are ordered by composite Fuel/RPM values. Due to the paper size limit, new frontier estimation results are not presented here. Interested readers can refer to [11] for more details.

TABLE IV. FUEL/RPM, INEFFICIENCY SCORES, AND RANKINGS OF THE 15 MAINLINE AIRLINES (WITH MAINLINE-REGIONAL AFFILIATIONS)

Carrier	Composite Fuel/RPM (10 <sup>-2</sup> gallon/RPM)	$FI_{ratio}^c$	Ratio rank change	$FI_{DF}^c$	DF rank change	$FI_{SF}^c$	SF rank change
Spirit	1.5629	1.000	0	1.043	↓1	1.043	0
Hawaiian	1.5932	1.019	↑2	1.047	↓1	1.041	0
Virgin America	1.6266	1.041	↑2	1.153	↓1	1.167	0
Alaska	1.6844	1.078	↓1	1.026	↑2	1.019	↑3
Sun Country	1.7143	1.097	↑2	1.171	↑1	1.162	↑2
Jet Blue	1.7240	1.103	↑2	1.131	0	1.134	↓1
Continental	1.8042	1.154	↓5	1.064	0	1.048	↑2
Southwest	1.8412	1.178	↑3	1.085	0	1.069	↓4
Frontier	1.8539	1.186	↓3	1.123	0	1.100	↓1
United	1.9376	1.240	↓1	1.140	↑1	1.121	↑1
Allegiant	1.9533	1.250	↑2	1.305	0	1.296	0
AirTran	1.9589	1.253	↑3	1.195	0	1.173	↓3
Delta	2.0568	1.316	↓3	1.178	↓1	1.153	↓1
American	2.0985	1.343	0	1.265	0	1.248	0
US Airways	2.1050	1.347	↓3	1.183	0	1.148	↑2

Under the ratio-based approach, the seven mainline airlines that have regional affiliations experience increase in Fuel/RPM, by 6-14.6%, because regional carriers are less efficient in terms of Fuel/RPM. As a consequence, most of the remaining carriers with no regional affiliation see an improvement in ranking. Incorporating regional carriers also widens the efficiency gap

<sup>3</sup> Composite average aircraft size is calculated as the ratio of composite ASM over composite revenue aircraft miles; composite average stage length the ratio of composite revenue aircraft miles over composite flight departures.

between the first and last carriers, with latter now 35% less efficient than the former.

When the deterministic frontier model is employed, the effect of having regional carriers on fuel efficiency is no longer unidirectional, but depends upon two competing forces. First is the greater fuel burn per RPM of regional carriers, which tends to drag down the fuel efficiency of the associated mainline airlines. On the other hand, the inclusion of regional carriers increases the level of accessibility of the associated mainline airlines, thereby improving their inefficiency scores. As shown in Fig. 4, the dep/RPM ratios of the seven mainline airlines that affiliate with regional carriers rise considerably, by 50-137%. The accessibility effect is further enhanced by a larger coefficient for dep and a smaller one for RPM than in the mainline-only case, which are expected because of shorter average stage length of regional carriers and therefore a larger portion of fuel consumed in takeoff/landing operations. The resulting net ranking change is rather small.

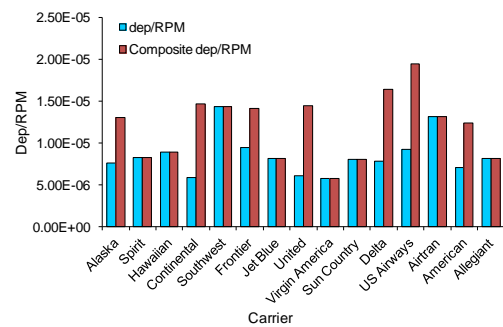


Figure 4. Dep/RPM ratios for the 15 mainline carriers with and without considering their regional carrier affiliations.

The above argument of competing forces applies as well to efficiency estimates using the stochastic frontier models. Again, the competing forces lead to non-unidirectional ranking changes, which are slightly more substantial than when the deterministic frontier model is applied.

## D. Efficiency with Routing Circuitry

### 1) Routing circuitry calculation

When routing circuitry is considered, the mobility output RPM is replaced by RPODM. The airline level circuitry measure is constructed as the ratio between total passenger itinerary miles and total non-stop passenger miles, using the BTS DB1B database. Because regional carriers are included in the DB1B database but their tickets are masked by their mainline partners, the passenger itinerary and non-stop miles are mainline-regional composite measures. The resulting efficiency therefore captures the joint efficiency of a mainline airline with its affiliated regional carriers in moving passengers from their origins to destinations.

Fig. 5 shows the results of the circuitry calculation for each of the 15 mainline airlines in 2010. Except for Allegiant which flew passengers only point-to-point, all the remaining airlines were involved, with varying degrees, in connecting services. The circuitry difference between the large, legacy carriers, which adopt primarily hub-and-spoke systems, and the other smaller airlines exists but is not substantial. This suggests that



the hub-and-spoke airlines take circuitry into account when routing passengers. The small circuitries also imply that the efficiency adjustment due to routing circuitry may not be significant. This conjecture is confirmed in the analysis results.

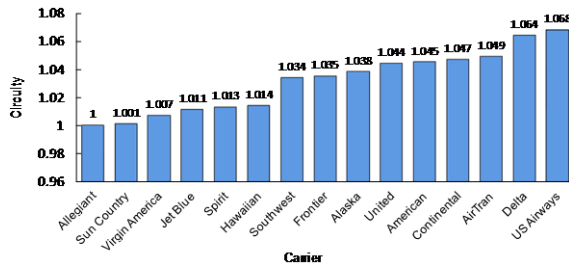


Figure 5. Routing circuitry of the 15 mainline airlines in 2010.

## 2) Adjusted fuel efficiency

We follow the same reporting format by presenting the efficiency estimates in Table V, where airlines are ordered by Fuel/RPODM values. Changes in ranking are with respect to those in the mainline-regional composite case.

TABLE V. FUEL/RPODM, INEFFICIENCY SCORES, AND RANKINGS OF THE 15 MAINLINE AIRLINES (WITH ROUTING CIRCUITY)

Carrier	Fuel/RPODM (10 <sup>-2</sup> gallon/RPM)	FI <sub>ratio</sub> <sup>circuitry</sup>	Ratio rank change	FI <sub>DF</sub> <sup>circuitry</sup>	DF rank change	FI <sub>SF</sub> <sup>circuitry</sup>	SF rank change
Spirit	1.5835	1.000	0	1.042	0	1.043	0
Hawaiian	1.6163	1.021	0	1.043	0	1.039	0
Virgin America	1.6376	1.034	0	1.160	0	1.175	0
Sun Country	1.7156	1.083	↑1	1.166	0	1.161	0
Jet Blue	1.7436	1.101	↑1	1.122	0	1.127	0
Alaska	1.7480	1.104	↓2	1.023	0	1.017	0
Continental	1.8895	1.193	0	1.061	0	1.046	0
Southwest	1.9039	1.202	0	1.069	0	1.056	0
Frontier	1.9185	1.212	0	1.118	0	1.098	0
Allegiant	1.9533	1.234	↑1	1.291	0	1.286	0
United	2.0235	1.278	↓1	1.132	0	1.117	0
AirTran	2.0550	1.298	0	1.202	0	1.183	0
Delta	2.1892	1.382	0	1.181	0	1.159	0
American	2.1923	1.384	0	1.263	0	1.249	0
US Airways	2.2483	1.420	0	1.186	0	1.154	0

Due to the small circuitry values, we observe that most Fuel/RPODM are marginally greater than the composite Fuel/RPM values. Because the inter-airline variation in circuitry is not substantial, only minor changes occurs to efficiency ranking. Since Spirit, the most fuel efficient airline, has low circuitry and US Airways, the most inefficient airline, has the highest circuitry, the maximum efficiency gap is further widened, with US Airways now 42% less efficient than Spirit.

Switching to the deterministic frontier estimates, the net effect of circuitry is not substantial across all airlines compared to the composite case. The efficiency rankings remain much the same. As in the deterministic case, no change occurs to the efficiency rankings based on re-estimated stochastic frontier models. These results imply that circuitry has only minor effects on the fuel efficiency of the 15 mainline airlines investigated.

## V. CONCLUSION

In this paper, we have investigated the fuel efficiency of 15 U.S. large jet operators in 2010 using ratio-based, deterministic and stochastic frontier approaches. The ratio-based method, measuring fuel consumption per unit mobility output, has been popular for its simplicity; whereas the frontier approaches are able to capture both the mobility and accessibility dimensions of airline production output. The deterministic frontier can be viewed as a special case of the ratio-based approach, but with mobility and accessibility components empirically determined and entering the denominator of the ratio. The stochastic frontier separates idiosyncratic errors from the true inefficiency, with the additional option of modeling the effect on efficiency of heterogeneity in operating environment. In the present study, this is through introducing environmental variables in the mean of the efficiency term in the stochastic frontier models. We find that the efficiency term dominates over the idiosyncratic errors. As a consequence, the stochastic frontier can be reasonably approximated by its corresponding deterministic frontier.

In addition to offering multiple approaches to measure airline fuel efficiency, one unique feature of our study is its consideration of regional carriers. Since regional carriers are in general less fuel efficient on a RPM basis, considering regional affiliations reduce the fuel efficiency of the mainline airlines under the ratio-based approach. On the other hand, regional carriers provide services with high accessibility. The frontier models, by recognizing accessibility as an output, offer a more nuanced picture of the impact of regional affiliations on mainline fuel efficiency. In these models, regional carrier affiliations can boost the measured efficiency and ranking of the corresponding mainline airlines.

Building upon the joint mainline-regional efficiency analysis, we have further investigated fuel efficiency with respect to moving passengers from their origins to destinations. Under the ratio-based approach, incorporating the circuitry effect penalizes airlines with significant portions of their service through hub airports. In the frontier models, although substitution of RPODM for RPM reshapes the frontiers, differences in efficiency scores with and without considering circuitry are rather small. Overall, our efficiency measurement results show that the average fuel efficiency of the 15 carriers is 9-20% less than that of the most efficient carrier in 2010, while the least efficient carriers are 25-42% less efficient than the industry leaders.

While the present study focuses on the efficiency of fuel, fuel represents only one input in airline production, and the corresponding frontier models can be interpreted as factor requirement functions [13]. In principle, substitution between fuel and other inputs can be possible. However, we believe that

the substitution effect is fairly weak. In the long run, fuel efficiency gains from technical advance are expected to be much stronger than those from factor substitution. This is analogous to the argument that technical efficiency tends to dominate in the overall changes in productive efficiency [14]. From the technical vantage point, the most plausible substitution for fuel is capital, which, as widely recognized in airline economics literature [15] [16], cannot be varied instantaneously, particularly at the present time when new aircraft order books are quite full. It is unlikely that airlines are willing and able to employ other forms of input substitution to improve fuel usage to any significant extent. Of course, these arguments aside, additional empirical investigation will still be very helpful to better understanding the relationship between airline fuel efficiency, input substitution, and overall productivity.

Taking this one step further, it must be remembered that the ultimate objective of an airline, like any other corporate firm, is to maximize profit, which is the result of the relationship between productivity, market power, regulatory controls, and the choice of markets to serve [17]. If an airline can generate higher profit with an existing, older fleet than from investing in improving its fuel efficiency, it can be expected to choose the former option. On the other hand, growth and volatility in fuel prices, which have historically played a significant role in driving airline fuel efficiency, are likely to continue to do so in the future. Policy interventions, such as the European ETS or the future global framework of ETS and aviation emission reduction, may also do. Another, still growing, force comes from those members of the general public whose travel choices may be influenced by their commitment to sustainability and perceptions of how different travel alternatives accord with this value. This in turn provides airlines—indirectly through the market mechanism—with an additional impetus to improve their fuel efficiency. For pressures of this kind to be effective, clear and credible fuel efficiency information is certainly important. Our study presents a start in this direction.

#### ACKNOWLEDGMENT

This research was funded by the International Council on Clean Transportation. The enthusiastic support from Dr. Mazyar Zeinali, Dr. Dan Rutherford, and Irene Kwan is gratefully acknowledged.

#### REFERENCES

- [1] International Air Transport Association (IATA), "Fact sheet: Carbon offset," available at: [https://www.iata.org/pressroom/facts\\_figures/fact\\_sheets/pages/carbon-offsets.aspx](https://www.iata.org/pressroom/facts_figures/fact_sheets/pages/carbon-offsets.aspx). Accessed on Aug 9, 2012.
- [2] S. Forbes and M. Lederman, "The Role of Regional Airlines in the U.S. Airline Industry," In: *Advances in Airline Economics* (D. Lee, ed.), Vol. 2, Elsevier, 2005.
- [3] M. Karlaftis and D. Tsamboulas, "Efficiency measurement in public transport: are findings specification sensitive?" *Transp. Res. Part A: Policy Practice*, vol. 46, pp. 392-402, 2012.
- [4] R. Windle and M. Dresner, "Partial productivity measures and total factor productivity in the air transport industry: limitations and uses," *Transp. Res. Part A: Policy Practice*, vol. 26, pp. 435-445, 1992.

- [5] T. Litman, "Measuring transportation: traffic, mobility and accessibility," available at: <http://www.vtpi.org/measure.pdf>. Accessed on Aug 2, 2012.
- [6] S. Kumbhakar and C. Lovell, *Stochastic Frontier Analysis*. Cambridge University Press, Cambridge, UK, 2003.
- [7] D. Aigner, C. Lovell, and P. Schmidt, "Formulation and estimation of stochastic frontier production function models," *J. Econom.*, vol. 12, pp. 21-37, 1977.
- [8] R. Stevenson, "Likelihood functions for generalized stochastic frontier estimation," *J. Econom.*, vol. 13, pp. 57-66, 1980.
- [9] G. Battese and T. Coelli, "A stochastic frontier production function incorporating a model for technical inefficiency effect," unpublished working paper, Department of Economics, University of New England, New South Wales, Australia, 1993.
- [10] G. Battese, A. Heshmati, and L. Hjalmarsson, "Efficiency of labour use in the Swedish banking industry: a stochastic frontier approach," *Empir. Econ.*, vol. 25, pp. 623-640, 2000.
- [11] B. Zou, M. Elke, and M. Hansen, "Evaluating air carrier fuel efficiency and co2 emissions in the u.s. airline industry," unpublished.
- [12] L. Truit and R. Hayes, "Evaluating service quality and productivity in the regional airline industry," *Transp. J.*, vol. 33, pp. 21-32, 1994.
- [13] H. Gathon and S. Perelman, "Measuring technical efficiency in European Railways: a panel data approach," *J. Product. Anal.*, vol. 3, pp. 135-151, 1992.
- [14] T. Oum, W. Waters II, and C. Yu, "A survey of productivity and efficiency measurement in rail transport," *J. Transp. Econ. Policy*, vol. 33, pp. 9-42, 1999.
- [15] M. Hansen, D. Gillen, and R. Djafarian-Tehrani, "Aviation infrastructure performance and airline cost: a statistical cost estimation approach," *Transp. Res. Part E: Logist. Transp. Rev.*, vol. 37, pp. 1-23, 2001.
- [16] B. Zou and M. Hansen, "Impact of operational performance on air carrier cost structure: evidence from us airlines," *Transp. Res. Part E: Logist. Transp. Rev.*, vol. 48, pp. 1032-1048, 2012.
- [17] D. Hensher, "Productivity and performance: Editorial," *Transp. Res. Part A: Policy Practice*, vol. 26, pp. 433-434, 1992.

#### AUTHOR BIOGRAPHY

**Bo Zou** is Assistant Professor of Civil and Materials Engineering at the University of Illinois at Chicago. Dr. Zou graduated from the University of California, Berkeley in 2012 where he pursued his doctoral studies under Professor Mark Hansen. Dr. Zou also holds a Master's degree in transportation planning and management from Tsinghua University and a Diplôme d'Ingénieur from the Ecole Centrale de Nantes, both in 2007. Dr. Zou's main research interests include aviation systems analysis, air transport economics, operations, and policy.

**Matthew Elke** received his B.S. in viticulture enology from UC Davis in 2003, a Master's degree in environmental science and management from UC Santa Barbara in 2007, and a second Master's degree in engineering from UC Berkeley in 2012. He has been a research assistant at the National Center of Excellence for Aviation Operations Research over the past two years and involved in research projects including airline fuel efficiency and air cargo.

**Mark Hansen** is Professor of Civil and Environmental Engineering at the University of California, Berkeley. He graduated from Yale with a Bachelor's degree in Physics and Philosophy in 1980, and has a PhD in Engineering Science and a Masters in City and Regional Planning from UC Berkeley. Since joining the Berkeley faculty in 1988, he has led transportation research projects in urban transportation planning, air transport systems modeling, air traffic flow management, aviation systems performance analysis, aviation safety, and air transport economics. Professor Hansen is the Berkeley co-director of the National Center of Excellence in Aviation Operations Research, a multi-university consortium sponsored by the Federal Aviation Administration. He is the former Chair of Transportation Research Board Committee AV-060, Airport and Airspace Capacity and Delay.