EVALUATING AIR CARRIER FUEL EFFICIENCY IN THE U.S. AIRLINE INDUSTRY

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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 fuel efficiency of mainline carriers 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) explicitly characterizing operating environment heterogeneity in the efficiency has very limited effects on efficiency measurement; 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 circuity on fuel efficiency is small; 5) potential cost savings from improved efficiency for mainline airlines can reach $2-3 billion in 2010.

Keywords: airline fuel efficiency; mainline airline; regional carrier; routing circuity; frontier model

INTRODUCTION

Airlines are more intent nowadays than ever to increase 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_2), one of the most visible and important greenhouse gases, is regulated under the European emissions trading scheme, is directly tied to the amount of fuel consumed in flight operations. Any monetization of CO_2, therefore, spurs further airlines 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 (IATA, 2012). Travel management companies, responsible for airline and airfare selection in business travel, have growing interests in incorporating fuel efficiency in their decision making process (Business Travel news, 2009).[1] 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 the status quo of the industry fuel use, 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. In addition, 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. When focus is on airline fuel efficiency with regard to passenger trips rather than airline itineraries, the efficiency results also need to be adjusted to account for routing circuity, which reflects how efficiently passengers were moved from their origins to their destinations. 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

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[1] The decision process of TMCs typically involve three boxes: fare, availability (e.g. when and where tickets are available), and intangible parts such corporate social responsibility (CSR). While the environmental piece remains largely missing in the decision making process, TMCs have the tendency to introduce greenhouse gas emissions as a factor in the intangible parts and place more weight on the third box. Through personal communication with the International Council on Clean Transportation.

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 airline industry organization in the U.S. 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 circuity. Further discussions on the correlation of different efficiency results, temporal evolution of efficiencies, and potential cost savings from fuel efficiency improvement are conducted in Section 5. Conclusions are presented in Section 6.

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 the above carriers, 30-50% of passengers completed their trips by connecting at least once at an intermediate hub airport.[2] 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 academic research as the economies of density, has helped legacy carriers reduce unit operating expense and offer low airfares to passengers. At the same time, hubbing enables 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 efficiencies. 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.

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[2] Based on authors' calculation using the Bureau of Transportation Statistics Airline Origin and Destination Survey (DB1B) data in 2010.

In addition to legacy and low-cost carriers, regional carriers constitute another integral components of the system. Regional carries 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 mainline airlines the lead partners in terms of marketing and branding. Regional aircraft liveries are based on their mainline partners, who also handle ticket sales and scheduling. This is reflected in the airline ticket reporting process to the U.S. Bureau of Transportation Statistics (BTS). For example, in the BTS Airline Origin and Destination Survey (DB1B) database, the portions of itineraries flown on regional carriers are displayed under the name of the affiliated mainline carriers.

The use of regional subsidiaries and hub-and-spoke operations by mainline carriers give rise to two issues which have not been considered in existing airline fuel efficiency studies. 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 based on conventional metrics; 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 is more appropriately measured by origin-to-destination distance than total distance travelled. Both of these two issues will be explicitly addressed in the remainder of the paper.

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 (Karlaftis and Tsamboulas, 2012). Specific to 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 virtues 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 accounts for inter-carrier differences in output characteristics that may significantly affect fuel requirements but are—at least arguably—not related to fuel efficiency per se. 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 methodologically dependent.

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, where as 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 (Windle and Dresner, 1992). Therefore, RPM and RTM are preferred. These reward 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 cargo, mail and other types of business (as shown later in sub-section 4.1). 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 RPM's 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 in sub-section 4.3, the data sources available for performing this task are all passenger based. Using RPM will preserve the 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, $\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}}$:

$$\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}}=\frac{\mathrm{Fuel}_{\mathrm{i}}+\mathrm{Fuel}_{\mathrm{j}_1}^{\mathrm{i}}+\mathrm{Fuel}_{\mathrm{j}_2}^{\mathrm{i}}+\cdots+\mathrm{Fuel}_{\mathrm{j}_\mathrm{n}}^{\mathrm{i}}}{\mathrm{RPM}_{\mathrm{i}}+\mathrm{RPM}_{\mathrm{j}_1}^{\mathrm{i}}+\mathrm{RPM}_{\mathrm{j}_2}^{\mathrm{i}}+\cdots+\mathrm{RPM}_{\mathrm{j}_\mathrm{n}}^{\mathrm{i}}} \quad (1)$$

where $(\mathrm{Fuel})_{\mathrm{j_k}}^{\mathrm{i}}$ and $(\mathrm{RPM})_{\mathrm{j_k}}^{\mathrm{i}}$denote, respectively, the fuel consumed by regional carrier jk that is attributable to mainline airline i's operations ($\mathrm{Fuel}_{\mathrm{j_k}}^{\mathrm{i}}$), and the RPM's from j_k (k = 1, …, n) that should be assigned correspondingly to i ($\mathrm{RPM}_{\mathrm{j_k}}^{\mathrm{i}}$). Essentially, $\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}}$ 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 RPM's across the mainline and the regional carriers. The exact estimation of $\mathrm{RPM}_{\mathrm{j_k}}^{\mathrm{i}}$ and $\mathrm{Fuel}_{\mathrm{j_k}}^{\mathrm{i}}$ 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 ratio metric needs to be further adjusted. We multiply $\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}}$ by the corresponding routing circuity, which is defined as the ratio between total RPMs and total revenue passenger O-D miles (RPODM) for each airline:

$$\left(\frac{\mathrm{Fuel}}{\mathrm{RPODM}}\right)_{\mathrm{i}} = \left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}} \times \left(\frac{\mathrm{RPM}}{\mathrm{RPODM}}\right)_{\mathrm{i}} \tag{2}$$

Because circuity always takes values no less than one, airlines with high circuity will be penalized compared to those flying direct routes.

The preceding discussion can be synthesized in a four-level hierarchical structure in Figure 1, where the arrows indicate that one metric at the higher level is comprised of lower-level metrics at which the arrows are directed. At the top level, $\left(\frac{\mathrm{Fuel}}{\mathrm{RPODM}}\right)_{\mathrm{i}}$ measures how efficient an airline (indexed by i) is in transporting passengers between their O-Ds. At the second level, we decompose $\left(\frac{\mathrm{Fuel}}{\mathrm{RPODM}}\right)_{\mathrm{i}}$ into the product of $\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}}$ and $\left(\frac{\mathrm{RPM}}{\mathrm{RPODM}}\right)_{\mathrm{i}}$, the latter penalizing airlines operating with circuitous routing structures. $\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}}$ is the adjusted fuel/RPM that takes into account the contribution of regional carriers' operations to mainline airline i. We express $\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}^{\mathrm{adjusted}}$ 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 (k = 1, …, n) that is attributable to mainline i. The "*" operator realizes the computation as shown in Equation (1). At the bottom level, $\left(\frac{\mathrm{Fuel}}{\mathrm{RPM}}\right)_{\mathrm{i}}$ is further decomposed into the product of $\left(\frac{\mathrm{Fuel}}{\mathrm{ASM}}\right)_{\mathrm{i}}$ and $\left(\frac{\mathrm{ASM}}{\mathrm{RPM}}\right)_{\mathrm{i}}$, the latter of which is the reciprocal of airline i's average load factor. This suggests that if the amount of output produced 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.

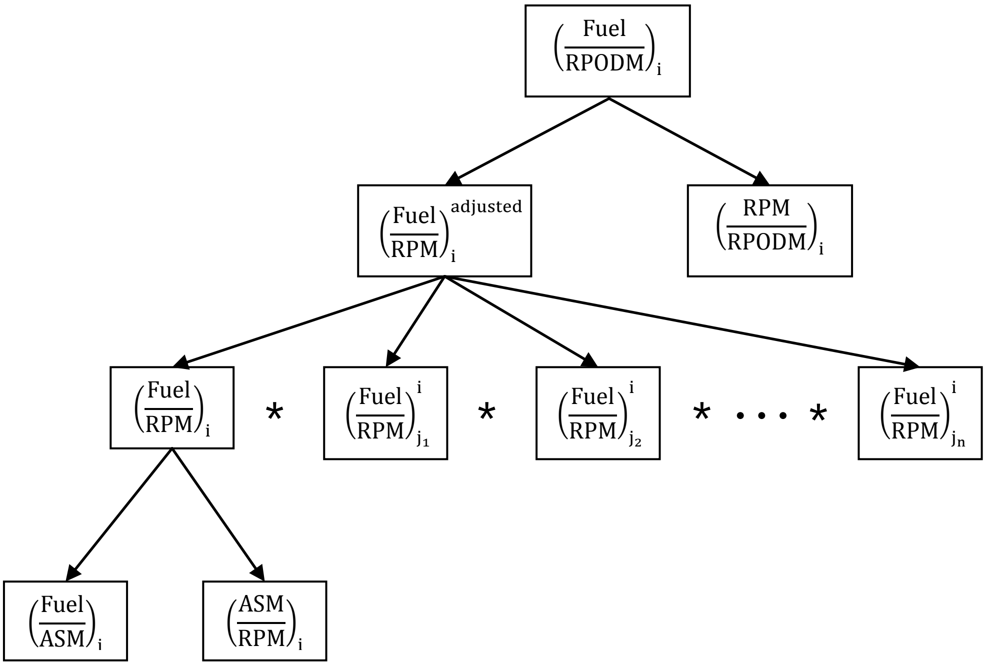

Figure 1 – Four-level Hierarchical Structure of Fuel Efficiency Metrics

Frontier approaches

A standard metric for airline production output, RPM used in the ratio based approach measures 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 (Litman, 2011). 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 RPM will yield a distorted measure of its fuel efficiency. It is therefore necessary to include both mobility and accessibility aspects in characterizing airline production output.

The rationale in applying frontier approaches to airline fuel efficiency measurement is that airlines consume no less than the amount of fuel under "best practice" on the fuel consumption frontier, given the same production output. The "best practice" frontier is constructed using observed fuel consumption, and indicate the minimum possible fuel burn in order to produce a given level of output. A general fuel consumption model can be specified as:

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

where subscript i denotes a specific airline, and t identifies the time period; $\text{f}(\text{RPM}_{\text{it}}, \text{dep}_{\text{it}})$ specifies the fuel consumption frontier; u_{it} is a non-negative deviation term. The inefficiency of airline i at time t is measured as $\exp(u_{it})$. 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 our assumption about $f(RPM_{it}, dep_{it})$.

Deterministic frontier

The deterministic frontier model assumes that the frontier part of the fuel consumption model, $f(RPM_{it}, dep_{it})$, can be deterministically characterized. We specify the fuel consumption model which follows a log-linear functional form:

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

The frontier model can be estimated using Corrected Ordinary Least Square (COLS) method, in two steps (Kumbhakar and Lovell, 2003). In the first step, we apply OLS to obtain consistent and unbiased estimates of the two slopes β_1 and β_2, and an initial intercept β_0', which is consistent but biased. Residuals $\hat{\eta}_{it}$ for each observation are then calculated. In the second step, we correct β_0' by shifting it downwards until it becomes β_0, in which case no residual in the sample is negative, and at least one is zero. Therefore, $\beta_0 = \beta_0' + \min_{i,t}\{\hat{\eta}_{it}\}$, and the inefficiency for airline i at time t is $\exp(u_{it}) = \exp[\hat{\eta}_{it} - \min_{i,t}\{\hat{\eta}_{it}\}]$.

The deterministic frontier attributes all deviations of the observed fuel burn from the frontier, characterized by the estimated coefficients $\beta_0, \beta_1, \beta_2$, to inefficiency in fuel usage. In effect, the inefficiency $\exp(u_{it})$ is equal to $\frac{1}{\exp(\beta_0)} \cdot \frac{(fuel)_{it}}{RPM_{it}^{\beta_1} dep_{it}^{\beta_2}}$, where $\frac{1}{\exp(\beta_0)}$ is a constant across observations. Therefore, the deterministic frontier approach can be also 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 associated regional subsidiaries, 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, which will be different from mainline-only frontier. When routing circuity is further considered, we substitute the corresponding RPODM values for the composite RPMs, and estimate a new frontier. The procedure for assessing efficiency remains unchanged once the appropriate frontier is obtained.

Stochastic frontier

The deterministic frontier model has the advantages of being easy to estimate. On the other hand, 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 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 two issues, we also consider stochastic frontier models, which are capable of separating shocks due to uncontrollable factors such as vagaries of weather and plain luck, from the true variation in fuel efficiency. Specifically, an idiosyncratic error term $\mathrm{v_{it}}$ is introduced to the frontier part of Eqn (4). The fuel consumption model becomes:

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

The associated fuel consumption frontier is $\mathrm{exp\,(\beta_0) RPM_{it}^{\beta_1} dep_{it}^{\beta_2} exp\,(v_{it})}$ which, because of the idiosyncratic error term $\mathrm{v_{it}}$, becomes stochastic.

Under the assumptions that 1) $\mathrm{v_{it}}$'s have identically and independently normal distributions, i.e. $\mathrm{v_{it}} \sim \mathrm{iid}\, N(0, \sigma_\mathrm{v}^2)$; 2) $\mathrm{u_{it}}$'s follow some non-negative identically and independent distributions; 3) $\mathrm{u_{it}}$ and $\mathrm{v_{it}}$ are distributed independently of each other, and of the regressors in (5), the parameters β's and those characterizing the distribution of $\mathrm{u_{it}}$ and $\mathrm{v_{it}}$ can be estimated jointly using maximum likelihood method (e.g. Aigner, Lovell and Schmidt, 1977; Stevenson, 1980). In the subsequent analysis, we first assume $\mathrm{u_{it}}$ to follow a half-normal normal distribution, one of the most widely used distributions in the efficiency literature. Since $\mathrm{u_{it}} \sim \mathrm{iid}\, N^+(0, \sigma_\mathrm{u}^2)$, σ_u^2 is the only distribution parameter to be estimated associated with $\mathrm{u_{it}}$'s.

The assumption that all $\mathrm{u_{it}}$'s have the same half-normal distribution is certainly restrictive. 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 iid normal assumption about the efficiency terms, and assume that $\mathrm{u_{it}}$'s are independently but not identically distributed as non-negative truncations of a general normal distribution, following Battese and Coelli, (1995):

$$\mathrm{u_{it}} \sim N^+\left(\sum_{\mathrm{j=1}}^{\mathrm{M}} \delta_\mathrm{j} z_\mathrm{j,it}, \sigma_\mathrm{u}^2\right) \tag{6}$$

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

Since $\mathrm{u_{it}}$ are not directly observable; the estimated residual of the model are realizations of $\mathrm{\varepsilon_{it} = v_{it} + u_{it}}$ rather than of $\mathrm{u_{it}}$ alone. In the present study, we use conditional expectation of $\mathrm{E[exp\,(u_{it})|\varepsilon_{it}]}$ as the point estimator. Further details about computing the point estimator for half-normal and truncated normal efficiency distributions can be found in Battese and Coelli (1993) and Battese et al. (2000).

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

APPLICATION TO US MAINLINE CARRIERS

Data

We focus on the domestic U.S. airline operations in 2010, the eve of two significant mergers in the industry (United with Continental; Southwest with AirTran), and assess the fuel efficiency of 15 large jet operators. The major data sources in the following analysis is the CD-ROM database product, distributed by Data Base Products Inc., a reseller of BTS Form 41 data series, which contain the financial and operational data reported from U.S. airlines on a quarterly basis.

The selection of the 15 operators is based on average aircraft size. Figure 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. Since their fleets consist of primarily narrow and wide body jets, the 15 carriers use similar technologies in their production. Carriers on the left hand side of the line are invariably regional airlines, mostly serving as subsidiaries of the 15 mainline airlines.

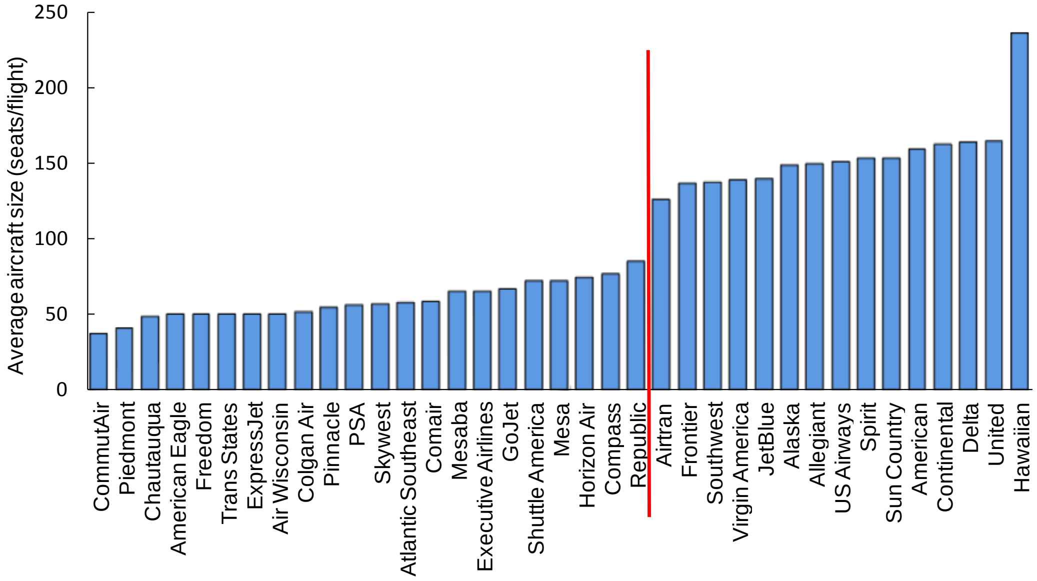

Figure 2 – Average Aircraft Size of U.S. Carriers (Source: Data Base Products)

Figure 3 shows that the 15 selected mainline carriers are all passenger oriented, with only a small fraction of services (in revenue ton-miles) dedicated to freight and mail. AirTran, Allegiant, Spirit, and Virgin America had virtually no non-passenger transport services. Hawaiian had the highest percentage of traffic in the form of cargo (9%). The overwhelming dominance of passenger service supports our choice of RPM as one of the output measures in representing the 15 airlines' production process.

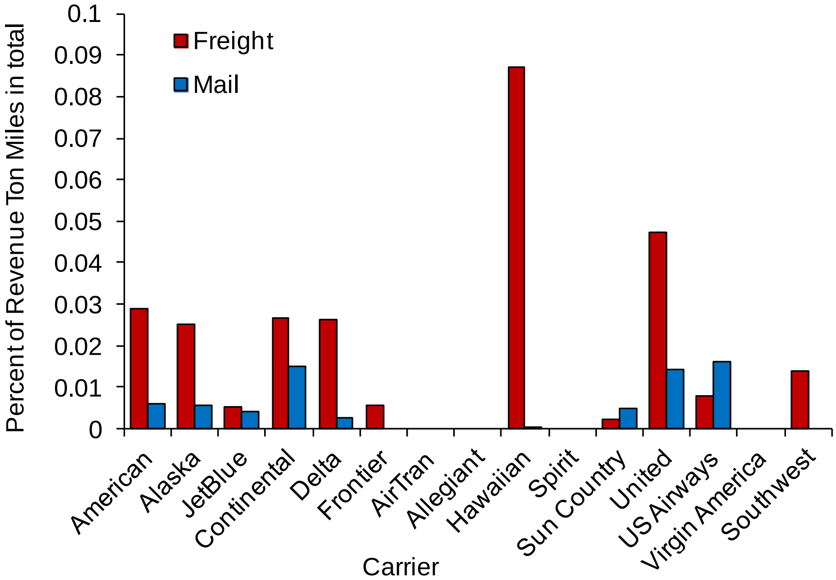

Figure 3 — Portion of Freight and Mail Services in Total Ton Miles among the 15 Mainline Airlines (2010)

Table I documents the fuel consumption, RPM, departures, average stage length, aircraft size, and load factor for the 15 mainline airlines in 2010.[3] Substantial inter-airline variations clearly exist in airline operations. American, Delta, Southwest, United, and US Airways operated on a much larger scale than carriers like Allegiant, Sun Country and Spirit. Hawaiian had the largest average aircraft size, due to a relative large portion of wide-body B767 and A330 aircraft in its fleet making frequent long haul flights to the U.S. west coast. However, because of many inter-island flights, the average haul of aircraft trips for Hawaiian was the smallest. The longest average stage lengths were seen in Virgin America, Continental, United, and Sun Country. Virgin America primarily provides long-haul, point-to-point service between major metropolitan cities on the Atlantic and Pacific seaboards; and Sun Country operates a large portion of flights between Minneapolis-St. Paul, its only hub, to cities on the two coasts. Most of the mainline airlines had on average more than 80% of seats filled, with Allegiant realizing the highest load factor (almost 90%), whereas Sun Country left 30% of the seats empty in its operation.

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[3] Average stage length is the ratio of revenue aircraft miles and departures; average aircraft size is the ratio of ASM and total aircraft miles; load factor is the ratio of RPM and ASM.

Table I – Fuel Consumption, Output, and Output Characteristics of the 15 Mainline Carriers in 2010

Carrier	Fuel (10^9 gallons)	RPM (10^9)	Dep	Aircraft size (seats/flight)	Stage length (statute miles)	Load factor
American	1.511	77.263	546025	159	1074	0.829
Alaska	0.298	18.733	142909	148	1069	0.830
JetBlue	0.418	24.224	197995	139	1075	0.819
Continental	0.652	41.410	243155	162	1240	0.849
Delta	1.707	92.707	729873	164	922	0.842
Frontier	0.160	8.554	80213	136	941	0.832
AirTran	0.367	18.738	246008	125	748	0.814
Allegiant	0.106	5.432	44308	149	914	0.899
Hawaiian	0.123	7.726	68524	235	557	0.861
Spirit	0.078	5.479	45258	153	949	0.832
Sun Country	0.023	1.356	10968	153	1159	0.698
United	0.991	57.317	350190	164	1176	0.849
US Airways	0.824	43.864	405593	151	862	0.832
Virgin America	0.101	6.236	35737	139	1546	0.815
Southwest	1.439	78.135	1115311	136	648	0.793

Source: Data Base Products (2011)

We also present in Table II the statistics for the remaining 22 carriers in 2010. These carriers will be the candidates when we consider the mainline-regional affiliations. By and large, the 22 regional carriers produced much smaller RPM's than their mainline counterparts, with the exception of American Eagle, ExpressJet, and SkyWest. The lower RPM's are attributable to their use of smaller aircraft sizes, shorter stage length, and lower load factors. However, the difference in departures between mainline and regional airlines is less significant—indeed SkyWest and American Eagle provided even more departures than United and US Airways. The consequent higher departure/RPM ratios suggest that regional carriers offered passengers service with higher accessibility than do some of the mainline airlines.

Table II – Fuel Consumption, Output, and Output Characteristics of the 22 Regional Carriers in 2010

Carrier	Fuel (10^6 gallons)	RPM (10^9)	Dep	Aircraft size (seats/flight)	Stage length (statute miles)	Load factor
Air Wisconsin	77.158	1.963	165473	50	326	0.727
American Eagle	263.622	7.802	454538	50	465	0.741
Atlantic Southeast	169.386	5.732	320502	57	389	0.799
Chautauqua	N/A*	2.093	164546	48	357	0.741
Colgan Air	24.626	0.693	104386	51	209	0.618
Comair	100.380	3.126	153332	58	465	0.756
CommutAir	N/A*	0.151	35373	37	173	0.670
Compass	55.259	2.337	57480	76	690	0.776
Executive	13.187	0.264	45121	65	169	0.532
ExpressJet	208.430	8.600	399082	50	547	0.788
Freedom	N/A*	0.315	21945	50	367	0.784

GoJet	30.369	1.627	51506	66	599	0.800
Horizon Air	59.112	2.451	131648	74	333	0.757
Mesa	91.273	4.074	175322	72	411	0.790
Mesaba	94.125	3.560	158094	65	448	0.773
PSA	60.383	1.696	121002	56	338	0.742
Piedmont	N/A*	0.518	115999	40	176	0.630
Pinnacle	148.244	4.668	272705	54	410	0.773
Republic	152.893	6.089	173709	85	531	0.779
Shuttle America	57.923	3.212	99531	71	615	0.735
SkyWest	352.900	13.260	625685	57	472	0.792
Trans States	N/A*	0.855	58813	50	389	0.747

* Chautauqua, CommutAir, Freedom, Piedmont, and Trans State did not report their fuel consumption data to BTS in 2010.
Source: Data Base Products (2011) and Bureau of Transportation Statistics (2011)

Overall, the 15 mainline airlines account for the bulk of fuel consumption and service provided in the U.S. domestic passenger air transportation system, as shown in Table III. Adding the 22 regional carriers, the 37 carriers together represent at least 99.4% in the system totals based on four metrics: fuel, RPM's, departures, and enplaned passengers. Analyzing the 37 carriers will therefore give an almost complete picture of fuel efficiency in the U.S. domestic passenger air transportation system.

Table III – Percentage of Mainline and Regional Carriers in the System Total (Excluding Cargo Carriers) under Different Metrics

	Fuel	RPM	Dep	Enplaned passengers
15 mainline carriers	80.7%	86.5%	51.9%	75.0%
22 regional carriers	19.0%	13.3%	47.5%	24.8%
Sum of both carrier types	99.7%	99.8%	99.4%	99.8%

Mainline-only fuel efficiency

Airline fuel efficiencies are estimated following the three approaches described in Section 3. The data reported in Form 41 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 airline-quarterly inefficiencies. These inefficiencies are then averaged to generate the airline-level efficiency 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.[4] Efficiency and the associated ranking results are presented in Table IV. 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

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[4] 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.

estimation results are presented in Table V, with D1 denoting the deterministic frontier, and S1-S4 indicating different versions of stochastic frontiers. The 4th and 6th columns in Table IV are the calculated inefficiency based on D1 (FI_{DF}) and S4 (FI_{SF}).

Table IV – Fuel/RPM, Inefficiency Scores, and Rankings of the 15 Mainline Airlines (Considering Mainline Airlines Only)

Carrier	Fuel/RPM (10^{-2}gallon/RPM)	FI_{ratio}	Ratio ranking	FI_{DF}	DF ranking	FI_{SF}	SF ranking
Spirit	1.5629	1.000	1	1.026	1	1.025	3
Continental	1.5745	1.007	2	1.044	4	1.053	6
Alaska	1.5885	1.016	3	1.030	3	1.028	4
Hawaiian	1.5932	1.019	4	1.027	2	1.022	2
Virgin America	1.6266	1.041	5	1.126	8	1.145	12
Frontier	1.6642	1.065	6	1.061	6	1.051	5
Sun Country	1.7143	1.097	7	1.161	11	1.169	13
Jet Blue	1.7240	1.103	8	1.061	7	1.093	7
United	1.7290	1.106	9	1.133	9	1.138	8
Delta	1.8408	1.178	10	1.151	10	1.139	9
Southwest	1.8412	1.178	11	1.056	5	1.015	1
US Airways	1.8782	1.202	12	1.162	12	1.144	11
Allegiant	1.9533	1.250	13	1.282	15	1.283	15
American	1.9563	1.252	14	1.247	14	1.242	14
AirTran	1.9589	1.253	15	1.173	13	1.140	10

Table V – Estimation Results of Frontier Models (Considering Mainline Airlines Only)

	D1	S1	S2	S3	S4
Ln(RPM)	0.869***	0.824***	0.824***	0.824***	0.824***
	(0.040)	(5.05e-05)	(7.64e-06)	(8.02e-06)	(7.73e-06)
Ln(dep)	0.150***	0.200***	0.200***	0.200***	0.200***
	(0.038)	(3.51e-05)	(6.73e-06)	(6.90e-06)	(6.17e-06)
Constant	-2.726***	-2.344***	-2.344***	-2.344***	-2.344***
	(0.494)	(7.61e-04)	(1.03e-04)	(1.09e-04)	(1.08e-04)
Ln(Stage length)			0.008		0.147**
			(0.006)		(0.070)
Ln(Aircraft size)				0.008	-0.189*
				(0.009)	(0.100)
R^2	0.997				
σ_v		1.65e-09	8.53e-09	8.24e-09	9.41e-09
σ_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

Under the ratio based approach, the FI value 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. An overall picture the results convey is that large, legacy carriers are in general less fuel efficient than their low-cost and smaller rivals.

Turning to the frontier model, we observe a very high R^2 in the frontier estimates, suggesting that the two outputs satisfactorily explain how airlines consume fuel. The estimates imply that: 1) controlling for dep, 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%. Additional fuel consumption is required when increasing either mobility or accessibility, but the former is the stronger driver of fuel requirements.

The scale economies implied by the coefficients for RPM and dep are worth noticing. Although scale economies have been examined extensively in airline economics literature (e.g. Cave et al., 1984; Gillen et al., 1990; Hansen et al., 2001; Zou and Hansen, 2012), the vast majority of existing studies are operating cost-based. Focusing on the scale economy of fuel input, we define the Returns-to-Scale (RTS) measure as the reciprocal of the sum of fuel usage elasticities with respect to RPM and dep, i.e. $1/(\beta_1 + \beta_2)$. The point estimate of RTS from the deterministic frontier model is 0.981, very close to 1, suggesting slight diseconomies of scale in fuel usage. However, we fail to reject the null hypothesis of constant RTS at 5% level of significance.

As in the ratio based results, Spirit remain the fuel efficiency champion under the deterministic frontier approach. Because FI_{DF}'s are the averages by airline and it is unlikely that all observations for an airline fall on the frontier, even for the most efficient airline its FI_{DF} will be greater than one. Most of the rankings either stay or change only a couple of places. 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 less efficient in general remains valid. Nonetheless, we observe a few drastic ranking changes. Southwest jumps from the 11th to 5th, now only about 3% less efficient than Spirit. Similar improvements are seen in AirTran. In contrast, Virgin America and Sun Country fall in the rankings by three and four places.

These 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 $\mathrm{Fuel}/[(\mathrm{RPM})^{0.869}(\mathrm{dep})^{0.150}]$, or $\frac{\mathrm{Fuel}}{\mathrm{RPM}} \cdot \frac{1}{(\frac{\mathrm{dep}}{\mathrm{RPM}})^{0.150}} \cdot \frac{1}{\mathrm{RPM}^{0.019}}$, in which the last two terms explain the departure from the ratio-based results. As shown in Figure 4, 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 Table I reveals that the major source contributing to the difference in dep/RPM is stage length.[5] For example, the average stage length of Virgin America is more than double that of Hawaiian

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[5] It can be easily seen that RPM = dep*(Average stage length)*(Average aircraft size)*(Average load factor), in which average aircraft size and load factor are fairly close among the 15 airlines (except for Hawaiian in aircraft size).

and Southwest.[6] In addition, the second term $\frac{1}{\mathrm{RPM}^{0.019}}$ suggests that, *ceteris paribus*, deterministic frontier penalizes airlines with smaller operation scales, such as Sun Country and Allegiant.

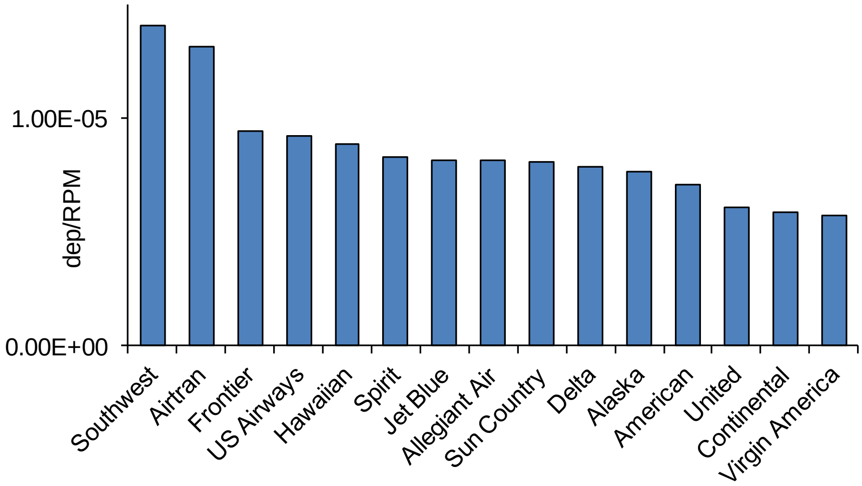

Figure 4 — Dep/RPM Ratio among the 15 Mainline Carriers

The four stochastic frontier models in Table V corresponds to four different specifications about $\mathrm{u_{it}}$. S1 presents the basic version in which $\mathrm{u_{it}}$ is assumed half-normally distributed. S2-S4 consider the heterogeneity of airline operations by incorporating output characteristics in the mean of $\mathrm{u_{it}}$, which now assumes 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.[7] We do not include constants in specifying the mean of $\mathrm{u_{it}}$ in S2-S4, as such models fail to converge based on our computational experiences. Somewhat surprisingly, all the four models produce essentially the same information 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. RTS's are slightly less than one. However, we reject the null hypothesis of constant RTS due to small standard errors for the estimated β's.

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 the conventional wisdom at the flight level: controlling for RPM, departures, and aircraft size, flying longer distance means not only more fuel burn but lower load factor. Operation therefore will be less fuel efficient. On the other hand, the negative sign appearing to aircraft size, significant at 10% level, seems counter-intuitive. It implies that, keeping RPM,

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[6] The effect of shorter stage length for Hawaiian is compromised by its significantly larger average aircraft size.

[7] 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.

departures, and stage length constant, flying larger, and thereby emptier, planes increases fuel efficiency. 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 stage length and aircraft size coefficients. This is further supported by testing results from Likelihood Ratio (LR) tests. In order to facility exposition, we express the general form of the mean efficiency term as $\mathrm{E}(\mathrm{u}_{\mathrm{it}}) = \delta_1$(Stage length)$_{\mathrm{it}}$ + δ_2 (Aircraft size)$_{\mathrm{it}}$. Table VI below shows that we reject H_0's in all three tests.

Table VI – Likelihood Ratio Tests across Models S1-S4

Null hypothesis	χ^2-statistic	Prob > χ^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 σ_v than σ_u, the stochastic frontier essentially collapses to a deterministic frontier. This can be shown (in Appendix 1) through the calculation of $FI_{SF,it}$, for which $\exp(\hat{\varepsilon}_{it})$ is a very good approximation. 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.[8] In the stochastic frontier models, further weight is given to departures. Airlines offering greater accessibility (i.e. with a higher dep/RPM ratio) will therefore 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 stay almost the same, with less glaring inefficiency and ranking changes. Compared to Southwest, the least efficient Allegiant burns on average 26.3% more fuel, still comparable to the numbers using the ratio and deterministic frontier approaches. Finally, the inefficiency estimates maintain the general impression that large, legacy carriers occupy the lower rungs of the efficiency ladder.

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[8] In this regard, using any model from S1-S4 will yield the same inefficiency results.

Mainline-sub affiliations

Assigning regional airlines' operation to mainline carriers

While the previous analysis considered mainline airlines only, we have argued that, since many mainline airlines depend on regional affiliates for much of their service, fuel efficiency metrics should incorporate both the fuel consumption and output of regional affiliates. The first step in the assessment of mainline-sub joint fuel efficiency is to accurately assign regional carriers' operations (in RPM's) to mainline carriers. We consider 22 regional carriers that are introduced in the beginning of this section. All the 22 regional carriers operate under some type of relationship with at least one of the 15 mainline airlines, who are responsible for the ticketing, marketing, and often scheduling of the regional airlines' flight operations (Forbes and Lederman, 2005). The subcontracted code share agreements usually belong to one of types (Truit and Hayes, 1994):

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

For the first two types, 100% of the regional carriers' RPM's are assigned to the corresponding mainline airline. Assignment under the third type is more difficult, especially in situations where the regional carrier services more than one mainline airline on a flight segment. We proceed by looking 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, their route maps, as well as other on-line resources such as Wikipedia and back-up confirmation.[9] 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 35 major U.S. airports, often referred to as OEP 35,[10] using the BTS T100 Domestic Segment Traffic Database. This captures the vast majority of RPM's in the regional carrier's total, over 90% for all but one regional airlines of this type, as shown in Appendix 2.

One particular situation that can arise for the type 3 regional carriers is the regional carrier servicing more than one mainline airline on a flight segment. We assign the regional carrier's

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[9] To be sure, because of the fluid relationship between some regional and mainline carriers, it is not always possible to apportion all the RPMs with complete accuracy for a given year at a later point in time. However, given that our assignment was performed in early 2012, it is still reasonable to expect that the number of changes in these relationships that take place over a year is small enough to preserve the validity of our aggregate results.

[10] The full list of OEP (Operational Evolution Partnership) airports can be found at: http://aspmhelp.faa.gov/index.php/OEP_35

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, despite the tickets being 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 about the true assignment should be rather small. The assigned RPM's on each segment are then aggregated over one regional carrier's entire network to obtain the RPM's and the percentages attributable to the incumbent mainline carriers. Those RPM's are then adjusted by the ratio between the total RPMs reported from Form 41 and T100, to maintain the consistency with aggregate fuel, departure reporting. Appendix 3 presents the final RPM assignment results for each mainline-regional carrier pair. It is clear that the use of regional carrier affiliations is largely a legacy carrier phenomenon. American, Delta, United, and US Airways are by far the heaviest users of regional carriers. The younger, quintessential low cost carriers—Southwest, Jet Blue, Virgin, and AirTran—have no affiliations with regional carriers at all. The case of Southwest is unique in that it has grown in size to rival that of the big legacy carriers but has never seen the need to adopt a similar operational strategy.

Adjusted fuel efficiency

Besides RPMs, the efficiency estimation also requires the assignment of fuel and departures. In the stochastic frontier models, we need to know 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. The latter two are used to calculate the composite average aircraft size and stage length.[11] A fuel regression model (with RPM and dep as the explanatory variables) is estimated using the available regional carrier data, to predict the fuel burn for the regional carriers whose records are missing.

Similar to the mainline-only case, we report the composite Fuel/RPM values, adjusted inefficiency scores under the three approaches ($\mathrm{FI}_{\mathrm{ratio}}^{\mathrm{c}}$, $\mathrm{FI}_{\mathrm{DF}}^{\mathrm{c}}$, $\mathrm{FI}_{\mathrm{SF}}^{\mathrm{c}}$), together with the ranking changes in Table VII (ordered by Fuel/RPM). Table VIII presents new frontier estimation results (D2 is the deterministic frontier model; S5-S8 the stochastic frontier models), with the same specifications.

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 other eight carriers with no regional affiliation see an improvement in ranking. This also widens the efficiency gap between the first and last carriers, with the ratio increased to 35%.

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[11] For example, we sum up total revenue aircraft miles and departures from the mainline and those attributable from the incumbent regional carriers, and then divide the new revenue aircraft miles by the new departures to obtain the composite average stage length.

Table VII – Fuel//RPM, Inefficiency Scores, and Rankings of the 15 Mainline Airlines (Considering Mainline-Regional Affiliations)

Carrier	Composite Fuel/RPM (10^{-2} gallon/RPM)	$\mathrm{FI}^{\mathrm{c}}_{\mathrm{ratio}}$	Ratio ranking change	$\mathrm{FI}^{\mathrm{c}}_{\mathrm{DF}}$	DF ranking change	$\mathrm{FI}^{\mathrm{c}}_{\mathrm{SF}}$	SF ranking 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

Table VIII – Estimation Results of Frontier Models (Considering Mainline-Regional Affiliations)

	D2	S5	S6	S7	S8
Ln(RPM)	0.848***	0.874***	0.843***	0.854***	0.807***
	(0.052)	(0.065)	(0.057)	(0.060)	(0.056)
Ln(dep)	0.165***	0.148***	0.171***	0.162***	0.203***
	(0.043)	(0.053)	(0.046)	(0.048)	(0.046)
Constant	-2.406***	-2.911***	-2.494***	-2.645***	-2.024***
	(0.703)	(0.884)	(0.771)	(0.817)	(0.759)
Ln(Stage length)			0.017***		0.115**
			(0.005)		(0.052)
Ln(Aircraft size)				0.019**	-0.136*
				(0.008)	(0.075)
R^2	0.997				
σ_v		0.025	1.30e-4	1.87e-4	2.09e-4
σ_u		0.120	0.007	0.008	0.006
Log-likelihood		71.063	72.889	72.023	75.478

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

When the deterministic frontier model is employed, the effect of having regional carriers on fuel efficiency is no longer unidirectional, and 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 incorporation of regional carriers increases the level of accessibility of the associated mainline carriers, thereby improving their inefficiency scores. As shown in Figure 5, the dep/RPM ratios of the seven mainline carriers with regional affiliates rise considerably, by 50-137%. The accessibility effect is further enhanced by a larger coefficient for dep and a smaller one for RPM than the mainline-only case, which are expected because of shorter average stage length of regional carriers and therefore larger portion of fuel consumed during takeoff/landing operations. Overall, the efficiency ranking change is rather small.

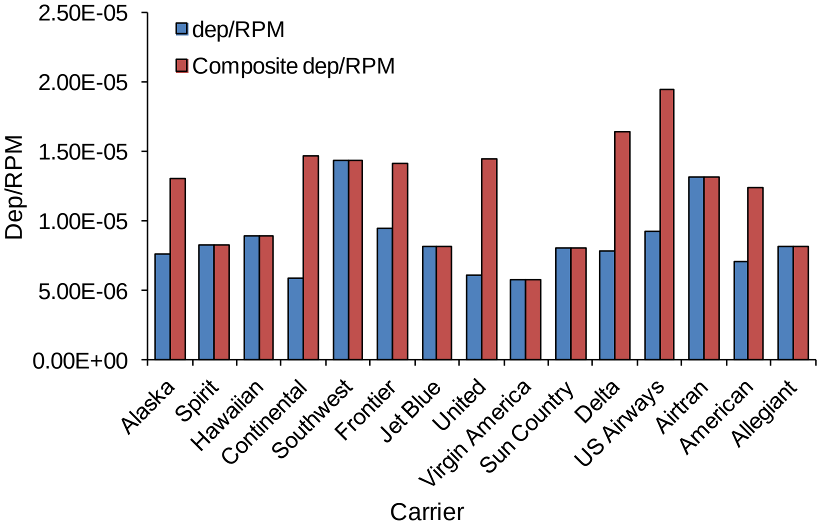

Figure 5 — Dep/RPM Ratios for the 15 Mainline Carriers with and without Considering their Regional Carrier Affiliations

The above argument of competing forces applies as well to efficiency estimates using stochastic frontier models. Compared to the mainline-only case, we observe larger and statistically significant coefficients for stage length and aircraft size in S6 and S7. The coefficients for stage length and aircraft size in S8 are of similar magnitude as in S4. Regional carrier affiliations have two additional impacts on model estimation. First, further source of random shocks and measurement errors are introduced in the data generation process. As a consequence, idiosyncratic errors become more dispersed. Second, the involvement of multiple airlines in each observation diversifies the set of aircraft types and technologies, therefore degrading the model fits, as evidenced by the smaller log likelihoods in Table VIII.

Similar likelihood ratio tests among S5-S8 suggest that S8 be the preferred model, in which σ_v is still much dwarfed by σ_u. Therefore, the stochastic frontier model can still be reasonably approximated by its corresponding deterministic frontier. The confounding forces again lead to non-unidirectional efficiency ranking changes, which are slightly more substantial than if the deterministic frontier model is applied.

Efficiency with routing circuity

Routing circuity calculation

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

Figure 6 shows circuity 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 circuity difference between the large, legacy carriers, which adopt primarily hub-and-spoke systems, and the other smaller airlines exists but is not substantial. The small circuitries imply that the efficiency adjustment due to routing circuity may not be significant. Such conjecture is confirmed in the subsequent analysis.

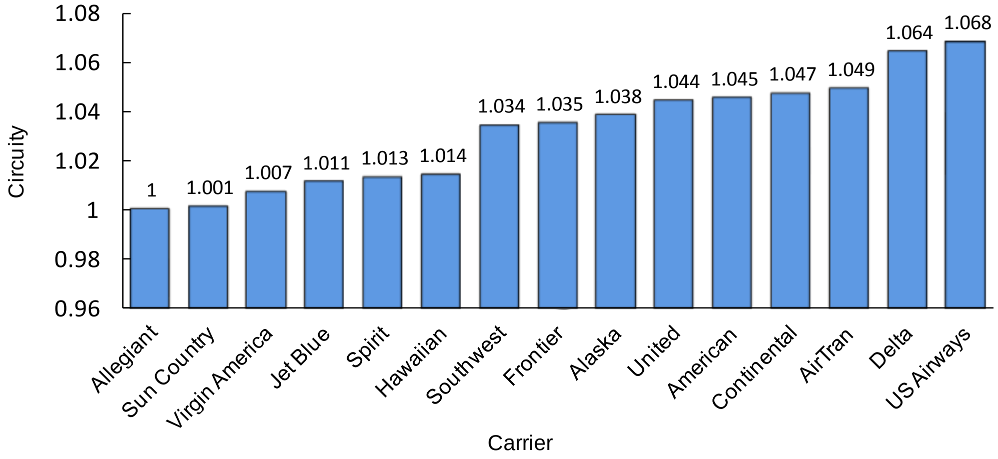

Figure 6 — Routing Circuity of the 15 Mainline Airlines in 2010

Adjusted fuel efficiency

We follow the same reporting format by presenting the efficiency and frontier model estimates, in Tables IX and X. Airlines in Table IX are ordered by Fuel/RPODM values. Changes in ranking are with respect to those in the mainline-regional composite case. D3 denotes the deterministic frontier model. Stochastic frontier model estimates are those under S9-S12.

Table IX – Fuel//RPODM, Inefficiency Scores, and Rankings of the 15 Mainline Airlines (with Routing Circuity)

Carrier	Fuel/RPODM (10^{-2} gallon/ RPODM)	$\mathrm{FI}_{\mathrm{ratio}}^{\mathrm{circuity}}$	Ratio ranking change	$\mathrm{FI}_{\mathrm{DF}}^{\mathrm{circuity}}$	DF ranking change	$\mathrm{FI}_{\mathrm{SF}}^{\mathrm{circuity}}$	SF ranking 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

Table X – Estimation Results of Frontier Models (with Routing Circuity)

	D3	S9	S10	S11	S12
Ln(RPM)	0.816***	0.839***	0.814***	0.825***	0.778***
	(0.050)	(0.064)	(0.055)	(0.058)	(0.054)
Ln(dep)	0.201***	0.186***	0.204***	0.197***	0.236***
	(0.041)	(0.051)	(0.044)	(0.045)	(0.043)
Constant	-2.066***	-2.535***	-2.182***	-2.331***	-1.725**
	(0.684)	(0.878)	(0.755)	(0.798)	(0.728)
Ln(Stage length)			0.016***		0.123**
			(0.004)		(0.053)
Ln(Aircraft size)				0.019**	-0.147*
				(0.007)	(0.076)
R^2	0.997				
σ_v		0.017	9.30e-5	1.37e-4	1.65e-4
σ_u		0.128	0.007	0.008	0.007
Log-likelihood		71.092	73.107	72.239	76.039

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

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

Switching to the frontier estimates, we observe smaller coefficients for RPODM than for RPM in the mainline-regional composite case, presumably due to reduced variations in RPODM as well as its correlation with fuel consumption. As a consequence, dep is given higher weight. Compared to the composite case, any deviation of efficiency results can be attributed to difference in three factors: dep/RPM, dep, and circuity.[12] Nonetheless, the net effect of

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[12] The equivalent ratio when circuity is considered is $\frac{\mathrm{Fuel}}{\mathrm{RPODM}^{0.816}\mathrm{dep}^{0.201}}$, which can be re-expressed as $\frac{\mathrm{Fuel}}{\mathrm{RPM}^{0.848}\mathrm{dep}^{0.165}}\frac{1}{(\frac{\mathrm{dep}}{\mathrm{RPM}})^{0.032}}\frac{1}{\mathrm{dep}^{0.004}}\mathrm{circuity}^{0.816}$. The first term is the equivalent ratio in the composite case,

circuity does not seem to be substantial across all airlines. As a result, the efficiency rankings remain much the same. In the stochastic frontier models, σ_v is still much smaller than σ_u. The stochastic frontiers therefore can still be approximated by their equivalent deterministic frontiers. We choose S12 as the preferred model based on similar likelihood ratio test results. As in the deterministic case, no change occurs to the efficiency rankings. Overall, these results suggest that circuity only has minor effects on fuel efficiency of the 15 mainline airlines investigated.

FURTHER DISCUSSION

Efficiency correlation

With the completion of efficiency measurement, we now proceed to a global view of the efficiency results. The box plot below shows the distribution of airline efficiency estimates under the three approaches, when considering only mainline airlines, mainline-regional affiliations, and routing circuity. Clearly, the variations of inefficiency scores yielded by the frontier approaches are less than those from the ratio based approach. The ratios are more sensitive to the inclusion of regional carriers, producing the highest and lowest sample average efficiency. The discrepancy in efficiency is further increased when routing circuity is considered. These observations are not surprising, given that regional carriers only contribute to the deterioration of the mainline airlines' efficiency if using the ratio method, and the least fuel efficient carriers (in terms of Fuel/RPM) are in general hub-and-spoke carriers and associated with high routing circuity. Under the frontier approaches, change in inefficiency scores reflect the net outcome of competing forces (higher fuel/RPM and greater accessibility) when regional subsidiaries are considered. The distributions when circuity is considered resembles those absent circuity adjustment since, as shown in the previous sub-section, circuity has only minor effects on the further variations in frontier inefficiency scores.

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the three remaining components, dep/RPM ratio, dep, and circuity, explain any departure from the composite case.

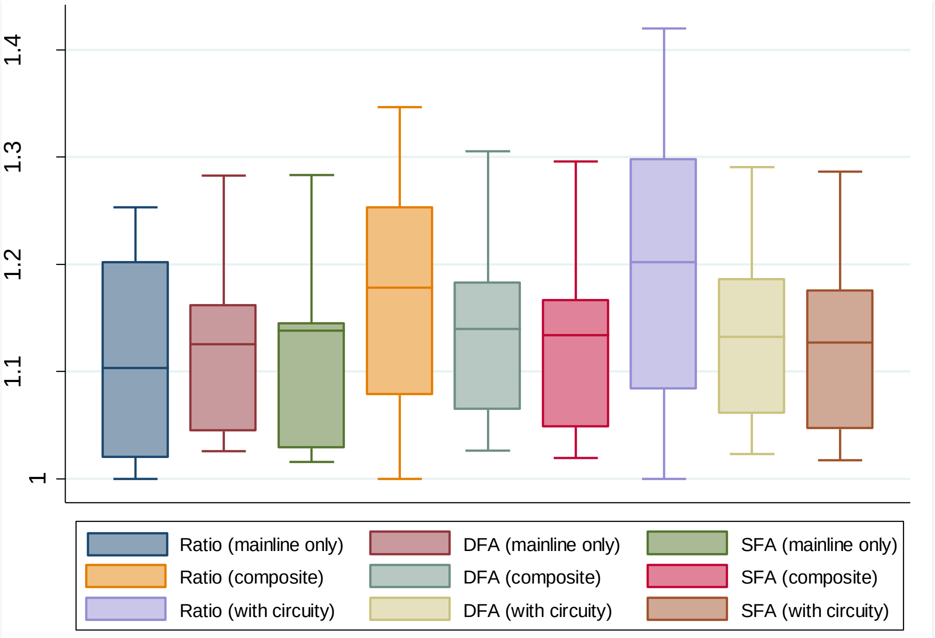

Figure 7 — Box plot of the Inefficiency Scores across the Three Approaches, Considering Mainline Airlines only, Mainline-Regional Affiliations, and Routing Circuity

To examine the extent of agreement among rankings arising from the various approaches, pair-wise inefficiency score and Spearman rank correlation coefficients are reported in Tables XI and XII. The three diagonal blocks in each table, highlighted in light grey, are of particular interest because they compare results from the three methods that are consistent in their exclusion or inclusion of regional affiliates, and consideration of routing circuity. Most of the cells have coefficients above 0.5. Consistent with the box plot above, the two frontier methods yield results that are in greater agreement with one another than with those of the ratio-based approach. We observe generally weaker similarities between the ratio-based and either of the frontier approaches after incorporating regional affiliates. When circuity is further considered, results using the ratio-based method deviate further from those under the frontier approaches.

Also worth attention are the diagonal elements (in dark grey) in the lower blocks in each table, which show the efficiency variation when sticking to one method but with different cases (mainline-only, composite, considering circuity). Again, the ratio-based estimates are sensitive to the different cases while the frontier approaches are less influenced by the inclusion of regional carriers, and even less so when circuity is further considered.

Table XI – Inefficiency Scores Correlation

	Ratio: mainline only	DF: mainline only	SF: mainline only	Ratio: composite	DF: composite	SF: composite	Ratio: circuity	DF: circuity	SF: circuity
Ratio: mainline only	1								
DF: mainline only	0.8271	1							
SF: mainline only	0.7071	0.9818	1						
Ratio: composite	0.8262	0.6784	0.5896	1					
DF: composite	0.8367	0.9837	0.9572	0.6955	1				
SF: composite	0.7789	0.9758	0.9657	0.5882	0.9882	1			
Ratio: circuity	0.7676	0.5845	0.4927	0.9901	0.5995	0.4831	1		
DF: circuity	0.8283	0.9810	0.9567	0.6975	0.9965	0.9842	0.6079	1	
SF: circuity	0.7732	0.9743	0.9657	0.5927	0.9863	0.9969	0.4935	0.9889	1

Table XII – Spearman Inefficiency Ranking Correlation

	Ratio: mainline only	DF: mainline only	SF: mainline only	Ratio: composite	DF: composite	SF: composite	Ratio: circuity	DF: circuity	SF: circuity
Ratio: mainline only	1								
DF: mainline only	0.8607	1							
SF: mainline only	0.5643	0.8964	1						
Ratio: composite	0.8357	0.7750	0.5143	1					
DF: composite	0.8536	0.9821	0.8857	0.7607	1				
SF: composite	0.7536	0.9321	0.9107	0.5857	0.9571	1			
Ratio: circuity	0.7893	0.7107	0.4464	0.9857	0.6821	0.4964	1		
DF: circuity	0.8536	0.9821	0.8857	0.7607	1	0.9571	0.6821	1	
SF: circuity	0.7536	0.9321	0.9107	0.5857	0.9571	1	0.4964	0.9571	1

Potential cost savings from improving fuel efficiency

The inter-airline fuel efficiency differences found in this study suggests that considerable cost savings could be realized if the less fuel-efficient carriers could match the fuel economy of their better-performing peers. Cost savings can be achieved by more efficient fuel usage of mainline airlines alone, or as a consequence of the joint efforts of mainline and affiliated regional carriers. In this sub-section, both cases are considered.

We choose four improvement scenarios with varying degrees of plausibility. The first—and perhaps most intuitive—assumes that inefficiency scores of all mainline airlines are reduced to the same lowest level observed in the data sample. However, this scenario may not be very realistic. It would be difficult—given the heterogeneity in operating scale and routing structure among the 15 carriers—to imagine efficiency to be improved to the same best level for carriers as different as Spirit and American. Three alternative scenarios are further examined. In each scenario, airlines are categorized and a given airline's fuel efficiency can only be improved to the "best practice" level observed within its category. In Scenario 2, we divide the 15 airlines into legacy and non-legacy carriers. The legacy group consists of American, Alaska, Continental, Delta, Hawaiian, United, and US Airways. These carriers (perhaps to a less extent for Hawaiian) have a long history of operating on hub-and-spoke networks. In Scenario 3, we consider grouping carriers according to the existence of regional carrier affiliations. As shown before, seven mainline airlines (American, Alaska, Continental, Delta, Frontier, United, US Airways) maintain certain types of contractual relationships with regional carriers. It is clear that only slight difference exists between groupings under the 2nd and 3rd scenarios. The last scenario uses simply the amount of RPMs produced as the criteria, resulting in three carrier groups, indicated by different colors in Figure 8.

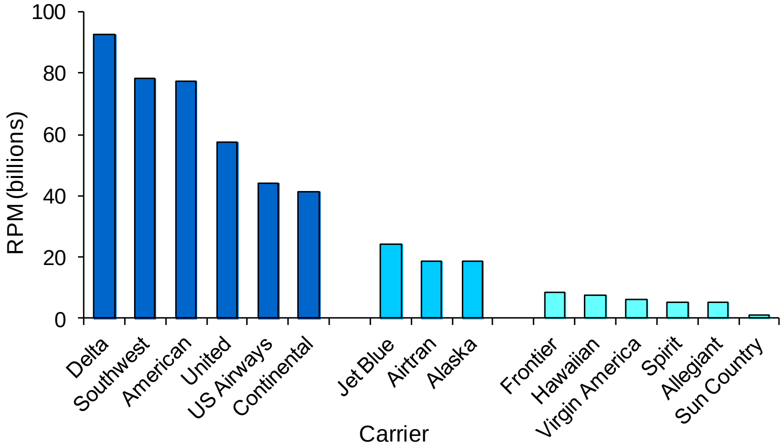

Figure 8 — Annual Airline RPMs in 2010

The procedure for estimating potential cost savings varies on the method employed to measure efficiency. Under the-ratio based approach, we compute the difference between the Fuel/RPM for each airline and the lowest Fuel/RPM observed in the group to which the airline belongs, and multiply the difference by the airline's RPM to obtain the amount of potential fuel saving for that airline. When the deterministic frontier approach is utilized, we take the exponential of the difference between the minimum residual in the group and the residual for a given airline-quarter observation, and multiply it by the observed fuel burn to obtain the counterfactual fuel burn. Potential fuel saving is then the difference between the observed and counterfactual fuel burns. Estimating fuel savings under the stochastic frontier approach follows a similar fashion, but with the above exponential replaced by the ratio between the inefficiency scores of the minimum in the group and the observation. This is certainly an approximation, in that the ratio of two expectations is used as proxy for the expectation of the ratio.[13]

The estimated fuel saving amounts need to be converted into dollar values. We multiply the above fuel savings with the corresponding unit fuel cost ($/gallon), collected from BTS Form 41 P-12(a) database (BTS, 2012). Improved fuel efficiency also leads to CO_2 emission reduction, which can be calculated based on the fixed ratio of 9.57 kg CO_2 per one gallon of jet fuel (EIA, 2012). A value of $21/ton of CO_2 (Greenstone et al., 2011) is used to monetize the benefits from the reduced CO_2 emissions.

Tables XIII-XV report the estimated fuel, CO_2 savings, and total cost (sum of fuel and CO_2 cost) reduction for the three cases (mainly only, composite, with circuity) respectively. When only mainline carriers are considered, the three approaches yield relatively close estimates of potential fuel, CO_2, and cost savings under the various scenarios. Overall, fuel efficiency improvement could save 0.84-1.17 billion gallons of fuel, 8.0-11.2 million tons of CO_2 emissions, and lead to overall about 2-3 billion dollar benefit gains for the year 2010. Due to the low social cost of CO_2, more than 90% in the total benefits stems from fuel use reduction. Savings estimates obtained from the frontier approaches are lower than those from the ratio-based approach, because the former controls for both RPM's and aircraft departures. Estimates under deterministic frontier are always larger than under the stochastic frontier, presumably as a result of random noise being purged from the efficiency term when stochastic frontier is employed. As expected, these numbers follow a non-increasing trend from the most idealized Scenario 1 to more realistic Scenarios 2 & 3, and finally to Scenario 4, which features the finest

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[13] Recall that the stochastic frontier model can be expressed as $\mathrm{fuel}_{it} = \exp(\beta_0+v_{it})\ \mathrm{RPM}_{it}^{\beta_1}\mathrm{dep}_{it}^{\beta_2}\exp(u_{it})$. Fuel burn under the improved scenario is $\mathrm{fuel}_{it}^{0} = \exp(\beta_0+v_{it})\,\mathrm{RPM}_{it}^{\beta_1}\mathrm{dep}_{it}^{\beta_2}\exp(u_{\mathrm{min}})$. Therefore, $\mathrm{fuel}_{it}^{0} = \mathrm{fuel}_{it} * \frac{\exp(u_{\mathrm{min}})}{\exp(u_{it})}$. As both u_{min} and u_{it} are stochastic, we can only take the expected value of fuel_{it}^{0}, which equals $\mathrm{fuel}_{it} * \mathrm{E}\{\frac{\exp(u_{\mathrm{min}})}{\exp(u_{it})}\}$. Here we use $\frac{\mathrm{E}[\exp(u_{it})|\varepsilon_{it}]}{\mathrm{E}[\exp(u_{\mathrm{min}})|\varepsilon_{\mathrm{min}}]}$ as an approximation for $\mathrm{E}\{\frac{\exp(u_{\mathrm{min}})}{\exp(u_{it})}\}$.

segmentation. We observe the same estimates across Scenarios 1-3 under the deterministic frontier approach, because the minimum residual, which occurs to Spirit (-0.1116336, 4th quarter), is very tightly followed by that in Alaska (-0.1115942, 3rd quarter), and the two airlines belong to different groups in Scenarios 2 and 3. The identical results when using the stochastic frontier is due to three data points on the frontier (Alaska-Q3; Hawaiian-Q3; Southwest-Q4). Therefore, each group will have the same "best practice" irrespective of the grouping choice.

As expected, we obtain larger cost savings when we include regional carriers, because of expanded scale of operations considered and range of efficiency differences. One exception is Scenario 4 under the ratio-based approach, in which the "best practice" airline (Continental) in the first group experience efficiency degradation. Under the ratio-based approach, including regional carriers widens the Fuel/RPM difference between the mainlines airlines with and without regional affiliations, and among the mainline airlines with varying degrees of involvement with regional carriers, yielding more significant inter-scenario difference in cost savings. These differences are less pronounced if the frontier approaches are employed, since they generate less drastic change in efficiency.

When circuity is incorporated, cost savings are further increased under the ratio based approach. Due to the greater efficiency gap between the most and least efficient airlines, the maximum potential savings could amount to over $6 billion under Scenario 1. Efficiency change with the frontier approaches is much moderate, resulting in only slight adjustment in cost savings.

Table XIII – Potential Fuel and CO_2 Reduction, and Cost Savings from Improved Fuel Efficiency (Considering Mainline Airlines only)

	Ratio based			Deterministic frontier			Stochastic frontier		
	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)
Scenario 1	1.17 (13.5%)	11.20	2.94	1.00 (11.5%)	9.58	2.49	0.91 (10.5%)	8.74	2.26
Scenario 2	1.13 (13.0%)	10.90	2.84	1.00 (11.5%)	9.57	2.49	0.91 (10.5%)	8.74	2.26
Scenario 3	1.13 (13.0%)	10.90	2.84	1.00 (11.5%)	9.57	2.49	0.91 (10.5%)	8.74	2.26
Scenario 4	1.11 (12.8%)	10.60	2.78	0.84 (9.6%)	8.01	2.08	0.91 (10.5%)	8.74	2.26

Table XIV – Potential Fuel and CO_2 Reduction, and Cost Savings from Improved Fuel Efficiency (Considering Mainline-Regional Affiliations)

	Ratio based			Deterministic frontier			Stochastic frontier		
	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)
Scenario 1	2.14 (19.8%)	20.50	5.33	1.44 (13.3%)	13.70	3.58	1.20 (11.1%)	11.50	2.98
Scenario 2	2.02 (18.7%)	19.30	5.02	1.39 (12.9%)	13.30	3.45	1.16 (10.7%)	11.10	2.88
Scenario 3	1.64 (15.2%)	17.70	4.09	1.39 (12.9%)	13.30	3.46	1.16 (10.8%)	11.10	2.89
Scenario 4	0.96 (8.9%)	9.18	2.39	1.09 (10.0%)	10.40	2.71	1.03 (9.5%)	9.82	2.55

Table XV – Potential Fuel and CO_2 Reduction, and Cost Savings from Improved Fuel Efficiency (with Routing Circuity)

	Ratio based			Deterministic frontier			Stochastic frontier		
	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)	Fuel reduction (billion gallons) & percentage in the total	CO_2 reduction (million tons)	Total cost savings ($ billions)
Scenario 1	2.43 (22.4%)	23.22	6.03	1.41 (13.0%)	13.48	3.50	1.20 (11.1%)	11.49	2.98
Scenario 2	2.29 (21.2%)	21.94	5.70	1.37 (12.6%)	13.08	3.39	1.16 (10.8%)	11.13	2.89
Scenario 3	1.78 (16.4%)	17.00	4.42	1.37 (12.7%)	13.09	3.40	1.17 (10.8%)	11.17	2.90
Scenario 4	0.98 (9.1%)	9.43	2.45	1.08 (10.0%)	10.34	2.69	1.03 (9.6%)	9.88	2.57

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, which provide different views of the airline fuel consumption and production process. 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 further separates idiosyncratic errors from the true inefficiency. In addition, the impact on efficiency of heterogeneity in operating environment can be explicitly modeled. 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, stochastic frontier can be reasonably approximated by a 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. By operating as mainline carriers' subsidiaries, it is possible for regional carrier to boost the measured efficiency of their mainline partners when accessibility is recognized as an output.

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 routing circuity penalizes airlines with significant portions of their service through hub airports. In the frontier models, substitution of RPODM for RPM reshapes the frontiers, with further weight given to departures. Although the resulting deviation of efficiency can be attributed to several factors, the estimated efficiencies turn out relatively insensitive to the presence of circuity.

The variations in fuel efficiency among the 15 carriers implies room for improvement, which could result substantial savings in fuel expenditures and reduced environmental impact. Despite the quite different approaches employed to quantifying these savings, estimates of potential cost savings to mainline airlines are rather close—between $2-3 billion. These figures do not consider potential fuel efficiency improvement by the affiliated regional carriers and the circuity of airline routing structures; taking them into account would further increase saving estimates, particularly those derived from ratio-based fuel efficiency metrics. The various estimates provide at least a magnitude of the potential savings from bringing industry fuel efficiency towards the fuel consumption frontier.

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 (Gathon and Perelman, 1992). 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 change is expected to be much stronger than input allocative efficiency. This is analogous to the argument that technical efficiency tends to dominate in the overall changes in productive efficiency (Oum et al., 1999). From the technical vantage point, the most plausible substitution for fuel is capital, which, as widely recognized in airline economics literature (e.g. Gillen et al., 1990; Oum and Yu, 1998; Hansen et al., 2001; Zou and Hansen, 2012), 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 non-capital inputs to improve fuel usage. 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 (Hensher, 1992). 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 latter only when there is some other incentives. Such incentives do exist and are pushing airlines toward greater fuel efficiency. One prominent example, as mentioned in the beginning of this paper, is volatile fuel price, which has played a significant role in driving airline fuel efficiency, and it is likely to continue to do so in the future. Another, still growing, force comes from those members of the general public whose travel choices may be influenced by commitment to sustainability and perception of how different travel alternatives accord with this value. This in turn provides airlines—indirectly through the market mechanism—with another source of impetus to constantly improve their fuel efficiency. For pressures of this kind to be effective in this context, clear and credible fuel efficiency information is required. The present study represents a start in this direction.

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APPENDIX 1: APPROXIMATION OF THE INEFFICIENCY UNDER THE STOCHASTIC FRONTIER MODEL S4

Following Battese et al. (2000), fuel efficiency for airline i at time t ($FI_{SF,it}$) is computed as

$$FI_{SF,it} = E[\exp(u_{it})\,|\varepsilon_{it}] = \{\frac{\Phi\left(\sigma_* + \frac{\mu_{*,it}}{\sigma_*}\right)}{\Phi\left(\frac{\mu_{*,it}}{\sigma_*}\right)}\}\exp\,(\mu_{*,it} + \frac{1}{2}\sigma_*^2) \qquad \text{(A-1)}$$

where $\mu_{*,it} = \frac{\varepsilon_{it}\sigma_u^2}{\sigma_S^2} + (\sum_{j=1}^{M}\delta_j z_{j,it})\frac{\sigma_v^2}{\sigma_S^2}$, $\sigma_* = \sigma_u\sigma_v/\sigma_S$ with$\varepsilon_{it} = \ln(\text{fuel})_{it} - \beta_0 - \beta_1\ln(\text{RPM})_{it} - \beta_2\ln(\text{dep})_{it}$ and $\sigma_S^2 = \sigma_u^2 + \sigma_v^2$. Of course, in performing the above calculation one will have to replace $\mu_{*,it}$, σ_*, and ε_{it} by their estimates using $\hat{\beta}$'s, $\hat{\delta}$'s, $\hat{\sigma}_v^2$, and $\hat{\sigma}_u^2$.

Given the extremely small value for $\hat{\sigma}_v^2$ relative to $\hat{\sigma}_u^2$, $\frac{\hat{\sigma}_v^2}{\hat{\sigma}_S^2}$ is practically zero. This suggests that while environmental factors can significantly affect the mean of the inefficiency, their direct influence on the conditional mean $E[\exp\,(u_{it})|\hat{\varepsilon}_{it}]$ is rather minimal. As a result of the dominance of $\hat{\sigma}_u^2$ in $\hat{\sigma}_S^2$, $\hat{\mu}_{*,it} \cong \hat{\varepsilon}_{it}$ and $\hat{\sigma}_* \cong 0$. The estimated $FI_{SFA,it}$ = $\left\{\frac{\Phi\left(\hat{\sigma}_* + \frac{\hat{\mu}_{*,it}}{\hat{\sigma}_*}\right)}{\Phi\left(\frac{\hat{\mu}_{*,it}}{\hat{\sigma}_*}\right)}\right\}\exp\left(\hat{\mu}_{*,it} + \frac{1}{2}\hat{\sigma}_*^2\right) \cong \left\{\frac{\Phi\left(0 + \frac{\hat{\varepsilon}_{it}}{0}\right)}{\Phi\left(\frac{\hat{\varepsilon}_{it}}{0}\right)}\right\}\exp(\hat{\varepsilon}_{it}) \cong \left\{\frac{\Phi(+\infty)}{\Phi(+\infty)}\right\}\exp(\hat{\varepsilon}_{it}) = \exp(\hat{\varepsilon}_{it})$. Therefore, the stochastic frontier inefficiency calculation collapses to the deterministic frontier case.

APPENDIX 2: OVERALL ASSIGNMENT RESULTS OF REGIONAL CARRIERS' RPMS

Airline	Apportioned RPM	% RPM apportioned	Affiliation type
SkyWest	10,971,400,000	93%	3
ExpressJet	7,808,116,996	95%	3
American Eagle	7,386,172,780	100%	1
Republic	5,569,788,120	94%	3
Atlantic Southeast	5,384,997,748	98%	3
Pinnacle	4,210,577,910	100%	2
Mesa	3,538,361,387	91%	3
Mesaba	3,381,681,196	99%	3
Comair	2,919,863,879	100%	1
Shuttle America	2,609,768,611	96%	3
Horizon Air	2,224,661,874	100%	2
Compass	2,210,100,086	100%	2
Air Wisconsin	1,820,269,811	100%	2
Chautauqua	1,690,870,678	79%	3
PSA	1,677,034,927	100%	1
GoJet	1,530,592,216	100%	2
Trans States	741,021,563	98%	3
Colgan	573,433,520	97%	3
Piedmont	518,216,513	100%	1
Freedom	315,123,971	100%	2
Executive	264,017,675	100%	1
CommutAir	145,073,561	100%	2

APPENDIX 3: REGIONAL CARRIER ASSIGNMENT RESULTS

Mainline carrier	Affiliated carriers	Apportioned RPM (10^6)	Total RPM (10^6)
American	American	77,263	85,501
	American Eagle	7,802	
	Executive	264	
	Chautauqua	172	
Alaska	Alaska	18,733	21,198
	SkyWest	14	
	Horizon	2,451	
JetBlue	JetBlue	24,224	24,224
Continental	Continental	41,410	49,772
	Colgan	537	
	CommutAir	151	
	Chautauqua	537	
	ExpressJet	7,136	
Delta	Delta	92,707	116,686
	Pinnacle	4,668	
	Compass	2,337	
	Atlantic Southeast	5,187	
	Freedom	315	
	Comair	3,126	
	SkyWest	4,031	
	Chautauqua	494	
	Shuttle America	405	
	Mesaba	3,416	
Frontier*	Frontier	6,407	8,126
	Chautauqua	120	
	Republic	1,598	
AirTran	AirTran	18,738	18,738
Allegiant	Allegiant	5,432	5,432
Hawaiian	Hawaiian	7,726	7,726
Spirit**	Spirit	4,007	4,007
Sun Country	Sun Country	1,356	1,356
United	United	57,317	73,416

	Colgan	81	
	Trans States	747	
	Atlantic Southeast	428	
	GoJet	1,627	
	SkyWest	8,261	
	Shuttle America	2,674	
	ExpressJet	1,057	
	Mesa	1,143	
	Republic	81	
US Airways	US Airways	43,864	54,661
	PSA	1,696	
	Piedmont	518	
	Colgan	54	
	Trans States	89	
	Chatauqua	327	
	Mesaba	97	
	Mesa	2,559	
	Republic	3,493	
	Air Wisconsin	1,963	
Virgin America	Virgin America	6,236	6,236
Southwest	Southwest	78,135	78,135

* The RPM's for Frontier and its two affiliated region carriers are only for Q1-Q3.
** The RPM's for Spirit are only for Q1, Q2, and Q4.