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Evaluating Air Carrier Fuel Efficiency and CO_2 Emissions 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) 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) efficiency rankings vary depending on the methodology, but nonetheless display high correlation; 4) regional carriers have two opposing effects on fuel efficiency of mainline airlines: increased fuel per revenue passenger mile but improved accessibility provision; 5) the net effect of routing circuity on fuel efficiency is small; 6) potential cost savings from improved efficiency for mainline airlines can reach $2-3 billion in 2010.

Table of Contents

List of Figures

List of Tables

1 Introduction

Airline fuel efficiency has never been so important. The airline industry, which depends critically upon fuel, has suffered from soaring fuel prices in recent years. Between 1995 and 2010, the portion of fuel cost in airline total operating expenses, within the U.S. airline industry, has increased from 25.6% to 47.3% (BTS, 2012). Nowadays, airlines are more intent than ever to improve fuel efficiency in their flight operations in order to ease the financial strains imposed by the increasing fuel price. Airlines are grounding and retiring older, less fuel-efficient aircraft, and upgrading their fleet by introducing more fuel efficient models. They are also adjusting operating practices to reduce fuel consumption, for example, by encouraging the use of single-engine taxi procedures. Customers in the air transportation system also feel the impact of fuel price hikes, with part of the additional fuel expenses passed onto them through higher airfares.

Furthermore, concern about anthropogenic climate change, and its related impacts, has added another layer of potential financial burden for airlines. The recent controversies surrounding global airlines in the European Emission Trading System directly represents this concern. The trading scheme could have a significant effect on airline operating costs. Aviation induced carbon dioxide (CO_2), one of the most important greenhouse gases, and regulated under the European emissions trading scheme, is directly tied to the amount of fuel consumed in flight operations. For this reason, any monetization of CO_2 also spurs airlines to improve their fuel efficiency by increasing the effective price of fuel.

On the demand side, whether traveling for leisure or business purposes, passengers are becoming more environmentally conscious. Worldwide, air passengers have voluntarily participated in carbon offsetting programs in an effort to "neutralize" their portion of aircraft carbon emissions during the journey (IATA, 2012). Anecdotal evidence suggests that travel management companies (TMC), which are 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, environmentally conscious demand. As the public's environmental awareness will only become stronger, some airlines may devote more resources to increasing their fuel efficiency in the future.

Fuel efficiency gains may also come from government initiatives. In the U.S., a major advance in fuel conservation, and emission reduction, will come from modernizing the nation's air traffic control (ATC) system (A4A, 2012). The Federal Aviation Administration's Next Generation Air Transportation System (NextGen) suite of solutions could improve system fuel efficiency by as much as 12% (A4A, 2012). A similar 10% reduction in CO_2 is also defined as one of the key performance goals in the on-going Single European Sky ATM Research Program (SESAR, 2010). In the UK, the Civil Aviation Authority together with NATS, the UK's air navigation service

[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.

provider, have recently agreed to introduce a new incentive scheme in which NATS will be financially rewarded or penalized in its air traffic control, based upon the fuel performance of flights in areas for which NATS is responsible (CAA, 2011a, b). At a larger, intercontinental scale, cooperative demonstrations have also been launched, such as Atlantic Interoperability Initiatives to Reduce Emissions (AIRE), and the Asia and the Pacific Initiative to Reduce Emissions (ASPIRE).

From a macroscopic perspective, air travel and the economic growth are closely linked, and a low level of fuel efficiency threatens the airlines' ability to serve the needs of the economy. The most direct impacts on the economy come through the jobs and revenue the industry directly generates in air transport-related activities, such as the expenditures of air travelers on auxiliary goods and services. Air transport supports local economies and creates new markets, and has become an essential economic and social conduit throughout the world (World Bank, 2012). Nowadays, many communities depend heavily upon access to the air transportation network for economic development. Using the U.S. as an example, the FAA estimates that, in 2011, commercial aviation was responsible for 4.9 to 5.2 percent of U.S. gross domestic product (GDP), helping generate $1.2-$1.3 trillion in annual economic activity, $370-$405 billion in annual personal earnings and 9.7 to 10.5 million jobs (FAA ATO, 2011). Only by improving fuel efficiency will the airline industry be able to move towards a more robust and sustainable development path, and thus fully support economic growth and development, in the face of fuel price and environmental challenges.

Given the volatility of fuel price, rising concern about and actions against climate change, and the importance of maintaining and promoting an operationally efficient airline industry to support continuous economic growth, developing the capability to evaluate airline fuel efficiency is critical. Policy makers, industry stake holders, and the general public require fuel efficiency information to assess the status quo and trends in industry fuel use, and help shape future strategies to improve fuel efficiency. To this end, the International Council on Clean Transportation has sponsored this study, with the first stage assessing fuel efficiency of U.S. airlines in their domestic operations. Focusing on the year 2010, on the eve of two significant mergers, United/Continental and Southwest/AirTran, this study assesses the fuel efficiency of 15 U.S. large jet operators. Multiple approaches are employed, based upon different models of the relationship between airline fuel consumption and production. In addition, we explicitly recognize——to our knowledge for the first time—that affiliations between these large jet operators and regional carriers must be taken into account when assessing the fuel efficiency of large jet operators. 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. By developing different models, considering large jet operators by themselves or in combination with their regional affiliates, and measuring carrier output in different ways, we obtain a range of fuel efficiency metrics and rankings. While we do not want to choose one best answer out of these, we do provide in this report a detailed exposition of alternative methods for measuring and ranking airline fuel efficiency, and the assumptions underlying the different methodologies. We compare the results from the different approaches, in an effort to provide additional insights into the factors that cause the ranking difference. Our ultimate aim in these efforts is to develop a robust, transparent, airline fuel efficiency assessment framework that can eventually be extended to other airlines around the globe as long as equivalent data are available.

The remainder of the report is organized as follows. Section 2 provides a brief overview of airline industry organization in the U.S. Three methodologies (ratio-based, deterministic frontier, and stochastic frontier) used for airline fuel efficiency measurement are presented in Section 3. These methodologies are then applied to 15 U.S. large jet operators (which later on are referred to as mainline airlines) in the ensuing section, where we present and analyze results from the different approaches, with and without considering mainline-regional carrier affiliations. 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.

2 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 travel services by extensively relying upon a relatively small number of hub airports. For the above four carriers in 2010, 30-50% of passengers completed their trips by connecting at least once at an intermediate 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 (OD) pairs on one segment, resulting in increased load factors and the use of large, more efficient narrow and wide body passenger jets. The benefits, widely recognized in academic research as the economies of density, has helped legacy carriers reduce operating expense and offer low airfares to passengers. At the same time, however, hubbing enables carriers to establish dominant competitive positions at their hub airports, and exploit their market power by charging higher fares in OD markets involving these hubs. Complementing this hub-dominance strategy are frequent flier programs, which increase brand loyalty and favor carriers with large networks.

On the other hand, deregulation has spurred the growth and expansion of low cost airlines, which constitute the second important group of large jet operators. Although these airlines provide connecting service to a small portion of their passengers, their services and networks are predominantly point-to-point. Compared to the legacy carriers, these low cost airlines in general are relatively young; thus their fleets generally consist of newer aircraft with better fuel efficiencies. Even within the group, however, substantial heterogeneity exists in terms of network structures and business models. For example, there are major differences between Southwest, the first low-cost carrier which provides services with a wide range of stage lengths on multi-stop routes, and Virgin America, a newly established airline focusing on long-haul coast-to-coast travel. Nonetheless, these low cost carriers, by targeting specific markets, have strengthened competition in the industry, and shaped the U.S. air transportation system into a more complex and extensive mixture of varied operating structures.

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

In addition to legacy and low-cost carriers, regional carriers are integral components of the system. Regional carriers support, and are sustained by, the hub-and-spoke network structure. Connecting passenger itineraries often feature a short flight on a small plane into or out of the hub, which is connected to a longer haul flight on a large jet aircraft, connecting at that 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 with access to the hub, through which they can access further destinations. Demand from these non-metropolitan regions is usually low, due to their relatively small populations and weaker socio-economic interactions with far-away regions. As a consequence, smaller regional jets and turboprops are used by regional carriers to serve the thinner demand. Regional and mainline carriers are mutually dependent, but the latter are the lead partners in terms of marketing and branding. Regional aircraft liveries are normally based on their mainline partners, who also handle ticket sales and scheduling. This is reflected in ticketing data that are reported to the BTS Airline Origin and Destination Survey (DB1B) database, which is based on a 10% sample of domestic airline tickets in the U.S. In the database, the portions of itineraries flown on regional carriers are included under the name of the affiliated mainline carriers. It is therefore useful to consider operations of the associated regional carriers when evaluating the fuel efficiency of a given mainline carrier. The complicated relationships between mainline and regional carriers, particularly in cases where one regional carrier provides services for multiple mainline airlines on the same segment, make this a challenging task. To our knowledge, the present study presents the first effort to investigate the impacts of regional airline affiliations on mainline carriers' fuel efficiency.

Hub-and-spoke itineraries, whether they involve regional affiliates or not, are usually more circuitous than non-stop flights. They also involve additional landings and takeoffs than itineraries serving the demand with non-stop flights. However, by increasing flight frequency in some cases, and making air service viable in others, they increase the accessibility of the air transport system. The accessibility advantage and circuity disadvantage of hub-and-spoke networks are taken into account in several of the fuel efficiency assessment methods described below.

3 Airline ranking methodology

In this section, we present several methods to compare airline fuel efficiency. These include simple methods based on ratios between fuel use and airline output, as well as more sophisticated approaches in which a "production frontier" is defined and airline efficiency is assessed relative to this frontier. The ratio-based methods have the virtues of simplicity and transparency. They do not, however, account for inter-carrier differences in output characteristics and scale that may significantly affect fuel requirements but are—at least arguably—not related to fuel efficiency per se. The frontier-based approaches do account for these differences, but entail more complex methodologies that involve statistical assumptions and are more reliant on analyst judgment. By using a range of methods to develop airline fuel efficiency rankings, we can identify conclusions that hold regardless of method, and are thus more definitive, as well as findings that are more contingent on methodology.

In this study, we use the terms “fuel efficiency” and “fuel inefficiency.” Although the former expression is the more natural one, from a technical point we consider the latter more appropriate. At a given time, there is an upper bound to how fuel efficient an airline can be, based on existing technology. In this report we define that bound based on the performance of the most fuel-efficient carriers, and use it as a benchmark for the other firms. In that sense, our results measure the “fuel inefficiency” of airlines compared to industry leaders. Since the latter term, although technically more precise, is also rather stilted, we often revert to the more common “efficiency” form.

3.1 Ratio approach

This section presents metrics that take the form of ratios. Such ratio-based metrics—analogous to miles per gallon for automobiles—are the most intuitive way to evaluate airline fuel efficiency. Ideally, a metric should be one that measures the amount of fuel usage to produce a unit output, or the amount of output produced with the consumption of one unit of fuel. In economic terms, the latter is essentially a fuel-based partial productivity measure.

To calculate such metrics, an airline output measure must be chosen. There are several well-established alternatives. These include available passenger 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 produced, 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 (Windle and Dresner, 1992). Therefore, RPM and RTM are preferred output measures. 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.

Regarding the choice between RPM and RTM, an advantage of the latter 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 of RTM needs to be weighed against several factors that favor the use of RPM. First, the 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 (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. Thus non-passenger RTM’s are inherently inefficient, and it seems inappropriate 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 consistency in the efficiency computation.

While the application of Fuel/RPM to examining fuel efficiency is straightforward if only mainline airlines are considered, it becomes less intuitive when the contribution of regional subsidiaries is incorporated. 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,

$\left(\frac{\text{Fuel}}{\text{RPM}}\right)_{\text{i}}^{\text{adjusted}}$:

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

Where $(\text{Fuel})_{\text{j}_\text{k}}^{\text{i}}$ and $(\text{RPM})_{\text{j}_\text{k}}^{\text{i}}$denote, respectively, the fuel consumed by regional carrier j_k that is attributable to mainline airline i's operations ($\text{Fuel}_{\text{j}_\text{k}}^{\text{i}}$), and the RPM's from j_k (k = 1, …, n) that should be assigned correspondingly to i ($\text{RPM}_{\text{j}_\text{k}}^{\text{i}}$). Essentially, $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_{\text{i}}^{\text{adjusted}}$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 RPM's across the mainline and the regional carriers. The exact estimation of $\text{RPM}_{\text{j}_\text{k}}^{\text{i}}$ and $\text{Fuel}_{\text{j}_\text{k}}^{\text{i}}$ will be discussed in Section 4.

The preceding discussion can be synthesized in a three-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, $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_{\text{i}}^{\text{adjusted}}$ is the adjusted fuel/RPM that takes into account the contribution of regional carriers' operations to mainline airline i. We express $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_{\text{i}}^{\text{adjusted}}$ as a function of a set of (Fuel/RPM)'s, which are the middle level 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, $\left(\frac{\text{Fuel}}{\text{RPM}}\right)_{\text{i}}$ is further decomposed into the product of $\left(\frac{\text{Fuel}}{\text{ASM}}\right)_{\text{i}}$ and $\left(\frac{\text{ASM}}{\text{RPM}}\right)_{\text{i}}$, 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.

As a further refinement, revenue passenger O-D miles (RPODM) can be used in place of RPM in equation (1). As discussed above, this captures the effect of itinerary circuity, which can be expressed as the ration of RPM to RPODM.

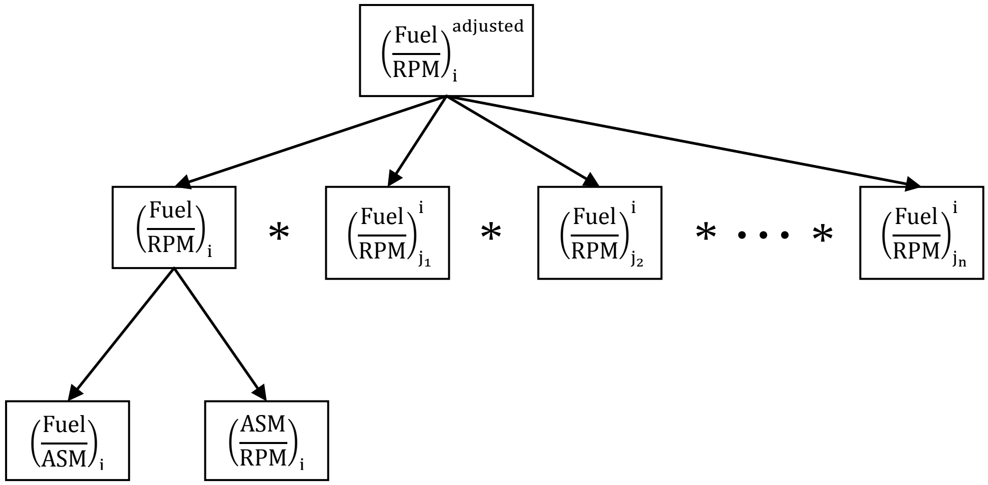

Figure 1: Three-level hierarchical structure of fuel efficiency metrics

3.2 Deterministic frontier approach

A standard metric for airline production output, RPM essentially measures the level of mobility airlines provide for passengers. Mobility refers to the movement of people. In addition to mobility, another important measure of transportation system performance is accessibility, which by definition evaluates the ability to reach desired goods, services, and activities (Litman, 2011). Specifically in the context of airline production, accessibility can be measured by the number of aircraft trips, or the number of flight departures (denoted here as dep). This is because each departure, like the stop of a bus or a train, affords an opportunity for passengers to embark or disembark. A comprehensive characterization of airline production should include both mobility and accessibility aspects of output. 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, any conventional ratio metric based on RPM will yield a distorted measure of its fuel efficiency. To circumvent this problem, an airline's fuel efficiency should take into account the number of departures as well as its RPM.

It is expected that, given the same quantities of RPM and dep, any two airlines will consume somewhat different amounts of fuel. Even for the same airline, its fuel usage for producing the same output in different time periods will not be identical. Based on the observed output and fuel consumption, we can define the minimum amount of fuel consumed for every possible combination of RPM and dep. All these minimum amounts constitute a fuel consumption frontier, which is *deterministic* since minimum fuel can be uniquely found given values of RPM and dep. An airline's fuel usage in any period should lie either on or above the frontier, expressed as

$$\mathrm{fuel}_{it} = f(\mathrm{RPM}_{it}, \mathrm{dep}_{it}) + \eta_{it} \tag{2}$$

where subscript i denotes a specific airline, and t identifies the time period; $f(\mathrm{RPM}_{it}, \mathrm{dep}_{it})$ specifies the fuel consumption frontier; and η_{it} is a non-negative deviation term. The concept of frontier is illustrated in Figure 2 when we consider only one output. The solid curve represents the fuel consumption frontier, constructed based on four observations (data points). Because the frontier is identified based upon the minimum fuel consumption observed for a given level of output, data points below the frontier will be unrealizable. Point C lies on the curve, denoting the most fuel-efficient production among the four observations. The deviation term for point C is zero. Observations above the curve (A, B, D) represent the cases in which fuel use did not achieve the most efficient level. The extent of inefficiency for any of these points is calculated as $[f(\mathrm{RPM}_{it}, \mathrm{dep}_{it}) + \eta_{it}]/f(\mathrm{RPM}_{it}, \mathrm{dep}_{it})$, which equals the ratio of two ordinates: the ordinate of the observation (actual fuel burn) and that of the intersection point of the corresponding vertical line with the frontier (most efficient fuel burn), e.g. ||BB"||/||B'B"|| for observation B.

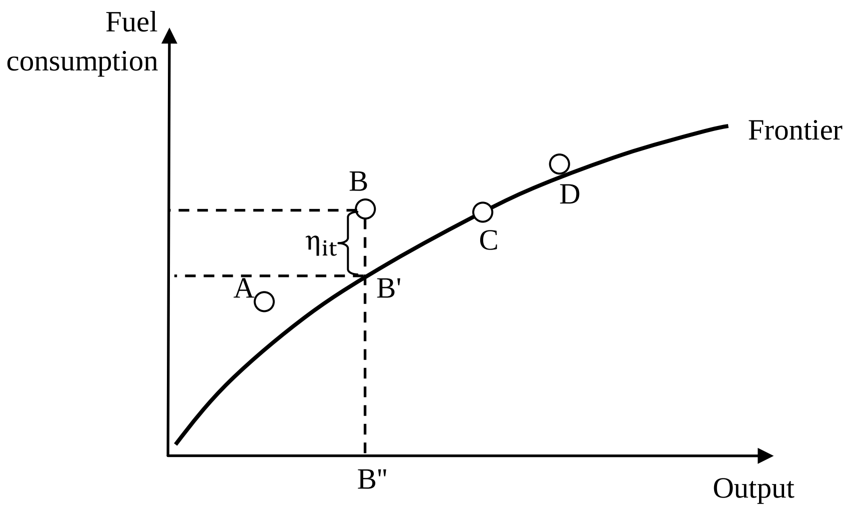

Figure 2: Illustration of fuel consumption efficiency frontier

In the present study we assume the frontier part $f(\mathrm{RPM}_{it}, \mathrm{dep}_{it})$ follows a log-linear functional form. Airline fuel consumption then becomes:

$$\ln(\mathrm{fuel})_{it} = \beta_0 + \beta_1 \ln(\mathrm{RPM})_{it} + \beta_2 \ln(\mathrm{dep})_{it} + \xi_{it} \tag{3}$$

where $\beta_0, \beta_1, \beta_2$ are the coefficients to be estimated using Correlated Ordinary Least Squares (COLS). To make this explicit, we first run an Ordinary Least Squares (OLS) regression to obtain estimates of two slope β_1 and β_2, and an initial intercept β_0', based on which residual $\hat{\varepsilon}_{it}$ for each observation is calculated. In the 2nd 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, $\beta_0 = \beta_0' + \min_{i,t}\{\hat{\varepsilon}_{it}\}$. The estimated $\beta_0, \beta_1, \beta_2$ characterize the fuel consumption frontier, with the deviation term $\xi_{it} = \hat{\varepsilon}_{it} - \min_{i,t}\{\hat{\varepsilon}_{it}\}$, which is essentially a multiplier of the minimum fuel burn suggested by the frontier. Based on (3), the inefficiency measure $\exp(\xi_{it})$ is equal to $\frac{1}{\exp(\beta_0)} \cdot \frac{(\mathrm{fuel})_{it}}{\mathrm{RPM}_{it}^{\beta_1} \mathrm{dep}_{it}^{\beta_2}}$, where $\frac{1}{\exp(\beta_0)}$ is a constant across observations. The deterministic frontier approach therefore can be regarded—at least numerically—as a more general ratio, with the denominator involving both mobility and accessibility measures, 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 an *a priori* assumption.

In the deterministic frontier approach, fuel efficiency is captured by $\exp(\varepsilon_{\mathrm{it}})$. In fact, however, variability in this term derives from three sources: technological progress, heterogeneity in airlines' operating environment, and productive fuel efficiency. Technological progress refers to the improvement in aircraft technology and operational prowess over time. Operation environment heterogeneity pertains to airlines' to variation in operating characteristics such as average stage length, aircraft size, and load factor. Productive fuel inefficiency results from the remaining technical, operational and managerial factors, such as inter-airline difference in aircraft technology, fleet age, aircraft maneuvering, air traffic management practices. Examples for the last aspect are deviation of actual flight path from point-to-point linear path, and single vs. full engine taxiing on the runway.

The deterministic frontier method can also be applied to the case that mainline airlines and regional carriers are jointly considered in efficiency measurement. In this case, fuel, RPM, and dep are all sums from those of the mainline airline as well as the assigned amounts from the affiliated regional carriers. Based on the composite values, a new fuel consumption frontier will be developed; this frontier will certainly be different from one in which only mainline airlines' fuel burn and operations are considered. On the other hand, the procedure to quantify the fuel inefficiency follows the exact procedure as in the mainline-only case. Additionally, by using RPODM instead of RPM, the method can also be adapted to account for the effects of circuity.

3.3 Stochastic frontier approach

In the deterministic frontier approach, all variations in fuel consumption 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. Not surprisingly, the deterministic approach is sensitive to outliers (Aigner et al., 1977). On the other hand, 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", an undesirably restrictive property of the deterministic frontier procedure. To address these two issues, stochastic frontier models are proposed as an alternative. These models 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, ξ_{it} in Equation (3) now consists of two stochastic error terms v_{it} and u_{it}:

$$\xi_{\mathrm{it}} = v_{\mathrm{it}} + u_{\mathrm{it}} \tag{4}$$

where v_{it} is a two-sided "idiosyncratic" error term which captures the effect of measurement error and random variation in the operational environment that is outside the airline's control. v_{it} is often assumed to be identically and independently distributed as $N(0, \sigma_v^2)$. u_{it}, in contrast, has a one-sided distribution with $u_{\mathrm{it}} \geq 0$, and represents the fuel efficiency. The most commonly made distributional assumption is that u_{it} has a half-normal distribution, i.e. $u_{\mathrm{it}} \sim N^{+}(0, \sigma_u^2)$. Following (3), the stochastic frontier fuel consumption function becomes

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

The associated fuel consumption frontier is $\text{F}^* = e^{\beta_0} \times \text{RPM}^{\beta_1} \times \text{DEP}^{\beta_2} \times e^{v}$ which, because of the random error term *v*, becomes stochastic. Similar to the deterministic frontier case, the non-negative disturbance u_{it} in (5) reflects the fact that fuel consumption must lie on or above the frontier.

Under the additional assumption that u_{it} and v_{it} are distributed independently of each other, and of the regressors in (4), the parameters β's, σ_v^2, and σ_u^2, can be estimated using the maximum likelihood method (Aigner, Lovell and Schmidt, 1977). We note that u_{it} are not directly observable; the estimated residual of the model are realizations of $\varepsilon_{\text{it}} = v_{\text{it}} + u_{\text{it}}$ rather than of u_{it} alone. A widely used point estimator of fuel inefficiency is the conditional expectation of exp(-u_{it}), conditional on the random variable ε_{it}. Following Battese and Coelli (1988), fuel inefficiency for airline i at time t ($\text{FI}_{\text{SFA,it}}$) is computed as:

$$\text{FI}_{\text{SFA,it}} = E[\exp(u_{\text{it}})\,|\varepsilon_{\text{it}}] = \{\frac{1-\Phi\left(-\sigma_* - \frac{\mu_{*,\text{it}}}{\sigma_*}\right)}{1-\Phi\left(-\frac{\mu_{*,\text{it}}}{\sigma_*}\right)}\}\exp\,(\mu_{*,\text{it}} + \frac{1}{2}\sigma_*^2) \tag{6}$$

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

Given the fact that airlines may experience different environmental conditions in their operations, the assumption of identical distribution among the inefficiency terms u_{it} may be relaxed. It is possible that output characteristics (or environmental factors), such as average stage length and aircraft size, can influence airlines' fuel inefficiency. To capture this heterogeneity, we can alternatively specify that u_{it} are independently but not identically distributed as the non-negative truncation of a general normal distribution (Battese and Coelli, 1995):

$$u_{\text{it}} \sim N^+(\sum_{\text{j=1}}^{\text{M}} \delta_{\text{j}} z_{\text{j,it}}, \sigma_u^2) \tag{7}$$

where δ's are the parameters to be estimated; and *z*'s represent environmental factor variables. The underlying assumption is that that all airlines share the same fuel consumption technology represented by the fuel consumption frontier (5) and that the environmental factors have an influence on the "distance" between airlines' actual fuel burn and the frontier.

The unknown parameters β's, δ's, σ_u^2 and σ_v^2 in (5) and (7) are estimated simultaneously using the maximum likelihood method. Subsequently, the inefficiency measure in (6) needs to be adjusted to account for the heterogeneity in the means of the inefficiency term u_{it} (Battese and Coelli, 1993):

$$\mu_{*,\mathrm{it}} = \frac{\hat{\varepsilon}_{\mathrm{it}}\sigma_u^2}{\sigma_S^2} + (\sum_{\mathrm{j}=1}^{\mathrm{M}} \delta_{\mathrm{j}} z_{\mathrm{j,it}}) \frac{\sigma_v^2}{\sigma_S^2} \tag{8}$$

While one might consider including environmental factors in the frontier instead of in the inefficiency term, the resulting fuel inefficiency measures will be ones net of environmental influences, and thus represent only part of the inefficiency sources we intend to capture, and are not consistent with the ratio or deterministic frontier approaches. Nonetheless, it is worth noting that (although we do not pursue the procedure here) one can also obtain inefficiency estimates inclusive of environmental influences from the net inefficiency (e.g. Coelli et al., 1999).

As a final remark, the stochastic frontier models can be applied to assessing joint fuel efficiency of mainline and affiliated regional carriers, in the same fashion as in the deterministic frontier case. The only addition here is that output characteristics are also based upon composite measures of RPM, departures, average stage length, and average aircraft size. Likewise, by using RPODM instead or RPM, the effects of circuity can be accounted for.

4 Application to US mainline carriers

4.1 Data

We focus on the domestic operations of 15 U.S. airlines in our analysis of fuel efficiency. The choice of airlines is based on the average aircraft size, calculated as the ratio of available seat miles and revenue aircraft miles for each carrier. We initially considered those carriers with at least 500,000 enplaned passengers for 2010. 40 carriers met this threshold, however the three smallest carriers did not report sufficient data to BTS, and therefore are removed from consideration. Figure 3 illustrates the average aircraft sizes among the remaining 37 carriers 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 15 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 very similar technologies in their production. Carriers on the left hand side of the line are invariably regional airlines, mostly operating as affiliates of the 15 mainline airlines.

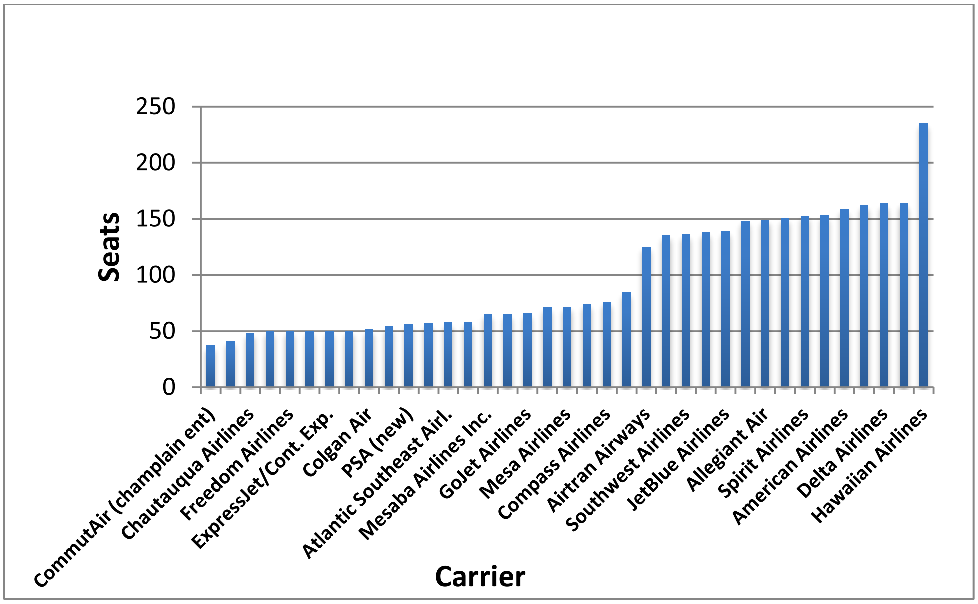

Figure 3: Average aircraft size of U.S. carriers (source: Data Base Products)

Figure 4 shows that the 15 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 an output measure.

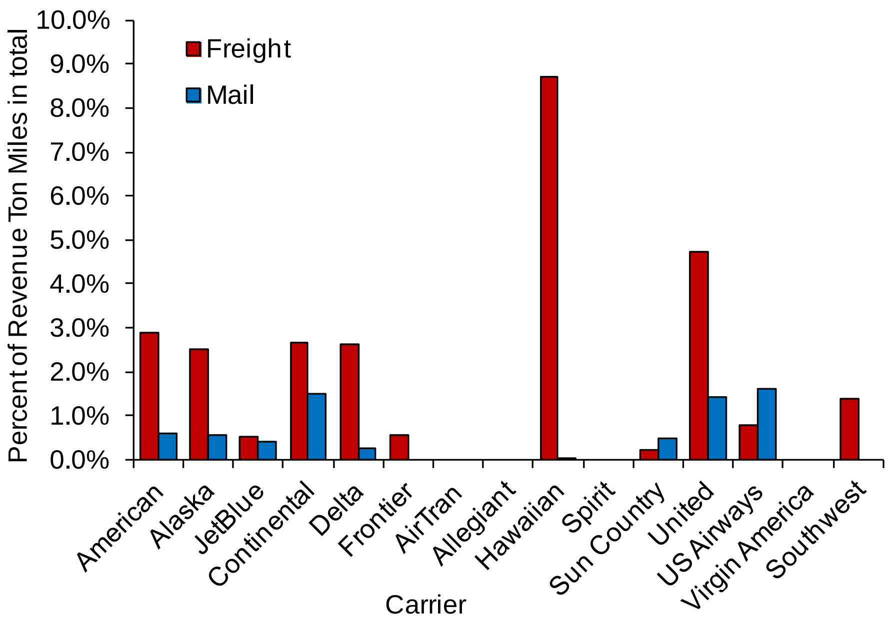

Figure 4: Portion of freight and mail services in the total 15 mainline airlines (2010)

Table 1 presents 2010 values for fuel consumption, output (RPM and Departures), and three environmental factors (in the sense of Equation (7) above)—average stage length, average aircraft size, and average load factor—for the 15 mainline airlines. Average stage length is obtained by dividing revenue aircraft miles (RAM) by aircraft departures. Average load factor is the ratio between RPM and available seat miles (ASM). These data are extracted from the CD-ROM database product, distributed by Data Base Products Inc., a reseller of BTS Form 41 data series, which contains the reported financial and operational data from U.S. airlines on a quarterly basis. The descriptive statistics of the airline-quarter data in 2010 are presented in Table 2.

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 long haul flights to the U.S. The heterogeneity of airline operating scales presents an important source of variation in the airline-quarter data sample (Table 2), which will be useful in the estimation of frontier fuel consumption models. However, because of many inter-island flights, the average haul of aircraft trips for Hawaiian is the smallest. The longest average stage lengths were seen in Virgin America, Continental, United, and Sun Country. In particular, 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 operated with 30% of its seats empty.

Table 1: Fuel consumption, and output characteristics of the 15 mainline carriers in 2010

Carrier	Fuel (10^9 gallons)	RPM (10^9)	Departures	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)

Table 2: Descriptive statistics of fuel, output, and output characteristics of 15 mainline carriers (airline-quarter observations, 2010)

Variable	Mean	Std. dev.	Min	Max
Fuel (gallons)	$1.47{\times}10^{8}$	$1.41{\times}10^{8}$	$5.09{\times}10^{6}$	$4.58{\times}10^{8}$
RPM (000)	$8.12{\times}10^{9}$	$7.54{\times}10^{9}$	$2.78{\times}10^{8}$	$2.54{\times}10^{10}$
Departures	71034	75643	2456	287415
Stage length (statute miles)	992	241	534	1592
Aircraft size (seats/flight)	154	25	124	238
Load factor	0.825	0.049	0.658	0.908

Source: Data Base Products (2011)

The remaining 22 carriers served as regional connectors under some form of operational relationship with the 15 mainline airlines. In the subsequent fuel efficiency analysis, these regional carriers will also be considered jointly with the 15 mainline airlines above. Table 3 presents fuel consumption, output, and output characteristics of the 22 regional carriers in 2010. Summary statistics of regional airline-quarter observations are reported in Table 4. Note that five carriers (Chautauqua, CommutAir, Freedom, Piedmont, and Trans State) did not report their fuel consumption data to BTS.

By and large, the 22 regional carriers produced much fewer RPM's than their mainline counterparts, with the exception of a few: 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, we do not observe as much discrepancy in the number of departures between mainline and regional airlines—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 greater accessibility than mainline airlines.

Table 3: Fuel consumption, output, and output characteristics of the 22 regional carriers in 2010

Carrier	Fuel (10^6 gallons)	RPM (10^9)	Departures	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

Source: Data Base Products (2011) and Bureau of Transportation Statistics (2011)

Table 4: Descriptive statistics of fuel, output, and output characteristics of 22 regional carriers (airline-quarter observations, 2010)

Variable	Mean	Std. Dev.	Min	Max
Fuel (gallons)	2.88×10^7	2.29×10^7	3.10×10^6	9.30×10^7
RPM (000)	8.63×10^5	8.04×10^5	3.08×10^4	3.58×10^6
Departures	44894	37328	3551	164715
Stage length (statute miles)	404	143	159	704
Aircraft size (seats/flight)	58	12	37	85
Load factor	0.737	0.074	0.484	0.828

Source: Data Base Products (2011)

Overall, the 15 mainline carriers account for the bulk of fuel consumption and service provided in the U.S. domestic air transportation system. Figure 5 plots the cumulative fuel burn of the 15 carriers (sorted from the largest to the smallest), with the last two bars denoting system totals excluding and inclusive of cargo carriers. Fuel consumption from the 15 carriers accounts for more than two-thirds of the grand total fuel burn when all carriers are considered. If attention is confined to non-cargo carriers, the percentage rises to over 80%. The dominance of the 15 airlines is also reflected in other metrics, such as RPM, aircraft departures, RAM, and enplaned passengers, as shown in Table 5. Considering all of these metrics, the 37 carriers together represent at least 99.4% in the system total, excluding cargo carriers. Results from analyzing the 37 carriers will therefore give an almost complete picture of fuel efficiency in the U.S. domestic passenger air transportation system.

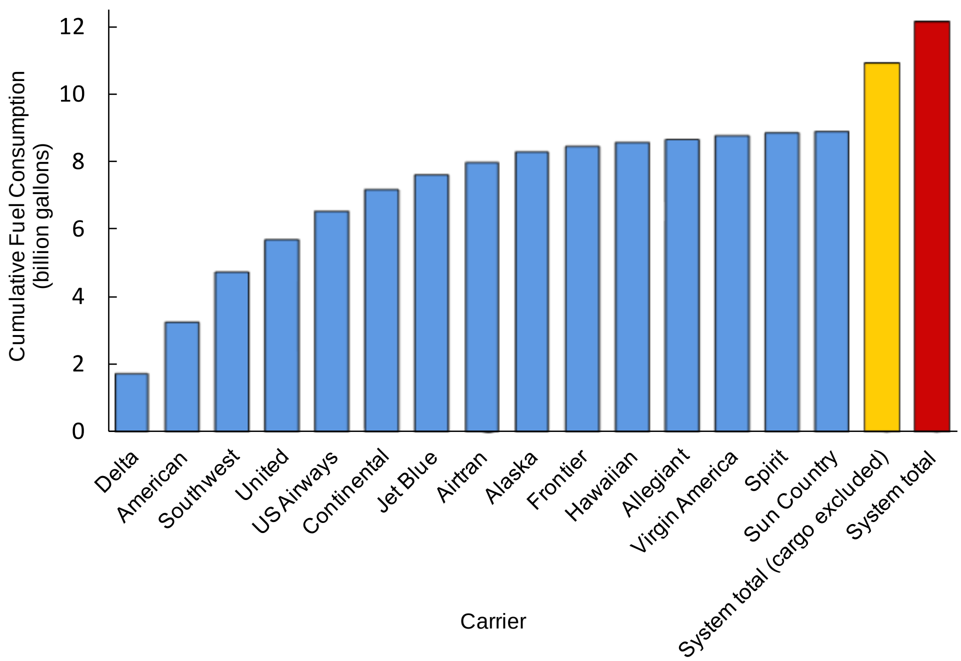

Figure 5: Cumulative fuel consumption of the 15 mainline carriers and system totals in 2010

Table 5: Percentage of mainline and regional carriers in the system total (excluding cargo carriers) under different metrics

	Fuel	RPM	Departures	RAM	Enplaned Passengers
15 mainline carriers	80.7%	86.5%	51.9%	69.4%	75.0%
22 regional carriers	19.0%	13.3%	47.5%	30.3%	24.8%
Sum of both carrier types	99.7%	99.8%	99.4%	99.7%	99.8%

4.2 Mainline-only fuel inefficiency

4.2.1 Ratio-based inefficiency

The measurement of fuel inefficiency under the ratio-based approach is straightforward--simply calculate the ratio of fuel over RPM for each of the 15 mainline airlines. Fuel and RPM are reported to BTS by quarter. Scrutiny of the data reveals that reported fuel burns for Spirit on the 3rd quarter and Frontier on the 4th quarter depart substantially from those of the remaining quarters, whereas RPM outputs stay similar. These two airline-quarter observations are identified as outliers and removed from the analysis.3 Table 6 below shows, in order, Fuel/RPM values of the 15 mainline carriers in 2010. They range from 0.0156 (Spirit) to 0.0196 (AirTran) gallons per revenue-passenger-mile. The Fuel/RPM values are further standardized and converted into fuel inefficiency scores FI_{ratio}, in which the value 1 is taken by the carrier with the lowest Fuel/RPM. The FI_{ratio} values indicate the percentage of extra fuel consumed as compared to the "best practice." Spirit ranks as the most fuel efficient carrier, followed closely by Continental, Alaska, and Hawaiian, whose Fuel/RPM values are within 2% of Spirit. The gap between Spirit and those next down on the list (Virgin America, Frontier, Sun Country) increases more significantly, with about 2-3% additional Fuel/RPM, incrementally, between each pair of consecutive airlines on the ranking list. Inefficiency scores of Sun Country, Jet Blue, and United cluster around 1.10, followed by Delta, Southwest, whose efficiencies are on par with one another at about 1.18, and US Airways at 1.2. The three remaining carriers (Allegiant, American, AirTran) have similar inefficiency scores, and are approximately 25% less efficient than Spirit. As mentioned before, many factors can contribute to the efficiency differences. In particular, we find that these scores are clearly associated with fleet age. The last column in Table 6 presents the average fleet age for each airline in 2010. The fleet age and FI_{ratio} values for the 15 airlines show a strong correlation of 0.612.

[3] The abnormality of the two data points will be further evidenced in the following frontier analysis. See section 4.2.2.

Table 6: Fuel/RPM, inefficiency scores, and ranking of the 15 mainline airlines

Carrier	Fuel/RPM (10^{-2}gallon/RPM)	FI_{ratio}	Rank	Average fleet age
Spirit	1.5629	1.000	1	3.6
Continental	1.5745	1.007	2	9.2
Alaska	1.5885	1.016	3	7.5
Hawaiian	1.5932	1.019	4	11.1
Virgin America	1.6266	1.041	5	2.9
Frontier	1.6642	1.065	6	5.5
Sun Country	1.7143	1.097	7	8.8
Jet Blue	1.7240	1.103	8	4.9
United	1.7290	1.106	9	14.0
Delta	1.8408	1.178	10	15.6
Southwest	1.8412	1.178	11	10.8
US Airways	1.8782	1.202	12	11.8
Allegiant	1.9533	1.250	13	20.9
American	1.9563	1.252	14	14.6
AirTran	1.9589	1.253	15	7.0

4.2.2 Deterministic frontier based inefficiency

We follow the discussion in sub-section 3.2 by first performing an OLS regression of fuel against RPM and dep, using airline-quarter data in 2010. Confirming the visual inspection in the preceding sub-section, residual plots identify Spirit of the 3rd quarter and Frontier of the 4th quarter as clear outliers. After deleting the two observations, OLS regression yields the following parameter estimates:

$$\ln(Fuel) = \underset{(0.494)}{-2.726} + \underset{(0.040)}{0.869} * \ln(RPM) + \underset{(0.038)}{0.150} * \ln(dep)$$

$$\text{Number of observations: } 58 \qquad R^2 = 0.997 \tag{9}$$

The goodness of fit (measured in R^2) of the model is very high, implying that the two outputs satisfactorily explain how airlines consume fuel. Coefficients for RPM and dep are both significant and have the expected signs. The estimates imply that: 1) controlling for dep, a 10% increase in RPM would lead to 8.69% more fuel consumption; 2) if one instead increases flight departures by 10% while preserving the total RPM, fuel consumption would rise by 1.5%.

These results imply that if RPM is increased while keeping dep constant, the fuel consumption per RPM will decline. By definition, an increase in RPM that preserves total departures implies that flights are either flying longer distances or carrying more passengers, as a result of up-gauging or higher load factors. These changes result in lower unit fuel consumption. On the other hand, increasing departures while keeping RPM constant implies either shorter flight distances or fewer passengers per flight, either of which result in greater fuel consumption per RPM. Put another way, additional fuel consumption is required to increase mobility and to increase accessibility, but the former is by far the stronger driver of fuel requirements.

Before turning into the inefficiency measurement, the scale economies implied by the estimated parameters are worth noticing. Although scale economies have been examined extensively in the airline cost modeling literature (e.g. Cave et al., 1984; Gillen et al., 1990; Hansen et al., 2001; Zou and Hansen, 2012, to name a few), the vast majority of existing studies are cost-based. The scale economy measure in the present study differs from the previous ones in that we focus on the fuel input, and define the Returns-to-Scale (RTS) measure as the reciprocal of the sum of fuel usage elasticities with respect to RPM and dep:

$$\mathrm{RTS} = \frac{1}{\beta_1 + \beta_2} \qquad (10)$$

A RTS value greater than one suggests that if RPM and dep increased by the same proportion, the increase in fuel consumption would be less than proportionate. In other words, fuel economies of scale exist. No scale economies and decreasing returns-to-scale occur when RTS is equal to or less than one respectively. The point estimate of RTS from the above deterministic frontier model is 0.981, very close to 1, suggesting slight diseconomies of scale in fuel usage. However, the null hypothesis of constant RTS cannot be rejected at 5% level of significance.

To translate the estimation results into fuel inefficiency scores, the fuel consumption frontier is obtained by shifting the intercept β_0' (-2.726) downward by $|\min_{i,t}\{\hat{\varepsilon}_{it}\}|$. Residuals are accordingly normalized against $\min_{i,t}\{\hat{\varepsilon}_{it}\}$. The fuel inefficiency score (FI_{DFA}) for airline i in time period t is defined as $\exp[\hat{\varepsilon}_{it} - \min_{i,t}\{\hat{\varepsilon}_{it}\}]$. As discussed in sub-section 3.2, FI_{DFA} is a multiplier of the minimum fuel burn to produce a given combination of mobility and accessibility that yields the observed fuel consumption value for a given airline and quarter. The minimum value of FI_{DFA}, lying on the frontier and therefore equal to 1, is for Spirit in the 4th quarter of 2010. Table 7 below shows the FI_{DFA} values averaged by airline. The FI_{DFA} value for Spirit, the most efficient airline, is greater than 1 because two other observations for Spirit (1st and 2nd quarters) do not fall on the frontier.

Table 7: Calculated FI_{DFA} values for the 15 mainline carriers

Carrier	FI_{DFA}	Ranking
Spirit	1.026	1
Hawaiian	1.027	2
Alaska	1.030	3
Continental	1.044	4
Southwest	1.056	5
Frontier	1.061	6
Jet Blue	1.100	7
Virgin America	1.126	8
United	1.133	9
Delta	1.151	10
Sun Country	1.161	11
US Airways	1.162	12
AirTran	1.173	13
American	1.247	14
Allegiant	1.282	15

As was the case in the ratio-based approach, Spirit remains the fuel efficiency champion, but it is now more tightly followed by Hawaiian, whose ranking swapped with Continental's and whose fuel burn is only about 0.1% higher than Spirit. Alaska remains in third place, but its relative efficiency has increased (the ratio of inefficiency scores between Alaska and Spirit has shrunken from 1.016 under the ratio-based approach to 1.004). The most drastic ranking change is seen in Southwest, whose ranking jumps from 11th to the 5th; AirTran and Jet Blue also see improvement, with ranking rising from 15th to 13th, and from the 8th to the 7th, respectively. In contrast, Virgin America, Sun Country, and Allegiant fall in the rankings by three, four, and two places, respectively. Rankings of the other five carriers (Frontier, United, Delta, US Airways, American) stay unchanged. Compared to the ratio results, the overall picture that large, legacy carriers are in general less fuel efficient is still a valid one under the deterministic frontier approach. The maximum range of relative inefficiency, defined as the ratio of scores between the least and most efficient airlines, is about 125.0% (1.282/1.026), almost identical to that (125.3%) under the ratio-based approach.

The primary reason for the ranking changes using the deterministic frontier approach comes from the introduction of dep, which rewards airlines with high accessibility (departures). As already mentioned in sub-section 3.2, the deterministic frontier approach is equivalent to the ratio-based approach, with the ratio being $\mathrm{Fuel}/[(\mathrm{RPM})^{0.869}(\mathrm{dep})^{0.150}]$. For two airlines with the same fuel usage and RPM output, the one with more departures will yield a smaller value for $\mathrm{Fuel}/[(\mathrm{RPM})^{0.869}(\mathrm{dep})^{0.150}]$. A higher number of departures means more take-offs and landings, which are much more fuel demanding than cruising in the air. Therefore, while the two airlines consume the same amount of fuel, the one with higher departures must be more efficient. This can also be graphically illustrated in Figure 6, where two observations A and B have identical fuel burn (same ordinates) and RPM's, but B offers more departures. We consider the frontier with given RPM's as produced by A and B. In this case, the frontier is only a function of departures, expressed as $\text{Fuel}_0 = K * (\text{dep})^{0.150}$, where K is some constant and subscript 0 denotes fuel usage on the frontier. Obviously, the frontier is a convex increasing function of dep, and B is more efficient since ||BB"||/||B'B"|| < ||AA"||/||A'A"||.

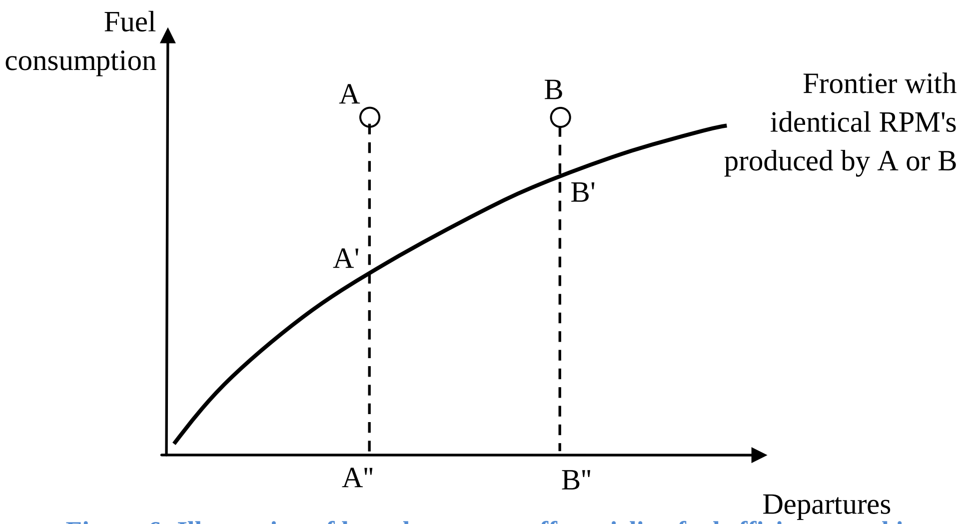

Figure 6: Illustration of how departures affect airline fuel efficiency rankings

The ranking change is also related to the diminished importance in RPM, as less weight (0.869) is given to RPM in the denominator $(\text{RPM})^{0.869}(\text{dep})^{0.150}$ as opposed to the denominator in the ratio-based approach, $(\text{RPM})^1$. As a consequence, even airlines with the same departures but different fuel consumption and RPM's would experience variation in their relative scores.

From an alternative perspective, the equivalent ratio metric $\frac{\text{Fuel}}{(\text{RPM})^{0.869}(\text{dep})^{0.150}}$ can be re-written as $\frac{\text{Fuel}}{\text{RPM}} \cdot \frac{1}{(\frac{\text{dep}}{\text{RPM}})^{0.150}} \cdot \frac{1}{\text{RPM}^{0.019}}$. For a given value of $\frac{\text{Fuel}}{\text{RPM}}$, airlines with higher $\frac{\text{dep}}{\text{RPM}}$ ratio will be rewarded. Figure 7 displays the dep/RPM across the 15 mainline airlines. Airlines with high $\frac{\text{dep}}{\text{RPM}}$ ratios, such as Southwest, AirTran, US Airways, and Hawaiian, all experience ranking increases, with the effect most pronounced in the case of Southwest.[4] By the same token, airlines that slip in the ranking are those having lower dep/RPM ratios, which is particularly true for Virgin America and Continental. In addition, given the same $\frac{\text{Fuel}}{\text{RPM}}$ and $\frac{\text{dep}}{\text{RPM}}$, the $\frac{1}{\text{RPM}^{0.019}}$ term means airlines with smaller operational scales will be (slightly) penalized. This may explain why Sun Country and Allegiant, despite having moderate dep/RPM ratios, both suffer a ranking drop.

[4] While US Airways does not experience a rank improvement, this is due to the fairly large gap between itself and its preceding carriers. In effect, US Airways is 20.2% less efficient than Spirit under the ratio-based approach but this number is reduced to only 13.3% (1.162/1.026-1) when accessibility is taken into account, and its inefficiency score is very close to that of Sun Country which sits in its immediate prior position.

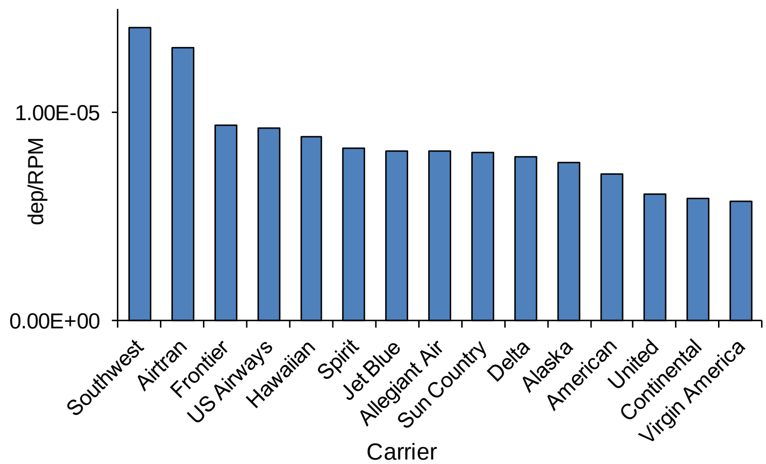

Figure 7: Dep/RPM ratio among the 15 mainline carriers

As mentioned above, different dep/RPM ratio values may result from different factors. This is easily seen from the relationship: RPM = dep*(Stage length)*(Aircraft size)*(Load factor). Therefore, the heterogeneity in stage length, aircraft size, and load factor explains the inter-airline difference in the dep/RPM ratio. Closer inspection of Table 1 reveals that stage length is the most significant contributor to dep/RPM variations. At the extremes, the average stage length of Virgin America is more than double that of Hawaiian and Southwest. For Hawaiian, the effect of shorter stage length is compromised by its significantly larger average aircraft size.

4.2.3 Stochastic frontier based inefficiency

Following the general discussion in sub-section 3.3, four stochastic frontier models are estimated, with results reported in Table 8. The first one (Model S1) presents the basic version in which the inefficiency term is assumed half-normally distributed. The other three models (Models S2-S4) consider the heterogeneity of airline operations by incorporating output characteristics in the mean of the inefficiency term. As the primary source of variation in these output characteristics comes from persistent inter-airline difference rather than fluctuation over time, including these variables will implicitly account for the panel structure of the dataset. In Models S2 and S3, we include stage length and aircraft size, respectively, as the lone explanatory variable for the mean of the inefficiency term. Both variables are included in Model S4. We do not include a constant in specifying the mean inefficiency in Models S2-S4, as such models failed to converge based in our computational experiences.

All the four models support essentially the same conclusions concerning the structure of the fuel consumption technology. Compared to the estimates under 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. Applying the RTS formula again results in a value slightly less than one. However, the extremely small standard errors for all coefficients lead us to reject the null hypothesis of constant RTS. In other words, decreasing fuel economies of scale is observed in the stochastic frontier model.

Table 8: Estimation results of stochastic frontier models

	Model S1	Model S2	Model S3	Model S4
Ln(RPM)	0.824***	0.824***	0.824***	0.824***
	(5.05e-05)	(7.64e-06)	(8.02e-06)	(7.73e-06)
Ln(dep)	0.200***	0.200***	0.200***	0.200***
	(3.51e-05)	(6.73e-06)	(6.90e-06)	(6.17e-06)
Constant	-2.344***	-2.344***	-2.344***	-2.344***
	(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)
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

The estimated coefficients for the environmental variables yield some interesting insights. Models S2 and S3 have the expected positive signs for the stage length and aircraft size coefficients, suggesting that flying longer distance or larger aircraft will consume more fuel. However, neither of these coefficients is statistically significant. When stage length and aircraft size are included simultaneously, both turn out to be statistically significant.[5] The coefficient for stage length remains positive and becomes much larger. This is consistent with what we would expect at the flight level: controlling for RPM, departures, and aircraft size, flying longer 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, after fixing RPM, departures, and stage length, 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. Indeed, this phenomenon is sufficiently widespread that it has been given a name—the "ecological fallacy."

It seems that Model S4 is preferred to the other three models for subsequent efficiency analysis, given the significance of both the stage length and aircraft size coefficients. This is further supported by testing results from Likelihood Ratio (LR) tests. In order to facilitate exposition, we express the general form of the mean inefficiency term as $E(u_{it}) = \delta_1 * (\text{stage length})_{it} + \delta_2 * (\text{aircraft size})_{it}$. Table 9, below, shows that we reject H_0 in all three tests.

[5] We have also experimented with a specification that further includes load factor in the mean inefficiency term. However, the coefficient for load factor is highly insignificant.

Table 9: Likelihood Ratio tests across models

Test	Null hypothesis	χ^2-statistic	Prob > χ^2	Decision
1	H_0: $\delta_1 = \delta_2 = 0$	6.39	0.0409	Reject H_0
2	H_0: $\delta_1 = 0$	5.97	0.0146	Reject H_0
3	H_0: $\delta_2 = 0$	5.43	0.0198	Reject H_0

Before turning to the inefficiency score values, it will be helpful to review how estimates of inefficiency are obtained. Recall that the inefficiency score in Model S4 is calculated using (6), in which $\mu_{*,\text{it}}$ is given by (8). Given the extremely small value for σ_v^2 relative to σ_u^2, the second term in (8) will be practically zero. This suggests that while environmental factors can significantly affect the mean of the inefficiency, their direct influence on the conditional mean $\text{E}[\exp(u_{\text{it}})|\varepsilon_{\text{it}}]$ is minimal. As a result of the dominance of σ_u^2 in σ_S^2, $\mu_{*,\text{it}} \cong \varepsilon_{\text{it}}$ in (8) and $\sigma_* \cong 0$ in (6). $\text{FI}_{\text{SFA,it}}$ $= \left\{\frac{1-\Phi\left(-\sigma_*-\frac{\mu_{*,\text{it}}}{\sigma_*}\right)}{1-\Phi\left(-\frac{\mu_{*,\text{it}}}{\sigma_*}\right)}\right\}\exp\left(\mu_{*,\text{it}}+\frac{1}{2}\sigma_*^2\right) \cong \left\{\frac{1-\Phi\left(-0-\frac{\varepsilon_{\text{it}}}{0}\right)}{1-\Phi\left(-\frac{\varepsilon_{\text{it}}}{0}\right)}\right\}\exp(\varepsilon_{\text{it}}) \cong \left\{\frac{1-\Phi(-\infty)}{1-\Phi(-\infty)}\right\}\exp(\varepsilon_{\text{it}}) = \exp(\varepsilon_{\text{it}})$. This carries two implications. First, given the identical estimates of the frontier parameters, realizations of the residuals ε_{it}'s from Models S1-S4 will be the same, which—according to the above derivation—would result in virtually identical inefficiency score for each observation, and consequently the efficiency rankings. Second, given the fact that $\text{FI}_{\text{SFA,it}} \cong \exp(\varepsilon_{\text{it}})$, the stochastic frontier inefficiency calculation essentially collapses to the deterministic frontier case. Any ranking difference between the two frontier approaches, therefore, should be attributed to the difference in parameter estimates for RPM and dep. It is also important to note that the difference in parameter estimates stems from the different assumptions about ξ_{it} in (3) and (4), in particular the specification of the inefficiency term.[6] Compared to the deterministic fuel consumption frontier, further weight is given to departures. As a consequence, airlines offering greater accessibility (i.e. with a higher dep/RPM ratio) will move up further in the rankings.

The actual ranking results confirm this. First, we find that the efficiency scores produced by Models S1-S4 are only different after the 7th decimal place, and rankings based on all four models are the same. Table 10 shows the FI_{SFA} averages across quarters by airline based on Model S4. Not surprisingly, the most drastic ranking movements observed in Table 10 occur to airlines with the highest or lowest dep/RPM values, as shown in Figure 7. Southwest, thanks to its large dep/RPM ratio, leaps forward to the top ranking; the ranking for AirTran, whose dep/RPM value is next highest to Southwest, 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 (from 4th to 6th). We also observe moderate efficiency drops for Alaska and United with respect to the frontier (Alaska: inefficiency score from 1.003 (1.030/1.026) to 1.012 (1.028/1.015); United: inefficiency score from 1.104 (1.133/1.026) to 1.121 (1.138/1.015)), again probably due to their relative small dep/RPM ratios. The ranking drop for Sun Country and Spirit may result from their small operation scales, since their dep/RPM ratios lie in the middle ground.[7] The other airlines

[6] To further clarify this point, recall that with the same assumption about ξ_{it}, maximum likelihood would yield exactly identical parameter estimates for RPM and dep.

[7] Recall that, given our estimates, the inefficiency calculation essentially collapses to the deterministic frontier case, and that the deterministic frontier approach is equivalent to the ratio-based approach, with the

stay almost the same, with ranking changes of at most one place. American and Allegiant remain the two least fuel efficient carriers; compared to Southwest (the most fuel efficient), the least efficient Allegiant burns on average 26.3% more fuel, comparable to the fuel efficiency differences found using the ratio and deterministic frontier approaches. Finally, the results maintain the general impression that large, legacy carriers occupy the lower rungs of the efficiency ladder.

Table 10: Calculated FI_{SFA} values for the 15 mainline carriers

Carrier	FI_{SFA}	Ranking
Southwest	1.015	1
Hawaiian	1.022	2
Spirit	1.025	3
Alaska	1.028	4
Frontier	1.051	5
Continental	1.053	6
Jet Blue	1.093	7
United	1.138	8
Delta	1.139	9
Airtran	1.140	10
US Airways	1.144	11
Virgin America	1.145	12
Sun Country	1.169	13
American	1.242	14
Allegiant	1.283	15

4.3 Considering mainline-sub affiliations

Thus far, we have considered fuel efficiencies of the 15 mainline carriers under ratio-based, deterministic, and stochastic frontier approaches. The above rankings thus focus on individual firms. However, business models adopted by many of the 15 carriers involve regional carrier operations. In particular, for those airlines with hub-and-spoke networks, a substantial portion of their flight segments between a small spoke city and a major hub are serviced by regional airlines that have established various forms of operational relationships with their mainline partners. Without the support from the regional airlines, the mainline carriers would not be able to transport passengers in the way they do. Alternatively, these mainlines would have to purchase and fly regional jets/turboprops themselves on those thinner segments. Therefore, any fuel efficiency analysis that focuses exclusively on mainline businesses will be incomplete, and

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ratio dependent upon the estimated RPM and dep coefficients. Then the inefficiency score here can be closely approximated by $\mathrm{Fuel}/(\mathrm{RPM}^{0.869}\mathrm{dep}^{0.200})$, which can be decomposed into the product of three terms: $\frac{\mathrm{Fuel}}{\mathrm{RPM}^{0.869}\mathrm{dep}^{0.150}}\frac{1}{(\frac{\mathrm{dep}}{\mathrm{RPM}})^{0.045}}\frac{1}{\mathrm{RPM}^{0.005}}$, where the first term is the equivalent ratio metric under the deterministic frontier approach. In addition to the implication from the second term that lower dep/RPM ratio leads to greater inefficiency score (less efficient), the third term further implies that carriers with smaller RPMs will be penalized (inefficiency score aggrandized).

potentially inaccurate. In this sub-section, we explicitly consider the impact of regional-mainline affiliations on the fuel efficiency of mainline carriers. Given the multiple types of affiliation structure, the first and most difficult step involves assigning regional carriers' operations to mainline carriers. Then, the fuel and output contributions from the regional carriers are incorporated into the efficiency modeling process. The resulting composite fuel inefficiency essentially measures the inefficiency of each mainline carrier—in association with its contracted regional carriers—in transporting passengers from their true origins to true destinations.

4.3.1 Assigning regional airlines' operation to mainline carriers

Before assigning regional carrier operations to mainline carriers, we need to determine the set of regional airlines to be included in the computation. Nearly 100 regional and local airlines currently operate in the U.S. domestic air transportation system. However, more than half of these airlines together contribute less than 1% in the system-wide output, measured in RPMs (as discussed below, assignment of regionals to mainlines is based on RPMs). The effort required to investigate the relationships of these very small operators with the 15 mainline carriers would not be worthwhile, even if sufficient data were available. In fact, many of their relationships with mainline carriers are *ad hoc* and may not be well documented. In light of this, we restrict our attention to the larger regional operators, setting the threshold at 500,000 enplaned passengers for 2010. This leaves 25 regional carriers. Of these 25, three of the smaller carriers are further dropped due to the lack of sufficient data. In total, 22 regional carriers are considered in the subsequent regional-mainline assignment process. The fuel consumption, output, and output characteristics of the 22 regional carries are already presented in Table 3 and Table 5 in sub-section 4.1. As pointed out there, the 22 regional carriers combined with the 15 mainline airlines essentially compose the entire U.S. commercial passenger air transportation industry in terms of aggregate output and fuel consumption.

All the 22 regional carriers analyzed operate under some type of relationship with at least one of the 15 mainline airlines, who are responsible for the ticketing, marketing, and often the scheduling of the regional airlines' flight operations (Forbes and Lederman, 2005). These subcontracted code share agreements usually belong to one of the following three 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. 100% of the regional carriers' RPM's are assigned to the corresponding mainline carrier.

2) A regional carrier is an independent company but contracts out all its operations to one mainline carrier. Similar to the first type, we simply assign the regional carrier's entire RPM's to the mainline airlines.

3) A regional carrier is an independent company and has code share agreements with multiple mainline airlines, depending upon geographic region and hub airport. Assigning such a regional carrier's RPM's to the mainline airlines becomes more difficult, especially in situations where the regional carrier services more than one mainline airline on a flight segment. The assignment process requires close scrutiny of detailed, segment level data depicting the relationship between the regional and mainline carriers. However, looking into all segments the regional carrier flies in

partnership with all its affiliated mainline carriers would be too time-consuming. Instead we only focus on flights in and out of the Operational Evolution Partnership (OEP) 35 airports, using the BTS T100 Domestic Segment Traffic Database. These flights account for the vast majority of RPM's in the regional carrier's total—over 90% for all but one regional airline of this type, as shown in Table 11.

Table 11: Overall RPM apportionment, its percentage in total RPM's, and affiliation type with the mainline(s)

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

The route map of SkyWest provides a good illustration of how complex and extensive a set of Type 3 relationships can be. SkyWest has code share partnerships with four separate mainline carriers: United, Delta, Alaska, and US Airways. The relationships are defined both geographically and by specific airports within that region. SkyWest flies for United out of United's west coast hubs of San Francisco and Los Angeles, plus two other major hubs (Denver and Chicago O'Hare), and Houston. Meanwhile, SkyWest also provides service for Delta, primarily out of Delta's hubs at Salt Lake City and Minneapolis. For Alaska and US Airways, SkyWest's services are almost exclusively in and out of Seattle and Phoenix respectively. Given these different relationships, the assignment process can be quite cumbersome and difficult (see route map, Figure 8). We resort to segment-level affiliation information, which are available through the regional and mainline airlines' websites based on their route maps, and other on-line resources such as Wikipedia and Airliners.net as back-up confirmation. Specific route-by-route relationships were determined by looking at the affiliate airlines’ websites and route maps to see which routes are flown for particular a particular mainline carrier. These affiliate mainline relationships were then cross-referenced with route assignment lists from various third party websites.

One particular situation that can arise for the Type 3 regional carriers is the regional carrier servicing 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 were likely to be transported by the regional carrier, despite the tickets being reported to BTS showing the names of the affiliated mainline airlines. This situation of flight segment “polygamy” occurs quite rarely—on a total of about 50 segments. Therefore, any potential error due to the lack of knowledge about the true assignment will be rather small. The assigned RPM's on each segment are then aggregated over the regional carrier's entire network to obtain the total RPM's attributable to the incumbent mainline carriers, and the ratios among them.

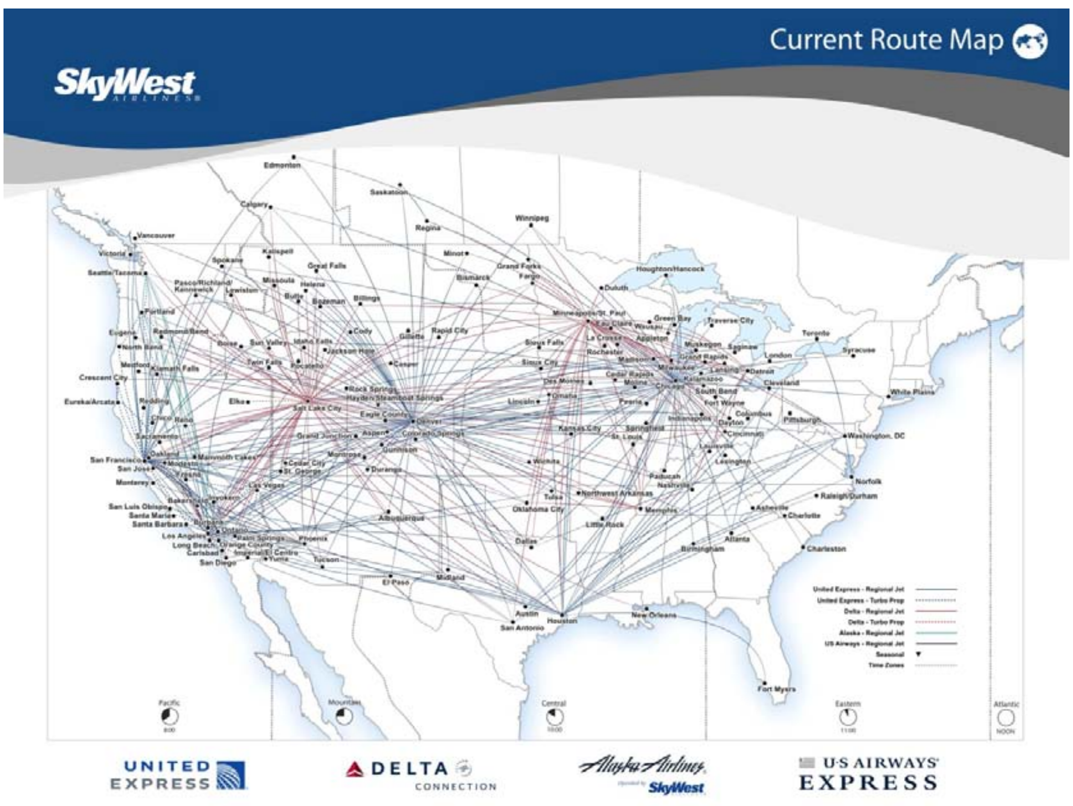

Figure 8: Route map of SkyWest
(source: http://www.SkyWest.com/fly-SkyWest-airlines/SkyWest-airlines-route-map/)

It must be emphasized that one of main difficulties in establishing these mainline-regional carrier relationships, and performing the subsequent apportionment, is that these relationships and affiliations are very fluid. Regional carriers may change the segments they fly for mainline carriers; they can be spun off or be given independence by their parent company; they may establish a new affiliation with a different mainline airline; they merge and even liquidate from year to year. Given the volatility in regional-mainline operational relationships, it is not possible to apportion all the RPMs with complete accuracy for a given year at a later point in time, based on the relationships that are current (and therefore documented on the World Wide Web) at the time of analysis. In our case, we performed this assignment process in early 2012, some 13 months after the end of the study period. Nonetheless, it is reasonable to expect that the number of changes in these relationships that take place over a year or two is small enough to preserve the validity of our aggregate results.

The total apportioned RPM's from a regional carrier is calculated by multiplying the percentage of RPM's apportioned (in Table 11), by the total number of RPMs flown by that regional carrier. These apportioned RPMs are then assigned to the corresponding mainline carrier(s) based upon the type of relationship and methodology described above. Table 12 below shows the RPM assignment results for each mainline-regional 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. By contrast, 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 employ regional affiliates.

Table 12: RPM assignment results

Mainline carrier	Affiliated carriers	Apportioned RPM (millions)	Total RPM (millions)
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 Winsconsin	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 the first three quarters.

** The RPM's for Spirit are only for the 1st, 2nd, and 4th quarters.

4.3.2 Adjusted fuel inefficiency

4.3.2.1 Ratio-based inefficiency

Having assigned regional carrier RPM to their respective mainline airlines, in this sub-section we present the results for the adjusted mainline fuel inefficiency, taking into account affiliated regional operations. In calculating the new Fuel/RPM ratio we need to know the assignment of fuel consumption as well as of RPM. Absent relevant information, we make the assumption that fuel assignment is proportional to RPM assignment. For example, if 30% of regional carrier A's RPM's were for mainline carrier 1's business, then we also allot 30% of regional carrier A's fuel burn to mainline carrier 1. Fuel and RPM data are again collected from the CD-ROM database product of Data Base Products, Inc. Five (Piedmont, Trans States, CommutAir, Freedom, Chautauqua) out of the 22 regional carriers have missing fuel burn records. Quarterly data of the remaining 17 carriers are used to estimate the fuel burn for those five carriers. After removing another five outliers (Shuttle America: 1st and 2nd quarters; GoJet: 1st and 2nd quarters; ExpressJet: 4th quarter) as suggested by preliminary regression results, we obtain the following fuel consumption model for regional carriers (standard errors in parentheses):

$$\underset{}{\ln(Fuel)} = \underset{(0.368)}{0.115} + \underset{(0.032)}{0.654} * \ln(RPM) + \underset{(0.043)}{0.324} * \ln(dep)$$

$$\text{Number of observations: } 63 \qquad R^2 = 0.977 \tag{11}$$

Given regional carriers' shorter flying distances and smaller aircraft size as compared to their mainline counterparts, it is natural to expect take-off/landing operations to account for a bigger portion in the regional carriers' fuel consumption, and thus a larger coefficient for dep and a smaller one for RPM as compared to mainline airlines. The obtained RTS measure has a value slightly greater than one (1.022), but we fail to reject the null hypothesis of no economies of fuel consumption scale. This model is used to generate predicted fuel consumption values for the aforementioned outliers as well as observations with missing fuel data.

The second column of Table 13 reports the composite Fuel/RPM values, which are—as in the mainline-only case—converted to composite fuel inefficiency (FI^{c}_{ratio}) scores, by dividing the composite Fuel/RPM by the minimum value across the 15 airlines. The last three columns of Table 13 indicate whether the mainline has regional carrier affiliations, Fuel/RPM percentage change compared with the mainline-only case, and ranking variations before and after considering such affiliations.

Table 13: Composite Fuel/RPM, inefficiency scores, ranking and ranking change of the 15 mainline carriers

Carrier	Composite Fuel/RPM (10^{-2} gallon/RPM)	FI^{c}_{ratio}	Rank	Regional carrier affiliation	Fuel/RPM percentage change	Ranking change
Spirit	1.5629	1.000	1	No	0%	0
Hawaiian	1.5932	1.019	2	No	0%	↑2
Virgin America	1.6266	1.041	3	No	0%	↑2
Alaska	1.6844	1.078	4	Yes	6.0%	↓1
Sun Country	1.7143	1.097	5	No	0%	↑2
Jet Blue	1.7240	1.103	6	No	0%	↑2
Continental	1.8042	1.154	7	Yes	14.6%	↓5
Southwest	1.8412	1.178	8	No	0%	↑3
Frontier	1.8539	1.186	9	Yes	11.4%	↓3
United	1.9376	1.240	10	Yes	12.1%	↓1
Allegiant	1.9533	1.250	11	No	0%	↑2
AirTran	1.9589	1.253	12	No	0%	↑3
Delta	2.0568	1.316	13	Yes	11.7%	↓3
American	2.0985	1.343	14	Yes	7.3%	0
US Airways	2.1050	1.347	15	Yes	12.1%	↓3

Based on the fuel efficiency ranking changes, the 15 mainline carriers can be divided into two categories. The first category, consisting of eight carriers that have no regional affiliation, experiences no change between the composite and mainline-only Fuel/RPM values. By contrast, the Fuel/RPM value for each of the seven airlines that do have partnerships with regional carriers increase by 6-14.6%. This finding is consistent with the conventional wisdom that regional carriers are in general less fuel efficient (in terms of the Fuel/RPM metric), and thereby reduce the overall fuel efficiency of the associated mainline airlines. It is worth noting that these results are based on a single output—RPM—and thus do not take into account the accessibility provided by regional carriers. Except for American, which remains next to last, the rankings of the other six airlines with regional carrier affiliations are pushed downwards, most dramatically for Continental (2nd to 7th). Since efficiency score and ranking are relative measures, carriers with no regional affiliation see an improvement in ranking, most prominently Southwest and AirTran, who jump ahead three places. Because of the degraded Fuel/RPM values for mainlines with regional partnerships, the efficiency gap between the first and last carriers is now much wider, with the ratio increased to 35%.

4.3.2.2 Deterministic frontier based inefficiency

Following the same rationale underlying sub-section 4.3.2.1, the deterministic frontier is constructed using composite fuel and output measures. We further assume that departure assignments are proportional to RPM assignments. Specifically, departures assigned from a given regional carrier to a mainline airline are obtained as the product of total departures from the regional carrier and the percentage of RPM's in the total that are assigned to the mainline carrier.

The new fuel consumption frontier deriving from the composite fuel, RPM, and departure measures has the following form:

$$\ln(\text{Fuel}) = \underset{(0.703)}{-2.406} + \underset{(0.052)}{0.848} * \ln(\text{RPM}) + \underset{(0.043)}{0.165} * \ln(\text{dep})$$

$$\text{Number of observations: } 58 \qquad R^2 = 0.997 \qquad (12)$$

Consistent with our *a priori* expectation, we observe a slightly smaller coefficient for RPM but a larger one for dep in (12) as compared to (9). This reflects the greater importance of the dep variable in driving regional carriers' fuel burn, as also observed above in (10). The point estimate of RTS is 0.987, very close to the previous estimate. We again fail to reject the null hypothesis of no fuel economies of scale. The procedure described in sub-section 4.2.2 is applied in order to produce the composite fuel inefficiency scores (FI^{c}_{DFA}), which are reported in Table 14 below. The last column reports the ranking change with respect to the deterministic frontier results when only mainline airlines are considered.

Table 14: Calculated FDI^{c}_{DFA} values for the 15 mainline carriers

Carrier	FI^{c}_{DFA}	Ranking	Regional carrier affiliation	Ranking change
Alaska	1.026	1	Yes	↑2
Spirit	1.043	2	No	↓1
Hawaiian	1.047	3	No	↓1
Continental	1.064	4	Yes	0
Southwest	1.085	5	No	0
Frontier	1.123	6	Yes	0
Jet Blue	1.131	7	No	0
United	1.140	8	Yes	↑1
Virgin America	1.153	9	No	↓1
Sun Country	1.171	10	No	↑1
Delta	1.178	11	Yes	↓1
US Airways	1.183	12	Yes	0
Airtran	1.195	13	No	0
American	1.265	14	Yes	0
Allegiant	1.305	15	No	0

In addition to the somewhat different estimated coefficients for RPM and dep which can certainly change airlines' inefficiency scores (those providing greater accessibility, or higher dep/RPM ratios, will be slightly favored), incorporating regional carriers' affiliation introduces two competing forces in the efficiency calculation. First, as already seen in the preceding sub-section, regional carriers often operate less fuel efficient aircraft in terms of fuel/RPM, which tends to drag down the fuel efficiency of the mainline carriers. However, inefficiency under the frontier approach also depends upon the level of accessibility provided. Given the same amount of RPM output, regional carriers are characterized by a higher number of departures. This is reflected in the dep/RPM ratios for the mainline carriers with and without considering the regional-mainline affiliations (Figure 9). For the seven mainline carriers that affiliate with regional carriers, dep/RPM ratios rise by 50-137%, considerably increasing the service accessibility offered by the mainline carriers. In this respect, the existence of mainline-regional affiliations will increase mainline airlines' fuel efficiency scores. With these factors working in opposite directions, it is not surprising that the ranking change compared to the mainline-only deterministic frontier case is small, and no longer unidirectional. The most drastic change is seen in Alaska, which replaces Spirit as the most fuel efficient carrier. Spirit and Hawaiian shift one place downwards. United and Virgin America, which are next to each other in the rankings, swap positions. So do Sun Country and Delta. In contrast to the ratio-based approach, the ranking gains for Alaska and United suggests that association with regional carriers can actually improve efficiency scores for mainline airlines.

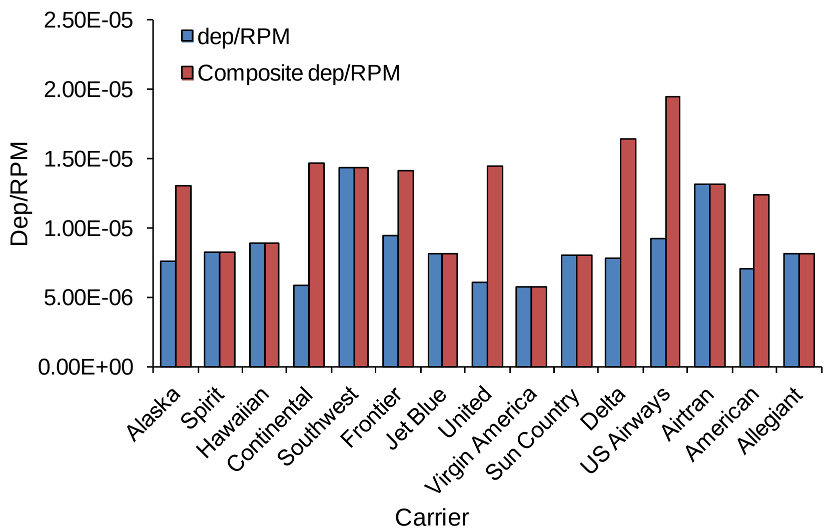

Figure 9: Dep/RPM ratios for the 15 mainline carriers with and without considering their regional carrier affiliations

4.3.2.3 Stochastic frontier based inefficiency

Similar to the model presented in sub-section 4.2.2, we report in Table 15 four versions of the stochastic frontier model, among which Models S6-S8 account for the heterogeneity of the inefficiency term by including output characteristics in the inefficiency mean function. New stage length and aircraft size values are recalculated based upon the sums of departures, RAM's, and ASM's from the mainline and affiliated regional carriers. We observe a larger degree of variation (as measured by σ_u) in the frontier parameter estimates than in the mainline-only case. This implies that carrier inefficiency is more variable when regional affiliations are taken into account. Compared to the mainline-only case, Models S6-S7 yield larger, and more statistically significant coefficients for stage length and aircraft size, respectively. As in the mainline-only case, however, a negative coefficient for aircraft size appears when both stage length and aircraft size are included (Model S8). The RTS measures range from 0.978 to 0.990. Different from the conclusion in the mainline-only case, however, the null hypothesis of no fuel economies of scale cannot be rejected at 5% level across Models S5-S8.

The introduction of regional carriers has two additional impacts on model estimation. First, it introduces further sources of random shocks and measurement error in the data generation process. Not surprisingly, the idiosyncratic error term becomes much more dispersed, although the variance is still dwarfed compared to the variance of the inefficiency term. Second, the involvement of multiple airlines in each observation diversifies the set of aircraft types and technologies, and therefore degrades the fits of the composite frontier models, as shown by the smaller log likelihoods in Table 15 as compared to those in Table 8.

Table 15: Estimation results of stochastic frontier models considering affiliations between mainline and regional carriers

	Model S5	Model S6	Model S7	Model S8
Ln(RPM)	0.874***	0.843***	0.854***	0.807***
	(0.065)	(0.057)	(0.060)	(0.056)
Ln(dep)	0.148***	0.171***	0.162***	0.203***
	(0.053)	(0.046)	(0.048)	(0.046)
Constant	-2.911***	-2.494***	-2.645***	-2.024***
	(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)
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

In order to choose the "best" model for the subsequent efficiency analysis, LR tests are performed in a similar fashion as in sub-section 4.2.3. Table 16 below shows that Model S8 is preferred against all the other three models, at a 5% significance level, and against Model S6 at a 1% significance level.

Table 16: Likelihood Ratio tests across models

Test	Null hypothesis*	χ^2-statistic	Prob > χ^2	Decision
4	H_0: $\delta_1 = \delta_2 = 0$	8.83	0.0121	Reject H_0
5	H_0: $\delta_1 = 0$	6.91	0.0086	Reject H_0
6	H_0: $\delta_2 = 0$	5.18	0.0229	Reject H_0

* As before, the mean of the inefficiency term equals δ_1 * $(\text{stage length})_{it}$ + δ_2 * $(\text{aircraft size})_{it}$.

Fuel inefficiency scores ($\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{c}}$) and the associated rankings based on Model S8 are reported in Table 17, together with ranking changes from the mainline-only case. Although the estimated σ_v is substantially larger than the mainline-only estimate, its absolute value, i.e. the stochastic component of the frontier, remains relatively small. As a consequence, $\varepsilon_{\mathrm{it}}$ and σ_v are still good approximations of $\mu_{*,\mathrm{it}}$ and σ_*; so is $\exp(\varepsilon_{\mathrm{it}})$ for $\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{c}}$. The arguments in sub-section 4.3.2.2 remain largely applicable to the stochastic frontier results. In essence, the sharply rising dep/RPM ratios due to regional carrier affiliations result in ranking gains for Alaska, Continental, United, and US Airways. Mainline airlines without regional affiliates, such as Southwest, AirTran, and Jet Blue, suffer ranking drops. As noted above, regional carriers have higher Fuel/RPM than mainlines and thus increase this value for the mainline-regional combinations. The ranking drop of Delta and Frontier is presumably attributable to the dominance of this effect over dep/RPM ratio rise. The difference in the RPM and dep coefficients between the mainline-only and composite models is a further source of inefficiency score adjustment and ranking change. With diminishing importance in RPM (0.807 vs. 0.824) and almost invariant coefficients for dep, airlines with low dep/RPM ratios will score worse in efficiency. This may explain why Sun Country surpasses Virgin America.

Table 17: Calculated $\mathrm{FDI}_{\mathrm{SFA}}^{\mathrm{c}}$ values for the 15 mainline carriers

Carrier	$\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{c}}$	Ranking	Regional carrier affiliation	Ranking change
Alaska	1.019	1	Yes	↑3
Hawaiian	1.041	2	No	0
Spirit	1.043	3	No	0
Continental	1.048	4	Yes	↑2
Southwest	1.069	5	No	↓4
Frontier	1.100	6	Yes	↓1
United	1.121	7	Yes	↑1
Jet Blue	1.134	8	No	↓1
US Airways	1.148	9	Yes	↑2
Delta	1.153	10	Yes	↓1
Sun Country	1.162	11	No	↑2
Virgin America	1.167	12	No	0
AirTran	1.173	13	No	↓3
American	1.248	14	Yes	0
Allegiant	1.296	15	No	0

One might be concerned about the robustness of the results with respect to other stochastic frontier models. To this end, $\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{c}}$ scores and rankings are computed under Models S5-S7 as well as S8. The pair-wise correlation coefficients among the airline-specific $\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{c}}$ scores from Models S5-S8 are reported in Table 18. Table 19 presents the corresponding Spearman rank correlation coefficients. The coefficients in both tables are all very close to 1, suggesting efficiency measurements and rankings are not sensitive to the specific model chosen.

Table 18: Correlation among FDI^{c}_{SFA} from Models S5-S8

	Model S5	Model S6	Model S7	Model S8
Model S5	1			
Model S6	0.9932	1		
Model S7	0.9905	0.9993	1	
Model S8	1	0.9932	0.9905	1

Table 19: Spearman rank correlation among Models S5-S8

	Model S5	Model S6	Model S7	Model S8
Model S5	1			
Model S6	0.9857	1		
Model S7	0.9893	0.9964	1	
Model S8	0.9571	0.9607	0.9679	1

4.4 Inefficiency with Circuity

Although hub-and-spoke systems allow airlines to take advantage of the economies of density by consolidating passengers on many O-Ds onto a single flight segment, hub-and-spoke itineraries force passengers to travel longer and farther than non-stop ones. As a consequence, airline efficiency will be affected if one measures output in terms of O-D miles instead of RPM's. For a route which is highly circuitous, i.e. the actual itinerary mileage far exceeding the point-to-point, non-stop mileage, and fuel burn per passenger O-D mile will be much greater than fuel burn per passenger itinerary mile.

In order to account for this, we introduce circuity in the efficiency ranking process. For a given passenger trip, circuity is the ratio between the itinerary miles flown, and the non-stop (O-D) miles between the origin and destination airports. By definition, circuity always takes values no less than one, and equals one only when the trip is non-stop, or flight segments are perfectly aligned along the great circle in the case of making intermediate stop(s). Circuity can also be constructed at the airline level, by aggregating total passenger itinerary miles and non-stop miles, and taking the ratio for each airline. The calculation is made possible thanks to the BTS Airline Origin and Destination Survey (DB1B) database, which documents in detail information from a 10% sample of domestic travel itineraries in the U.S. Recall that regional carriers are included in the DB1B database but under the name of their affiliated mainline airlines. Therefore, the passenger itinerary miles used for circuity calculation represent the mainline-regional composite RPMs, and the resulting efficiency is for the mainline airline combined with its affiliated regional carriers.

Figure 10 below presents the results of the circuity calculations 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. At the extreme, US Airways made passengers fly on average 6.8% more than the non-stop distances. This suggests that the hub-and-spoke airlines—and their customers—take circuity into account when routing passengers. The small circuity measures may also imply that the efficiency adjustment due to routing circuity should not be significant. This conjecture is confirmed in the subsequent analysis.

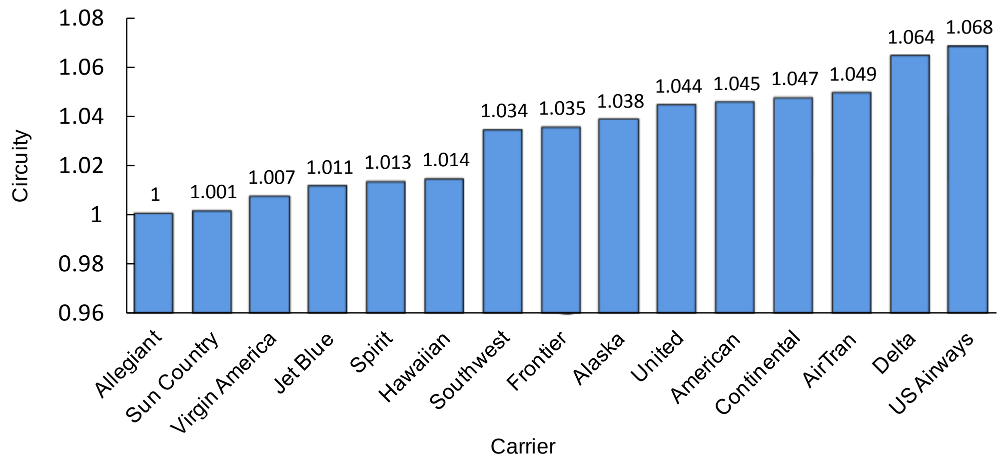

Figure 10: Circuity of the 15 mainline airlines in 2010

4.4.1 Ratio-based inefficiency

Under the ratio-based approach, the appropriate fuel efficiency metric becomes fuel per revenue passenger O-D mile (RPODM), the average fuel consumption by transporting one passenger one mile along the point-to-point route. Fuel/RPODM is obtained by multiplying the composite Fuel/RPM in sub-section 4.3.1 by the airline-level circuity measure. Because of the small circuitries, the Fuel/RPODM values are only marginally greater than Fuel/RPM. The inter-airline circuity variation is not substantial. Consequently, one would expect only minor changes in the efficiency ranking. We observe that high circuity carriers Alaska and United slip respectively two and one place. Airlines with lower circuity, including Allegiant, JetBlue, and Sun Country, witness ranking improvements—each by one. We again standardize the Fuel/RPODM values (denoting them by $\mathrm{FI}_{\mathrm{ratio}}^{\mathrm{circuity}}$ in the table). Since the most fuel efficient airline (Spirit) has low circuity and the most inefficient one (US Airways) has the highest circuity, the efficiency gap between the two airlines is further widened (US Airways is 42% less efficient than Spirit, compared to 34.7% based on composite Fuel/RPM, as shown in Table 13).

Table 20: Fuel/RPODM, inefficiency scores, ranking and ranking change of the 15 mainline carriers, with circuity considered

Carrier	Fuel/RPODM (10^{-2} gallon/RPM)	Composite Fuel/RPM (10^{-2} gallon/RPM)	Circuity	$FI_{ratio}^{circuity}$	Rank	Ranking change
Spirit	1.5835	1.5629	1.013	1.000	1	0
Hawaiian	1.6163	1.5932	1.014	1.021	2	0
Virgin America	1.6376	1.6266	1.007	1.034	3	0
Sun Country	1.7156	1.7143	1.001	1.083	4	↑1
Jet Blue	1.7436	1.7240	1.011	1.101	5	↑1
Alaska	1.7480	1.6844	1.038	1.104	6	↓2
Continental	1.8895	1.8042	1.047	1.193	7	0
Southwest	1.9039	1.8412	1.034	1.202	8	0
Frontier	1.9185	1.8539	1.035	1.212	9	0
Allegiant	1.9533	1.9533	1.000	1.234	10	↑1
United	2.0235	1.9376	1.044	1.278	11	↓1
AirTran	2.0550	1.9589	1.049	1.298	12	0
Delta	2.1892	2.0568	1.064	1.382	13	0
American	2.1923	2.0985	1.045	1.384	14	0
US Airways	2.2483	2.1050	1.068	1.420	15	0

4.4.2 Deterministic frontier based inefficiency

In the deterministic frontier model specification, we now replace the composite RPM by RPODM as the new mobility output, and re-estimate the model. The new fuel consumption frontier based on the composite fuel, RPODM and departure measures has the following form:

$$\ln(\text{Fuel}) = \underset{(0.684)}{-2.066} + \underset{(0.050)}{0.816} * \ln(\text{RPODM}) + \underset{(0.041)}{0.201} * \ln(\text{dep})$$

$$\text{Number of observations: } 58 \qquad R^2 = 0.997 \tag{13}$$

We find a smaller coefficient for RPODM than the one for RPM in (12), and a bigger coefficient for dep. This may be because hub-and-spoke operations involve more departures per RPODM, so that inter-carrier circuity differences are absorbed into the dep variable. The point RTS measure is 0.983, very close to the previous estimates. Again, we fail to reject the null hypothesis of no fuel economies of scale at 5% level. Table 21 reports the efficiency scores $FI_{DFA}^{circuity}$, constructed from the regression residuals in the same manner as FI_{DFA}^{c}. Differences of the fuel efficiency results from those based on RPM (Equation 12) are attributable to three factors: difference in dep/RPM, dep, and circuity.[8] The overall circuity effect on efficiency, however, does not seem to be

[8] As pointed out in sub-section 4.2.2, the equivalent ratio-based on which fuel efficiency ranking is $\frac{\text{Fuel}}{\text{RPODM}^{0.816}\text{dep}^{0.201}}$, which can be re-expressed as $\frac{\text{Fuel}}{\text{RPM}^{0.848}\text{dep}^{0.165}}\frac{1}{(\frac{\text{dep}}{\text{RPM}})^{0.032}}\frac{1}{\text{dep}^{0.004}}\text{circuity}^{0.816}$. The first

substantial across all airlines, and the efficiency rankings remain intact despite the changes in frontier parameters and the use of RPODM.

Table 21: Fuel inefficiency values $\mathrm{FDI}_{\mathrm{DFA}}^{\mathrm{circuity}}$ and ranking of the 15 mainline carriers, with circuity considered

Carrier	$\mathrm{FI}_{\mathrm{DFA}}^{\mathrm{circuity}}$	$\mathrm{FI}_{\mathrm{DFA}}^{\mathrm{c}}$	Ranking
Alaska Airlines	1.023	1.026	1
Spirit Air Lines	1.042	1.043	2
Hawaiian Airlines	1.043	1.047	3
Continental Airlines	1.061	1.064	4
Southwest Airlines	1.069	1.085	5
Frontier Airl. (New)	1.118	1.123	6
Jet Blue	1.122	1.131	7
United Air Lines	1.132	1.140	8
Virgin America	1.160	1.153	9
Sun Country Airlines	1.166	1.171	10
Delta Air Lines	1.181	1.178	11
US Airways Inc	1.186	1.183	12
Airtran / Frontier (Old)	1.202	1.195	13
American Airlines	1.263	1.265	14
Allegiant Air	1.291	1.305	15

4.4.3 Stochastic frontier based inefficiency

Similar results are found when incorporating circuity into the stochastic frontier models. By substituting RPODM for the composite RPM in Models S5-S8, we obtain consistently larger dep coefficients in Models S9-S12, and smaller RPODM coefficients than those for RPM in Models S5-S8 (Table 22). On the other hand, the estimated parameters for the environmental factors in Models S10-S12 are very close to those in S6-S8. So are the estimates for σ_u and σ_v. All RTS measures across S9-S12 are slightly less than unity, but we cannot reject the null hypothesis of no fuel economies of scale at the 5% level. Table 23 presents the associated fuel inefficiency scores ($\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{circuity}}$) with $\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{c}}$ scores also included for comparison. As in the deterministic case, no change is observed in efficiency rankings. According to the results from all three approaches, we may draw the conclusion that circuity has only minor effects on fuel efficiency of the 15 mainline airlines investigated.

term is the equivalent ratio corresponding to Equation (12), the departure from which consists of three components: dep/RPM ratio, dep, and circuity.

Table 22: Estimation results of stochastic frontier models, with circuity considered

	Model S9	Model S10	Model S11	Model S12
Ln(RPODM)	0.839***	0.814***	0.825***	0.778***
	(0.064)	(0.055)	(0.058)	(0.054)
Ln(dep)	0.186***	0.204***	0.197***	0.236***
	(0.051)	(0.044)	(0.045)	(0.043)
Constant	-2.535***	-2.182***	-2.331***	-1.725**
	(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)
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

Table 23: Fuel inefficiency values $\mathrm{FDI}_{\mathrm{SFA}}^{\mathrm{circuity}}$ and ranking of the 15 mainline carriers, with circuity considered

Carrier	$\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{circuity}}$	$\mathrm{FI}_{\mathrm{SFA}}^{\mathrm{c}}$	Ranking
Alaska	1.017	1.019	1
Hawaiian	1.039	1.041	2
Spirit	1.043	1.043	3
Continental	1.046	1.048	4
Southwest	1.056	1.069	5
Frontier	1.098	1.100	6
United	1.117	1.121	7
Jet Blue	1.127	1.134	8
US Airways	1.154	1.148	9
Delta	1.159	1.153	10
Sun Country	1.161	1.162	11
Virgin America	1.175	1.167	12
AirTran	1.183	1.173	13
American	1.249	1.248	14
Allegiant	1.286	1.296	15

5 Results comparisons, temporal evolution, and potential cost reductions

5.1 Results comparisons

With the completion of our efficiency measurements, it is now possible to obtain a global view of the results. The box plot below (Figure 11) shows the distribution of airline efficiency scores under the three approaches, considering mainline airlines only, mainline-regional affiliations, and routing circuity. It is clear that the variations of efficiency scores yielded by the frontier approaches are less than those from the ratio-based approach. Nonetheless, results from all of the analyses are broadly consistent. The ratio-based approach is more sensitive to the inclusion of regional carriers, producing the highest and lowest sample average efficiency. Such discrepancy in efficiency is further accentuated when circuity is considered. This is not surprising, given that regional carriers only contribute to the deterioration of the mainline airlines' efficiency, 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, the effect of considering regional affiliates on efficiency scores represents the net outcome of two competing forces—higher fuel/RPM and greater accessibility. The distributions when circuity is considered resemble those without circuity adjustment since, as shown in sub-section 4.4, circuity has only minor effects on frontier efficiency scores.

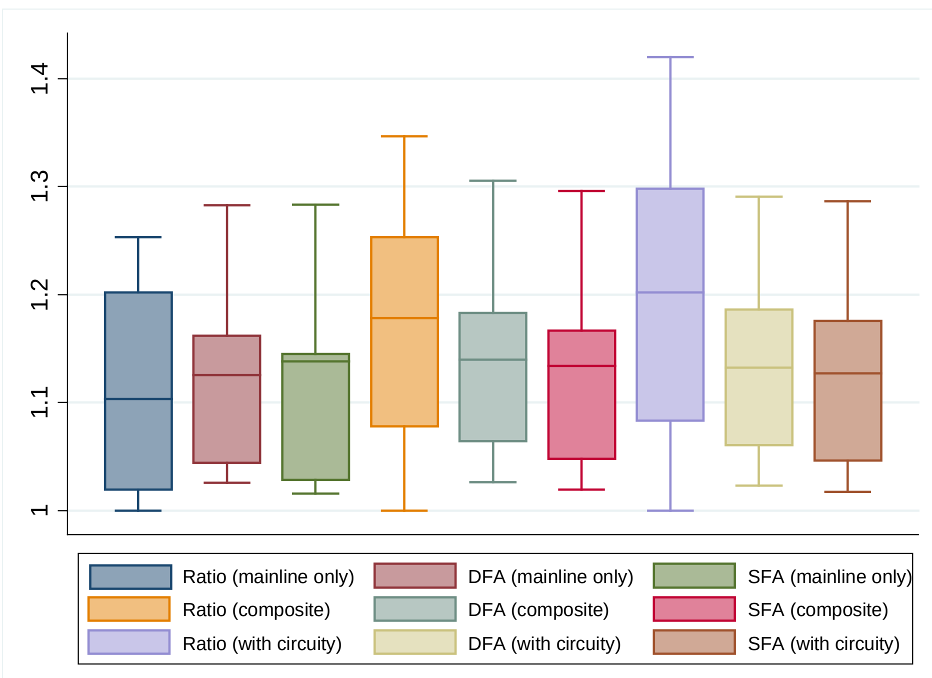

Figure 11: Box plot of the efficiency scores across the three approaches, considering mainline airlines only, mainline-regional affiliations, and circuity

To examine the extent of agreement among rankings arising from the various approaches, pair-wise efficiency score and Spearman rank correlation coefficients are reported in Table 24 and

Table 25. 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 0.6, indicating high correlation among the efficiency estimates from different techniques. The two frontier methods yield results that are in greater agreement with one another than with those of the ratio-based approach, and the agreement in both score and ranking based on these methods is maintained (or even strengthened in the case of rank correlation) when regional carriers and routing circuity are taken into account. On the other hand, we observe generally weaker score and rank similarities between the ratio-based and either of the frontier approaches once regional affiliates are introduced, again due to the inability of the ratio-based approach to capture the accessibility-enhancing effect brought from regional carriers. Consistent with the box plot above, when circuity is also considered, results using the ratio-based method deviate further from those under the stochastic frontier approaches.

Also worth attention are the diagonal elements (in dark grey) in the lower blocks in each table, which show the effect of considering regional carrier affiliations and routing circuity on the efficiency measurements. Consistent with our previous discussion in sub-sections 4.3.2 and 4.4, and the distribution shown in the previous box plot, the ratio-based rankings and ratings are affected more by the introduction of regional affiliates and circuity. In contrast, the frontier approaches, as a result of the offsetting fuel/RPM and accessibility effects, are less strongly influenced by the consideration of regional carriers; so effect is weakened still further when circuity is included.

Table 24: Efficiency scores correlation

	Ratio: mainline only	DFA: mainline only	SFA: mainline only	Ratio: composite	DFA: composite	SFA: composite	Ratio: circuity	DFA: circuity	SFA: circuity
Ratio: mainline only	1								
DFA: mainline only	0.8271	1							
SFA: mainline only	0.7071	0.9818	1						
Ratio: composite	0.8262	0.6784	0.5896	1					
DFA: composite	0.8367	0.9837	0.9572	0.6955	1				
SFA: 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		
DFA: circuity	0.8283	0.9810	0.9567	0.6975	0.9965	0.9842	0.6079	1	
SFA: circuity	0.7732	0.9743	0.9657	0.5927	0.9863	0.9969	0.4935	0.9889	1

Table 25: Spearman efficiency ranking correlation

	Ratio: mainline only	DFA: mainline only	SFA: mainline only	Ratio: composite	DFA: composite	SFA: composite	Ratio: circuity	DFA: circuity	SFA: circuity
Ratio: mainline only	1								
DFA: mainline only	0.8607	1							
SFA: mainline only	0.5643	0.8964	1						
Ratio: composite	0.8357	0.7750	0.5143	1					
DFA: composite	0.8536	0.9821	0.8857	0.7607	1				
SFA: 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		
DFA: circuity	0.8536	0.9821	0.8857	0.7607	1	0.9571	0.6821	1	
SFA: circuity	0.7536	0.9321	0.9107	0.5857	0.9571	1	0.4964	0.9571	1

5.2 Temporal evolution of fuel efficiency

Although our primary objective is to evaluate U.S. airline fuel efficiency in 2010, the methodologies developed in the present study can be applied to more extended time periods. In this sub-section, we present annual efficiency score and ranking results from 2008 to 2010. The analysis dates back to 2008 because Virgin America did not start service until August of 2007. Under the frontier approaches, the frontier is different from year to year, because each is estimated using data covered in the respective period. We only look at mainline carriers, as regional carriers' routing structure and contracting relationships vary over time, and that information them becomes increasingly unreliable as we go further back in time.

Table 26 - Table 28 document the rankings and inefficiency scores under the ratio-based, deterministic, and stochastic frontier approaches. The rankings are relatively stable overall, suggesting that the 2010 ranking may be used to reflect the general picture of airline efficiency in recent years. Nonetheless, some notable ranking changes do exist, examples of which include Alaska and Virgin America. Given their fairly consistent changes under all three approaches, it is likely that they reflect true changes in efficiency rather than statistical noise. While Virgin America’s performance appears somewhat erratic, this is probably because it was a young carrier whose network and operations were revolving rapidly over this period.

Table 26: Efficiency scores and rankings under the ratio based approach between 2008 and 2010

Carrier	FI_{ratio} 08	Ranking 08	FI_{ratio} 09	Ranking 09	FI_{ratio} 10	Ranking 10
Spirit	1.021	2	1.014	2	1.000	1
Continental	1.087	4	1.021	3	1.007	2
Alaska	1.154	10	1.061	6	1.016	3
Hawaiian	1.000	1	1.032	4	1.019	4
Virgin America	1.099	5	1.000	1	1.041	5
Frontier	1.099	6	1.094	7	1.065	6
Sun Country	1.041	3	1.054	5	1.097	7
Jet Blue	1.111	7	1.144	10	1.103	8
United	1.146	9	1.114	8	1.106	9
Delta	1.145	8	1.144	9	1.178	10
Southwest	1.302	15	1.208	12	1.178	11
US Airways	1.207	11	1.180	11	1.202	12
Allegiant	1.274	13	1.245	14	1.250	13
American	1.295	14	1.276	15	1.252	14
AirTran	1.264	12	1.243	13	1.253	15

Table 27: Efficiency scores and rankings under the deterministic frontier approach between 2008 and 2010

Carrier	FI_{DFA} 08	Ranking 08	FI_{DFA} 09	Ranking 09	FI_{DFA} 10	Ranking 10
Spirit	1.120	2	1.039	3	1.026	1
Hawaiian	1.088	1	1.025	1	1.027	2
Alaska	1.217	10	1.057	5	1.030	3
Continental	1.171	4	1.037	2	1.044	4
Southwest	1.215	8	1.056	4	1.056	5
Frontier	1.160	3	1.077	6	1.061	6
Jet Blue	1.191	5	1.129	11	1.100	7
Virgin America	1.288	13	1.079	7	1.126	8
United	1.214	7	1.112	8	1.133	9
Delta	1.208	6	1.120	9	1.151	10
Sun Country	1.217	9	1.137	12	1.161	11
US Airways	1.234	11	1.124	10	1.162	12
AirTran	1.253	12	1.150	13	1.173	13
American	1.359	14	1.246	14	1.247	14
Allegiant	1.416	15	1.280	15	1.282	15

Table 28: Efficiency scores and rankings under the stochastic frontier approach between 2008 and 2010

Carrier	FI_{SFA} 08	Ranking 08	FI_{SFA} 09	Ranking 09	FI_{SFA} 10	Ranking 10
Southwest	1.037	3	1.037	4	1.015	1
Hawaiian	1.016	1	1.016	1	1.022	2
Spirit	1.028	2	1.033	2	1.025	3
Alaska	1.067	10	1.050	5	1.028	4
Frontier	1.040	5	1.066	6	1.051	5
Continental	1.038	4	1.036	3	1.053	6
Jet Blue	1.052	7	1.122	11	1.093	7
United	1.053	8	1.109	8	1.138	8
Delta	1.045	6	1.115	10	1.139	9
AirTran	1.078	11	1.132	12	1.140	10
US Airways	1.059	9	1.114	9	1.144	11
Virgin America	1.162	14	1.079	7	1.145	12
Sun Country	1.106	12	1.133	13	1.169	13
American	1.151	13	1.240	14	1.242	14
Allegiant	1.249	15	1.273	15	1.283	15

The relationship of the efficiency scores and ranking over time can be further explored in a quantitative manner, by computing the score and rank correlation coefficients, for each of the three approaches. Results are shown in Table 29 - Table 34. All score correlation coefficients are greater than 0.8, and all rank correlation coefficients above 0.7, again suggesting the consistency of the results over time.

Table 29: Inefficiency score correlation using ratio-based approach between 2008 and 2010

	Ratio 08	Ratio 09	Ratio 10
Ratio 08	1		
Ratio 09	0.9011	1	
Ratio 10	0.8507	0.9525	1

Table 30: Inefficiency score correlation using deterministic frontier approach between 2008 and 2010

	DFA 08	DFA 09	DFA 10
DFA 08	1		
DFA 09	0.8715	1	
DFA 10	0.8747	0.9586	1

Table 31: : Inefficiency score correlation using stochastic frontier approach between 2008 and 2010

	SFA 08	SFA 09	SFA 10
SFA 08	1		
SFA 09	0.8079	1	
SFA 10	0.8396	0.9496	1

Table 32: Spearman rank correlation using ratio-based approach between 2008 and 2010

	Ratio 08	Ratio 09	Ratio 10
Ratio 08	1		
Ratio 09	0.8750	1	
Ratio 10	0.8036	0.9179	1

Table 33: Spearman rank correlation using deterministic frontier approach between 2008 and 2010

	DFA 08	DFA 09	DFA 10
DFA 08	1		
DFA 09	0.7357	1	
DFA 10	0.7786	0.9321	1

Table 34: Spearman rank correlation using stochastic frontier approach between 2008 and 2010

	SFA 08	SFA 09	SFA 10
SFA 08	1		
SFA 09	0.8000	1	
SFA 10	0.8821	0.8714	1

5.3 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. This scenario, however, 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. To at least partly address this concern, three alternative scenarios, in each of which airlines are categorized and a given airline's fuel efficiency can only be improved to the "best practice" level observed within its category, are further examined. In the 2nd scenario, we divide the 15 airlines into legacy vs. non-legacy carriers. The legacy group consists of American, Alaska, Continental, Delta, Hawaiian, United, and US Airways. These carriers developed in an era of economic regulation and low fuel prices. We also consider a carrier grouping based on 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 12.

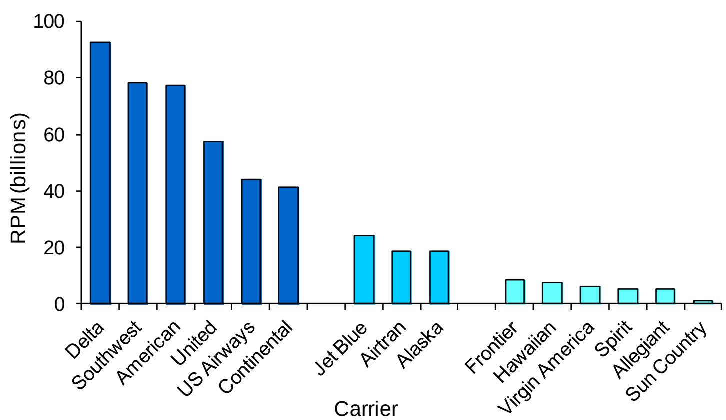

Figure 12: Annual airline fuel consumption in 2010

The procedure for estimating potential cost savings varies according to the method employed to measure efficiency. Under the ratio-based approach, it is particularly straightforward. For a given mainline airline, we compute the difference between its Fuel/RPM and the lowest Fuel/RPM observed in the group to which the airline belongs, and then multiply the difference by the airline's RPM to obtain the amount of potential fuel saving for that airline. Note that Fuel/RPM is measured on an annual basis; whereas saving estimates under the frontier approaches are based upon airline-quarter observations. When the deterministic frontier approach is utilized, we take the exponential of the difference between the minimum residual observed in the corresponding airline group and the residual for a given airline-quarter observation, and multiply this quantity by the observed fuel burn. This gives fuel consumption under the counterfactual that the fuel efficiency of the airline matches that of the leader of its assigned group. 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 approach, but with the above exponential replaced by the ratio between the inefficiency scores of the minimum in the group and the airline-quarter observation. This is certainly an approximation, in that the ratio of two expectations is used as proxy for the expectation of the ratio.[9]

The estimated fuel savings need to be converted into dollar values. To this end, we collect total fuel cost data from BTS Form 41 P-12(a) database, which are aggregated to either airline-year or airline-quarter levels, and divided by the corresponding fuel consumption, to obtain the unit fuel cost ($/gallon) for each airline. The total fuel cost saving is given by the product of the unit fuel cost and the amount of fuel savings, summed over all observations. Furthermore, improved fuel efficiency leads to CO_2 emission reduction, which can be conveniently 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, recommended in Greenstone et al. (2011), is used to monetize the benefits from the reduced negative externalities.

Table 35 - Table 37 report the estimated fuel, CO_2 savings, and total cost (sum of fuel and CO_2 cost) reduction from improved fuel efficiency considering mainline carriers only, mainline-regional affiliations, and circuity respectively. Each table consists of a panel of results in four scenarios, and under ratio-based, deterministic, and stochastic frontier approaches. In generating results in Table 36, it would be ideal to use unit fuel costs that are composites of mainline and regional carriers. Unfortunately, 30 out of 88 regional carrier-quarter fuel cost data points are either missing or recorded as zero in BTS Form 41 P-1.2(a) database. To circumvent this reporting problem we instead use mainline unit fuel cost as proxy. Any potential errors arising from this substitution should not be large given the predominance of mainline carriers' operations in the each mainline-regional composite.

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

The three approaches yield relatively similar estimates of potential fuel, CO_2, and cost savings under the various scenarios when only mainline carriers are considered. As shown in Table 35, 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. More than 90% in the total benefits stems from fuel use reduction, due to relatively low social cost of CO_2 compared to jet fuel unit cost. Savings estimates obtained from the frontier approaches are lower than those from the ratio-based approach, as expected, because the former controls for both RPM and the number of departures. Estimates under deterministic frontier are always larger than under the stochastic frontier, presumably as a result of random noise being purged from the inefficiency term under the stochastic frontier approach. As expected, these numbers follow a decreasing trend in general from the most idealized Scenario 1 to more realistic Scenarios 2 & 3, and finally to Scenario 4, which features the finest 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). As the consequence, whether the 15 carriers are considered as a whole or divided into two groups, for which Alaska and Spirit are the efficiency leaders, the "best practice" levels are close enough such that the difference in the estimated numbers is masked by the rounding errors. On the other hand, the identical results in the stochastic frontier case is due to the fact that three data points lie on the frontier (Alaska, 3rd quarter; Hawaiian, 3rd quarter; Southwest, 4th quarter). Therefore, each group will always share the same "best practice" level irrespective of the grouping choice.

One would certainly expect larger cost saving numbers from including contributions from regional carriers; incorporating regional carriers expands the scale of operations considered as well as the range of efficiency differences. The one exception is Scenario 4 using the ratio-based approach, which results from more substantial efficiency degradation of the "best practice" airline (Continental) in the 1st mainline airline group after incorporating regional carriers. Incorporating regional carriers widens the Fuel/RPM gap between the mainline airlines with and without regional affiliations, as well as among the mainline airlines with varying degrees of involvement with regional carriers. The ratio-based approach therefore yields more significant cost saving differences under these different scenarios, with total cost savings more than doubled between Scenarios 1 and 4. These differences are less pronounced if the frontier approaches are employed, since they yield less drastic differences in efficiency score and ranking. We again obtain very similar estimates for Scenarios 2 and 3. Focusing on the differences between composite and mainline-only estimates, total potential cost savings under the ratio-based approach can be up to 81% greater (Scenario 1). If frontier approaches are employed, however, the maximum percentage increase is considerably less--44% (Scenario 1 using the deterministic frontier method).

Finally, when circuity is incorporated, we observe further increases in cost saving estimates under the ratio-based approach compared to the mainline-regional composite case. The additional savings are due to the greater efficiency gap between the least efficient airlines, most of which are large, legacy carriers, whose hub-and-spoke networks entail more circuitous routings, and the more efficient airlines. The maximum potential savings could amount to over $6 billion under Scenario 1. On the other hand, efficiency score change based on the frontier approaches is more moderate, resulting in only slight differences (on the order of tens of millions) compared to the estimates in Table 36.

Table 35: Potential fuel and CO2 reduction, and cost savings from improved fuel efficiency (mainline 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 36: Potential fuel and CO2 reduction, and cost savings from improved fuel efficiency (composite)

	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 37: Potential fuel and CO2 reduction, and cost savings from improved fuel efficiency (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

6 Conclusion

In this report, we have investigated fuel efficiency of 15 U.S. large jet operators in 2010 using macroscopic airline fuel consumption and production output data. Multiple approaches have been employed. In addition to straightforward ratio-based methods, we also present alternative efficiency analyses that are built upon fuel consumption frontiers. The key difference between these two approaches is that the latter recognizes that airline output is multi-dimensional: in addition to mobility, it is also important to account for the level of accessibility that airlines produce. The simpler version of the frontier analysis assumes that the frontier itself is deterministic. Then efficiency measurement can be viewed as a special case of the ratio-based approach, except that both mobility and accessibility measures enter the denominator of the ratio, in an expression whose coefficients are determined empirically. A more refined version of frontier models recognizes that fuel consumption is subject to random shocks and measurement error, suggesting that the fuel consumption frontier is stochastic. The separation of such "noise" from the true inefficiency results in a somewhat different frontier, as well as the magnitude and variance of the inefficiency term. In the present study, the major reason for ranking variations under the stochastic frontier approach as compared to the deterministic one is the change of the frontier.

In addition to offering multiple approaches to measure fuel efficiency, another unique feature of our study is its consideration of regional carriers. Regional carriers play an integral part in the U.S. air transportation system, particularly in supporting the hub-and-spoke network structure as adopted by many mainline airlines. When mainline carriers employ regional affiliates, it is appropriate to incorporate their operations in assessing mainline carrier fuel efficiency. Since regional carriers' operations are in general less fuel efficient on a RPM basis, regional affiliations reduce the fuel efficiency of mainline carriers when efficiency is measured using the ratio-based approach. However, regional carriers also 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 mainline carriers' regional carrier affiliations can boost their measured efficiency and ranking.

Recognizing the fact that the ultimate goal of air transportation is to move travelers from their origins to destinations, we have further investigated the airline fuel efficiency with respect to revenue passenger O-D miles instead of the conventional revenue passenger miles. Under the ratio-based approach, incorporating the circuity effect penalizes airlines with significant portions of their service through hub airports. Because the least fuel efficient airlines under the Fuel/RPM metric are also those performing a greater degree of hub-and-spoke operations, these airlines become even less efficient than their competitors when circuity is considered. In the frontier models, substitution of RPODM for RPM will reshape the frontiers, with further weight given to departures in determining the "best practice" fuel consumption. Differences in efficiency scores with and without considering circuity can therefore be attributed to several factors. Nevertheless, these differences are small.

The observed variation in fuel efficiency among the 15 carriers implies room for improvement for the less efficient ones, which could result substantial savings in fuel expenditures and environmental impact. Despite the quite different approaches to quantifying these savings that we have employed, estimates of potential cost savings are rather close—between $2 and $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 the cost saving benefit estimates, particularly those derived from ratio-based fuel efficiency metrics. The cost savings due to less fuel consumption dominates those from reduced CO_2 emissions. At the very least, the various estimates reveal the magnitude of the potential savings from bringing industry fuel efficiency to the production frontier.

An obvious question is: among the many efficiency rankings presented here, which one is the most valid? The answer is subjective. From a purely technical perspective, stochastic frontier models appear to be the most methodologically sound approach, although different specifications can lead to somewhat different results. From a conceptual standpoint it is more appropriate to take regional airline operations into account in assessing mainline carrier fuel efficiency, but doing so with publicly available data involves assumptions and approximations that introduce some error into the results. When fuel efficiency in transporting passengers between their O-Ds becomes the concern, it is necessary to further incorporate routing circuity in the modeling process. One of the major purposes of the report is to provide different perspectives on airline fuel efficiency measurement, along with transparency on the assumptions and methodologies used to construct the different rankings. Readers and stakeholders must ultimately rely on their own judgment—ideally not clouded by which ranking is most favorable to them—to weigh the pros and cons of the different approached to efficiency assessment presented here.

While the primary attention of this report is focused on fuel usage, fuel is only one input in the airline production process. 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 (Oum et al., 1999). From the technical vantage point, the most plausible substitution for fuel is capital (the other inputs are labor and materials) which, as widely recognized in airline economics literature (e.g. Gillen et al., 1990; Oum and Yu, 1997; Hansen et al., 2001; Zou and Hansen, 2012), cannot be varied instantaneously, particularly at the present time when new aircraft order books for 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. Technically, the frontier models under these circumstances can be interpreted factor requirement functions (Gathon and Perelman, 1992). 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 do so. 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 Emissions Trading Scheme or the future global framework to reduce aviation emissions, may also do so. 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 required. We hope that this report has provided it.

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