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Aircraft trip cost parameters: A function of stage length and seat capacity

William M. Swan [a,*], Nicole Adler [b]

[a] Boeing Corporation, Seabury Airline Planning Group, LLC, 2232 157th PL SE, Bellevue, WA 98008, USA
[b] School of Business Administration, Hebrew University of Jerusalem, Mount Scopus, Jerusalem 91905, Israel

Abstract

This paper disaggregates aircraft operating costs into various cost categories and provides background for an engineering approach used to compute a generalized aircraft trip cost function. Engineering cost values for specific airplane designs were generated for a broad spread of operating distances, enabling a direct analysis of the operating cost function and avoiding the problems associated with financial reporting practices. The resulting data points were used to calibrate a cost function for aircraft trip expenses as they vary in seating capacity and distance. This formula and the parameter values are then compared to econometric results, based on historical data. Results are intended to be used to adjust reported costs so that conclusions about industry structure based on cost regressions correctly account for differences in stage lengths and capacities. A Cobb–Douglas cost function is also computed, providing elasticity parameters for both economies of density, through seat capacity, and distance as they would be determined from clean airline-neutral data. The results are particularly useful for route network design because they establish a simple planar connection between frequency, capacity and costs. Although the econometric cost functions are no less accurate, it is generally much less convenient for subsequent analysis.

Keywords: Operating cost functions; Aircraft; Air transport; Econometrics

1. Introduction

This research evaluates and presents a cost function for commercial passenger aircraft operating costs. The formula expresses trends in aircraft costs that have stood up in general form and approximate size for over 30 years of jet aircraft designs. The planar function is calibrated against data derived from engineering considerations for aircraft models in current production. The engineering data had been indirectly calibrated from reported airline cost details. The study offers background explanations of the structure of the formula and the data. The paper should help to answer the comment made in Brueckner and Spiller's (1994) paper, where they

* Corresponding author.
E-mail addresses: bill.swan@cyberswans.com (W.M. Swan), msnic@huji.ac.il (N. Adler).

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state "unfortunately, information that would allow us to directly estimate a cost function at the spoke level is not available".

Analyzing transportation cost functions has been a subject of discussion for the past 150 years and a good survey of the more recent academic research can be found in Oum and Waters (1996). Waters and Tretheway (1989) compare the highly aggregated econometric approach with the disaggregated empirical approach to cost function estimation in transport. This research will try to bridge the gap between the two approaches, by including factor pricing and avoiding assumptions of separability. This study will undertake a disaggregate analysis by examining the long-run average cost of a scheduled flight, given aircraft size (seat configuration) and stage length. The results may be useful to researchers interested in the broader cost structure of the industry, because size and distance adjustments can be made to airline reported costs, leaving differences to be explained by structural issues. The results are also intended to assist those analyzing alternative airline strategies, such as network choice and merger/alliance acquisitions, requiring the use of a reasonably accurate cost function. A large area of research in this field is based on O'Kelly's (1986) seminal paper describing the p-hub median formulation, which solves network choice decisions based on a cost component. To the best of the authors' knowledge, whilst much research has discussed solving this formula, no published paper has considered the computation of c_{ij}, the cost of a flight from node i to node j. Hence, this paper fills in the gap, by identifying the two major factors defining the level of unit cost and the value of the parameters required to compute the unit cost. One of the main contributions of this paper to the academic literature is the use of engineering design data to better analyze the true cost function, as it avoids the data problems associated with airline financial reporting analysis.

The engineering approach generated costs at various stage lengths for families of comparable airplanes over a wide spread of trip lengths. In this way, many data points are available and they broadly cover both size and distance. Instead of one observation per airline, there is one data point for each airplane type for each distance flown. The generated data is independent of a particular airline and its idiosyncratic efficiencies. The data is comprehensively focused on the costs of size and distance. The objective is to understand the normal relationship of average cost with average distance and average airplane size.

2. Cost categorization

In this section, we will discuss the different cost components that when aggregated, compute the cost of one flight. Engineering costs are summed and calibrated from distinct activities, separately tracked by all airlines and separately reported by US carriers. The data was collected from 1996 to 2001 and draws on Form 41 from the US Department of Transport and from individual airline maintenance log schedules.

The cost categories include pilot, cabin crew, fuel, airframe maintenance, engine maintenance and the ownership costs of the aircraft. Fig. 1 illustrates the approximate share of airplane operating costs that can be attributed to these various categories. These values vary in practice, hence Fig. 1 merely provides a sense of proportion.

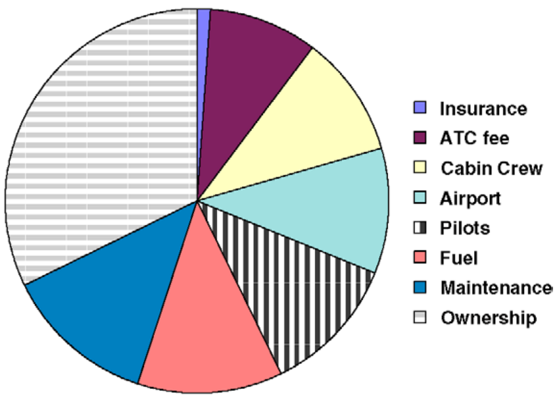

Fig. 1. New aircraft cost breakdown.

Most airplane costs are proportional to the hours flown, and hours flown are linear in distance. It takes about a half an hour for taxi, departure, climb, maneuver, descent and landing, and at cruise level airplanes travel at approximately 822 km/h, where distance is the great circle trip distance between departure and arrival points. Therefore, time costs are all proportional to distance plus a per-departure amount. Non-time costs are also commonly proportional to departure cycles and kilometers. Consequently, most costs are linear in distance, based not on statistical calibration but on how they truly accrue.

Pilots contribute roughly 12% to overall airplane costs. Pilot (flight crew) costs differ amongst airlines, depending on the union contract and the base country of each airline. See, for example, Oum and Yu (1997) for a detailed unit cost analysis comparing North American, European and Asian-Pacific airlines. Within the US, one union has monopolized the workforce, so contract provisions are fairly uniform. Outside the US, although levels of pay can greatly differ, the structure remains consistent. Pilots are paid for the hours they fly. In some cases, pilots receive additional pay if the hours they spend waiting to fly are overly burdensome. Pilots wait while the airplane is "turned" from one flight to another or the pilots are transferred between airplanes. Extra pay for waiting hours can be a problem for operations that are exclusively short-haul, depending on how tight the turns are and on the particular pilot contract. However, the cost functions in this analysis follow the more typical case of no wait-time penalties. The other driver of pilot costs is airplane type. Pilots flying larger airplanes are usually paid more than those that fly smaller ones. There are other pay details (called "duty rigs") in pilot contracts, however the core relationship worldwide bases flight crew costs according to the aircraft block hour and airplane size.

Pilot costs for distances beyond 6000 km display one additional complication that appears to be important in cost terms. Trips longer than 8 h require the addition of a (third) relief pilot, and trips beyond 12 h a fourth pilot. These rules are widespread and not entirely unreasonable. However, the complete crew must be paid for the entire flight time, which introduces a non-linearity in pilot costs over long trip lengths. The data used in this analysis viewed the pilot supplements not as a step function at a specific distance, but as the fraction of flights requiring crew supplementation given the average stage length of a fleet type serving a mix of longer and shorter distances.

Fuel is approximately 12% of modern airplane costs. Fuel burn for airplanes is a matter of constant detailed design, considering both the aerodynamics of shape and lift and the engine efficiency. Fuel burn for a particular airplane is linear in distance flown. Across aircraft sizes, fuel burn is almost linear in weight, which in turn is almost proportional to seating capacity. In general, fuel consumption is one of the most easily estimated cost items and actual fuel usage is also clearly defined within the accounting books of airlines.

Ownership represents approximately 32% of new airplane costs. There are many ways to calculate ownership costs for a flight and this can create large differences across airlines. If the aircraft are fully owned, only depreciation costs are reported. Some reporting includes interest costs, and there may also be tax depreciation and other tax advantages depending on the national regime of the airline's home country. In short, accounting and allocation issues dominate the reporting of ownership costs. The simplest way to overcome this complication is to consider a monthly lease cost for a new airplane at about 0.8% or 0.9% of the market price, where the former is applied to long-haul aircraft and the latter to single-aisle aircraft. Leasing costs per year were allocated to specific flight segments, based on the relationship of trips per year versus stage length that was calibrated from reports for individual airplane tail numbers. For reasons of maintenance monitoring, each airplane must report the number of block hours and cycles undertaken each year. For practical purposes, the relationship between average block distance, BD, in km and the trips per year, T, can be approximated as in Eq. (1).

$$T = 12.5 * \frac{365}{1.5 + \frac{BD}{822}} \tag{1}$$

Eq. (1) represents an average value based on worldwide data, although it must be noted that values vary over different regions of the world and across airlines. The number of trips per aircraft also varies per year, depending on whether the specific fleet mix is too large or too small for the demand as it cycles. Most famously, dedicated short-haul airlines achieve a longer working day and a faster average turn around time, which is not reflected in the function presented.

The values in Eq. (1) have practical interpretations. The constant 822 represents the average airplane cruise speed against great-circle distance, taking into account circuity, winds, and en-route air traffic control delays. The number 12.5 represents the fleet-wide working hours per day as an annual average. The parameter 1.5 is composed of a 1 h average turn around time and 0.5 h of climb-and-decent flying.

The ownership cost is then allocated to trips per year, which themselves are dependent on stage length. This methodology shares out ownership costs by the hour, charging for both block hours and ground time equally. A further complication would be to consider the allocation of ownership costs over peak seasons or peak times of day only. However, most cost studies consider average annual costs, thus the idea of marginal cost ownership is not developed within the scope of this paper.

Maintenance costs for airplanes compose 13% of airline operating costs, in general. This figure includes direct overheads associated with the upkeep of maintenance facilities and tools. Maintenance costs for airframes and engines are commonly reported separately. The expense of major inspections accrues based on block hours or cycles flown. The most expensive of these inspections occurs once every 3–4 years. Responsible accounting captures these accruals. However, it is clear from airline financial reports that some of the year-to-year variations in reported costs arise from imperfect accrual treatment. The cost functions employed here are for airplanes in "steady-state maintenance." That means the maintenance savings associated with the first 5 years of operation of a newly manufactured airplane have finished and the airplane accrues expenses according to a "half-life" maintenance for all its various parts over their respective lives.[1]

Cabin crew (flight attendant) costs compose approximately 10% of airplane operating costs. Cabin crew manning requirements are based on seat counts, with a typical ratio of 1 crew to every 40 seats. The legal minimum for safety can rise as high as 1:50. Lower ratios are sometimes employed in practice to increase onboard service levels. A short flight with a full meal service will require extra crew. Extra crews are not included in the costs reported in this research, particularly since a supplementary crew is becoming rare. The base cabin crew is distributed evenly for take-offs and landings due to safety considerations and then allocated disproportionately to the first and business class cabins during the flight. Cabin crew pay is based on hours worked and is relatively unaffected by different airplane types.

Landing fees paid to airports are conventionally based on the maximum take-off weight of the relevant aircraft type. They comprise 8–14% of costs, depending on the length of the haul. The share is lower for long-haul flights and in the United States, where airport charges are lower. Other airport charges, including transfer and non-transfer passenger fees, security charges, air traffic control charges, noise charges, night surcharges, parking fees, freight loading and unloading charges, baggage handling costs and gate fees are not included in the direct costs estimated here, as they are considered outside the scope of the aircraft operating cost. These charges are most naturally proportional to the passenger count, although in practice they also rise with the length of haul. They provide a component of costs that is less dependent on stage length and airplane size than the airplane-related costs that are the subject of this research. It should be noted that airport costs have been small but are rising, while other costs have tended to benefit from productivity gains. Current practice often allocates them as an overhead on revenues.

En-route air traffic control charges are also rising over time. These are usually based on airplane size (as approximated by their weight) and distance flown. These charges run from 2% to 6% of the total aircraft operating costs. The lower percentage applies to long-haul flying, frequently over oceans. The higher percentage affects regional flying, where there is both congestion and operational inefficiency, particularly in Western Europe. An additional en-route charge, to cover environmental externalities such as CO_2 emissions, may well be introduced within the E.U. borders over the next 5 years. On the other hand, the US charges in this category are substantially lower.

Insurance, absent acts of war, represents less than 1% of costs, although this category increased dramatically post 9/11 (Goodrich, 2002). Whilst risk is proportional to departures, insurance costs are traditionally computed on an annual basis, hence charges per trip are lower on short-haul flights.

[1] It should be noted that maintenance costs for older aircraft designs are higher than new designs but they are compensated for by lower ownership costs. Since the total cost is simply the sum of ownership and operating costs, and since the second-hand price of aircraft represent the new-aircraft price less the additional maintenance costs due to the older design such that the same cost frontier is achieved, we have used new-aircraft prices to represent the cost frontier.

3. Operating costs as a function of distance and seat capacity

The methodology followed here provides a contrast between an engineering-based function approach and the more conventional econometric cost functions. The fundamental data consists of trip cost estimates for aircraft models covering the entire range of sizes available in the new airplane market today from both major manufacturers. For each aircraft model, operating costs were computed for a set of stage lengths spanning all practical ranges. Cash costs draw on internal engineering estimates for Boeing and Airbus designs that were computed by OPCOST, a Boeing cost model that has been gradually developed over the past 25 years and whose precise details are proprietary. The OPCOST model uses engineering sub-category cost formulas and the parameters were calibrated from detailed airline data including variables such as fuel burn, labor hours, maintenance parts costs, ownership and insurance costs. Factor input costs such as fuel cost per kilo and crew cost per hour are standardized. Total operating costs are based on the sum of cash costs, by category, and ownership costs based on lease rates, that were in turn based on new airplane prices published by Avmark (September 2002). The use of Avmark lease rates (0.9% per month for short-haul and 0.8% per month for long-haul) and Avmark market prices eliminates distortions caused by the use of catalogue prices. Market prices generally reflect inconsistent discounts off catalogue prices and inconsistencies can occur both between manufactures and across models.

The airplane models in the sample set include all products offered for sale first-hand in 2002. Particular models, such as the Boeing 737, and type (such as the −800), typically include many varieties of weights, thrusts and engines. One version of each model type was selected, such that the aircraft all had comparable capabilities in range and engine. The data included a full matrix of costs with respect to range and seating capacity. The cost function was then calibrated through regression analysis using the data points abstracted from the analysis.

This section continues with individual discussions and analysis of costs as a function of distance (Section 3.1), as a function of seat capacity (Section 3.2) and any remaining costs are discussed in Section 3.3.

3.1. Costs as a function of distance

The linear relationship between trip cost and distance can be seen in Fig. 2. Fig. 2 illustrates that for a particular aircraft type, in this case the 737-800, the trip cost is very nearly linear in distance across stage lengths ranging from 1000 km to the maximum capability of the aircraft, approximately 5000 km. This is an interesting, if not surprising, result as it suggests that the operating cost, at an average distance, captures the costs for a fleet operated over any mix of stage lengths.

Fig. 3 presents the trip costs over longer stage lengths with respect to long-haul designs, for example the Boeing 777-200, which is also close to linear for all designs.

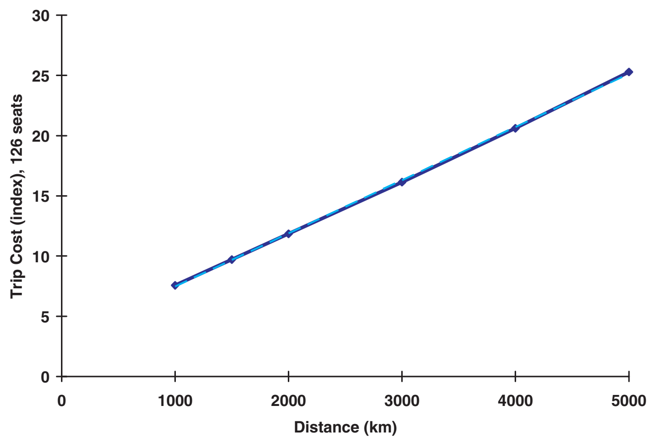

Fig. 2. Short-haul trip cost is linear with distance.

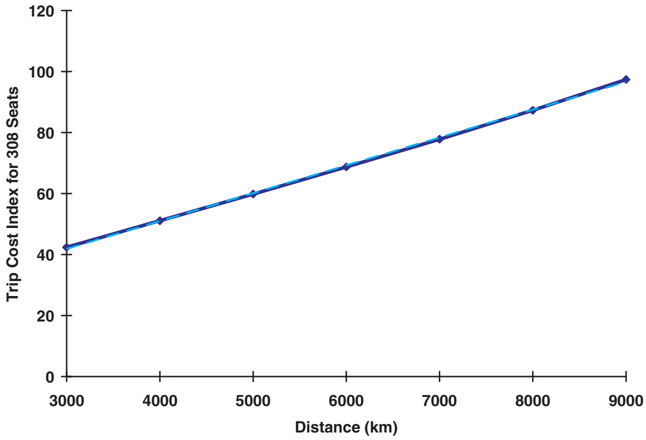

Fig. 3. Long-haul costs are linear with distance.

3.2. Costs as a function of seat capacity

The seat counts used in this research are presented in Table 1 for the airplane types used in the study. Column 2 presents the nominal seat counts of an all-coach seating configuration. Column 3 introduces the manufacturers' seat counts for airplanes comparably configured in the standard, long-haul, 2-class configurations. Airlines in practice use different seat counts, depending on service requirements, premium cabin share and operational considerations. For long-haul designs, these counts include a more spacious layout with more galley and lavatory space per seat than for short-haul designs. The 2-class configurations for long-haul designs tend to apply to flights longer than 10 h. There is considerable variation in long-haul configurations amongst airlines and across regions, hence the seat counts in these tables are for comparable standards across the various airplane designs. Ratio adjustments can be made for alternative service standards.

In general, seat counts are a frequently contentious issue between the two manufacturers. Convincing the industry that an airplane can hold another row of seats is highly leveraged, as it can lead to a 5% reduction in

Table 1
Seat counts for various airplane models

Airplane	Nominal	2-Class
Regional configurations		
A318	117	107
737-600	122	110
737-700	140	126
A319	138	126
A320	160	150
737-800	175	162
737-900	189	177
A321	202	183
757-200	217	200
757-300	258	243
Long-haul configurations		
767-200	238	163
767-300	280	200
767-400	315	229
A330-2	355	233
A330-3	379	268
777-200	415	308
777-300	510	385
747-400	553	429

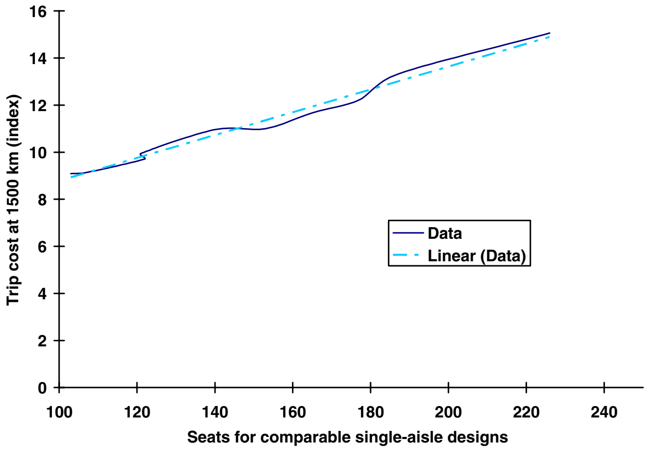

Fig. 4. Short-haul costs are linear with seats across models.

seat costs per trip, since the airplane costs per trip barely change. Researchers are advised to pay attention to the matter of seat counts and be aware that differences among airlines can represent differences in product quality, while differences between manufacturers can represent product posturing.

Fig. 4 shows the cost increase over aircraft capacity for short-haul flights. Yet again, the relationship is nearly linear for airplanes with the same mission capabilities. The association is not as linear as those of Figs. 2 and 3, because the cost methodology is not as consistent across models and across manufacturers as it is for costs of the same airplane across different distances.

Clearly, there is a fixed expenditure associated with the cost of crews, instrumentation and basic design complexity, and there is a smaller incremental cost for aircraft types with increasing seating capacity. The fixed costs amount to approximately 100 seats in short-haul design and twice that for long-haul designs used in long-haul operations.

We are unable to highlight any obvious reason as to why costs rise linearly in capacity. Some physical costs, such as structural needs, tend to scale more rapidly than size, whereas other costs rise more slowly. For example, maintenance costs increase slowly with larger engines, because the cost of taking apart an engine is similar, independent of the size of the parts. In the aggregate, the engineering considerations lead to a linear rise in cost with respect to capacity across the ranges currently in use. This result can also be seen in theoretical design studies of airplanes of various sizes, where the technology and mission parameters can be identical. Fig. 5

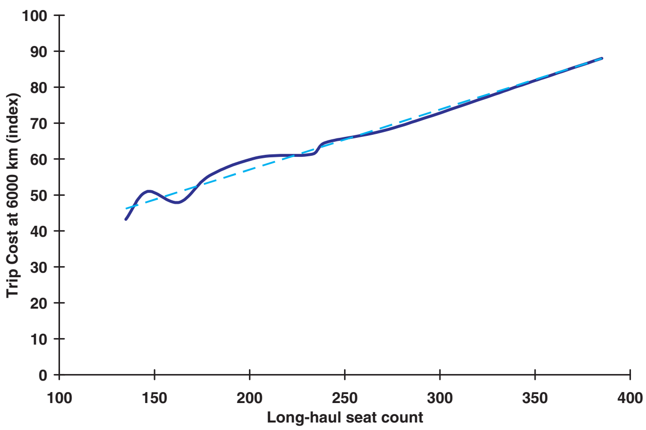

Fig. 5. Costs are linear with seat count for long-haul designs.

shows the same, almost linear, rise in costs over seats for longer-range designs, as was evident for short-haul airplanes.

3.3. Remaining costs

The data analyzed in this research considers aircraft trip costs alone, which represent on average 50–60% of total airline costs. General administrative overheads represent an additional 30% of costs approximately. The costs of commissions and sales expenses make up approximately 20% of the total costs remaining.

There is also a growing level of relatively new costs, which in general, are proportional to the number of passengers carried. Airport passenger transfer and non-transfer charges, security screening costs, baggage handling and some part of ticketing expenses and commissions add up to between \$5 and \$50 per passenger. Many of these costs elude airline reporting because they are passed on to the customers in the form of charges and taxes and are not part of reported ticket revenues. Nonetheless, they affect demand and may distort policy considerations. These costs are not included in the results section, and they do not scale in the same way as the costs in the formulas. Users will need to decide whether adjustments are required based on the individual case at hand.

4. Results

In this section, we first present the planar-form cost function parameters based on engineering generated data. Section 4.1 then compares the results to a classic Cobb–Douglas function and presents the elasticity results with respect to seat capacity (economies of density) and distance. Sections 4.2 and 4.3 discusses potential adjustments that may be necessary due to airline specific and aircraft specific information, respectively.

The result of the unbiased least-squares estimates of the cost function over the short-haul data points generated, as explained in Section 3, computes aircraft trip cost, C, based on design seat count, S, and trip distance, D, as shown in Eq. (2).

$$C = (D + 722) * (S + 104) * \$0.019 \tag{2}$$

This is the value for single-aisle operations between 1000 and 5000 km. The cost function does extend to approximate the case for larger, twin-aisle airplanes when they are purchased at lower gross weights and configured in short-haul seating densities.

This "planar" form is not the same as a linear form, as it contains the cross-product $D * S$ term, nor is it the same as a generalized form with an independent calibration of the factor for the $D * S$ term. In the planar form, the $D * S$ factor is derived and not independent. Thus, the planar form has only three parameters, and not the four degrees of freedom of the more generalized version. However, for this data the $D * S$ factor was not significantly different from the value implied in the planar form, so it was not included as an additional degree of freedom. This keeps Eqs. (2) and (3) relatively simple and especially useful for network design models. The intuitive appeal of a planar approximation to costs was considered more convenient. The attraction of the planar shape is that the total costs of an assortment of trips and distances can be made from a simple knowledge of the average distance and size.

For longer-haul operations using twin-aisle airplanes configured for long-haul, 2-class seating configurations, the corresponding formula is:

$$C = (D + 2200) * (S + 211) * \$0.0115 \tag{3}$$

The values for short and long-haul are noticeably different. This is because the cost function for international travel has higher airport costs and the airplane designs are significantly different. Long-haul airplanes have two aisles, large freight capabilities, extra redundancy and weight for over-water operations and carry larger amounts of fuel.

The regression results presented here possess a relatively small distance intercept because the engineering-based cost study considers a straightforward flight between uncongested airports. Taking into account the heavy congestion occurring today at major hub airports would require at least an additional 150 km to be added to the distance intercepts reported in Eqs. (2) and (3).

4.1. Cobb–Douglas comparison and elasticity results

A regression analysis was undertaken using the same input data points as applied to the parameter computation in Eqs. (2) and (3), pertaining to a traditional Cobb–Douglas cost format:

$$\ln(\text{cost}) = A + B * \ln(\text{seats}) + C * \ln(\text{distance}) \tag{4}$$

The A parameter was then adjusted so that real cost forecasts were unbiased (not in log-space but in dollars). The unbiased forecasts still show double the error sizes (root-mean-square error, minimum error and maximum error, in both dollars and percentage of cost) for short-haul and 25% larger for long-haul analyses. For the record, the short-haul values for A, B, and C were 0.905, 0.593, and 0.744, respectively. The long-haul values were 0.620, 0.499, and 0.886, respectively. It should also be noted that a translog cost function was analyzed with very little difference to the end result, hence the simpler Cobb–Douglas parameters are presented.

Economists have traditionally used translog and Cobb–Douglas cost functions to establish economies of density (measured by average seat count) and range (measured by average distance). Such examples include Caves et al. (1984), Gillen et al. (1990) and Brueckner and Spiller (1994). The data that drives such analysis is typically annual US airline data for a cross-section of airlines over a number of years, for which calibration has proven challenging. Airlines change their average stage lengths and seat counts extremely slowly, so time series information is quite thin. Changes in labor rates, during years when contracts are renegotiated, can overwhelm small differences. As for cross-sectional information, that too suffers from a paucity of data points, due to the fact that there are only nine major US airlines. With so few airlines, idiosyncratic differences may dominate. Some of those differences are real, such as different labor rates or different cost airports. Some are temporary, such as different aircraft utilizations based on a mismatch of fleet plans given competition and demand. Furthermore, accounting issues can explain yet more variations, for example, aircraft ownership leads to a return on capital, which is defined as profit, whilst aircraft leasing is categorized as a cost. In addition, expanding the list to include small or start-up airlines captures qualitatively different product offerings. These issues are what motivated the use of engineering data in an attempt to compute aircraft trip costs and evaluate economies of density and range, clean of these considerations.

A Cobb–Douglas function was calibrated using the more traditional method (linear unbiased least-squares in log-space) using the same raw airplane data as above. Alternatively, data can be manufactured by generating data points from the engineering cost formula, in order to compute Cobb–Douglas elasticities given the planar data. Both approaches lead to very similar solutions. The advantage of either of these methods is that data is created for a much broader set of densities, ranges and points than are available from historical data. The parameters presented in Eqs. (5) and (6) were calibrated using data points generated from the planar cost formula. Points were selected covering the entire ranges of data, however a denser set of points was generated for the shorter distances so that the average seats and ranges would correspond to industry averages. With cost per seat kilometer c, seat count S and distance D, the traditional results according to the Cobb–Douglas function are presented for short-haul in Eq. (5) and long-haul operations in Eq. (6).

$$c = 2.44S^{-0.40}D^{-0.25} \quad \text{for regional single-aisle services} \tag{5}$$

$$c = 0.64S^{-0.345}D^{-0.088} \quad \text{for long-haul twin-aisle services} \tag{6}$$

Elasticity with respect to density (seats) is between −0.40 and −0.35. Elasticity with respect to range (distance) is −0.09 for long-haul operations and −0.25 for regional service. This new data may help to sort out the previously published literature, which show no clear direction. Caves et al. (1984) argued that airlines enjoy constant returns-to-scale and that economies of density and average stage length are the most important factors explaining the cost differences between different airlines. The elasticity of density, computed from US airline financial data drawn from 1970 to 1981, was approximately −0.264 and the elasticity with respect to stage length was −0.148 (clearly, in the light of our results, representing an average of short and long-haul operations). On the other hand, a paper by Gillen et al. (1990) on Canadian Airlines, found short-run marginal cost elasticity with respect to traffic density at almost −0.5. Brueckner and Spiller (1994), drawing on an analysis of

US carriers in the fourth quarter of 1985, computed the elasticity of marginal cost with respect to distance at 0.35 and the marginal cost with respect to spoke traffic to lie between −0.4 and −0.35.

4.2. Airline specific costs

In practice, airlines show different costs to those presented in the formulas. Some of these differences can be explained by differing global labor rates, cost of capital, airport and en-route sector charges and exchange rates. Oum and Yu (1997) analyzed the differences in unit costs and productivity of airlines around the world and reached the general conclusions that Asian-Pacific airlines, for the most part, enjoy substantially lower costs and European airlines substantially higher costs than their North American counterparts. However, this does not eliminate the usefulness of the cost formulas. A specific airline trip cost as a function of stage length and seat counts can be evaluated based on these formulas, with overall rescaling up or down as required. The seats and distance parameters are useful, even though the dollar parameter may need to be adjusted according to the circumstances. The connection between the three variables still holds true.

It should be noted that there are circumstances under which the formula's cost computation may be quite far off in absolute terms, for example when considering the low cost, no-frill carriers. The best-known examples are Southwest Airlines in the United States and Ryanair in Europe. Low cost airlines specialize in turning airplanes from one flight to another very quickly, so the trips per year are 20% higher than the relationships above imply. This changes the importance and level of ownership costs. Second, low cost airlines use specialized short-haul seating configurations, which add 15% to the seat counts. Similar comments apply to the performance of other carriers specializing in the very short-haul market. It is generally acknowledged that airplane costs for international and regional services cannot be compared without adjustments for the different service qualities. Similarly, adjustments need to be made when comparing specialized very-short haul operations with more conventional regional services.

4.3. Aircraft specific costs

For an aircraft to sell, its operating costs must fall on the cost frontier established by the cost formula, otherwise airlines can use an airplane one size larger or smaller for their trips. Clearly, most airlines need a mix of airplane sizes and not simply one seat count. Assignment of airplanes to routes always leaves some error, which may be smoothed over in part by demand on each route being uncertain and variable. Extra seats will always be used some of the time, on peak days for example, while a few seats short merely fail to carry the lowest fare tickets and then only on peak days. The formulation of this trade-off is called "spill" modeling by airlines and has been the subject of extensive discussion (see, for example, Li and Oum, 2000; Swan, 2002). The important result to note is that an aircraft whose costs fall even slightly above the cost frontier becomes economically uncompetitive. Exceptions have existed, but only for the very smallest available size.

Not every aircraft has the same excellence in terms of weight, fuel burn, and maintenance costs. However, designs that are nearly competitive in cost become more exactly competitive through the mechanism of lower purchase price and thus lower ownership cost. As aircraft designs improve, the cost frontier moves lower. Newly manufactured airplanes of technically older designs compensate for their higher relative operating costs through lower prices. At some point the designs become unprofitable to manufacture and are retired from offer.

Used airplanes provide the clearest example of price adjustment enabling airplanes to fall on the cost frontier. Relatively new designs of used airplanes suffer in price only because they have passed beyond the five-year "maintenance holiday" that freshly manufactured airplanes enjoy. Older, less-efficient designs change hands at prices small enough to compensate for their higher cash operating costs through a lower ownership cost trade-off. Used airplane lease rates account for the expected shorter economic life of older airplanes, the risk associated with regulatory obsolescence and the risk associated with the liquidity of the used market for the particular type. The driver of used airplane values is the need to establish a cost position along the cost frontier.

The cost frontier itself is designated by the price of newly manufactured airplanes. New airplanes average 6% of the existing fleet each year. Except in a very strong downturn, new airplanes establish the marginal cost of aircraft. Thus new airplanes set the cost frontier, to which the second-hand market responds.

5. Conclusions

Engineering data can be used to establish cost functions for aircraft operations of differing airplane sizes and operating ranges. Using costs for comparable airplane designs, a cost function can be calibrated that captures the underlying physical and economic scale effects. This function can then be compared to the existing results from econometric approaches derived from airline historical data. Research that reaches conclusions about industry structure may choose to normalize cost data to a standard stage length and airplane size using relative costs from this engineering data before proceeding to statistical calibrations. Such a step could substitute for calibrating the difficult issues of density and range simultaneously with policy questions. Since the data points available are few and time series data is not truly independent, decreases in degrees of freedom may be welcome. In other cases, the results here may be found useful as a comparison to econometric results. Econometric elasticities greatly different from the results here may suggest that other correlations with these size and distance variables may be confounding the allocation of causality to policy variables. Finally, the simple planar function depicted in this paper which separates out stage length and capacity will be much more convenient for network design studies in the future (see, for example, Adler and Hashai, 2005).

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