



USDOT Region V Regional University Transportation Center Final Report

NEXTRANS 086OY04

Air Freight Hubs and Fuel Use

By

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TECHNICAL SUMMARY

NEXTRANS Project No. 086OY04

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Title: Air Freight Hubs and Fuel Use

Introduction

The aim of the project is to examine air express/freight to (a) come up with more accurate representation of the types of active links; (b) convert the links to aircraft movements; (c) make reasonable estimate of fuel/energy use by fleet operations; and (d) allocate the costs of these movements to hubs in a realistic way. Data on over FedEx 180,000 flights provide the basis for these calculations.

The project successfully addressed these aims by computing and allocating fuel costs to almost all the data for one year of operation by FedEx. (The data do not include segments which begin and end outside the US, and the data are for air only.) Ancillary reports and data analysis addressed some of the broader issues of the integration of modes, as discussed below.

Please refer to attached PDF of O'Kelly, JATM 2014.

Findings

1. An important finding is that various patterns in the air freight system are influenced by factors such as network hubs and geographical location. As planned, the study provides details for Memphis (MEM) and Indianapolis (IND) and shows the range of national and international links (MEM) as well as the interesting complementary role played by IND. Other hubs are also allocated their share of fuel costs, (see published paper: JATM, 2014; attached).
2. Because of particular fleet allocations to specific hubs, and because of the spatial organization of the destinations served, it is clear that some hubs provide more efficient output in return for the fuel used. This is a combination of the aircraft and route patterns flown from each hub.
3. The results are reported in the attached publication (JATM, 2014). An approximation of the FedEx system aircraft fuel usage, from data on their aircraft operations, is developed. Using simple additive models of over 180,000 flights, fuel consumption is captured.

4. Aircraft type usage is shown to vary across hubs such as Memphis, Indianapolis, Oakland, Newark, and Anchorage. FedEx aircraft deployment reflects constraints on available aircraft, and is expected to adjust with more efficient aircraft.

Recommendations

The study focuses on three types of hubs: Memphis (MEM) a large air express operation including long range international routes; Indianapolis (IND) primarily domestic air express; and, other gateway locations such as Miami and Anchorage.

The basic idea is that air freighters have a set of range and payload parameters, and these can be used to assign fuel costs to the multiple daily departures from an origin node (fuel is assigned to the origin of the trip). The data revealed a variety of types of activity patterns: (1) domestic short range flows: based at a variety of major and regional hubs; (2) inter-facility flow: especially important as a balance between MEM and IND; and (3) international flow: primarily based on MEM and ANC. The detailed research findings are reported in a peer reviewed paper (JATM, 2014). The results can be used to assess the efficiency of fuel use out a particular hub.

The main recommendation and implication from the study is to refine the fuel burn estimation using actual payload data, real flight paths. Further, there is a need to reconcile the link flows with a better model for true O-D flows (currently unavailable without proprietary data). In turn, the true OD demand might provide a basis for a model to incorporate different levels of transport service (1-day, 2-day, ground...) and different levels of transport technology. Web based data exploration tools are also developed and provide useful visualizations for air freight data.

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Air freight hubs in the FedEx system: Analysis of fuel use[☆]



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A B S T R A C T

Keywords:
Air freight
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This paper provides a data based analysis of FedEx air freighter activities from selected hub locations. The basic idea is that air freighters have a set of range and payload parameters and their corresponding fuel burn depends on weight and distance. Data from 2011 to 12 (FlightAware) are used for 180,000 + flights on origin, destination and aircraft type. The particular aircraft vary widely in payload, but additional parameters may be derived from industry web sites and BTS. The research uses flight activity at hubs such as Memphis and Indianapolis (among others) and computes the aggregate distance flown on specific aircraft. The linkage between the hub and aggregate fuel use (assuming that the out bound flights are allocated to the hub) will give some quantifiable measures of the costs allocated to the hub. The paper examines particular aspects of the air freight system that are especially vulnerable to a spike in the costs of aviation fuel. These observations suggest that traffic to regional air express and air freight hubs is likely to respond in complex ways to fuel costs.

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1. Introduction

Air freight networks of integrators such as FedEx and UPS represent a significant and well-studied component of US and global transport systems. An excellent overview of the challenges of moving freight by air is in [Morrell \(2011\)](#). All-cargo carriers and combination passenger/cargo carriers are also important for freight and mail, but these are not discussed here. The reader is referred to [Morrell \(2011\)](#) for a detailed comparison of these other forms of air freight. In this paper the term air freight is used in a broad sense to refer to the materials carried by the integrators. It combines packages, documents, and larger freight items. A detailed comparison of operational aspects of FedEx and UPS is in [Cosmas and Martini \(2007\)](#). More specifically, [Bowen \(2012\)](#) compares the structure of UPS and FedEx networks, emphasizing the significant role of network organization for these carriers. The macro design of such networks has also been given a lot of attention ([O'Kelly and Miller, 1994](#), [Campbell and O'Kelly, 2012](#)). At a more micro level, such

networks solve a complex geographic distribution problem using feeders, spokes, and high volume inter-hub links ([Kuby and Gray, 1993](#)). Prior work has proposed models of certain aspects of these systems ([Hall, 1989](#)) but there is a need for further detailed examination of hubs in the freight sector, especially with respect to the network's usage of circuitous routes and their intensive use of fuel as an input.¹

There is considerable interest from both applied policy and academic modeling perspectives in the efficient use of aircraft and their impact in terms of GHG and other emissions (see [World Bank, 2012](#); [Brian et al., 2009](#), GHG in airports).² From an operational point of view, air carriers devote a very large fraction of their total costs to jet fuel, and they are vulnerable to uncontrollable variations in these costs. In an effort to minimize costs, freight carriers optimize fleets and plan their flights in the most effective way (see [Armacost et al., 2002, 2004](#)). They may also pursue other options, such as: equipment changes, modification of route structure, substitution of bio-fuels, and hedging (The [World Bank, 2012](#)). This paper considers the role of hubs in air express and air freight

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¹ See also excellent coverage of hub location in [Kara and Taner \(2011\)](#), [Liu et al. \(2013\)](#), [O'Kelly \(1986, 1987\)](#), and a general text book introduction in [Taaffe et al. \(1996\)](#). A recent case study for Turkey is in [Oktal and Ozger \(2013\)](#).

² The [World Bank \(2012\)](#) has issued a comprehensive overview of the status of air transport efficiency from the energy/fuel burn point of view. While primarily related to passenger traffic, special circumstances in freight applications are evident.

transportation, with particular attention to the estimated total fuel cost as well as the share attributable to individual hubs.

2. Key aspects of air freight

While there are similarities between air freight and air passenger traffic, there are some particular issues for air freight with relevance to fuel consumption.

2.1. Integrated decision making

An integrated air freight operation may exercise control over package routing to a much greater extent than is possible in the passenger airlines. Systems with a centrally planned set of location and routing decisions have been described as “delivery systems” by O'Kelly (1998). These contrast with “user attracting” systems typically seen for air passenger transportation. Centralized sorting at a hub is very concentrated and packages are generally not routed directly to their destination. In the case of domestic freight, flows are routed through mid-continent hubs, largely in one major overnight sort, with secondary peak flows related to international departures and arrivals. Since the freight hub airport is not necessarily a major traffic generator, it is reasonable to expect that air freight units are carried on a more circuitous path than a comparable passenger for the same OD pair. These extra ton miles are offset by the efficiency of the large scale central sorting hub.

2.2. Exclusive access

With a night time peak operation, the carrier has exclusive access to multiple runways. This has allowed FedEx, with four runways at Memphis (MEM), to devote considerable attention to optimization of arrival and departure patterns. Adjustment to inter-aircraft spacing has also proven to be extremely beneficial.³ Because the single operator of a major freight hub has exclusive access, the merits and benefits of any technological improvement to the fleet accrue to that carrier. There is generally no need to compete for access, and the benefits of coordinating operations are fully captured. The FedEx fleet, for example, has been widely refitted with upgrades that improve the performance at their main hub airport (see Cosmas and Martini, 2007, p 28). By contrast, a passenger fleet gains less benefit if it operates from a hub where the majority of the other carriers have not also been upgraded, or where its improved performance confers un-priced benefits to other carriers.

2.3. International RTW paths for pilots/crew

Of course all the issues in crew scheduling that arise in passenger systems also arise in freight, and the aircraft movements are scheduled separately from the crews (Belobaba et al., 2009). Crew schedule and positioning is a separate matter from aircraft deployment – the aircraft keep moving and the crew is assigned to them, based on rest and work rules. However, there are also significant added complicating factors arising from the global freight network, such as long range, and round-the-world (RTW) flow patterns.

FedEx pilots bid on flights and schedules based on their seniority. For example, a senior pilot's preference for achieving flight hours in large blocks might have a mission connecting Memphis to Paris, Paris to Delhi, Delhi to Shanghai, and Shanghai back to Memphis. [Notes from interview with FedEx Pilot, 1/24/

2013.] A pilot with seniority can devise a contiguous block of long range flights in this global network, because after rest they may continue on to the east. A tour might also include several segments and even intra-European short haul operations from the Cologne hub. Others, to be clear, may have different patterns based on domestic routes, with the daily/nightly arrival and departure pattern at Memphis. This crew and equipment flexibility can be advantageous in the case of asymmetric flows, as discussed next.

2.4. Exploiting asymmetry/long range and Backhaul

A fourth significant difference between freight and passenger flows is the presence of asymmetries. For passengers, most journeys are round trip and return home. For freight, in view of trade imbalances, and the different locations of sources and sinks, there are asymmetric flows. The addition of long range B-777 has opened the possibility of global links which were previously infeasible, and may allow the system to avoid some extra fueling stops. Also, while a route from A to B for passengers is essentially reversible (possibly routing the same way or through a different hub) air freight actually opens the possibility of round the world (RTW) freighter tours, as mentioned above. These links chain together links to form a global backbone, in a way somewhat different from the local feeder spokes in the domestic system.

3. Research goals

The study focuses on two main types of flows – domestic and international. In turn these are concentrated on two types of hubs: Memphis (MEM) a large air express operation including long range international routes; and Indianapolis (IND) primarily domestic air express and other similar US regional hubs. The basic idea is that air freighters have a set of range and payload parameters and their corresponding fuel burn depends on weight and distance. Some long range international linkages are highly dependent on particular aircraft range and performance characteristics, but shorter domestic links might be more flexible and could involve realignment of some equipment. Initial observations suggest that traffic from regional air freight hubs is likely to respond in complex ways to fuel costs. Of course there are lags in adapting to a change in fuel costs, but in a longer term planning sense, anticipating the costs of these interactions is a useful precursor to modeling alterations in aircraft use and other types of change. While the air carriers undoubtedly deal with such operational planning as part of their own proprietary cost optimization, there are opportunities to analyze sensitivity to energy costs in a generic fashion.

This paper primarily focuses on the consumption of fuel, with a view to fuel cost reduction (lower miles or better aircraft). In particular, following much work on idealized hub models (Campbell and O'Kelly, 2012), this paper presents a data-driven assessment of some aspects of the FedEx air freight system from the perspective of the main components of their use of fuel in aircraft. With these issues in mind, the author obtained one year of US-based FedEx air traffic from FlightAware for research purposes.⁴ These data for 5/1/2011 through 4/30/2012 include more than 180,000 flights with at least one end in the continental US or its outlying territories. For example, while the interaction between Honolulu and Sydney is included, we are unable to observe flights from Paris to onward points such as Guangzhou. With this caveat and a few other data cleaning issues to deal with, the goal was to approximate the total fleet miles as a driver of fuel costs. In other

³ <http://www.commercialappeal.com/news/2013/jan/30/faa-changes-in-memphis-save-jet-fuel-cut-and/>.

⁴ FedEx has been the subject of numerous prior academic and business related case studies (Chan and Ponder, 1979; Mason et al., 1997; Bowen, 2012).

words, using FedEx observed flights, factoring in their operational use of aircraft, the goal is to assemble an account of the main users of fuel by equipment type and location. The account is incomplete because some flight segments are not included in the data. We also omit smaller short range light aircraft (such as Cessna) and entirely ignore the use of fuel in the ground fleet. However, opportunities to validate these data and calculations against macro system measures are also pursued e.g. by comparison with FedEx Quarterly Status Reports, and BTS data such as Table 41 P 5.2 operational financial results (hereafter P-52 data).

The goal of this research is to understand a large part of the FedEx airside operation and detect the main components of costs using spatial analysis. There is adequate evidence that the system is a large consumer of fuel (about 1.1 b gallons of fuel, at an average of \$3.31 per gallon for a total cost of \$3.86 b in fuel in FY 12; Source: Q3 2013 FedEx Stat Book) but the system is also constantly undergoing adjustments. Clearly, even a 1% change in prices or consumption applied to this huge base is a large amount of saving. By looking at micro data it is expected that parts of the system might provide reductions in fuel costs. These forms of sensitivity analysis are developed by aggregating up the micro level data. The goal is to focus on the levels of interaction at nodes, for example, by measuring the arrival and departure rate from the Memphis super hub as well as other hubs.

Given the enormous amounts of money spent on jet fuel, the paper begins with the assumption that operations research in the FedEx system has already evolved to the point that the system is quite efficient (FedEx, 2013a, b, p. 7 refers to multiple energy savings efforts). FedEx has the incentive and expertise to find improvements, and their fleet contains aircraft that are well suited to the task of moving millions of packages per day on a continental and global scale (Morrell, 2011). With an operation of this complexity and size, it is fair to say that the difficulties of making marginal improvements are already well known.

3.1. Challenges

Lacking access to industry and proprietary data sets, this analysis focuses on system level measures. Part of the challenge is to try to make sense of existing data, and to determine reasonable estimates for missing or partial information. Much more detail is possible – such as actual engines and flight paths, payload, and take-off weight, but data limits prevent these steps at this time. From the pieces of the FedEx network that we can see, we would like to understand more about the use of fuel from regional hubs (Oakland, Newark, and Indianapolis for example). What share of the total fuel bill is allocable to the operations based in each hub? There are city pairs that have direct connections, but the hub aspects of the network are fairly evident with a large number of the hub-to-hub interconnections. Not all paths are available, especially since the hub protocol requires sorting and switching of flows to occur only at major consolidation points. Thus if two nodes (A and B) are connected via a third (C), it is not necessarily the case that the flows goes A C B, but rather, the flows may go A to C to HUB to C to B. This circuitous routing through connection points requires extra ton mile of lift and typically does not allow the package to travel by what might appear to be a short, direct, path. Cases with multiple choices are handled by the proprietary routing systems used by FedEx.

3.2. Domestic patterns

Air freight operations concentrate activity at the hub, with numerous departures and arrivals in peak waves. The air freight operator tends to have exclusive access to the airport for night time operations, and as the main user of the runways at that time, is in a

particularly good position to optimize conservation strategies (see FedEx report on fuel efficiency, Report 2013). The data also permit some insight into the decision to deploy particular equipment on some routes. Nevertheless, there are some systemic issues that warrant close examination. It would be useful to gauge system efficiency for example, assessing the potential gains from aircraft better suited to existing and future routes.

The web site FlightAware allows data to be collected on the flights (by airport and aircraft type) and provides lists of flights by time. The main work will be based on 'stylized fact' or estimates from industry web sites and resources: for example average air time and payload can be derived from P-52 data. To give a further idea of the data that is involved, in the recent 24 h period ending at 7 AM (EDT) on 6/30/2011, FedEx dispatched 220 jets from Memphis and 69 from Indianapolis. In addition, four large jets flew from the Indianapolis hub to Memphis, a short one hour flight. One assumes that the IND to MEM trips carried items outbound from MEM to places that are not connected by air to IND (otherwise the material could have passed through the hub at IND). The mix of types of aircraft, and the places that connect to both hubs can easily be determined from the data.

The dominance of the MEM operation for FedEx has been well covered and will not be repeated here. (US connections from selected hubs are shown in Figs. 1–6). Memphis (MEM) is the primary hub and the other the top cities in terms of Indianapolis (IND), Oakland (OAK), Newark (EWR), Anchorage (ANC), Los Angeles (LAX) and Dallas-Fort Worth (AFW). Other cities not singled out here but which are important for particular regional interactions are Greensboro (with connections to a truck hub and also to Puerto Rico), Miami (an important gateway to the Caribbean), Seattle (connections to major west coast cities and Alaska), and Honolulu (onward connections to Guam and Australia). Routes that do not involve Memphis as an origin or a destination focus on IND, OAK, LAX, EWR; the biggest cross country flows are connecting east to west via IND and also some direct connections from EWR to west coast.

Several cities connected to the hub(s) are served by a mix of aircraft. While the exact logic is proprietary to FedEx, it appears on the surface that they are solving a version of a knapsack problem as modeled in O'Kelly (2012). An additional useful fact that may be exploited is that major hubs dispatch multiple aircraft per day/night cycle to the same destination, and in some instances use different aircraft. A small example is that Boston was connected in the FedEx system (24 h between 7 AM EDT on 6/29/2011 and 7 AM on 6/30/2011) by five jets: 2 from IND (DC10s) and 3 from MEM (one each: B722, DC10 and MD11). Clearly there is a complex load and demand balance going on, within the constraints of fleet availability. A limiting factor in the use of the ideal aircraft is the size of the fleet and its composition. As these fleet mix issues are resolved, the opportunity to gain increased benefits from the "best use" of aircraft for payload and range should be highly favorable for a system with hub consolidation. (See Fig. 2 with map of domestic US inter-hub connections).

The data show that the air freight system (at the major hub in Memphis) has not de-peaked the banks of arrivals and departure in the way that has been used by the passenger airlines; the flows are organized into waves of arrivals and departures. This is pattern is consistent with the "latest arrival" problem (Kara and Tansel, 2001) and is repeated each daily cycle using clusters of in-bound and out-bound flights, separated by a (short) sorting period. This in turn hinges on the ability of FedEx to have complete access and control of the nightly air traffic flows at their Memphis hub. There is some day-to-day variation and there is seasonal variability, but this pattern, especially for domestic links is very highly routinized. The implication for fuel use lies in the ability of the intense sort period to orchestrate the arrival and movement of materials, including

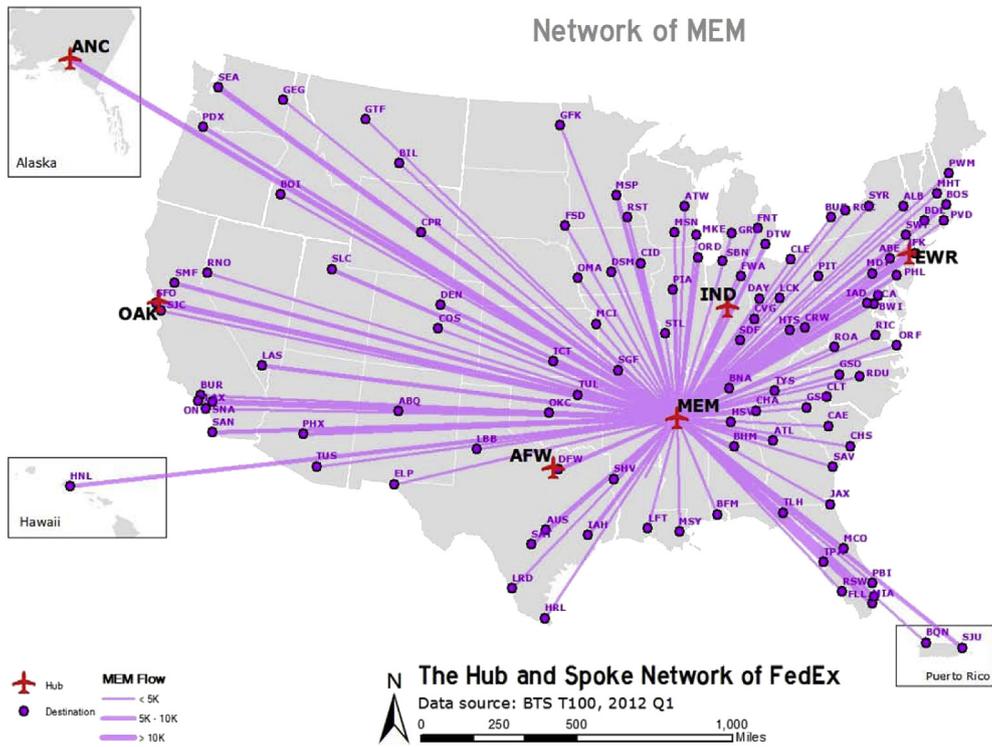


Fig. 1. Memphis hub.

shutting down aircraft engines, and use of fuel efficient hub vehicles to move containers.

4. Long haul routes

Another way to examine the flows is to look at the FedEx US gateway to international (non-US) destinations. The largest flow

from each base point (emphasized as the shaded number in each row in Table 1) shows that although several hubs have interaction with multiple destinations there are some particularly large patterns: including massive flows to Alaska and the Pacific from EWR, MEM, OAK, and SEA. Anchorage has a major interaction with Japan/Taiwan/Korea (J/T/K). And while the overall dominance of Memphis is evident, it is in fact the flows to Canadian cities which represent

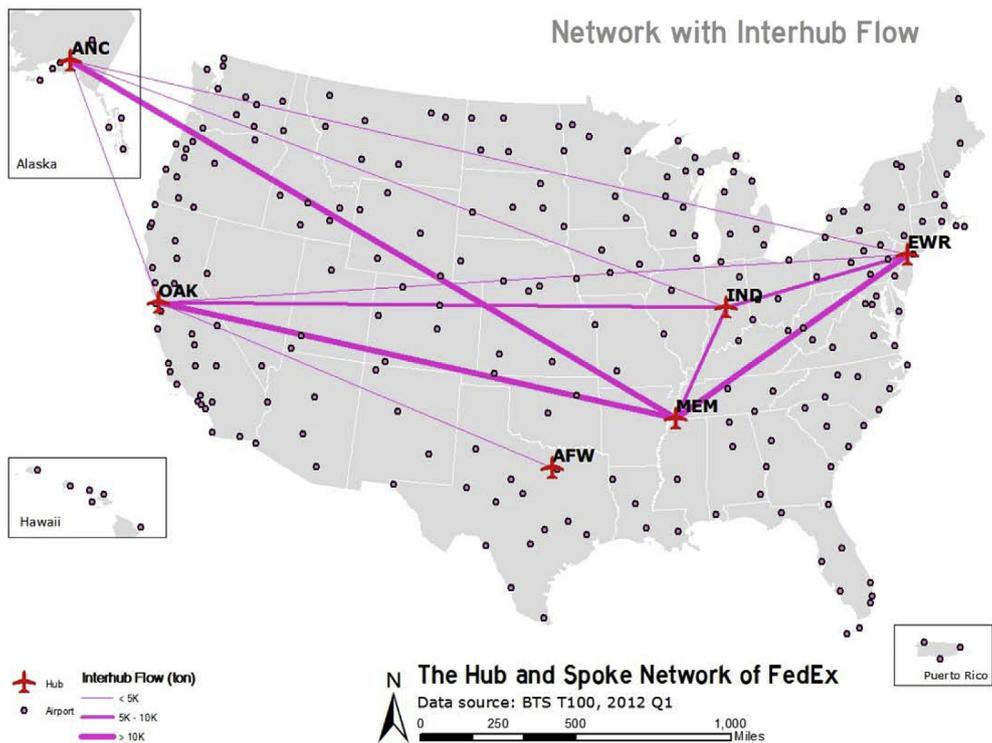


Fig. 2. Interhub flow.

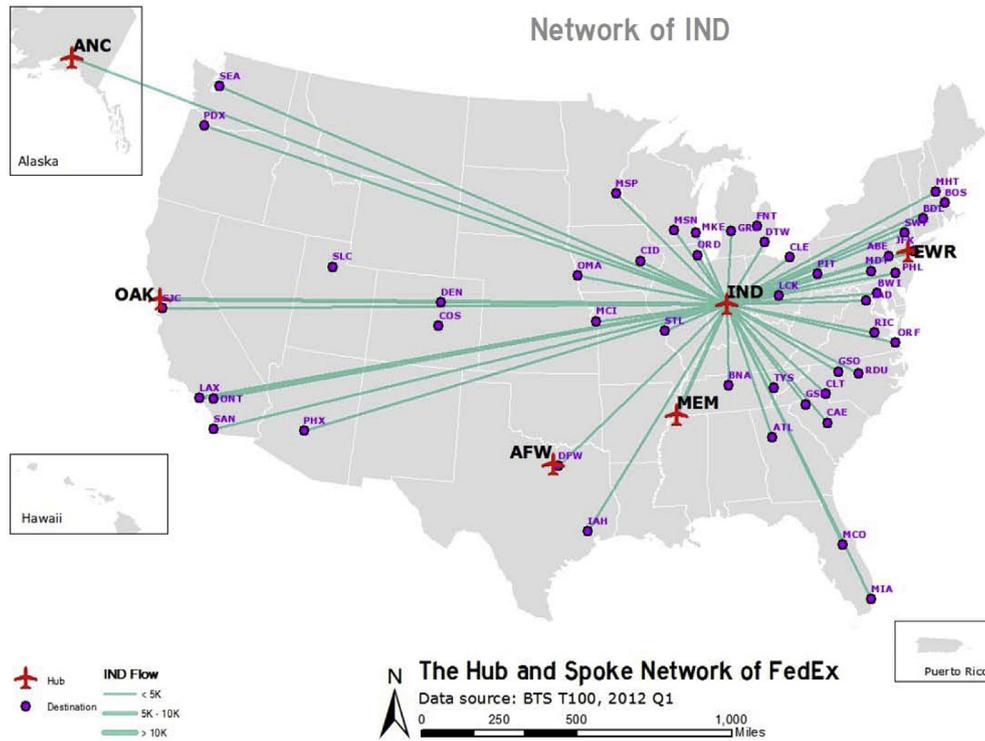


Fig. 3. Indianapolis hub.

the largest volume of international flights. Next, examining the largest number in each column, the chart emphasizes that MEM is the major source for each column with the exception of J/T/K (PANC wins) and a close tie with MIA for South America. Note that the table emphasizes the major place each airport goes to; the origins include all US places and the Pacific; excluding US destinations (as

the bulk of all flight are of course into the US). Several aspects of FedEx routes involve interesting long haul patterns (a topic reviewed recently by Bowen, 2012). In addition to their use of heavy domestic backbone routes, the MD-DC-10 and MD-11 are the workhorses of some international long haul flights – especially MD-11 to Europe, and MD-DC-10 to Anchorage and Hawaii and

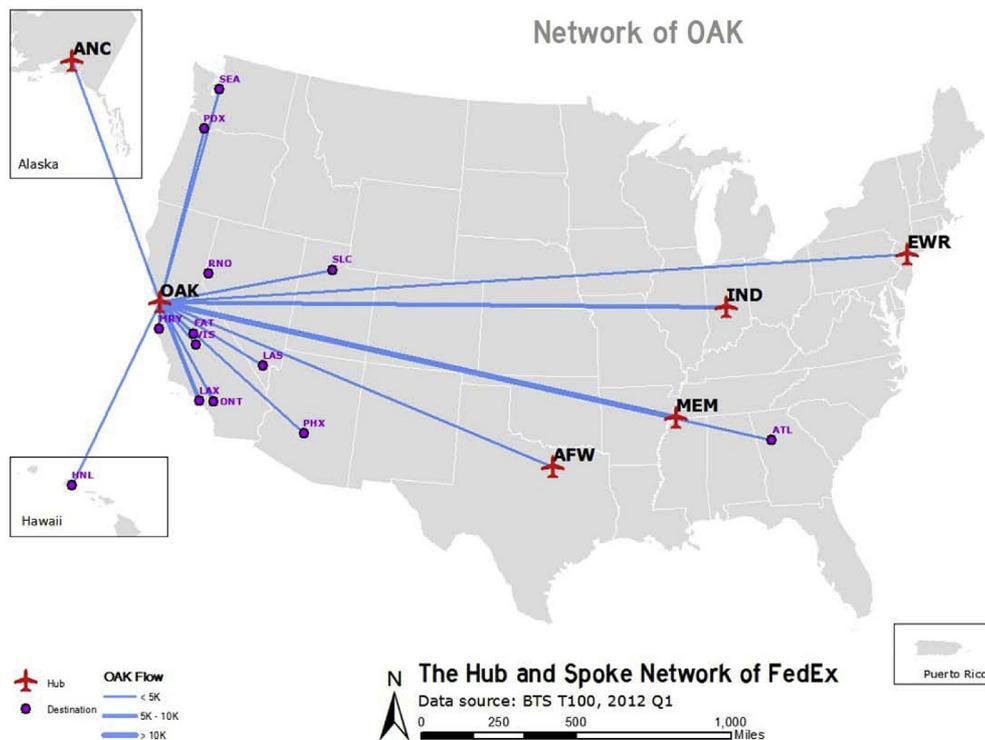


Fig. 4. Oakland hub.

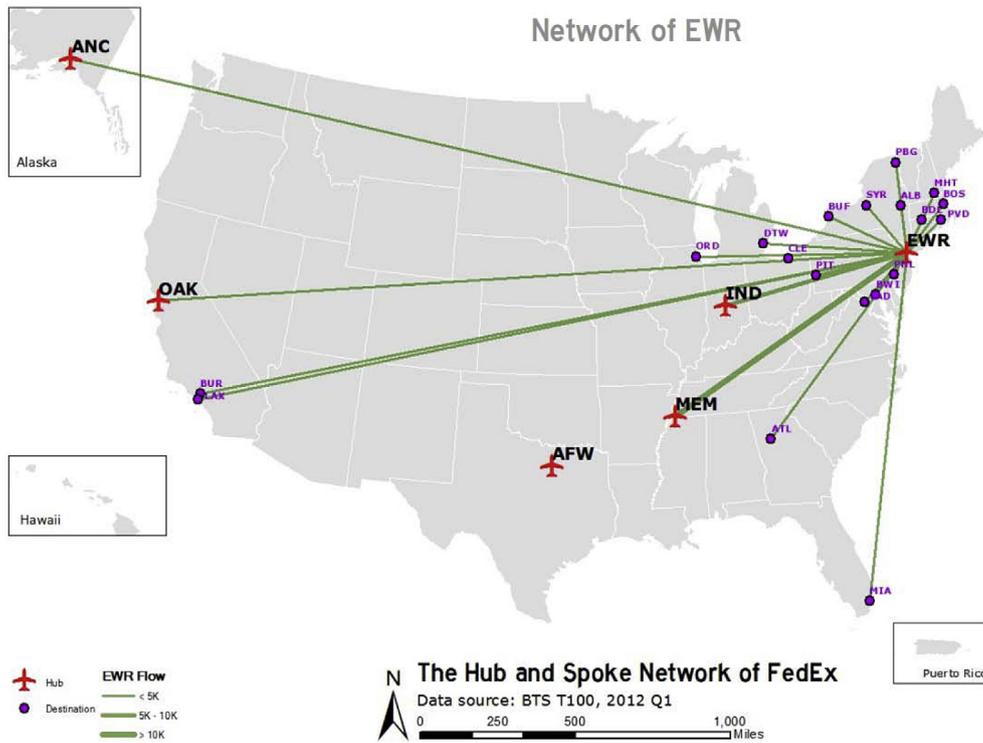


Fig. 5. Newark hub.

beyond. The B-777 has introduced significant range improvements, because it avoids a fuel stop at Anchorage. The B-777 presents the possibility of a lower share of movement through Anchorage. Changes in integrator routing have reduced some activity at Honolulu (Webber, 2013). Past system changes have already

dramatically altered the importance of fuel points such as Subic Bay (Bowen, 2012).

Another key observation is that in this instance, the long range freighter B77L is deployed only from MEM and serves Anchorage Intl (PANC), Incheon Int'l (RKSI/ICN), Kansai Int'l (RJBB/KIX), London

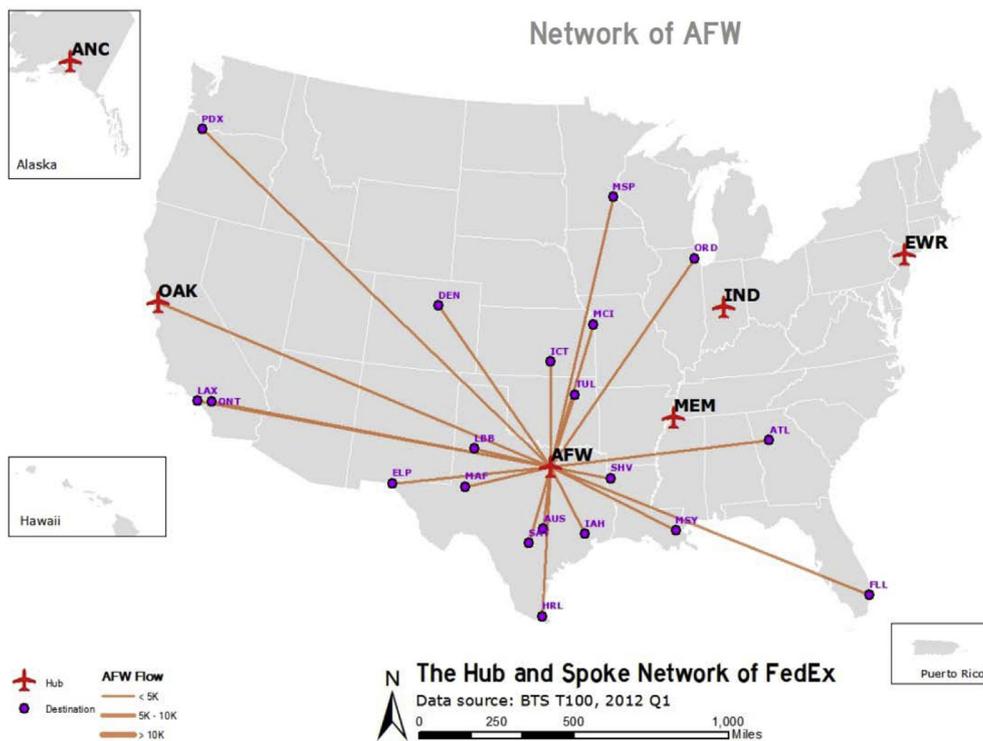


Fig. 6. Dallas Fort Worth hub.

Table 1
FedEx hubs with domestic and international activity.

DESTINATION	Canada	EU 1	EU 2	Mexico	Dubai	As & Pac	J/7/K	Str Am	Pt Rico	HK, De	Sydney	China
KEWR	134	114	236		1	313						798
KGSO									254			254
KIND	408	171	203			259			238			1279
KLAX						262						262
KMEM	2110	602	408	999	208	1494	606	263	844			7534
KMIA				1				260	249			510
KOAK						726	154					880
KSEA	6					272						278
PANC						52	1556			167		170
PHNL						209				8	301	518
	2658	887	847	1000	209	3587	2316	523	1585	175	301	170
												14258

Note: (AFW is not included here among the main domestic hubs); hubs include GSO, MIA, SEA and HNL. Source: Author's calculations from FlightAware Data.

Stansted (EGSS/STN), and Narita Int'l (RJAA/NRT). The other long range high capacity aircraft (MD11) predominantly flies out of MEM but interestingly there are a number of IND connections too. These patterns are reflected in terms of fuel use by aircraft and origin point, as shown below.

5. Notation

Accounting for all arcs ($i = 1, \dots, n, j = 1, \dots, n$) and all aircraft ($k = 1, \dots, m$) the data are (all counts are for one calendar year):

$$X_{ijk} \text{ units of type } k \text{ aircraft on arc } (i, j) \tag{1}$$

$$N_{ik} = \sum_j X_{ijk} \text{ sum of all type } k \text{ aircraft leaving from } i \tag{2}$$

$$M_{ik} = \sum_j X_{ijk} D_{ij} \text{ total vehicle miles on type } k \text{ aircraft from } i \tag{3}$$

$$L_{ik} = \sum_j X_{ijk} D_{ij} C_k \text{ total ton miles on type } k \text{ aircraft from } i \tag{4}$$

$$N_k = \sum_i N_{ik} = \sum_i \sum_j X_{ijk} \text{ sum of all operations by type } k \text{ aircraft} \tag{5}$$

$$M_k = \sum_i M_{ik} = \sum_i \sum_j X_{ijk} D_{ij} \text{ total vehicle miles on type } k \text{ aircraft} \tag{6}$$

$$L_k = \sum_i L_{ik} = \sum_j X_{ijk} D_{ij} C_k \text{ total ton miles on type } k \text{ aircraft} \tag{7}$$

Collecting data from each city base (i.e. from selected hubs) we know the weight, distance, and ton miles generated from that base point. Applying the relevant aircraft fuel burn parameters to that combination, we know how much fuel is used from that origin on that aircraft. Using a fuel burn model from O'Kelly (2012), we have a relationship for each flight range and aircraft type

$$f_k = a_k + b_k D \tag{8}$$

where

- f_k fuel in kg, for aircraft type k
- a_k , Intercept, aircraft k (kg/ft)
- b_k , slope, aircraft k (kg/nm)
- D is in nautical miles (nm)

Note that a and b parameters are approximations for similar aircraft from 2007 (Lee et al., 2007; SAGE). From the overall total, we wish to find out which bases of operation have more efficient patterns for each aircraft. Total fuel used over all pairs (i, j) and aircraft is:

$$\begin{aligned} \Phi &= \sum_i \sum_j \sum_k X_{ijk} (a_k + b_k D_{ij}) \\ &= \sum_k a_k \sum_i \sum_j X_{ijk} + \sum_k b_k \sum_i \sum_j X_{ijk} D_{ij} \end{aligned} \tag{9}$$

The data allow us to see the efficiency of aircraft when used in different ways from different bases – many short trips vs a few longer ones can make for comparable ton miles, with consequences for fuel burn. Slicing the total at the most detailed level by city and aircraft type:

$$\Phi_{ik} = a_k \sum_j X_{ijk} + b_k \sum_j X_{ijk} D_{ij} \tag{10}$$

Aggregating these across aircraft into city specific totals:

$$\Phi_i = \sum_k a_k \sum_j X_{ijk} + \sum_k b_k \sum_j X_{ijk} D_{ij} \tag{11}$$

From (5) and (6) N_k is the sum of all operations of aircraft type k , and the aircraft miles of type k is M_k . Multiplying N_k by a constant for each of those flights and multiplying M_k by the slope for each of those aircraft, we obtain the total fuel used by each type of aircraft

$$\Phi_k = a_k N_k + b_k M_k \tag{12}$$

Finally, total fuel across the entire system is recovered as the same as the initial value above (9):

$$\Phi = \sum_k a_k N_k + \sum_k b_k M_k, \tag{13}$$

Assume we are able to get the generic capacity of each of the type k aircraft and that they all fly almost all missions at some large fraction of their capacity (or we can measure capacity by other means; see below): then the ton-miles load (L) lifted by this operation of aircraft type k are in (7) above,

$$L_k = \sum_i L_{ik} = \sum_i \sum_j X_{ijk} D_{ij} C_k \tag{14}$$

Table 2
Aggregate Fuel Burn Characteristics across All Airports. Source: Author's calculations from FlightAware Data.

Aircraft	Nk	ak	Mk	bk	Nk ak	Mk bk	Sum	fuel share	Avg PT52
units	count	kg	nm 10 ⁶	kg / nm	kg 10 ⁶	kg 10 ⁶	kg 10 ⁶	%	%
A306	43576	1118	31.68	13.20	48.72	418.22	466.94	15.8%	13.4
A310	18772	951	11.43	10.60	17.85	121.19	139.04	4.7%	5.8
B722	20121	564	9.07	9.73	11.35	88.22	99.56	3.4%	3.8
B752	18464	501	11.92	8.12	9.25	96.76	106.01	3.6%	3.7
B77L	5372	1300	22.87	13.00	6.98	297.26	304.24	10.3%	13.6
DC10	48189	1178	42.39	16.78	56.77	711.24	768.01	26.0%	21.7
MD11	29861	1104	57.43	17.89	32.97	1027.42	1060.39	35.9%	38.1

Notes: Miles here are nautical miles. N_k and M_k are from data. The M_k column is converted from statute miles to nautical miles (nm) +4% adjustment. The nm slope is applied directly to these data. The final column is the same share data computed from aggregate data. The PT52 data are from 2011 q2, q3, q4, and 2012 q1 which closely matches the data studied from FlightAware.

Table 3
Variations in fuel index by hub. Source: Author's calculations from FlightAware Data.

FedEx system Aircraft	OVERALL	FUEL INDEX IN EACH PLACE						
	FUEL INDEX	KAFW	KEWR	KIND	KLAX	KMEM	KOAK	PANC
A306	132.32	99.35	130.58	122.59	128.96	131.26	130.45	151.62
A310	158.41	126.82	159.91	154.71	145.17	156.65	152.08	177.03
B722	226.29	175.36	238.58	212.28	205.99	222.69	257.87	n/a
B752	155.32	118.09	158.81	150.67	146.29	153.37	159.25	180.46
B77L	56.79	n/a	59.66	52.88	n/a	56.79	57.95	71.21
DC10	110.03	86.49	111.45	101.15	106.47	110.11	105.69	131.30
MD11	90.66	71.07	92.41	83.64	90.37	91.28	89.46	111.60

Notes: computed by author; see Equations 14–16. Uses the distance measure as the driver for fuel (see discussion in text).

Finally we compare the share of the aircraft in the particular city origin from the point of view of fuel share f_{ik} and load λ_{ik} share:

$$\phi_{ik} = \Phi_{ik} / \sum_k F_{ik} \quad (15)$$

$$\lambda_{ik} = L_{ik} / \sum_k L_{ik} \quad (16)$$

The ratio $100 \phi_{ik} / \lambda_{ik}$ measures the extent to which aircraft k at base i are using less (<100) or more (>100) fuel share than the share of ton mile load carried. This is reported in the tables below.

6. Fuel burn implications

A number of distance unit conversions are needed. Flights are treated as a general path from A to B (straight line distance) but the data show particular aircraft sometimes deviate from the minimum time due to variations in conditions (see Ben-Ayed, 2013). As an adjustment it is assumed that actual flight distance is +4% over the direct inter-point distance.⁵

6.1. Analysis 1 total system and hub based costs

Table 2 summarizes at a very aggregate level the total number of point to point operations by aircraft type, and the associated share of statute miles, derived from straight line distance plus 4% between airports. Detailed route data, which are not available here, could be used to refine this calculation. To calculate fuel from distances, convert to nautical miles. Finally, fuel (weight) is then converted to gallons, and to a cost (applying the \$ cost per gallon). In addition to knowing the total system miles, and fuel use, the model also allows the data to be disaggregated by each originating hub.

The aggregate fuel expenditure in the model accounts for approximate 3 billion kgs of fuel: as shown more precisely in Table 3, 2956.25 m kg of fuel, which at 3.79 kg/gallon is about 780 million gallons. Depending on fuel costs this can approach \$3.1 b. Further, it is evident from this table that the data can be further disaggregated by aircraft or markets, as discussed in the notation section. [The company spent \$3.86 b on jet fuel in 2012 compared to \$3.2 b in 2011; obviously we are approximating this reasonably well given the omitted observations in the global links.] An added column on the right shows the observed share by aircraft from P-52 data for roughly the same period (2011 Q2/3/4 and 2012 Q1).

Consider an arc (from i to j) that is primarily served by one type k of aircraft— so X_{ijk} is a number. Weight carried is $X_{ijk} C_k$ which is the number of flights times the average load. Fuel needed is $X_{ijk} (a_k + b_k 1.04 d_{ij})$ where d_{ij} is in nautical miles. On a per flight basis fuel (kg) per ton is calculated as

$$= (a_k + b_k 1.04 d_{ij}) / C_k \quad (17)$$

$$= [a_k / C_k] + [b_k 1.04 / C_k] d_{ij} \quad (18)$$

The intercept and slopes for patterns and packages that are primarily flown by one aircraft type are linear – with the slopes = $b_k 1.04 / C_k$. Larger slopes are more expensive per ton at all distances. The results are linear in distance but observe a series of different rates that fan out from the origin: the steepest ones are associated with the least fuel efficient aircraft (see Fig. 7).

There are several important observations from these results. Many OD pairs are served by one primary type of equipment so the above analysis makes sense, and the resulting fuel burn on that pattern of demand is related to the underlying operational characteristics of that one aircraft. What is perhaps less obvious is that not all OD pairs with the same distance are served by the same dominant jet. This makes sense however when one realizes that there are limited numbers of each piece of equipment and so the OD pair must be serviced by the available equipment best suited to the load that is carried. So some OD pairs in the 2000 mile range might use an MD11 and others could use an MD10. As the range increases the available and suitable aircraft become more limited. The cone formed by the rays (extreme ray for B-722 and B-77L) in Fig. 7 represents the potential aircraft capabilities. Now suppose that at some distance D there are two possible aircraft suited to this range. A vertical line segment between the two rays represents the set of combinations of the two aircraft that can serve the mission. Surprisingly, a large number of cases with these choices, end up with 100% utilization of the comparatively less fuel efficient vehicle. Presumably this reflects the outcome of (a) trade-offs in available equipment, and (b) a form of comparative advantage, whereby a proficient aircraft is best for a wide variety of situations, but must be used in the situation where it has the highest comparative advantage. Some OD pairs (i to j) that are served by a mix of aircraft that is either blended (to perhaps include some less ideal choices) or using an atypical choice for that distance band. Taking vertical strips through this diagram, we see some market distance ranges that have costs per ton that are higher than the comparable elements in other equipment configurations.

6.2. Analysis 2 aircraft mix by hub

Note that different aircraft are used in slightly different ways from each hub, although there is not a lot of variability, we can

⁵ A full re-analysis of this issue with times and fuel burn per minute, with aircraft load factor would require more detailed data than are available, or alternatively some additional assumptions about aircraft speed (Kim et al., 2007).

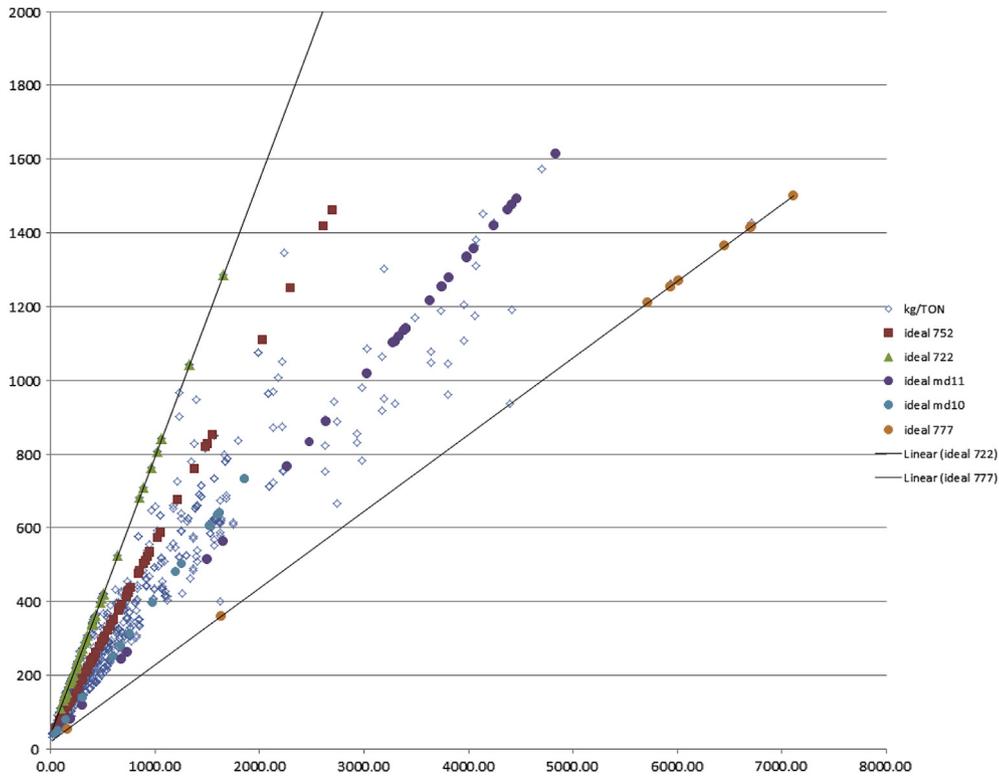


Fig. 7. Fuel burn [kg per ton] (Y-axis) on missions of distance [nautical miles] (X-axis) with the solid overlaid dots representing trend if 100% of that link is flown by a particular aircraft type [from L to R 722, 752, MD10, MD11, B-77L]. Actual results lie along these trends and also in the blended combinations shown by open dot symbol. The ray to the left represents the B722 (now retired) as the least efficient aircraft and the ray to the right the B-77 as an example of a very efficient aircraft, whose capacity, range and limited availability makes it best suited for long range missions. (Shown to the right of MD11.) Source: Author's calculations from FlightAware Data.

judge the airport basis from which a particular aircraft seems to be more efficient (in terms of fuel use). Distributions of connected arcs (or flights) for each hub are plotted in Figs. 1–6. The shorter range aircraft are more efficient when flown from areas with primarily short service aircraft (KAFW for example is very effective in its use of A-306 and A-310). Long range aircraft are most efficient in terms of fuel use when deployed from MEM and IND. Not surprisingly then, aircraft do best in the situations that are suited to their configuration, and when they are sometimes used on non-ideal missions, they are not as effective. (See the Fuel Index = Fuel Share/Load Share.) This finding reiterates the claim in the introduction that the system is already very well adjusted to the costs. This index is less than 100 when an aircraft type from a particular base point has a set of flights that consume a lower share of the base fuel than the share of the base ton-miles delivered. Since KAFW is primarily a short haul domestic hub, with no B-777 flights, it makes sense that the aircraft used are well suited to the relatively small number of specialized missions based there. In contrast, the range and number of flights from MEM on this same aircraft is over a lot short range flights and the sum of ton miles lifted is small share compared to the large loads carried on longer range.

This conclusion would be modified considerably if the intercept or slope for the longer range flights needed to be increased. It also points to the need to assess efficiency in the context of the overall mix of flight lengths. Nevertheless, it seems to support the idea that there are relatively efficient fuel results obtained by the longer range flights, perhaps because these are the components of the fleet that are being quickly upgraded and the MD-11 (a workhorse of the longer range) appears in the model to have a good fuel consumption rate.

6.3. Analysis 3 aircraft efficiency and potential for improvement

The overall share of total system fuel used by each aircraft is a result from the model and this can be compared to actual data. Overall the fit is quite good, and by assessing the aggregate P-52 results, we are able to see that the share of fuel in each aircraft matches intuition and is generally moving in the direction that is suggested by efficiency arguments (Table 2). This use of shares avoids some of the scaling problems inherent in the domestic vs global costs. Suppose as a simple case that two similar aircraft in terms of capacity are being used and that the opportunity to shift aircraft occurs. The idea is to measure the exposure to (positive) change, due to the anticipated improved efficiency of the newer aircraft. This abstracts from the fact that the slightly larger capacity aircraft may also alter the routes. Equipment choice and adjustments to fleet capacity are a clear possibility as a means to reduce fuel costs.

This can be modeled by simply substituting the parameters for the replacement aircraft. Shifting aircraft from B-722 to B-752 we see that the aggregate fuel use by swapping the aircraft parameters would drop to 83.70 from 99.56 (i.e. a savings of 15.86 kg 10⁶) assuming that the same number of missions and miles is flown. In fact the lift capacity on these links could also increase and thereby provide other advantages in addition to fuel savings.

$$N_k a_k + M_k b_k = [(20121 * 564) / 1000000] + (9.07 * 9.73) = 99.56 \tag{19}$$

$$N_k a'_k + M_k b'_k = [(20121 * 501) / 1000000] + (9.07 * 8.12) = 83.70 \tag{20}$$

Here type $k = B-722$ and the a_k, b_k refer to that aircraft, and the a'_k and b'_k are the revised parameters assuming these same missions can be flown with a more efficient aircraft. The cost difference is \$17 m. Although this is a relatively small impact, it reflects the already reduced usage of B-722 in this operation and the relatively small share of fleet ton miles. More recent reports show that FedEx has retired a large portion of their B 727-200 with the remaining aircraft retired as of July 2013, and is accelerating its retirement schedule.⁶

This is not surprising in that the B-752 dominates the performance over payload and range at a better fuel efficiency. A related sensitivity analysis anticipates the larger savings from replacement of MD-10 by B-767, assuming we can make broad estimates of the parameters. Longer term, MD-10 is scheduled to be phased out, and the B-767F is expected to be a new workhorse for the longer range flights. The 2013 report contains an overview from the company:

“Replacing older, less efficient aircraft is lowering operating costs globally. In FY13, we decided to permanently retire or accelerate retirement of nearly 90 aircraft as we continue to modernize our aircraft fleet. In June, FedEx Express completed the final retirement of the B727 fleet. The B757 is significantly more fuel efficient per pound of payload and has 20-percent additional payload capacity than the B727 it replaces. Our new Boeing 767s will provide similar capacity as the MD10s we are retiring, with improved reliability, and about a 30-percent increase in fuel efficiency.” (FedEx Annual Report 2013, page 2; see also Berman, 2012).

Fed Ex has 46 B-767s on order according to Q3 2013 statistical fact book, but none are in service at this time (2013). As these new aircraft come on line a matching reduction in the use of MD-10 is expected. It is of some interest to see exactly how much of the current system costs might be saved if these newer technologies could be instantaneously swapped in for the replacement aircraft.

7. Data alternatives: discussion

There are two main sources of data, each with advantages: (1) FlightAware has detailed micro data, and (2) BTS T-100 data has counts of flights on segments. Each can be used to reach roughly the same calculation, and analysis shows that they produce similar counts of aircraft operations. In essence these are counts of the aircraft used on particular segments. It would seem to make sense to express all these operations in terms of air hours.

FlightAware allows the elapsed time to be computed from departure and arrival times; but there are significant missing (unknown) data for arrival times and also some examples of non-revenue and repositioning flights with spurious (very short) times, so it is advantageous to use the distance generic variable. The disadvantage there is that the straight line distance between origin and destination needs to be modified by a measure of cruise track. With the distance data with the generalized fuel burn parameters (SAGE) per unit of distance provides the initial estimates in the main portion of the paper.

T-100 has similar flow data and some indication of the air time. Capacity utilization varies significantly by aircraft and mission type. This is a good reason to use the T-100 data as the observational basis for missions completed, rather than assuming that the entire fleet is flying at some (fixed) percentage of capacity. Whatever weight and fuel was used and time take on these flights is reported at a monthly summary level. It is reasonable to use the observed average payload and range data from T-100. Also, since payloads are reflected in the total ton-miles flown, the actual average fuel

consumption is related to the actual average payload and range. These data are available monthly and have been reconstruction to match the FDX Fiscal Year (ends May 31).

Knowing departures and air time allows the T-100 data to approximate fuel usage. P-52 provides the “fuel operation expense.” P-52 is very well-suited to our needs because the actual freighter aircraft used by FDX are reported there. Provided the same basic number of departures (the denominator) can be established, the rate of fuel use in gallons per hour is likely to be very useful in establishing a separate estimate of fuel use. Both T-100 and P-52 have a regional break out sub-total, and common information on air hours. The difference in air hours for each quarter between T-100 and P-52 varies from 1% to 5% (a few as high as 10%) but P-52 always has a larger number than T-100. There are significant differences for the total air hour between T-100 and P-52, in the Atlantic and Pacific regions. The domestic portion is consistently reported in both T-100 and P-52.

A disadvantage of the data is that P-52 gives us only aggregate data by quarter. Of course we can calculate the corresponding departures, total miles, total freight in the same period. For the aggregated data, there is a very strong linear relationship between fuel burn and total air hours, and also between total air hour and total traveled distance. As an illustration of this, consider the use of T-100 for the same 12 month period as the FlightAware data. The values of X_{ijk} , X_{ik} , and X_k are available and are computed from records of the operation of FDX. Making similar assumptions about distance and unit conversion, and applying the linear fuel burn model to the observed quantities, returns a comparable estimate of total fuel burn. This is not in itself an independent validation of the model, simply a demonstration that the two data sets can be used to access similar total counts.

To calculate an independent estimate of fuel from the time factor, consider the total fuel issued to specific aircraft in regions, (from P-52). One important difference here is that the intercept and slope of the specific hourly fuel burn equation can be computed from the data. Suppose an individual flight has $f = a + b h$. The total of all flights in a bundle has $F = a N + b H$. It turns out that departures and hours are correlated and this multi-collinearity results in an implausible negative coefficient for “a.” Therefore the model was estimated as $F = a + b H$ (where a is constrained to be non-negative). Overall the fuel burn per hour is computed and is used to generate total fuel from the air hours (see Table 2). The results are not perfectly comparable but as a “proof of concept” they establish that an analyst could generate the same results from aggregate statistics.

8. Summary and conclusions

Data from FlightAware were used to tabulate the detailed operations and to examine the day-to-day variations of the carrier (FDX). For example, the raw data are essential for examining issues such as peak loads and latest arrivals. It is possible to use the FlightAware data to compute the actual flight time – except for 9547 records with missing data, the departure and arrival times are given, and with careful date and time processing, the elapsed minutes can be computed. Individual day-to-day variability in the elapsed flight time for a specific OD pair and piece of equipment confirms that the FDX operation works within very tight tolerances. The variability in time (on a specific mission) from day to day is quite small for a fixed piece of equipment.

It is useful to have access to the underlying detailed daily descriptions because this helps us to know that a city pair has a particular mix of aircraft and that this is the resultant of a day-to-day packaging of flows into a set of suitable aircraft. For example a monthly summary from O to D might suggest 20 F1, and 40 F2 aircraft. Daily data would allow a confirmation of this as a week day daily package of 1 F1 and 2 F2 flights; to be clear other packages

⁶ Berman (2013). http://www.logisticsmgmt.com/article/fedex_announces_plan_to_retire_selected_aircraft_and_related_assets.

with the same aggregate outcome cannot be ruled out with aggregate data alone.

T-100 segment data may be used to obtain very similar results; there are four main advantages of this added step. (1) It is possible using T-100 segment data to establish the same data from a widely available source. (2) This computation may be used to check the results from the disaggregate work. (3) Furthermore, this technique has the added advantage that the few instances where rather broad assumptions (load factor, path deviation etc.) in the original data analysis were made can be either refined using more complete empirical data, or can be experimentally adjusted in order to gauge the sensitivity of the results to these assumptions. (4) Finally, although this is not pursued here, the method is reproducible for other time frames and other carriers.

As an alternative approach, the fuel calculation was re-done with the departures and the flight time, using fuel burn rate per hour (from P-52 quarterly data). The fuel prediction from the distance based model in this paper is strongly linearly related to the fuel prediction from a time accounting approach. This of course is because the fuel consumption per minute or per mile relate to the same physical problem of lift. The P-52 report gives a larger number: the discrepancy is due to the more complete account in P-52, the fact that the aircraft fly more than the minimal amount of fuel, and that the actual paths may deviate from the straight line or great circle distance by larger factors than assumed here, and of course the fact that T-100 only reports trips with one end in US.

Equipment implications: continued reliance on equipment that is superseded by more efficient ones is suboptimal, but understandable in view of the fixed investment and difficulty in making instantaneous adjustments. Solutions may include equipment swap, opportunities to bundle two or three smaller flights into one; opportunities to optimize refueling stops or stage length, and so on. Against this cost scenario too, the carrier has to recognize that the demand for air freight is cost sensitive, and if fuel price surcharges make the service prohibitive, alternative modal arrangements are likely to become desirable (FedEx Annual Report 2013). The option to switch from air to truck or to combine stages with trucking to an air-hub is clearly also very attractive (O'Kelly and Lao, 1991), and related research is continuing to explore that option. This issue is not covered in the present paper but could be the topic of further research.

Another interesting “next step” is the kind of focused detailed data presented in Heinitz and Meincke (2013). Their paper recognizes some aspects of a complex real system that are often simplified away in models, and encompass an unusually comprehensive set of all cargo carriers, belly freight, and intermodal connectivity. The wealth of operational detail, unfortunately limits the spatial scope: they represent the interacting entities at a more aggregate 90 zone level for the world (i.e. trade off more realism for lower level of spatial detail). In the other direction, even further disaggregation beyond what is used here is possible. The data could, potentially, provide the detailed flight trajectories of all the system data – allowing for example the detailed individual flight paths. This could be extremely beneficial for an analysis involving controlled descent or for the operational reconstruction of the flight paths (Cosmas and Martini, 2007). The concern is that with these detailed data, we might not be able to “see the woods for the trees” and there are many interesting questions at the slightly more macro level. That topic requires access to more detailed information, and in the future the scope of this work might be expanded to cover these concerns.

The ideal would be a constrained model with a fixed fleet of available aircraft that could in turn be gauged as to the financial merit of replacement. This tactic would make sense because in the absence of a constraint the ideal combination of aircraft will simply be to select the ones with the highest efficiency. As shown in this

paper, the reality in the results is that there is much more complex balance of desired and available aircraft.

9. Data source

P-52: Air Carrier Financial Reports (Form 41 Financial Data); Schedule P-5.2. The table contains detailed quarterly aircraft operating expenses for large certificated U.S. air carriers. It includes information such as flying expenses (including payroll expenses and fuel costs), direct expenses for maintenance of flight equipment, equipment depreciation costs, and total operating expenses.

Source: www.transtats.bts.gov.

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