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Fuel burn and environmental implications of airline hub networks

Morton E. O'Kelly

Department of Geography, 1036 Derby Hall, 154 N. Oval Mall, Columbus, OH 43210, United States

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ABSTRACT

Hubs act as switching points for interactions and so are places through which flows are concentrated. This research uses the interactions between a system of cities as an experimental context for understanding selected environmental costs and benefits of concentrated flow. Whether hub based networks create additional environmental costs has been debated in the literature. In this paper, fuel burn is used as an indicator of environmental cost. The essential ideas are: (1) to examine fuel costs associated with larger aircraft; (2) to determine implications of higher loads on dense routes; and (3) to model the resulting implications for hub and gateway location. Variants of these questions apply to passenger and freight flows, and the paper will initially concentrate on passenger models.

The paper shows that by modeling fuel burn and introducing a fixed charge (like a set up cost), a multiple allocation hub and spoke model can be adjusted to direct more or less flow onto the inter-facility connector. In other words, usage of multiple connections and direct links can be controlled and modeled as a function of the fixed charge. The resulting networks are characterized by quite different levels of passenger miles, aggregate fuel burn and fixed charges. The preferred network in terms of minimal fuel burn is found by subtracting the fixed set up charge, thereby focusing attention on the modeled fuel burn. The lowest cost set up is a network with a high degree of connectivity, and a pure single assignment hub network has the highest fuel cost (as a result of larger passenger miles needed by connecting paths). The data also allow a tabulation of total passenger miles, which, not surprisingly, track very closely with the fuel burn. In an interesting application of the ideas, it is shown that a fuel efficient network may require a large number of smaller regional jets, and in the interests of avoiding noise and congestion from so many extra airport operations, the carriers may choose to substitute a smaller number of larger planes, thereby slightly increasing fuel needs. This paper also provides a key ingredient for models of an international network where it is impossible to serve many long distance market pairs without consolidation.

1. Introduction/overview

This paper is primarily concerned with air passenger networks connecting regions through a hub and spoke system. Within the capacity and range limits of aircraft, the marginal cost of an extra unit of flow is small in such situations. However, there are major capacity and equipment range issues: longer distance flows require larger aircraft, and larger flows may require multiple aircraft. Long range aircraft require more fuel at take off, and the weight of the fuel carried is a significant factor in fuel consumption. There are potentially lower unit operating costs when flows are handled by certain types of infra-

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structure (wide body aircraft). Thus, providers of transport services may reduce their average unit costs by bundling flows and channeling them on spokes leading to hubs (Jeng, 1987). The resulting facility locations and allocation decision are highly interdependent because of the flows between hubs (O'Kelly and Bryan, 2002). Among the types of questions that might be addressed using this approach is the consideration of feasible and possibly optimal ways to connect two fairly distant nodes, with only a moderate expected flow. The idea is that such a flow is unlikely to be economically served by a direct connection. The question is whether they should be provided with a non-stop trip or if it would be better to route them through an intermediate hub facility? This is particularly amenable to analysis in very simple network cases: if a flight from I to J is broken into two legs simply for the purposes of refueling, the total costs of the direct and one-stop flights can be compared. Since fuel burn includes a substantial fixed cost for take-off and landing, and it requires fuel to fly fuel it would seem to be a simple problem to optimize the stage length of the aircraft. An important additional factor is, however, that a stop at a hub provides the opportunity to redistribute passengers, and will probably increase load factors on the legs of the trip. The topic has more than just theoretical implications, as it might be expected that the desire to avoid long distance flights into the European Union (with a pending carbon tax) would provoke airlines to consider a variety of hub arrangements with a view to avoiding particular routes.

This research begins to examine the efficiency of hubs from an environmental point of view. The idea in this paper is to attempt to determine whether economies of scale from bundled flows derive from equipment and fuel use, and if necessary to isolate other factors that contribute to the amalgamation of flow. An additional complication is the existence of thresholds (flows must exceed a minimum) and capacity constraints (aircraft and airports have finite limits, and fleet composition is fixed in the short run). It is quite obvious that allowing origins to connect to multiple hubs can potentially dilute the consolidation effect. Whether a few "thick" flows and the implied indirect routing (circuity) beats a more completely connected network is the topic of this work. Among the possible added effects are the improved load management that comes from amalgamated flow, and the efficient operation of a maintenance base at the hub. In this context, there is a pressing need for network optimization models to use more realistic, environmentally relevant, parameters.

2. Selected literature review

In an important recent literature review, OECD (2010) has reported on the environmental consequences of many aspects of transportation. The chapters related to air transport are particularly useful. Chapter (4) by Button and Pels (2010) outlines the issue concisely:

> "The formation of hub-and-spoke networks concentrates large passenger flows on a limited number of links, allowing the use of relatively large aircraft. Hub-and-spoke networks thus offer potential reductions in environmental damage per seat because of the possibility to use larger aircraft. On the other hand, hub-and-spoke networks are centered on large airports, which are often congested, while passengers travelling indirectly cause a relatively large amount of pollution because of the detour, and more importantly, the double take-off and landing."

Notice the cautious language ("potential reductions") and the reference to passenger detours. Pels (2010, p. 191, section 7.3 of OECD Report) describes the possibility of "economies-of-scale" in environmental terms, due to passenger concentration. Pels (2010, p. 191) also correctly notes that a passenger connecting to fly on a higher capacity inter-hub link will reach the hub airport via a "short-haul flight, with relatively high environmental cost" (this seems to place short haul flights in the less desirable category). Similarly, Schipper (2004) noted the existence of environmental economies of scale.

This finding is not without criticism though, as Peeters et al. (2001) found that point-to-point networks have a lower environmental impact than hub-and-spoke networks even though larger aircraft may be in use in concentrated flows. Peeters et al. explain their finding on the basis of the technological status at the time of their study, when efficiency improvements had occurred primarily in short haul aircraft. (Arguably these innovations may be extended to long haul over time.) Their study is perhaps not the final word for another reason – the relatively restricted set of interactions examined. In fact a common complaint about much research in this area is that the evaluation is based on an extracted set of flows or OD pairs. For example, Morrell and Lu (2007) in a generally excellent study, used a relatively small idealized network, and concluded that direct (i.e. hub bypass) gave savings in noise and emissions costs. Thus, they confirmed the results of Peeters et al. (2001) that hub and spoke networks have a relatively high environmental impact (Button, 2002).

What this analysis misses, however, is the possibility that many smaller flows can be replaced by a few larger ones, an issue examined carefully by Givoni and Rietveld (2009). They contrasted two short haul markets – one in Europe served by a large number of small aircraft operations, and one slightly longer connection in Japan served by specially equipped jumbo jets (B747). They were interested in the ways that the larger capacity aircraft seemed to minimize some of the congestion effects caused by very frequent departures in the European case. The flavor of this analysis is very similar to the theme of this present paper, but a key shortcoming in their paper is that the city pairs are essentially short haul high volume intercity pairs. The quantification of the impacts of the larger flows on the limited number of inter-hub routes is in need of a more thorough technical and model-based analysis. Expectations about environmental economies of scale more generally are quite speculative.

Several papers (Morrell and Lu, 2007; Nero and Black, 1998) have attempted to compare the costs of point to point versus hub and spoke connections, including a very wide range of effects such as noise and land values around airports (which are