AIRLINE NETWORK DESIGN

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(Received April 1995; revision received September 1996; accepted July 1997)

The goal of this paper is to understand choices of networks and schedules by a profit maximizing airline. By "network" we mean the routing pattern for planes and by "schedule" we mean the frequency of service between cities *and* the amount of time put into the schedule to assure on-time arrival. This paper analyzes network and schedule choice using an "idealized" model that permits derivation of analytic, closed form expressions for airline and passenger costs. Many important conclusions are obtained. It is optimal for a profit maximizing airline to design its network and schedule to minimize the sum of airline and passenger costs. Profit maximizing choice of schedule frequency depends on the network. Direct service has lower schedule frequency than other networks.

Parametric studies are performed on the effect of distance between cities, demand rate, and the number of cities served on the choice of the network. Some conclusions are: (1) If the distance between cities is very small, then direct service is optimal; otherwise, other networks, such as hub and spoke are optimal. (2) Similarly, for very high demand rates, direct service is optimal; and for intermediate values, hub and spoke is optimal. (3) If the number of cities is small, direct service dominates; and if it is large, hub and spoke is optimal.

We note that any airline's schedule includes safety time as a buffer against delays, and we demonstrate that schedule reliability is highest for direct routing. Surprisingly, the amount of time that is added to the schedule to buffer delays is relatively less in direct networks than in other networks. This can explain the superior on-time performance and high equipment utilization of direct carriers such as Southwest Airlines.

There have been dramatic changes in the routing structure of airlines in the past fifteen years. Since deregulation in the United States and elsewhere, hub and spoke systems have emerged as the dominant network design. Recently however, the business press has noted the financial success of carriers offering direct service. One of these carriers, Southwest Airlines, has been judged America's most profitable airline and the industry's leader in on-time performance in 1992 (*N.Y. Times*, July 15, 1993, D1). Also, many airlines offering direct service have recently begun operation. Although the economic advantages of hub and spoke networks have been studied in the transportation and economics literatures, there has been limited examination of other types of airline networks. With the emergence of nonhub networks, study of alternate networks is required. In particular, questions such as "when do we expect direct service to be more profitable than hub and spoke?" and "do we expect direct service schedules to be more reliable than those of other networks?" need to be addressed.

In this paper we answer these questions by studying the design of an airline's network and its schedule. We interpret the "network" as the routing pattern for planes and the schedule as the frequency of service between cities *and* the amount of time put into the schedule to assure on-time arrival. Our goal is to examine how network choice and scheduling decisions affect airline cost and passenger service quality. Airline cost is the carrier's cost of operating its network, and passenger service quality is measured by the cost borne by passengers due to travel time, *schedule delay* (the time difference between the ideal departure time and the actual departure time), and incidents of late arrival. These costs are important because a necessary condition for an airline's profit maximizing choice of network and schedule is that the sum of these costs are minimized.

Four different types of networks are studied, which we call *direct*, *hub and spoke*, *tour*, and *subtour* routings. Direct routing is a network where all cities are directly connected. Hub and spoke routing is a network where all passengers travel by airplane to a hub and then catch a flight to their final destinations. A tour routing is a network where each plane travels from city to city until all have been visited. A subtour routing is a network where passengers take a plane from their origin city, and travel on this plane to the hub, generally making some stops at other cities before reaching the hub. At the hub, they catch another plane that takes them to their destinations, perhaps making some stops along the way. We show that each routing can maximize airline profit under some conditions.

This paper analyzes network and schedule choice using an "idealized" model. The idealized model permits derivation of analytic, closed form expressions for airline and passenger costs. With the model, important characteristics of the real system can be captured, while the model remains simple enough to derive formulae for the costs. Using our understanding of the relationship between

Subject classifications: Networks: design of airline networks. Transportation: economics. Economics: consumer choice, production cost.
Area of review: SERVICES.

0030-364X/98/4606-0785 $05.00

network/schedule choices and airline profit, we study how such factors as distance between cities, number of cities served, and demand rates affect the choice of profit maximizing network and schedule.

Many important conclusions are obtained. It is optimal for a profit maximizing airline to design its network and schedule to minimize the sum of airline and passenger costs. This is because changes in the network or schedule that decrease passenger costs can be captured by the airline though price increases. We show that profit maximizing choice of schedule frequency depends on the network, and that direct service has lower schedule frequency than other networks. It is also shown that if passengers are very sensitive to schedule frequency because schedule delay costs are high, then a tour is the profit maximizing network choice.

Parametric studies are performed on the effect of distance between cities, demand rate, and the number of cities served on the choice of the profit maximizing network. Some conclusions are: (1) If the distance between cities is very small, then direct service is optimal; if it is very large, then a tour is optimal; and for intermediate distances, other networks, such as hub and spoke are optimal. (2) Similarly, for very high demand rates, direct service is optimal; for very low, a tour is optimal; and for intermediate values, hub and spoke is optimal. (3) If the number of cities is small, direct service dominates; if it is large, hub and spoke is optimal; and for intermediate values, other networks are best.

We note that any airline's schedule includes safety time as a buffer against delays. This planned delay time increases passengers' travel time and airline cost since more craft are required, but reduces passengers' chances of arrival after the scheduled time. It is shown that if schedule reliability is chosen to minimize total airline and passenger costs, schedule reliability is highest for direct routing. Surprisingly, the amount of time that is added to the schedule to buffer delays is relatively less in direct networks than other networks. That is, relatively less time is included in direct schedules to protect against delays, but the reliability of direct networks is highest. This can explain the superior on-time performance and high equipment utilization of non hub carriers such as Southwest Airlines. Finally, an example shows that congestion at the hub does not change optimal network choice unless delays at the hub are very much larger than at spoke cities.

Literature Review

Study of airline networks spans several disciplines. Economics researchers, operations researchers, and transportation engineers all have made contributions to understanding airline networks.

In the economics literature, several analytical papers consider the effect of network topology on competition within the airline industry. Lederer (1993) models competition as a noncooperative game where airlines select network designs and prices for transportation between any two nodes. Oum et al. (1993) study strategic use of hub networks to discourage entry. Brueckner and Spiller (1991) model economies of scale and study the public welfare effects of competition between airlines due to cost externalities.

Several empirical economics papers consider airline cost economics. Bailey et al. (1985) show that a hub and spoke system can decrease airline cost compared to direct routings by exploiting economies of scale by using larger, lower cost aircraft. Caves et al. (1984) study passenger airlines demonstrating economies of traffic density and constant returns to scale for the number of cities served. Oum and Tretheway (1990) demonstrate the evolution of several airline networks from linear to hub systems, and describe a hub's effects on airline cost and passenger travel time. McShan and Windle (1989) measure the change in hub and spoke routing in the United States since deregulation and estimate the effect of this change on airline costs. Transportation engineers predict consumer choice of transportation services using random utility models; see for example Ben-Akiva and Lerman (1985). Morrison and Winston (1985) present a detailed econometric analysis of business traveler's modal choice as a function of factors such as transportation price, transit time, and time between departures. They find that price, travel time, and *schedule delay* are the most important passenger choice factors.

Several operations research papers present analytic models of airline cost. The most relevant to our approach is Jeng (1988), who analyzes an idealized airline routing problem. His purpose is to study the mix of hub and direct routing flights chosen by an airline. He shows how network parameters such as demand level, geographical distance between cities, and number of cities served affect the routing choices. Unlike this paper, his assumes that passenger demand is inelastic and does not consider aircraft schedules or the effect of networks on schedule reliability. Kanafani and Ghobrial (1985) study the effect of congestion at hub airports. Using a case study and an analytic model, they show that hubs are efficient even when landing fees are used to reduce hub delays. Kuby and Gray (1993) study package delivery systems and generalize hub networks to allow stopovers and feeders. They formulate a mixed integer mathematical program to solve for the cost minimizing network. Similarly, Marsten and Muller (1980) formulate a mathematical program to design an air cargo carrier's route and plane assignment for spider-shaped networks. Trietsch (1993) uses a generalized newsboy model to study optimal choice of ground time in hub systems with the objective of minimizing airline and passenger costs due to delay.

The rest of this paper is organized as follows. In Section 1, we discuss the notation used in the paper and develop the basic model. Detailed expressions for passenger and airline costs are presented in Section 2. Section 3 obtains the optimal frequency for different types of networks. Section 4 discusses the nature of optimal network and its cost under various conditions. Section 5 studies the optimal