

Modeling Framework for Evaluating Sensitivity of Airline Schedules to Airport Congestion Pricing

Ahmed Hassan, Khaled Abdelghany, and Ahmed Abdelghany

This paper presents a modeling framework for evaluating the sensitivity of airline schedules to the congestion pricing of airports. The framework allows airport agencies and aviation management authorities to examine the effectiveness of airport pricing schemes in reducing flight delays at congested airports. The framework replicates airlines' schedule planning decisions in a free market as it considers the effect of applying time-varying landing fees and associated delay externalities. The framework adopts the concept of Wardrop's network equilibrium as the basis for modeling competition among air carriers. A hypothetical airline network with two competing air carriers is used to illustrate the capabilities of the developed framework. The results of the conducted experiments show the importance of considering the network effect in developing effective pricing strategies.

Air carriers usually target high-demand markets to maintain profitable levels of passenger loads for their flights. Thus, high service concentration has been observed in these markets, which results in considerable congestion at associated airports, especially during peak periods. According to a recent report for the U.S. FAA, many major U.S. airports are operating near their capacity and will soon suffer capacity constraints when the current growth trend is considered (1). With airports' limited ability to expand their physical capacity to accommodate growing flight demand, airport congestion pricing has emerged as one plausible approach that could be used to reduce flight delays (2). The idea is to apply flight-based charges at congested airports to force air carriers to reduce the number of their landing flights during the peak period either through adjusting their arrival times or through rescheduling these flights to neighboring airports, if any. Most airport pricing schemes make landing fees a function of the aircraft weight and size, and very few schemes have considered pricing on the basis of landing times (e.g., peak and off-peak) (3). Nonetheless, a common shortcoming among these schemes is that they were designed locally (4). They ignore the responses of air carriers, which include adjusting their schedules at the network level to maintain profitability in the face of the applied fees and avoiding shifts of flights to other airports to avoid the congestion. They also ignore the impact of pricing strategy on the fairness of the competition among air carriers. For instance, increasing the landing fee at one or more airports is expected to increase air

carriers' operation cost in associated markets. If the fee is greater than an air carrier's profit in a market, this carrier can be expected to exit that market and seek other profitable markets. The exit of one air carrier could attract other competing air carriers with generally lower operation cost to enter the market or to increase their number of flights, which could result in no change in the airport's congestion level. Similarly, if the number of scheduled flights at an airport was reduced because of a charged congestion fee, fewer flight delays would be expected. Hence, reduced flight delays would encourage air carriers to schedule more flights or attract new entries to this airport.

Furthermore, considerable debate is under way about the correct congestion pricing policy that could be used at congested airports (5). This debate returns to the disagreement about whether delay internalization occurs at major hubs. For example, Brueckner and Dender (5) argue that dominant air carriers with major operations at a hub already internalize most of the delay occurring at this hub, and hence they should not be charged for the congestion. This argument is opposed by Daniel (6) and Daniel and Harback (7), as they suggest that the flight cutback of a dominant air carrier to reduce congestion will encourage fringe carriers to schedule more flights so as to leave overall congestion unchanged. This disagreement returns primarily to the difference in the modeling assumptions used to prove the two viewpoints. In this context, evaluating the effectiveness of a congestion pricing policy requires a modeling framework that considers the different factors that affect air carriers' scheduling decisions in a deregulated, competitive environment. Considerable research work has been reported over the last few decades to model airline competition while considering different operation scenarios [Panzar (8), Oum et al. (9), Berechman and Shy (10), Zhang (11), Hendricks et al. (12), Wei and Hansen (13), Daniel and Pahwa (14), Hansen (15), Hsiao and Hansen (16), Adler (17), Hassan et al. (18)]. The developed models differ in their assumptions about airline behavior, demand sensitivity to provided flight services, and the level of detail at which a problem is represented. Nonetheless, they lack the capability for accurate modeling of the impact of congestion pricing at the network level while considering multiple competing air carriers. For example, most models do not explicitly consider airport congestion pricing as part of an air carrier's cost structure. They ignore the time variability in air travel demand and the impact of peak and off-peak airport delays on the air carriers' scheduling decisions. Most models also ignore the heterogeneity of the air carriers attributes related to fleet size, operation cost, airport access, etc. Finally, they oversimplify the representation of the demand split among the different itinerary services provided by the competing air carriers, which reduces the accuracy of the revenue estimates and the resulting flight schedule.

This paper presents a modeling framework for studying airlines' schedule sensitivity to airports' congestion pricing. The framework

A. Hassan and K. Abdelghany, School of Engineering, Southern Methodist University, P.O. Box 750340, Dallas, TX 75275-0340. A. Abdelghany, College of Business, Embry-Riddle Aeronautical University, 600 South Clyde Morris Boulevard, Daytona Beach, FL 32114. Corresponding author: K. Abdelghany, khaled@enr.smu.edu.

allows airport agencies and aviation management authorities to examine the effectiveness of pricing schemes not only at a single airport but also for the entire system. The framework determines changes in the air carriers' schedule at the network level in response to implementation of congestion pricing at one or more airports. Development of the pricing scheme itself is considered beyond the scope of this paper. The framework replicates airlines' decisions on planning their flight schedules in free-market competition, while considering (a) the within-day temporal variability in air travel demand at the market level, (b) the heterogeneity in the aircraft resources and operation cost of the competing air carriers, (c) demand and revenue split among the different air carriers as a function of the attractiveness of their scheduled itineraries, (d) pricing schemes applied at the different airports in the network, and (e) the effect of congestion externalities at the different airports. The framework adopts the concept of Wardrop's network equilibrium as the basis for modeling the competition among the air carriers. Given the air travel demand along the different markets and the applied congestion pricing schemes at the airports, all air carriers are assumed to simultaneously construct their flight schedules, with the goal of maximizing their profits until a state of equilibrium is achieved. At equilibrium, it is assumed that no air carrier can improve its profit by unilaterally changing its flight schedule.

This paper is organized as follows. In the next section, the problem of airlines' competition with consideration of airport congestion pricing is formally defined. The solution approach to the problem is then presented. Next is a description of a set of experiments designed to illustrate the different capabilities of the model. The results of these experiments are then presented. Finally, main conclusions and considered extensions of this research work are offered.

PROBLEM FORMULATION

Given is a set of air carriers A competing in an airline network that consists of a set of markets I . It is assumed that all competing air carriers have perfect information on all markets and that they adopt a rational profit-maximizing behavior. Each market $i \in I$ is defined in relation to its origin and destination metropolitan areas. In addition, each market is defined in relation to its departure time window (e.g., 2 h) $t \in H$, where H represents the analysis horizon. Each market $i \in I$ is also assumed to have a fixed passenger demand d_i . This demand splits among the different itineraries scheduled by the air carriers in this market. The term y_{aj} is the number of itineraries of form j scheduled by air carrier $a \in A$ in market $i \in I$. Each itinerary j could include zero or more stops. The term x_{ai} is the number of nonstop flights scheduled by air carrier $a \in A$ in market $i \in I$. The binary parameter δ_{ij} is equal to 1 if a nonstop flight along market i is part of itinerary j and 0 otherwise. The term e_{aij} is the average fare of itinerary j along market i that is operated by air carrier $a \in A$. A set of airports L is defined for the airline network. Each metropolitan area could have one or more airports. An airport $l \in L$ could adopt a congestion pricing strategy with w_l as the charged fee in time window $t \in H$.

The airline competition problem that considers airport congestion pricing is represented by using an extension of the equilibrium-based network flow model developed by Hassan et al. (18). The network model defines the spatial and temporal connectivity between the different markets. Figure 1 illustrates an example of the network of five hypothetical air travel markets that involve three metropolitan areas. As the figure shows, each travel market is represented by one link. The upstream-downstream node of a link represents the market's origin-destination (O-D) metropolitan area and the asso-

ciated departure-arrival time window. A node that represents a metropolitan area at a certain time window is further decomposed to two subnodes representing the arrival and departure events at the metropolitan area. In addition, one subnode is used to represent each airport in the metropolitan area at this time window. Each airport's subnode is connected to its corresponding departure and arrival subnodes by two dummy links. Each airport subnode is also connected with its clones in previous and consecutive time windows, respectively. In addition, dummy source and sink nodes are included to represent the start and the end of the considered scheduling activities in the horizon H . A set of dummy links are used to connect the source and sink nodes to each airport subnode and also to connect the source and sink nodes directly to each other.

Each air carrier is assumed to have a limited number of aircraft n_a . An aircraft covers a set of flights in the planned schedule to form an efficient route that maximizes its utilization. Thus, the schedule of air carrier a could be described in the form of a set of aircraft routes K_a with q_{ka} as the number of aircraft assigned by air carrier a to route k_a . The binary variable β_{ki} is equal to 1 if the nonstop flight along market i is part of route k_a and 0 otherwise. Each air carrier tries to maximize its profit by scheduling as many profitable flights as possible with the available set of aircraft. If each air carrier is represented as a commodity and its aircraft as the flow of this commodity, sending one unit of flow (aircraft) of this commodity on a link is equivalent to scheduling a flight by this air carrier in the market represented by this link. The cost associated with scheduling one aircraft route is the negative of the net revenue generated by the flights along this route. The net revenue of the route is the sum of the net revenue of its flight legs, which can be computed as the difference between (a) the revenue that this flight is generating while all itineraries of which this flight is part are considered and (b) the flight's operation cost and (c) the landing fee and the congestion externalities at the destination airport.

The travel demand of a market is assumed to split among the available itineraries for all air carriers as a function of their attractiveness to passengers. For instance, an itinerary could be attractive if it is less expensive, includes fewer connections, and is operated by a highly reputed air carrier. If p_{aj} is defined as the demand share of itinerary j along market $i \in I$ for air carrier $a \in A$. The revenue r'_{aj} of an itinerary j can be described as follows:

$$r'_{aj} = \frac{p_{aj} \cdot d_i \cdot e_{aij}}{y_{aj}} \quad \forall a, i, j \quad (1)$$

Air carriers are assumed to divide the revenue of an itinerary among all their constituent flight legs in accordance with a predefined rule (e.g., equally among all flights or in proportion to their flight times). If one assumes (a) an equal revenue split among all flight legs and (b) the number of flight legs in itinerary j is θ_j , the revenue r'_a of the scheduled nonstop flight by air carrier a in market i is given by Equation 2.

$$r'_a = \frac{\sum_i \sum_j p_{aj} \cdot d_i \cdot \frac{\delta_{ij}}{\theta_j} \cdot e_{aj}}{\sum_i \sum_j y_{aj} \cdot \delta_{ij}} \quad \forall a, i \quad (2)$$

The term c_{ai} is used to represent the average operation cost (fuel, passenger services, etc.) for air carrier a associated with operating a flight along market i . By subtracting the operation cost from r'_a , the net revenue of the nonstop flight r_{ai} along market $i \in I$ is given in Equation 3.

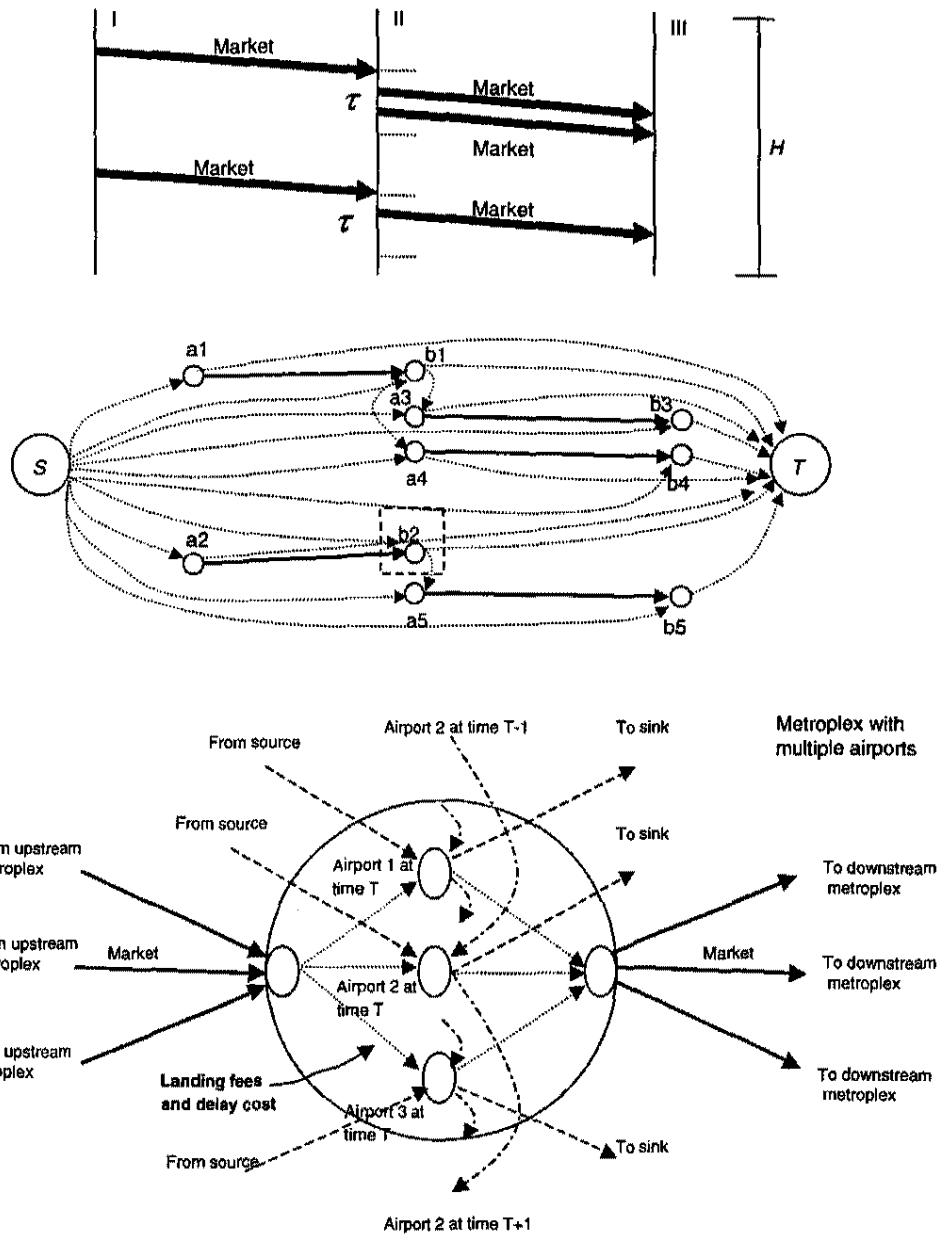


FIGURE 1 Network representation of air travel markets.

$$r_{ai} = \frac{\sum_{i'} \sum_{j'} p_{ai'j'} \cdot d_{i'} \cdot \frac{\delta_{ij'}}{\theta_{ij'}} \cdot e_{ai'j'}}{\sum_{i'} \sum_{j'} y_{ai'j'} \cdot \delta_{ij'}} - c_{ai} \quad \forall a, i \quad (3)$$

It is assumed that l_i and t_i are, respectively, the arriving airport and the time window of a scheduled nonstop flight along market i . Then the terms $w_{l,t}$ and $v_{l,t}$ are defined as, respectively, the landing fee and the expected delay cost for this nonstop flight. The latter cost element is assumed to be a monotonically increasing function of the number of flights that land in airport l in time window t . For example, Morrison and Winston (19) estimated an exponential delay function in relation to the number of flights and the airport capacity. If a fixed cost per minute delay is assumed, the delay cost at any given congestion level can be estimated for all airports in the different time windows. As

described earlier, the network model uses dummy links to represent the flight landings at an airport in a certain time window. As Figure 1 shows, the landing charges and delay costs are associated with their corresponding links. The cost of these links is as given in Equation 4.

$$r_{it} = -w_{l,t} - v_{l,t} \quad \forall l, t \quad (4)$$

SOLUTION PROCEDURE

Given the network model described above, the problem is to determine the schedules of the competing air carriers at equilibrium, which is described in relation to the routes of their aircraft. At equilibrium, no air carrier can improve its profit by unilaterally modifying any of its aircraft routes. Hassan et al. (18) provide a nonlinear

mathematical formulation for this problem and shows the equivalence between the given formulation and the network equilibrium conditions. The convex combination algorithm is used to solve for the equilibrium pattern. The algorithm solves iteratively by performing two primary steps at each iteration: (a) finding the optimal moving direction along the nonlinear objective function and (b) determining the optimal moving step along this direction. The optimal direction is determined by solving a linear approximation of the objective function. This linear approximation is obtained by assuming that the profit is no longer a function of the number of itineraries scheduled by the different air carriers. In addition, the flight delay cost is assumed to be independent of the number of flights landing at the airport. Nonetheless, the delay cost of a flight is evaluated by using the flight schedule obtained at the current iteration. Given the optimal direction, the inverse of the iteration counter is used as an approximation of the optimal moving step to update the solution at the current iteration. Based on the obtained solution, the net revenue and the delay cost for each flight are updated. The main steps of the developed solution algorithm are given below.

Step 0. Initialize the algorithm.

- Construct the network.
- Set iteration counter $itr = 0$.
- Generate initial feasible solution $(x_{ai}^0, y_{aj}^0, p_{aj}^0, r_{ai}^0, \forall a, i)$

Step 1. Find direction (for each air carrier $a \in A$).

- Set the cost of each market link as the negative of its net revenue per nonstop flight.
- Determine the shortest route between the source and the sink nodes for each air carrier a .
- Assign all aircraft of air carrier a to the shortest route (all or nothing).
- Determine the auxiliary number of aircraft routes g_k^{itr} for each air carrier.

Step 2. Update the number of flights for each market and air carrier.

$$f_{k_a}^{itr+1} = f_{k_a}^{itr} + \frac{1}{itr+1} (g_{k_a}^{itr} - f_{k_a}^{itr}) \quad \forall k, a$$

$$x_{ai}^{itr+1} = \sum_{k_a} \beta_{k_a}^i f_{k_a}^{itr+1} \quad \forall i, a$$

Step 3. Update the operation cost and net revenue for all flights.

- Construct the set of feasible itineraries J for all markets $i \in I$.
- Determine the number of itineraries $y_{aj}^{itr+1} \forall a, i, j$.
- Determine the demand share p_{aj}^{itr+1} of all itineraries as function of their relative attractiveness.
- Determine the expected delay cost v_{ai}^{itr} for all airports for all time windows.
- Update the net revenue per flight for all links:

$$r_{ai}^{itr+1} = \frac{\sum_i \sum_j p_{aj}^{itr+1} (Y) \cdot d_i \cdot \frac{\delta_{ij}}{\theta_j} \cdot e_{aij}}{\sum_i \sum_j y_{aj}^{itr+1} \cdot \delta_{ij}} - c_{ait}$$

$$r_a^{itr+1} = -w_{it} - v_{it}^{itr}$$

Step 4. Check convergence.

Terminate, if

$$\frac{|z^{itr}(x) - z^{itr-1}(x)|}{z^{itr}(x)} \leq \eta$$

and number of markets that satisfies $|x_{ai}^{itr} - x_{ai}^{itr-1}| \leq \epsilon$ is greater than M , where η , ϵ , and M are predefined parameters. Otherwise, update iteration counter to $itr = itr + 1$ and return to Step 1.

The algorithm starts by constructing the airlines network and creating an initial feasible solution. An initial feasible solution could be based on the air carriers' current published schedules. The initial solution provides the number of flight legs that are scheduled by each air carrier. The itinerary builder is activated to determine the set of feasible itineraries along each market. By using an itinerary choice model, the corresponding demand share p_{aj}^{itr} for each itinerary and the net revenue for each flight are determined. Given the flight schedule of the current iteration, the delay cost v_{ai}^{itr} at each airport is determined and added to the congestion pricing fees, if any. After the convex combination algorithm, the next step is to determine an efficient moving direction. The path with the highest net revenue is determined for each air carrier. An all-or-nothing assignment step is performed in which the entire fleet for each air carrier is assigned to the route with the highest net revenue for the air carrier. The results of the assignment step determine the auxiliary flows g_k^{itr} for each route and air carrier. The number of flights for each market and air carrier is updated. The algorithm is then checked for convergence. If it is not converged, the iteration counter is incremented and these steps are repeated. The algorithm continues until the convergence criterion in Step 4 is satisfied.

EXPERIMENTAL DESIGN

A hypothetical airline network is used to study the sensitivity of an airline's schedule to airport congestion pricing in a free-market competition. The network consists of six metropolitan areas that are named alphabetically from A to F. A metropolitan area could be an origin or a destination of a travel market. Each metropolitan area is assumed to have a single airport. Two air carriers are assumed to compete in the markets between these metropolitan areas. Under the assumptions of a horizon of 10 h (7:00 a.m. to 5:00 p.m.) and a time window of 2 h for each market, each O-D pair is assumed to have five markets with different demand levels. Time windows between 7:00 and 11:00 a.m. are considered to be the morning peak, while time windows between 1:00 and 5:00 p.m. are considered to be the afternoon peak. Each airport is assumed to be able to accommodate a maximum of six flights during each 2-h window. Table 1 provides this network's main data elements, which include (a) the average flight times between these metropolitan areas, (b) the total demand between the metropolitan areas, and (c) the average fare values for each market. The maximum and minimum connection times between any two flights are assumed not to exceed, respectively, 4 h and 1 h. Travelers are assumed to choose itineraries with total travel time not more than three times that of the corresponding direct flight. In addition, travelers are assumed to choose their itineraries on the basis of a simplified version of the itinerary choice model developed by Coldren and Koppelman (20); see Hassan et al. (18) for more details.

A set of experiments was conducted to illustrate the different capabilities of the model and to study the effect of congestion pricing while considering different operation scenarios related to (a) the characteristics of the airports, (b) the level of air travel demand, and (c) the characteristics of the competing air carriers. In the first set of experiments, the effect of airport delays on the schedule pattern was examined. In this experiment, an exponential delay cost function was used to estimate the amount of delay occurring at an airport in relation to the number of landing flights and the capacity of the airport. Equation 5 gives the delay cost function used in this experiment (19).

TABLE 1 Basic Data Elements of Modeled Airline Network

	A	B	C	D	E	F
Flight Time in Hours						
A	—	1	2	1	2	3
B	1	—	1	2	1	2
C	2	1	—	3	2	1
D	1	2	3	—	1	2
E	2	1	2	1	—	1
F	3	2	1	2	1	—
Total Demand Between Metropolitan Areas						
A	—	800	562	800	562	402
B	800	—	1,202	1,600	1,352	800
C	562	1,202	—	1,202	800	562
D	800	1,600	1,202	—	1,202	800
E	562	1,202	800	1,202	—	562
F	402	800	562	800	1,162	—
Average Fare Price Between Metropolitan Area Pairs						
A	—	100	141	100	141	173
B	100	—	100	141	100	141
C	141	100	—	173	141	100
D	100	141	173	—	100	141
E	141	100	141	100	—	100
F	173	141	100	141	100	—

$$v = dc \cdot e^{\bar{a} \cdot f / \text{cap}} \quad (5)$$

where

v = total delay cost,

cap = airport capacity per hour,

f = number of landed flights per hour,

\bar{a} = constant that describes delay (in min) sensitivity to the flight demand landing at airport, and

dc = average flight delay cost per minute (taken as \$50).

In Equation 5, the constant \bar{a} could be interpreted as a measure of airport efficiency. A small value of \bar{a} implies that the airport manages the flight demand efficiently with minimum delays and vice versa. In the first experiment, the effect of the amount of experienced airport delays on the schedule was studied. The value of the parameter \bar{a} was changed from 0 to 15 in steps of five. A value of $\bar{a} = 0$ indicates that no delay is occurring at the airports—or that the air carriers are ignoring the effect of the delays on their scheduling decisions. In contrast, flights are encountering high delays when the value of \bar{a} is 15. In this experiment, no congestion fee was applied at any of the six airports. The air travel demand portion of Table 1 was used. The two competing air carriers were assumed to be identical in their fleet size and average operation cost.

In the second experiment, the two largest airports (B and D) were assumed to adopt a congestion pricing scheme. The horizon was assumed to be divided into peak and nonpeak periods. Any flight that lands in the peak periods was assumed to be charged \$100, \$150, \$200, and \$250, respectively. No charges were applied for flights landing in the nonpeak period. In this experiment, the two competing air carriers were assumed to be identical. The demand level given above was used. In addition, the delay parameter \bar{a} was

assumed to be 10. The next experiment considered the application of airport congestion pricing at different air travel demand levels. The O-D demand portion of Table 1 was uniformly multiplied by a factor that ranges from 0.50 to 1.50 in steps of 0.25. Again, the two largest airports, B and D, were assumed to apply congestion pricing during the peak period. Two pricing scenarios were considered. In the first, each landing flight was charged \$50, while in the second, the fee was increased to \$200. In this experiment, the two competing air carriers were assumed to be identical. In addition, the delay parameter \bar{a} was assumed to be 10.

In all previous experiments, the two considered air carriers were assumed to be identical in their operation cost structure. Thus, the impact of the congestion pricing on their schedules was expected to be identical. As noted earlier, most congestion pricing schemes ignore the impact on the competition between air carriers (21). In the last set of experiments, the effect of congestion pricing on two air carriers with different average operation costs was examined. The first air carrier (Carrier X) was assumed to operate at an average operation cost of \$0.12/mi per seat, while the second air carrier (Carrier Y) was assumed to operate at an average operation cost of \$0.08/mi per seat. Both air carriers were assumed to have the same fleet size of 30 aircraft. In this set of experiments, the air travel demand portion of Table 1 was used and the delay cost factor \bar{a} was assumed to be 10. The two largest airports, B and D, were assumed to apply congestion pricing during the peak period. The landing fee was assumed to change from \$0 to \$250 per flight.

RESULTS AND ANALYSIS

Figure 2 illustrates the impact of airport delays on the total number of scheduled flights and the corresponding average profit per flight. As Figure 2 shows, as the delay increases and air carriers account for this delay in their scheduling decisions (i.e., higher values of the parameter \bar{a}), a reduction in the number of flights is recorded. For example, at \bar{a} equals 0, the two air carriers scheduled 188 flights. The number of flights was reduced to 176 flights at $\bar{a} = 15$. As air carriers try to maximize the usage of their aircraft fleet, they avoid scheduling flights to airports with excessive delays. Flights with lower profit levels (i.e., low load factors) are more likely to be eliminated. In this experiment, one can observe that the cut in the number of flights was associated with an increase in the average profit per flight. Demand for the eliminated flights was redistributed over the remaining flights, and this redistribution results in an increase in their load factor and average profit. Figure 2 further shows that the profit per flight increased from \$64 to \$147 as the number of flights was reduced from 188 to 176.

The impact of imposing a landing fee for the purpose of congestion pricing is illustrated in Figures 3 and 4, respectively. In the general case, it is expected that air carriers will try to minimize the impact of airport congestion pricing on their levels of profitability. Thus, under the assumption that air carriers are not increasing fares, they would generally cut unprofitable flights, shift to other more profitable markets (if any), or do both. As illustrated in Figure 3, both air carriers reduced the number of flights as the landing fee increased. The increase in the landing fees at the different airports was expected to increase the flights' operation cost and hence reduce their profits. Flights with weak revenues are more likely to be eliminated from the schedule. At zero landing fees, the two air carriers scheduled 182 flights. The number of scheduled flights was reduced to 175 as the landing fee increased to \$250. The cut in the number of flights occurred mainly at Airports B

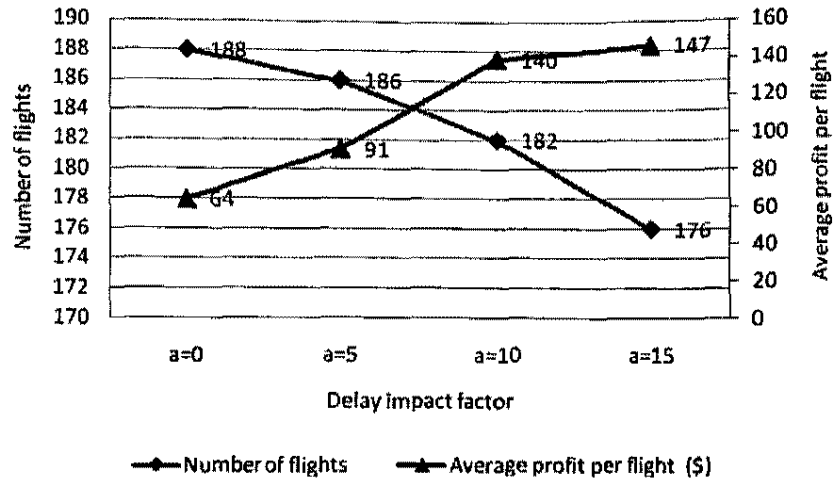


FIGURE 2 Impact of airport delays on total number of flights and average profit per flight.

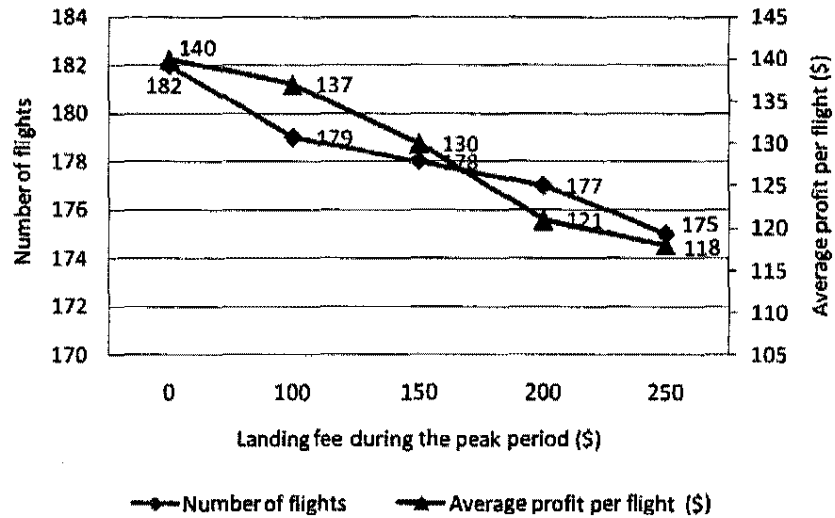


FIGURE 3 Impact of congestion pricing at Airports B and D on total number of flights and average profit per flight.

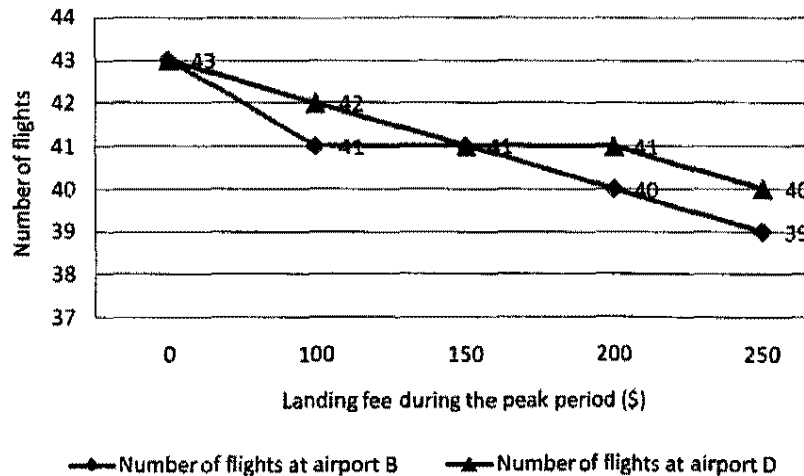


FIGURE 4 Number of flights landing at Airports B and D at different congestion pricing levels.

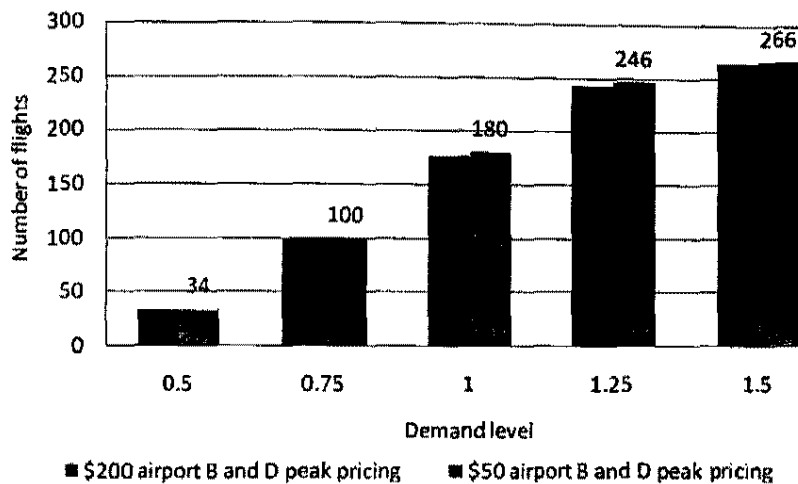


FIGURE 5 Impact of applying congestion pricing while considering different air travel demand levels.

and D, where congestion pricing was applied. As Figure 4 shows, the number of flights at Airport B was reduced by four flights while the number of flights at Airport D was reduced by three flights. In this experiment, the average profit per flight decreased as the value of charged fee increased. The profit declined from \$140 to \$116 as the landing fee increased from zero to \$250.

Figure 5 illustrates the results for the experiment in which congestion pricing was applied and different levels of air travel demand were considered. Two congestion pricing scenarios were applied. In the first, each landed flight at Airports B and D was charged \$50. The landing fee was increased to \$200 in the second scenario. In this set of experiments, the delay cost at the airports was considered by the two air carriers as described earlier. As Figure 4 shows, at the low demand levels (i.e., demand factor less than or equal 0.75), the two air carriers showed to be indifferent to the applied congestion pricing. The number of scheduled flights in both pricing scenarios was recorded to be the same. The low demand levels were expected to be associated with low average profit per flight. For example, for the scenario in which the demand level was 0.75, the average profit per flight in the \$50 and \$200 pricing scenarios was recorded to be \$38 and \$20, respectively. At this low level of average profit, the two air carriers were resisting the reduction in the number of scheduled flights. In addition, the low number of flights associated with the low demand resulted in no delays at the airports. Thus, the only cost element that the air carriers were subject to was the landing fee. The delay cost element was minor, which helped the air carriers to maintain the number of flights in these two pricing scenarios. As the demand level increased, the two air carriers increased the number of flights to accommodate the new demand level. The increase in the demand was expected to also improve the flights' load factors and hence to increase their profits. In contrast, the increase in the number of flights was expected to result in more congestion at the airports, which would increase the average delay cost per flight. As the fee value increases, air carriers evaluate the tradeoff between (a) reducing or rescheduling their flights to avoid the high landing fee and the excessive delay cost at the airports, and (b) the loss in revenue associated with reducing their schedules. From the results of this set of experiments, both air carriers were shown to reduce their flights as the landing fee increased. For example, for the case with a 1.25 demand factor, the total number of flights was reduced from 246 to 242 as the landing fee increased

from \$50 to \$200. In this experiment, the air carriers were able to maintain comparable average profit per flight in these two pricing scenarios. The average profit per flight was recorded to be \$188 and \$187 for the \$50 and \$200 pricing scenarios, respectively.

Figure 6 gives the results for the experiment in which the effect of congestion pricing on the schedule of two air carriers with different average operation cost is examined. In this experiment, Air Carrier Y was assumed to operate at lower operation cost than Air Carrier X. As Figure 6 shows, the low operation cost of Air Carrier Y gave it an advantage over Air Carrier X. In the scenario in which no pricing was applied, Air Carrier Y scheduled 140 flights in the different markets, while Air Carrier X scheduled only 59 flights. When congestion pricing was applied at Airports B and D, Air Carrier X could not maintain profitability on some of these flights, which resulted in cutting these flights from its schedule. For example, Air Carrier X cuts two to three flights at different tested pricing scenarios. In contrast, the low operating cost of Air Carrier Y helped it to maintain profitability for all its flights. Figure 6 shows that Air Carrier Y kept its 140 flights for all tested scenarios. The results illustrate that the effects of a pricing scheme could differ from one air carrier and another on the basis of their operational characteristics. The presented model is capable of capturing the changes in the schedule for each air carrier in the system.

SUMMARY

A modeling framework for evaluating the sensitivity airline schedules to congestion pricing of airports was presented. The framework allows airport agencies and aviation management authorities to examine the effectiveness of airport pricing schemes in reducing flight delays at congested airports. The framework replicates airlines' schedule planning decisions in a free market while considering the effect of applying time-varying landing fees and the associated delay externalities. Given air travel demand along the different markets and the applied congestion pricing schemes at the airports, all air carriers are assumed to construct their flight schedules simultaneously with the goal of maximizing profit until a state of equilibrium is achieved. At equilibrium, it is assumed that no air carrier can improve its profit by unilaterally changing its flight schedule. Several experiments were designed to illustrate the different capabilities of the model. The results of these

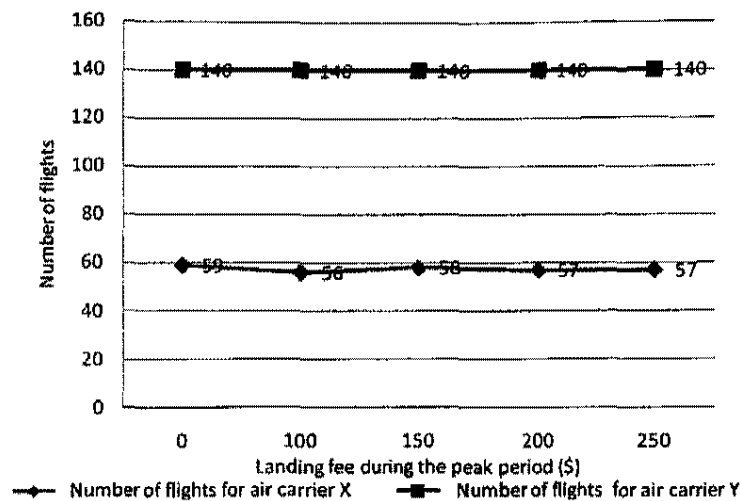


FIGURE 6 Impact of applying congestion pricing while considering two air carriers with different operation cost structures.

experiments show that airport delays could affect the air carriers' decisions about scheduling a flight to a congested airport. Air carriers would generally cut flights to congested airports, especially if the profitability of these flights is low. In addition, congestion pricing increases the average operation cost per flight. As the charged fees increase, air carriers cut their schedule and maintain only profitable flights. In addition, the effects of a pricing scheme could differ from one air carrier to another on the basis of their operational characteristics.

Several extensions are considered for this research work. For example, the model presented in this paper could be used as the basis for solving for the optimal pricing strategy that can be applied to achieve a desired objective or objectives. Together with an efficient search mechanism, the model can be used to evaluate any potential solution and provides direction to find an improved one. In addition, due to space limitations, the results in this paper were confined to the application of the model to a hypothetical network. The model application to real-world networks is another possible extension to this research. Finally, the current version of the model limits air carriers' reaction to pricing to schedule adjustments. A likely scenario is that air carriers would also modify their ticket prices to compensate for the additional fees. However, when the elasticity of air travel demand is considered, the change in ticket prices would also change the demand levels in different markets. The presented model would be extended to account for the elastic-demand version of the problem.

REFERENCES

1. *Capacity Needs in the National Airspace System 2007–2025: An Analysis of Airports and Metropolitan Area Demand and Operational Capacity in the Future*. FAA, U.S. Department of Transportation, May 2007.
2. Levine, M. E. Landing Fees and the Airport Congestion Problem. *Journal of Law and Economics*, Vol. 12, No. 1, 1969, pp. 79–108.
3. Schank, J. Solving Airside Airport Congestion: Why Peak Runway Pricing Is Not Working. *Journal of Air Transport Management*, Vol. 11, No. 6, 2005, pp. 417–425.
4. Mayer, C., and T. Sinai. Network Effects, Congestion Externalities, and Air Traffic Delays: Or Why Not All Delays Are Evil. *American Economic Review*, Vol. 93, No. 4, 2003, pp. 1194–1215.
5. Brueckner, J., and K. Dender. Atomistic Congestion Tolls at Concentrated Airports? Seeking a Unified View in the Internalization Debate. *Journal of Urban Economics*, Vol. 64, No. 2, 2008, pp. 288–295.
6. Daniel, J. Congestion Pricing and Capacity of Large Hub Airports: A Bottleneck Model with Stochastic Queues. *Econometrica*, Vol. 63, No. 2, 1995, pp. 327–370.
7. Daniel, J., and K. Harback. (When) Do Hub Airlines Internalize Their Self-Imposed Congestion Delays? *Journal of Urban Economics*, Vol. 47, No. 1, 2008, pp. 1–38.
8. Panzar, J. Equilibrium and Welfare in Unregulated Airline Markets. *American Economic Review*, Vol. 69, No. 2, 1979, pp. 92–95.
9. Oum, T., A. Zhang, and Y. Zhang. Airline Network Rivalry. *The Canadian Journal of Economics*, Vol. 28, No. 4a, 1995, pp. 836–867.
10. Berechman, J., and O. Shy. *Airline Deregulation and the Choice of Networks*. In *Advances in Spatial Equilibrium* (P. Nijkamp, ed.). Springer: Berlin, 1996, pp. 138–156.
11. Zhang, A. An Analysis of Fortress Hubs in Network-Based Markets. *Journal of Transport Economics and Policy*, Vol. 30, 1996, pp. 293–308.
12. Hendricks, K., M. Piccione, and G. Tan. Equilibria in Networks. *Econometrica*, Vol. 67, No. 6, 1999, pp. 1407–1434.
13. Wei, W., and M. Hansen. Impact of Aircraft Size and Seat Availability on Airlines' Demand and Market Share in Duopoly Markets. *Transportation Research Part E*, Vol. 41, No. 4, 2005, pp. 315–327.
14. Daniel, J., and M. Pahwa. There and Back Again: Airline Routes, Fares and Passenger Flows in Network Equilibria. Working Paper No. 2005-07. University of Delaware, Newark, 2005.
15. Hansen, M. Airline Competition in a Hub-Dominated Environment: An Application of Noncooperative Game Theory. *Transportation Research Part B*, Vol. 24, No. 1, 1990, pp. 27–43.
16. Hsiao, C.-Y., and M. Hansen. Air-Transportation Network Flows: Equilibrium Model. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1915, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 12–19.
17. Adler, N. Hub-Spoke Network Choice Under Competition with an Application to Western Europe. *Transportation Science*, Vol. 39, No. 1, 2005, pp. 58–72.
18. Hassan, A., K. F. Abdelghany, and A. Abdelghany. Modeling Framework for Airlines Competition in the U.S. Domestic Network. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2106, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 47–56.
19. Morrison, S. A., and C. Winston. Another Look at Airport Congestion Pricing. *American Economic Review*, Vol. 97, No. 5, 2007, pp. 1970–1977.
20. Coldren, G., and F. Koppelman. Modeling the Competition Among Air Travel Itinerary Shares: GEV Model Development. Presented at 10th International Conference on Travel Behavior Research, Lucerne, Switzerland, 2003.
21. Brueckner, J. Airport Congestion when Carriers Have Market Power. *American Economic Review*, Vol. 92, No. 5, 2002, pp. 1357–1375.