Using Auction-Based Slot Allocation for Traffic Demand Management at Hartsfield Atlanta International Airport: A Case Study

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Abstract:

This paper presents our ongoing research on an auction model - a hybrid demand management approach for congested airports. It is intended to optimize the utilization of airport time slots by maximizing passenger throughput within safe capacity, decreasing congestion and delay. The two sub-models mathematically formulate conflicting optimization problems of efficiency-driven airport regulators and cost-driven airlines. By taking many key factors such as flight OD-pair, commercial aircraft size, historical on-time performance, airlines' prior investment and monetary bid into a ranking function with respective weights, we put forward a framework that opens for many design alternatives. Along with a baseline, two special instances of the model are analyzed in a case study of Hartsfield Atlanta International Airport (ATL) to compare different auction formats and the resulting airport performance. The latter was made possible by a simulation queuing model. We propose that by varying these weights, the effects of administrative coordination and market force upon outcomes of the auction process could be monitored to achieve airport-specific desirable results. We also suggest that the conventional auction format that uses monetary bidding alone could lead to potential distortions of the marketplace and fail to meet air transportation officials' concerns in terms of efficient utilization of national resources, policy makers' concerns in terms of market structure and competitiveness. Future work will enlist the inputs from airlines and airports.

1. INTRODUCTION

1.1 Background

Demand management refers to any set of administrative or economic measures - or combinations thereof –aimed at balancing demand in aircraft operations against airport capacities. The International Air Transport Association (IATA) provides demand management guidelines for 3 different categories of airports ([1]) wherein slot allocation procedures rely on airlines' voluntary cooperation through IATA coordination at biannual conferences. The reader is referred to ([2]) for an excellent survey on airport demand management systems around the world.

In the United States, four High Density Rule (HDR) airports, New-York/Kennedy and LaGuardia, Chicago/ O'Hare, and Washington/Ronald Reagan (HDR restrictions at Newark airport were lifted in the early 1970s) limit the number of slots for IFR takeoffs/landings, by hour or half hour, during certain hours of the day, and use a "use-it-or-lose-it" provision (or grandfather rights): current holders of slots allocated to domestic operations under the HDR may sell or lease them, and have to return a slot back to a pool of unused slots for re-allocation if it's used by the current holder for less than 80% of the time. AIR-21, enacted in April 2000, exempted certain flights from the HDR limits and provided for theses airports to change their slot control agreements in 2007.

As for other airports in the US, they operate today with no limits on access other than those imposed by air traffic management requirements or by technical constraints such as availability of passenger terminal gates. Overall, air traffic controllers follow a first-come first-served acceptance rule. The current system is therefore a random access system, highly asynchronous with non-uniform schedules reflecting airlines' pressure to accommodate travel time preferences of passengers and flight banking at hub airports.

1.2 Problem Identification

The asynchronous non-uniform scheduling induces many problems such as high delay, potential loss of separation ([3]), inefficient fleet mix (*6*) and lack of competition. ATL has a reported VMC optimum rate for arrivals (or departures) of 25 operations per quarter hour ([4]) although the actual rate is typically slightly less, yet the airport is over-scheduled during peak periods, resulting in corresponding peaks in average runway queuing delay estimated by our simulation queuing model, as shown in Fig. 1. Not only does high demand/capacity ratio increase exponentially queuing delay and consequent operational cost to the airlines, Fig. 2 ([5]) also indicates that over-scheduling results in an increasing number of hazards during the landing phase. On the other hand, valleys in the scheduled traffic imply the underutilization of scarce airport time slots whose use should be synchronously monitored to efficiently balance traffic demand and capacity.

This unbalance is also accompanied with an inefficient use of time slots by small aircraft. This is shown in Fig. 3, which plots the cumulative seat share against the cumulative flight share in decreasing order of the number of seats. The box symbols are read against the x-axis and diamonds read against the left y-axis, with any two corresponding values align vertically. Large aircraft having more than 210 seats (747, 777, L10) make up only a very small fraction in ATL's fleet mix, in terms of seat share (3.9%) as well as flight share (1.6%). 75.1% of the flights have between 97 to 210 seats (767, 757, M80, 72S, D9S…), and represent 87.8% of the total seats. Finally, 21.7% of the flights have less than 70 seats (AT7, CRJ, EM2) and only provide the remaining 8.3% of the total seats, and the cargo flights occupy 1.6% of the slots.

A heterogeneous fleet mix composed mainly of small and large aircraft implies a loss in operation capacity due to greater in-trail separation requirements and slower approach speeds of small aircraft, hence a loss in passenger throughput. The wake vortex separation constrains runway departure/arrival capacity. Table 1 presents the required distance separations under IMC conditions, along with time-based translations calculated in ([6]), which also correlate well with those under VMC. In terms of time-based separations, a small aircraft would be much better off leading a heavy, whereas it needs the highest separation when following a heavy aircraft.

Airlines are given considerable leeway in scheduling. In addition, growing consolidation within the airline business through forming alliances has raised the issue of increasing market dominance and the possible abuse of that dominance when alliances operate as monopolists or duopolists in particular international markets. The risks of abuse will be greatest when and where an alliance dominates a major airport hub ([7]). High industrial concentration levels are observed at hub airports due to dominating airlines' organizing flight banks. These airports have Hirschman-Herfindahl indexes (HHI) - a common metric in economics used to measure the industrial concentration level, and hence the competition within a market place - greater than 1800, a level that indicates a lack of competition. ATL's HHI based on OAG schedule in summer 2000 is 3406 and indeed, Delta is the dominating airline with the largest share both in terms of number of seats (77.5%) and flights (73.5%). This virtual monopoly at hub airports, along with the US standard practice of charging uniform landing fees, encourage the airlines to undervalue their assets, removing the incentive for them to efficiently use airport time slots by consolidating traffic onto larger aircraft.

1.3 Current Approaches

Economists have long argued that the airport delay problem is exacerbated by failure to properly price runway use. Indeed, it is clear that demand management systems using only administrative procedures that are almost entirely detached from economic considerations may lead to potential distortions of the marketplace. Hybrid systems using both administrative and economic procedures have emerged, beginning with congestion pricing methods ([8])([9]). These methods applied uniform landing fees as a measure to decrease peak periods and also as an incentive for the airlines to use larger aircraft. This approach requires a high level of monitoring and may not discover the true value of a time slot.

Market-based approaches using auctions date back to 1979 ([10]). Grether et al. proposed to use the competitive sealed-bid auctions for primary market, complemented by the oral double auction for the secondary market. However, establishing separate markets would lead to aggregation risks (airlines could win some slots but fail to acquire synergistic slots at other times) and unnecessary complexity. This was addressed in the combinatorial auction model of Rassenti et al ([11]). Whereas these mainly focused on the economic dimension at the expense of the administrative aspect, there are many practical concerns inherent to the system that must be considered. ([12])([13]) provided a detailed analysis of the feasibility and potential design guidelines for future auction models. ([14])([15]) suggested that any viable solution should be based on hybrids of economic and administrative measures. Besides the auction approach's promise of optimizing allocation, the very stochastic nature of the system poses the question of feasibility on the day of operation. With today's enabling technologies such as Refined Flow Management through Gate-to-Gate 4D Flight Planning and its Required-Time-of-Arrival (RTA) function, auctioning airport slots has appeared more feasible as the aircraft could arrive within their slots with time-of-arrival errors of 21 seconds with a standard deviation of 12.7 seconds ([16]).

1.4 Contribution

This paper is concerned with airport demand management at the strategic level using an auction approach. This paper and our previous paper ([17]) differ from previous contributions in several ways. First, it provides the two main stakeholders – airlines and airport regulators - with mathematical models that factor in other decision-making variables in addition to the financial gain, as usually seen in conventional auction formats. A balance between economic and administrative measures is adjusted using the weighting factors of those variables. Second, we use of a simulation queuing model that enables us to compare the original schedule's impact on airport performance vs. that by an auction-created schedule. This methodology allows us to investigate a) the extent to which administrative regulation should be applied; b) the feasibility of an auction based on airlines' sensitivity to making schedule changes; and c) the effect of auction parameters upon airport fleet mix changes – and hence, airport passenger throughput – as a result of airlines' optimization. However, as an ongoing research effort, we have left out, for the time being, many important issues such as combinatorial bidding constraints and slot pricing, which are the focus of our future work. The tactical slot allocation on the day of operation is a different, yet related, issue and will be dealt with separately. This paper therefore presents our attempt of putting forward a framework for strategic auction-based airport demand management that opens to many alternative models, with preliminary analysis of its impact. Our case study is ATL airport with input data taken from the Official Airlines Guide (OAG) schedule of summer 2000.

Section 2 introduces our auction model, which is composed of two main sub-models: airport optimization model and airline optimization model. The case study in section 3 reports scenarios using simple instances of the auction model, along with analysis of various metrics to compare those instances. Finally, our summary and direction for future work are provided.

2. SLOT AUCTION MODEL

2.1 Design Issues

Any auction model should optimize the utilization of airport time slots by maximizing passenger throughput within safe capacity, decreasing congestion and delay at minimum price. Given the complex nature of the air transportation system, there are many technical, economic, and socio-political concerns to be considered.

Technically, the takeoff slot and landing slot of a flight are not independent. Connecting flights that have several interdependent legs further complicates this matter. Airlines are therefore subject to aggregation risks in failing to obtain synergistic value of contingent slots. For auction to be a feasible solution, combinatorial bidding should be provided for the airlines to specify those schedule constraints.

Economically, any auction design would inevitably face airlines' resentment to lose their freedom in scheduling and to have their long-established schedules be unduly affected by force and unpredictable reallocations of slots, unless these can justify the benefits while minimizing changes and providing a transition path. How to make the airlines reveal their own evaluations of slots in incomplete information bidding context is also an open question from the perspective of auction theory.

Socially, FAA's regulations require any demand management options to consider important public policy objectives, such as airline competition and small community access to important air travel markets. On the other hand, there is the airlines' need to leverage their prior infrastructure investment at hub airports. It may be possible for a dominant carrier to restrict competition by purchasing a large number of slots. Therefore, an auction system should not be introduced without safeguards against market power.

Politically, slot allocation is also subject to government agreements. At the four HDR airports, only two (New York/Kennedy and Chicago/O'Hare) have international traffic. At these airports, priority is given to international flights over domestic and operators of domestic flights can ultimately be required to surrender slots needed for international flights.

And finally, auction models should be flexible enough to adapt to different traffic configurations and operational preferences at different airports. We believe that auction models should be airport-specific, and the implementation should be phased in, in terms of airports to be involved as well as the number of slots to be auctioned, airlines and market segments. Beside a primary market at strategic level, a secondary market mechanism for slot trading at tactical level is also called for (*12*).

2.2 Auction Model

The auction process, being a combination of Simultaneous Multiple-Round auction and Package Bidding models ([18]), is an iterative and interactive process that involves airlines – bidders - and airport regulators - auctioneers. The Department of Transportation (or the Federal Aviation Administration as its agent) would auction off slots (takeoff and/or landing) clustered by 15min time periods. We assume that airlines could make use of the slots they bid for. This is intended to set up a sequential schedule at the strategic level, though usage rules at a tactical level are to be provided.

From the optimization point of view, each stakeholder has an objective function to achieve. Airlines aim to maximize profits whereas the airport network is concerned with optimizing the use of their scarce assets while ensuring safety. Airlines need to maintain a stable schedule and leverage their prior investments at hub airports, but equity and competitiveness issues require airports to provide fair market access opportunity to every airline. Five criteria are taken into account: 1) passenger throughput, 2) flight OD pair, 3) prior airline infrastructure investment, 4) statistical on-time performance and 5) monetary bids. Their weights and how they are combined are airport-specific, and this is made public. Our model proposes a linear combination of those as a way to rank the bids. Through each round, airlines submit values for those five factors; auctioneers apply the ranking function and inform the airlines about the leading bids. The auction process proceeds in this manner through multiple rounds until the closing round or a specified deadline whichever comes first.

2.2.1 Airport Optimization Model

Airport regulators, as auctioneers, are mainly concerned with three questions: What slots to allocate, to whom, and how much to charge. Beside the upper bound set by airport safe capacity, the first question is also constrained by public policy.

A package bid submitted by an airline would include the takeoff/landing slots of interest, and is associated with a five-component normalized vector P_i, and let W^T be the weighting vector of the five factors, the airport regulators could calculate the score of each bid as follows:

Ranking function:

$$\tau(P_i) = W^T \cdot P_i$$

The purpose of the ranking function using five factors to evaluate airlines' bids is twofold. First, it sets up a generic framework for a range of possible auction formats. The conventional auction, in which only money matters, is derived from the model by having the fifth factor's weight to be 1 and others' 0. Second, it allows assessing how much administrative regulation has to intervene and tradeoff with market forces. Further analyses are needed to exclude the irrelevant factors and include other relevant ones.

Let:

A = the arrival slot bidding matrix with time periods in rows and package bids in columns, in which A_{ij}=1 if arrival time period *i* is included in package P_j.

D = the departure slot bidding matrix with time periods in rows and package bids in columns, in which D_{ij}=1 if departure time period *i* is included in package P_j. D_{ij} is the number of slots package P_j bids for in time period *i*

X^T = the binary row vector with $X^T_j = 1$ if P_j leads a round or 0 otherwise

Then the airport optimization model is formulated as:

Objective function:

$$\text{Max} \quad \sum_j \tau(P_j) \cdot X_j$$

Subject to:

$((A \cdot X)_i, (D \cdot X)_i)$ lies within the pareto frontier $\forall i$ *(*)*

Airlines' combinatorial constraints

The capacity constraint (*) is illustrated in Fig. 4(a) wherein LGA's departure and arrival operations are interdependent. Since the slots are auctioned by 15-min intervals, the chart should be scaled down by four to give LGA's operational rates by quarter hour:

$$\begin{cases} (A \cdot X)_i \leq 10 \\ (A \cdot X)_i + 4(D \cdot X)_i \leq 50 \end{cases}$$

Arrivals and departures at ATL are independent, as shown in Fig. 4(b), so it has capacity constraints:

$$\begin{cases} (A \cdot X)_i \leq 25 \\ (D \cdot X)_i \leq 25 \end{cases}$$

This provides an upper bound of the actual number of slots, which depends on the fleet mix and its sequencing. For separation purpose, the order Small-Large-B757-Heavy proves to be optimum, so the leading bids of a time period for each round would, in decreasing ranks, be scheduled in this order until the period is filled up.

Although airlines' exclusion constraints (either this slot or another but not both) and inclusion constraints (all or nothing) can be easily formulated using integer-programming techniques, it is to determine how to balance airlines' flexibility to specify combinatorial constraints and the tractability of the model.

How to determine a reasonable initial bid vector and how much to charge the winner airlines remain open questions. The true values of airport time slots are unknown, and in the context of incomplete information bidding, auction theory states that bidders would tend to undervalue to avoid the winner's curse. In this case, second-price auction format proves efficient in revealing bidders' own evaluations. Besides, the fundamental principle of congestion pricing theory indicates that, in order to achieve an economically efficient utilization of a congested facility, one must impose a congestion toll on each user equal to the external cost associated with that user's access to the facility ([19])([20]). Knowing that marginal delay cost generated by an additional customer is composed of an internal cost and an external cost, the initial bid vector would be the internal cost and the equilibrium prices that the winning airlines have to pay would lie between the initial bids and the external costs.

2.2.2 Airline Optimization Model

Not only will the application of airport time slot auctions affect airlines' cost models by imposing extra fee, but it also creates changes in airlines' schedules. Scheduling is one of the most important tasks of a well-functioning, cost effective airline, and whose understanding would help simulate how airlines place bids in an auction scenario.

The two major categories of scheduling are scheduling by revenue requirements and scheduling by operational needs and constraints of the airlines. These two, sometimes with opposite objectives, have to be reconciled. Most airlines make significant changes to their flight schedule at least twice a year, to reflect marketing objectives and to adjust for the different travel patterns between winter and summer months. Minor changes are made to the schedule on a monthly basis to reflect such things as holiday travel patterns, competitors' scheduling and pricing changes, and changes to key resources such as number of aircraft, number of crew, airport modifications, etc. To avoid high cost from excessive changeover of operations, each schedule represents an incremental change from one or more previous schedules. Over the years, airlines have established highly connected networks that balance operational and economic constraints. Making changes to one flight is likely to proliferate throughout the network to other flights. Each airline has its own sophisticated system of traffic demand forecasting, schedule simulation, complex cost structures and models. We assume that airlines would try to stay as close to their original schedules as possible.

Placing package bids amounts to establishing one-stop services, which correspond to 2 flight legs from *o* to *d*, and connecting services, which correspond to 2 flight legs from *o* to *i* to *d* not flown by the same aircraft. At hub airports there are also banks of flights that arrive and depart within a short time span. Airlines' cooperation is therefore strongly sought for to participate in the simulated bidding process. The model presented here assumed only airlines' moving flights back and forth, although changing aircraft type is also likely.

Let:

B_j	=	monetary offer of package bid P_j
R_j	=	airline's expected gross revenue by contingent slots included in P_j
M	=	a big positive value
$y_j = \begin{cases} 1 \\ 0 \end{cases}$		if airline submits package bid P_j otherwise
α	=	airline's upper bidding threshold fraction of the expected revenues
B_0	=	initial offer of bid P_j, determined by the sum of time period *i*'s initial bid with *i* included in P_j whichever greater.
B_j'	=	airline' monetary bid for slot s in previous round, or B_0 in the first round

Beside B_j' being the bidding lower bound, the upper bound is assumed to be a fraction α of R_j. Given the publicly known rules of determining the winner, an airline can calculate its own rank $\tau(B_j)$. Comparing that to the minimum score $\min_i(\tau)$ of the leading bids of time period i, the airline would have to offer $\frac{\min_i(\tau) - \tau(B_j)}{(W)_5}$ more to get a slot in *i*, with $(W)_5$ being the weight of the fifth factor. Airlines' combinatorial constraints can be formulated easily using techniques of integer programming. For example, the exclusion constraint "Either package m or n but not both" can be written as:

$$\begin{cases} B_n <= Mx_1 \\ B_m <= M(1-x_1) \text{ , } x_1 \text{ is binary, M is large positive number} \end{cases}$$

Then the following model formulates mathematically airline optimization problem:

Objective function:

$$\textbf{Max} \quad \sum_j [R_j - B_j]$$

Subject to:

$$\begin{cases} B_j \le M \cdot y_j \\ B_0 \le B_j + M \cdot (1 - y_j) \\ B_j \le \alpha \cdot R_j \\ \left(B_j' + \frac{\min_i(\tau) - \tau(B_j)}{(W)_5} \cdot B_0 \right) \cdot y_j \le \alpha \cdot R_j \cdot y_j \\ \left(B_j' + \frac{\min_i(\tau) - \tau(B_j)}{(W)_5} \cdot B_0 \right) \cdot y_j \le \alpha \cdot R_j \cdot y_j \\ \text{Airline' package bidding constraints} \end{cases}$$

3. HARTSFIELD ATLANTA INTERNATIONAL AIRPORT: A CASE STUDY

3.1 Assumptions and Scenarios

We simulated an auction of landing slots at ATL using input data as the OAG schedule of summer 2000 and ATL's runway configuration (That departure slots could have been auctioned in combination of landing slots is an area for further research). After filtering the OAG schedule for duplicated flights due to code sharing and different effective periods, scheduled arrivals at ATL amounted to 1243 operations per day. Frequency distribution through the day along with characteristics of the fleet mix and airlines' shares can be observed in Fig. 1, Fig. 2 and Fig. 3. ATL has 2 parallel runways for arrival that arriving aircraft use simultaneously. The facility-reported VMC optimum rate is 25 arrivals per quarter hour, with i.e. 50 landing slots per hour for each arrival runway. To compare the effect of auction-produced schedules vs. that of the OAG schedule on airport performance, we built a simple simulation queuing model. In this model, all the flights are assumed to arrive at their respective scheduled arrival times, and estimated runway queuing delay is estimated using time-based separation standards calculated in (*15*).

The auction process auctioned off landing slots of each hour. It is simplistically assumed that the airlines bid for each slot independently, and that they bid reasonably and homogeneously by setting an upper bid threshold proportional to aircraft size, i.e. expected gross revenues. The initial bid value was normalized to be 1, and all airlines placed monetary bids in terms of factors of this initial bid, up to their respective upper thresholds. No combinatorial constraints were specified for simplicity's sake. For all airlines, we assumed the same initial value of maximum deviation, which is one hour from original schedule times, although this is subject to a subsequent sensitivity analysis. Airlines alternatively bided for most adjacent slots if they failed to acquire the current ones, i.e. airline a would bid for slot *s*, *s-1*, *s+1*, *s-2*, *s+2*, *s-3*, etc… No provisions for aircraft type change in the model

Two scenarios were carried out. The baseline scenario ran the OAG schedule; the simple auction scenario enabled only the fifth factor, which is monetary bid.

3.2 Results and Interpretations

With the maximum deviation being 60 minutes, Fig. 5 plotted the levels of scheduled departures of the baseline and the simple auction scenarios in the upper panel; the lower panel showed the respective estimated average runway queuing delay plots. Note that the simple auction constrained the arrival demand at the airport-reported optimum rate by cutting off the peaks and filling in the neighboring valleys. The resulted average queuing delay was reduced sharply from 6 min/aircraft down to 1.4 min/aircraft for the period 6:00-24:00, or a decrease of 76.7%. This amounts to a 133-hour or 21.7% decrease in total runway queuing delays for arrival operations. The other benefit is the gain in safety, since the airport is no longer overscheduled, and ATC does not have to accommodate more aircraft than the allowed operational rate. The histogram of airlines' deviation in Fig. 5 showed a skewed distribution to the right of flights that had to deviate from original arrival times, which represent 66% of the total flights (822 out of 1243), with 75.3% of them deviated within 15 minutes.

However, the tradeoff for this is that 6 flights were to be rerouted. Yet, the two-hour window assumption for airlines' elasticity could still turn out to be overoptimistic, 41 runs were executed with different values of maximum deviation ranging from 12 to 60 minutes for the auction scenario. Since the true values of this metric are not readily available, conducting sensitivity analysis on this metric gave insight into the possible implications of different assumptions. Fig. 6 summarizes effects of changing values of hypothetical values of airlines' maximum deviation on the number of rounds, the average deviation per flight in minute, the number of deviated flights, the number of seats to be rerouted, the number of flights to be rerouted. It can be seen that the more flexible the airlines are in changing their schedules, the more rounds the auction process takes, and the fewer flights have to be rerouted to other airports.

4. SUMMARY AND FUTURE WORK

An efficient performance of the US's complex aviation environment operated by many stakeholders with conflicting interests is called for *(2)(10)*. The virtue of market-based control mechanisms has proved efficient in allocating scarce resources in telecommunication bandwidth management, computer science and energy distribution. Hybrid solutions to allocating time slots at congested airports that have provisions for both market forces and administrative coordination are shown to be feasible.

This paper presents an ongoing research on our auction model that is intended to optimize the utilization of airport time slots by maximizing passenger throughput within safe capacity, decreasing congestion and delay. By taking many key factors such as flight OD-pair, commercial aircraft size, historical on-time performance, airlines' prior investment and monetary bid into a ranking function with respective weights, we put forward a framework that allows for many design alternatives. By varying these weights and the combination of administrative coordination and market forces, the outcome of the auction process is observed to achieve airport-specific desirable results.

We have simulated two models for ATL's arrival slots allocation. The simple auction amounts to the conventional auction format that uses money as the sole allocation criterion. The results show that the auction model spreads the arrival demand during peak periods down to airport-reported safe operational rates while filling in under-utilized periods. As a result, the model predicts a considerable decrease in arrival queuing delay. The more flexible the airlines are in changing their schedules, the less flights are to be rerouted, and hence, less disruptions and cost implications.

Future research is structured around three main issues. First, working with airlines and airports. We are acquiring more actual input data and improving our model assumptions in terms of airlines' bidding strategy and gaming behavior. Second, we are extending the model with cross-airport combinatorial bidding and equilibrium slot prices determination. And third, we are conducting airport-specific analysis for various congested airports (hub as ORD, non-hub as LGA and LAX) to exclude any irrelevant factors as well as include other relevant ones; and to determine the percentage of slots to be auctioned off for different market segments depending on airport-specific operational requirements. Ultimately, recommendations about airports that are eligible for the auction process and process parameters will be provided, along with a transition plan for a phased implementation.

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LIST OF TABLES AND REFERENCES

TABLE 1 Wake Vortex Separation Standards (nmiles/seconds)

Leading aircraft \ Trailing aircraft	Small	Large	B757	Heavy
Small	2.5/80	2.5/68	2.5/66	2.5/64
Large	4/164	2.5/73	2.5/66	2.5/64
B757	5/201	4/115	4/102	4/101
Heavy	6/239	5/148	5/136	4/104

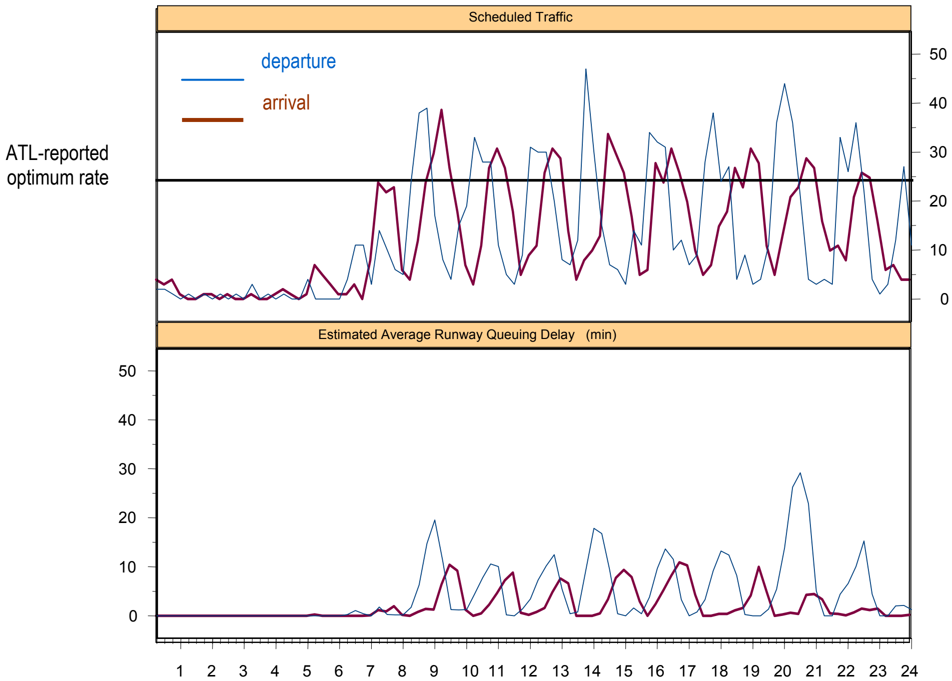


FIGURE 1 Daily Scheduled Traffic and Calculated Average Runway Queuing Delay at ATL Actual delays are consistent but longer and are only partially caused by arrival queuing delays (Schedule Source: OAG Summer 2000)

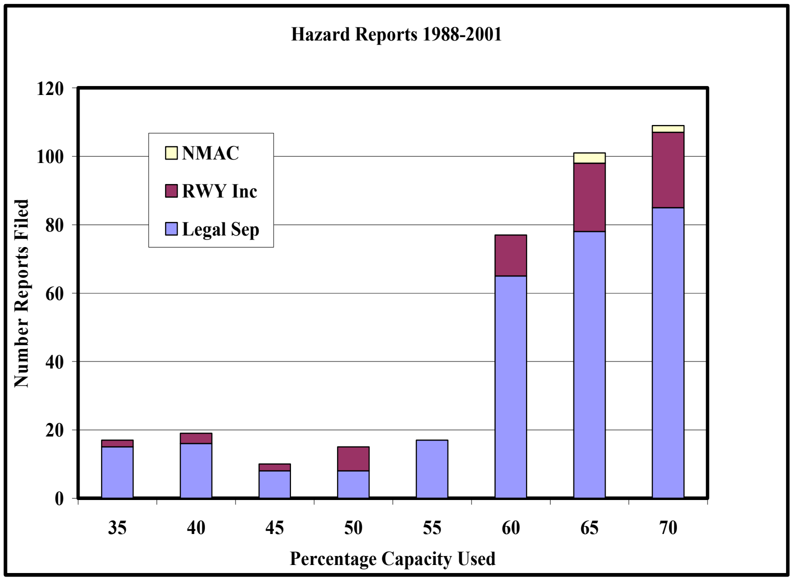


FIGURE 2 Number of Near Midair Collisions (NMAC), Runway Incursions and Loss of Legal Separation Reports filed at ATL, BWI, DCA and LGA airports over the last 13 years correlates with the capacity fraction the airports were operating at the time the incidents occurred (*4*)

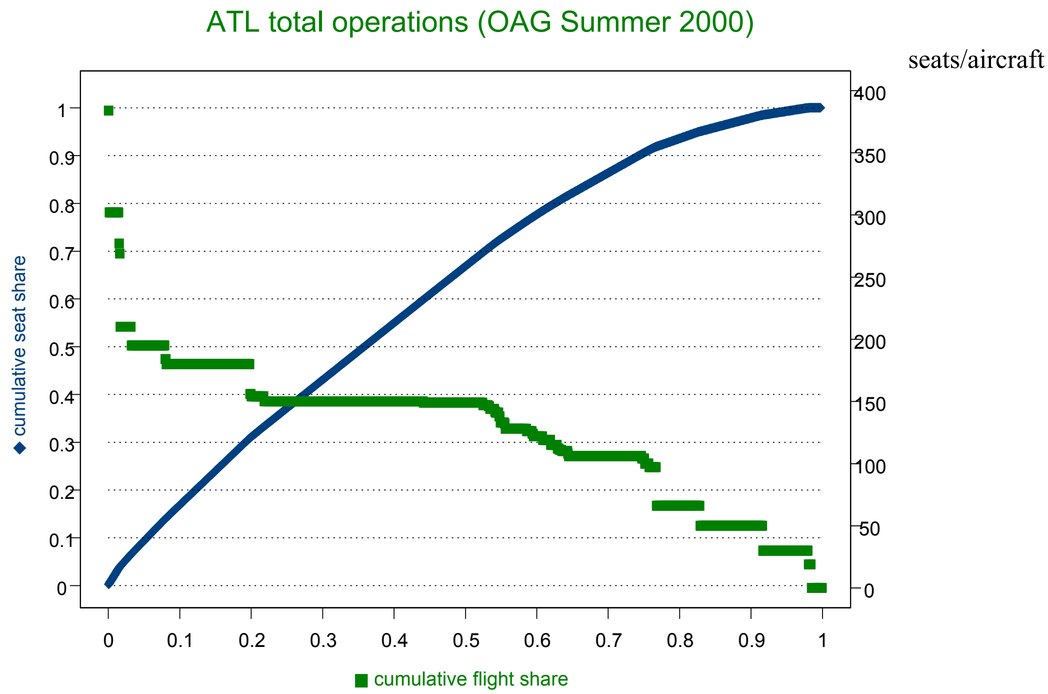
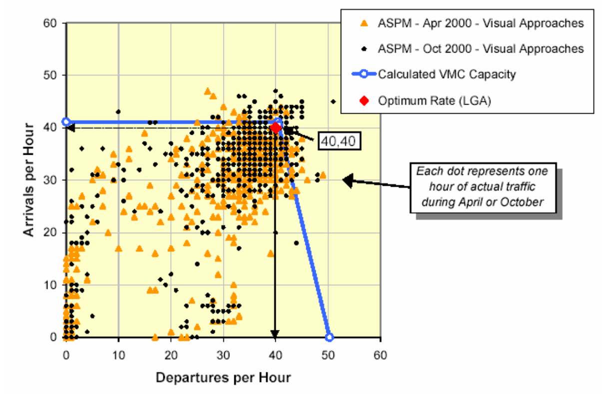
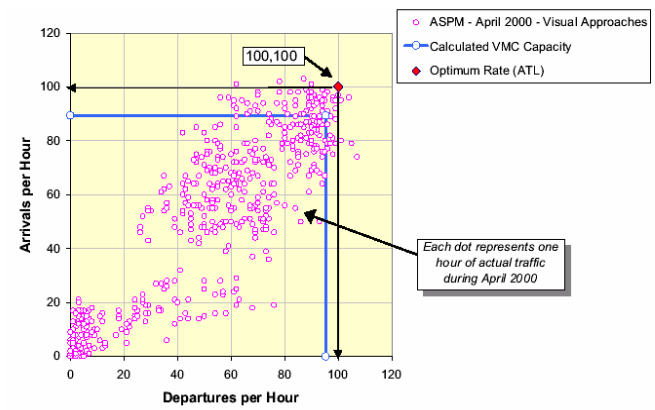


FIGURE 3 Cumulative Seat Share vs. Cumulative Flight Share and Aircraft Size
The box symbols referencing to the x-axis are aligned vertically with corresponding values of the left y axis and horizontally with corresponding values of the right y axis.

Large aircraft (>210 seats) make up 3.9% seat share (1.6% flight share), 75.1% of the flights have between 97 to 210 seats and represent 87.8% of the total seats. 21.7% of the flights have less than 70 seats and only provide 8.3% of the total seats. Cargo flights occupy 1.6% of the slots.



(a) Operation Capacity of LGA airport's dependent runways



(b) Operation Capacity of LGA airport's dependent runways

FIGURE 4 Pareto frontiers of airport capacity during VMC (*3*)

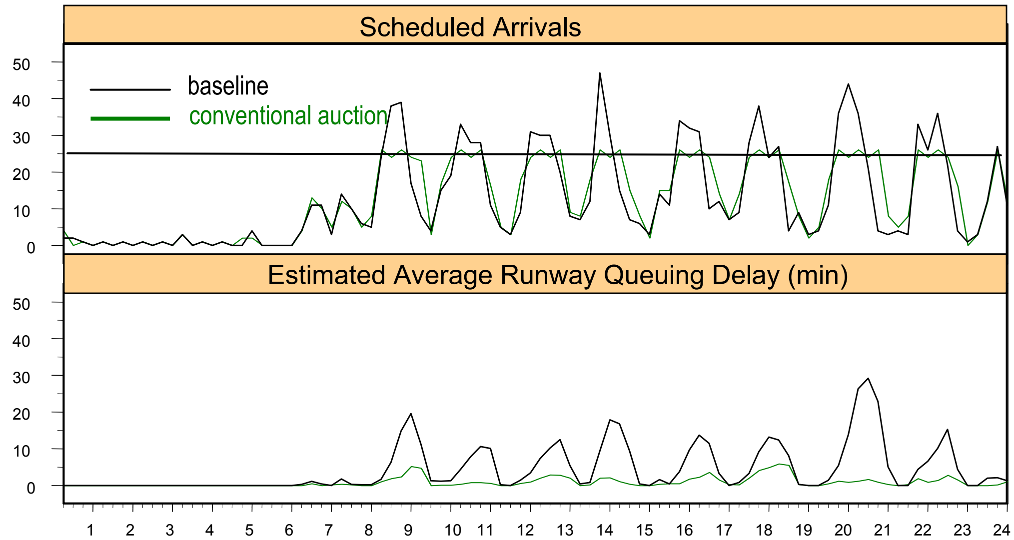


FIGURE 4 Scheduled Arrivals and Resulted Estimated Delays for Baseline and Conventional Auction (60 min maximum schedule deviation allowed)

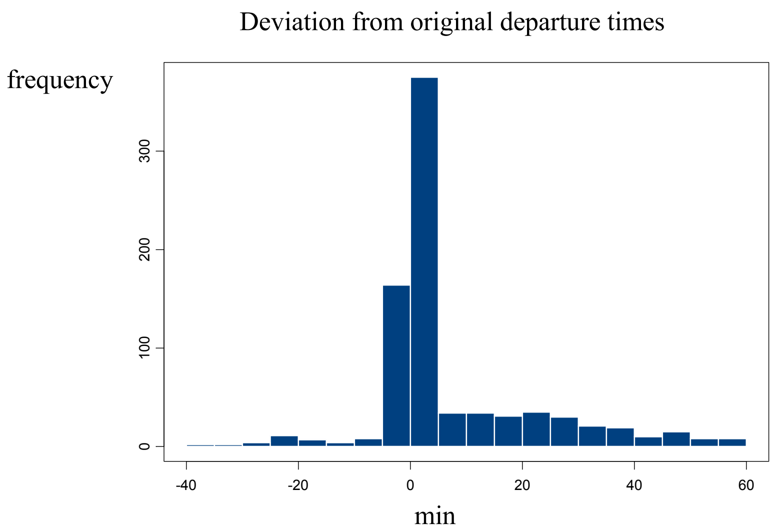


FIGURE 5 Conventional Auction Scenario's Histogram of Flight Schedule Deviations (60 min maximum schedule deviation allowed)

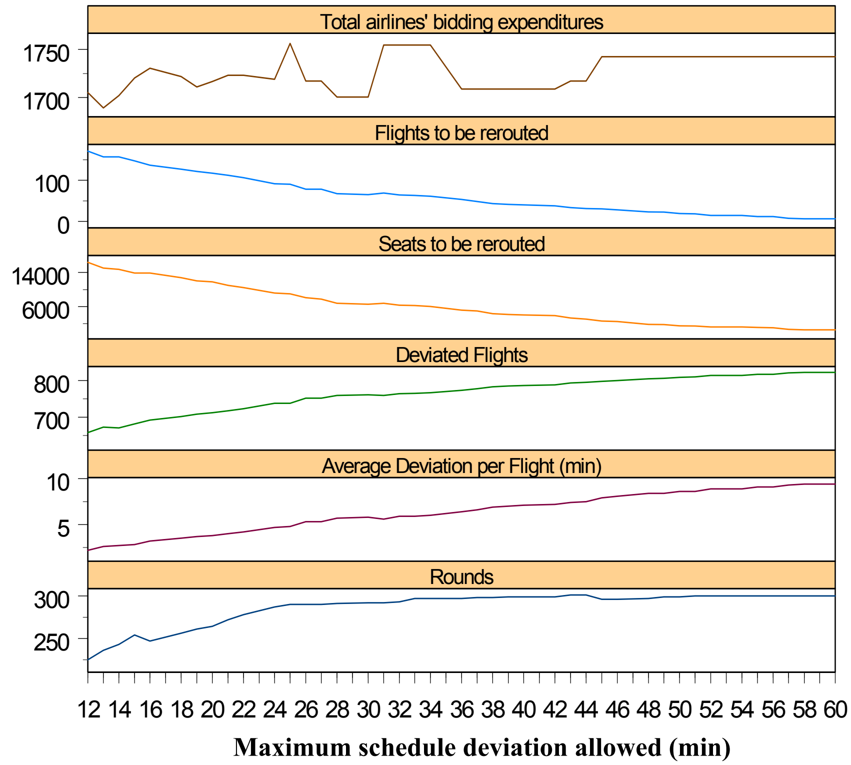


FIGURE 6 The simulation varied the allowed schedule deviation parametrically. These results show how the auction results differed based upon this parameter

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