MOVEMENT TIME AS A COST IN AIRPORT OPERATIONS

By Joseph V. Yance*

Increased air traffic has brought significant increases in landing or take-off delays at some of the large metropolitan airports – for example, those at New York – and at Washington National Airport. Various schemes are being proposed, or tried, to limit traffic, particularly general aviation – a category made up primarily of light aircraft, such as those owned by businesses and individuals for their own use, air taxis and small charter planes. For instance, the Federal Aviation Administration, which operates air traffic control towers, recently proposed hourly quotas for landings and take-offs at the three major New York airports, O'Hare Airport in Chicago and Washington National Airport (*N.Y. Times*, 5 September 1968). The quotas would require severe reductions in general aviation traffic.

One way in which general aviation movements could be limited, other than through quota systems, is through revision of landing fees. At most airports landing fees are proportional to the gross weight of the aircraft, but gross weight is probably not closely correlated with the costs of landing or taking off an airplane. A more significant variable is the length of time that a movement takes, and a general aviation aircraft takes almost as much time to land or take off as does a carrier plane. Assuming landing fees for large planes are the correct ones, a revision of landing fees to take into account the average time that aircraft of various types occupy the runways and approach paths would result in higher landing fees for general aviation traffic. That traffic would consequently tend to shift from major metropolitan airports to less-used general aviation airports, or prospective general aviation passengers would tend to shift to commercial flights.

Conceivably fees and costs should be brought into line by lowering fees for large planes; but, given the present degree of airport congestion, this does not seem reasonable. I discuss briefly the appropriate *level* of fees.

ESTIMATION OF THE RELATIVE DEMANDS OF VARIOUS AIRCRAFT TYPES

Probably the reason why movement time has not been used to determine landing fees is the difficulty of determining how long aircraft movements by different types of aircraft take. However, the work done for the FAA by the Airborne Instruments Laboratory in estimating airport capacity provides a means for estimating the relative time demands that various types of aircraft make upon an airport.

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Most airport operators are familiar with the AIL work; but, to summarise, the measure of delay is the average delay (in minutes) for departing aircraft. Arriving aircraft are usually given priority in airport operations, so that most delays occur to aircraft taking off. The average departure delay is determined from a model of airport landings and takeoffs constructed in terms of queueing theory. Average departure delay for a given runway configuration is determined for various movement rates and for various mixes of aircraft using the airport: four-engine jets (Class A), large propeller aircraft and three-engine jets (Class B), and smaller aircraft (Classes C, D and E), most of them general aviation. The results are given in a series of graphs; for a "population mix" of aircraft using the airport, the average departure delay is plotted as a function of the movement rate (total number of landings and departures per hour).[1] A typical graph is shown in Figure 1.

The AIL uses an average departure delay of four minutes as a rule of thumb in defining the "capacity" of an airport. It should be noted that an average departure delay of four minutes yields a fair number of delays exceeding ten minutes. The average delay increases rapidly with movement rate beyond the point defined as capacity.

The relative time demands that carrier aircraft and general aviation aircraft place upon an airport can be measured in various ways. One way is to ask the question: If the average departure delay is kept constant, what is the trade-off between the movement rates of the various classes of aircraft? Since the main problem is the allocation of capacity at peak hours, we shall examine the trade-off when an airport is operating at "capacity". Thus, holding the average departure delay constant at four minutes per aircraft, we first obtain the movement rates shown in Table 1 for three intersecting runways (the configuration at Washington National Airport, for example).

The figures in Table 1 are obtained as follows. With all movements consisting of general aviation aircraft, capacity is reached at 101.5 movements per hour, as shown on line 1. If the population mix is 90–95 per cent general aviation, with the remainder Class B aircraft, capacity is reached at 92 movements per hour. Since the mean percentage ranges for this population mix are 92.5 per cent general aviation and 7.5 per cent Class B, the movement rate of 92 implies a movement of 85.1 general aviation aircraft per hour (0.925) (92) and 6.9 Class B aircraft per hour, as shown on line 2. The rest of the table is similarly derived. The data are plotted in Figure 2.

Initially, an increase in the movement rate of Class B aircraft of 6.9 requires a reduction of general aviation movements by 16.4. The trade-off is therefore

$$(1) \qquad \frac{\Delta C}{\Delta G} = \frac{6.9}{16.4} = 0.42 = \frac{\text{time demands of a } G \text{ movement}}{\text{time demands of a } C \text{ movement}}$$

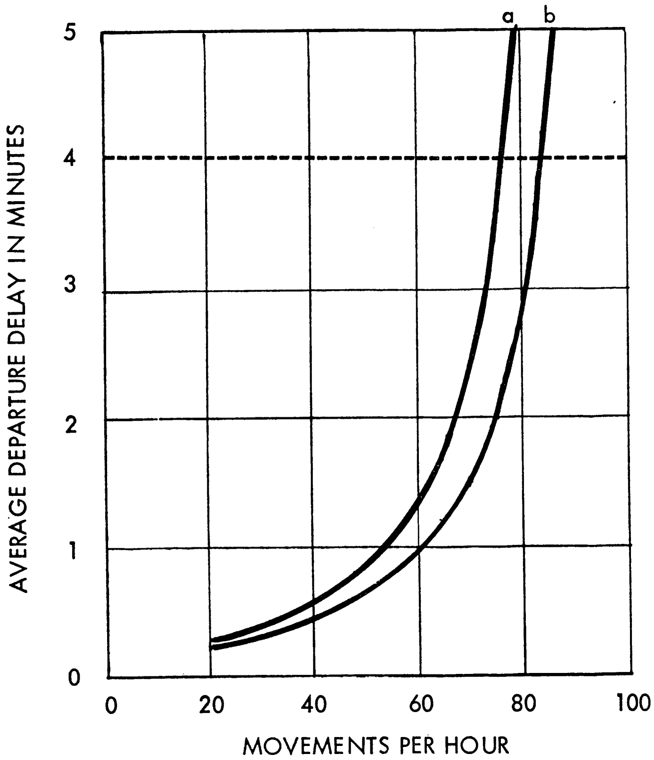
This equation defines the relative time demands of the two types, general aviation (G) and carrier (C).[2]

[1] *Airport Capacity*, prepared for the FAA by Airborne Instruments Laboratory, June 1963. The theory and the parameters of the models are presented in E. N. Hooton, H.P. Galliher, M.A. Warskow and K. G. Grossman, *Operational Evaluation of Airport Runway Design and Capacity*, prepared for the FAA by AIL, January 1963. Both are available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, U.S.A.

[2] Cf. Note 1.

Figure 1 Typical Graph from "Airport Capacity"

Visual Flight Rules, Mixed Operations
Three Intersecting Runways Only



Population Mix: A 0%; B 50–69%; C+D+E 50–31%

NOTE: "b" curve applies when ratio of landings to take-offs is low and only one runway is used for landing. "a" curve with landings on two of the three runways best characterizes Washington National Airport and is used below.

The relative time demands of general aviation aircraft to carrier aircraft are given in Table 2. This ratio increases as the proportion of carrier aircraft in the population mix increases, apart from a curious bump in the data at a trade-off of 0.66.[3]

[3]The trade-offs in Table 2 are for the case of an airport operating at a four minute average departure delay. At other levels of delay from two minutes to five minutes, the trade-offs are practically the same as in Table 2. At lower levels of delay, the relative time demands of small planes are less. At a one minute average delay, the numbers in Table 2 would range from 0.38 to 0.76; at a twenty second average delay, from 0.34 to 0.63.

Another way to picture this point is to consider that the typical trade-off for a 4 minute average delay is given by the slope of the curve in Figure 2 from vertical intercept to horizontal intercept, 73/101.5 = 0.72. For other levels of delay the slope is: 5 minutes, 75/103.8 = 0.72; 3 minutes, 70/98.5 = 0.71; 2 minutes, 64/92 = 0.70; 1 minute, 50/77.2 = 0.65; 20 seconds, 22.5/42.5 = 0.53.

TABLE 1

Capacity for three intersecting runways for various mixes of Class B and Class C, D, E Aircraft

TOTAL CAPACITY (movements/hr.)	CLASS B Percent	CLASS B No. of Aircraft/hr.	CLASS C, D, E Percent	CLASS C, D, E No. of Aircraft/hr.
101.5	0	0	100	101.5
92	5–10	6.9	95–90	85.1
86	11–24	15.0	89–76	71.0
83.5	25–34	24.6	76–66	58.9
79	35–49	33.2	65–51	45.8
76	50–69	45.2	50–31	30.8
73	70–100	62.1	30–0	10.9

Table 1 is from the report, *Economic Feasibility of Alternative Programs for Washington National Airport*, prepared for the FAA by Operations Research Incorporated, January 1966, Part II.

The source for the table is *Airport Capacity*, prepared for the FAA by Airborne Instruments Laboratory, June 1963: Figures 7–2 to 7–8, pages 7–5 to 7–11; "a" curve, four-minute average departure delay.

Class B includes mostly 4-engine propeller aircraft, but also smaller jets such as BAC-111 and Boeing 727, and 2-engine propeller planes such as CV-240 and CV-440.

Class C includes 2-engine planes such as Fairchild F-27, DC-3 and smaller aircraft.

TABLE 2

Trade-Off between Carrier and General Aviation Movements

Per Cent Carriers	ΔC/ ΔG	Relative Demands, General Aviation to Carrier
0– 7.5	6.9/16.4	0.42
7.5–17.5	8.1/14.1	0.57
17.5–29.5	9.6/12.1	0.79
29.5–42.0	8.6/13.1	0.66
42.0–59.5	12.0/15.0	0.80
59.5–85.0	16.9/19.9	0.85

This discussion of trade-offs and movement rates is in terms of aircraft size classes. The tower logs at Washington National Airport are in terms of air carrier (ACR) *vs.* non-air-carrier movements, but the categories correspond pretty closely: only about 5 per cent of the ACR planes are in Classes C, D, E. As an example, during June 1965, during the peak hours of 5–6 p.m. and 6–7 p.m., the number of movements on weekdays reached 70 and 75 movements per hour respectively (Table 3), and 63 per cent and 72 per cent of the movements were carrier movements, of which about 95 per cent are typically Class B. Hence operations were in a range where the trade-off is about 0.85.[4]

[4]In off-peak, but still busy, hours of the day, say from 7 a.m. to 12 noon, the relative time demands are less, ranging down to 0.63.

TABLE 3

Average number of Departures and Arrivals per hour in good weather (no ILS movements), June 1965, at Washington National Airport*

EASTERN DAYLIGHT TIME	WEEKDAY MOVEMENTS			WEEKEND MOVEMENTS		
	ACR	Non-ACR	Total	ACR	Non-ACR	Total
12–1 AM	7.8	2.1	9.9	5.0	1.5	6.5
1–2	3.5	1.1	4.6	3.0	1.9	4.9
2–3	2.9	0.6	3.5	1.9	0.7	2.6
3–4	1.4	0.2	1.6	0.8	0.4	1.2
4–5	3.8	0.4	4.2	3.7	0.5	4.2
5–6	6.2	1.1	7.3	5.8	0.6	6.4
6–7	7.5	2.2	9.7	8.3	1.0	9.3
7–8	22.2	6.9	29.1	15.3	3.4	18.7
8–9	35.4	19.8	55.2	22.9	8.1	31.0
9–10	38.5	23.1	61.6	25.7	11.3	37.0
10–11	37.0	18.9	55.9	27.1	12.6	39.7
11–12	35.4	20.0	55.4	27.4	15.5	42.9
12–1 PM	42.0	18.8	60.8	38.5	16.0	54.5
1–2	37.6	18.0	55.6	29.3	11.3	40.6
2–3	27.2	21.5	48.7	24.3	12.2	36.5
3–4	35.4	27.0	62.4	29.3	16.0	45.3
4–5	34.9	28.9	63.8	27.3	16.8	44.1
5–6	44.1	25.6	69.7	41.5	17.4	58.9
6–7	53.7	21.2	74.9	45.2	11.5	56.7
7–8	49.9	13.6	63.5	37.6	8.6	46.2
8–9	50.7	9.3	60.0	41.8	6.7	48.5
9–10	35.2	5.4	40.6	24.0	6.8	30.8
10–11	24.7	4.9	29.6	19.8	5.3	25.1
11–12	16.9	4.3	21.2	14.6	2.9	17.5
Total	653.9	294.9	948.8	520.1	189.0	709.1

Source: *Economic Feasibility of Alternative Programs for WNA*, page H-16. Compiled from tower logs.

*Figures are averages for the given hour over the month, provided the hour had good weather. "Bad weather" is defined as a situation in which there were instrument landings using the instrument-landing system (ILS).

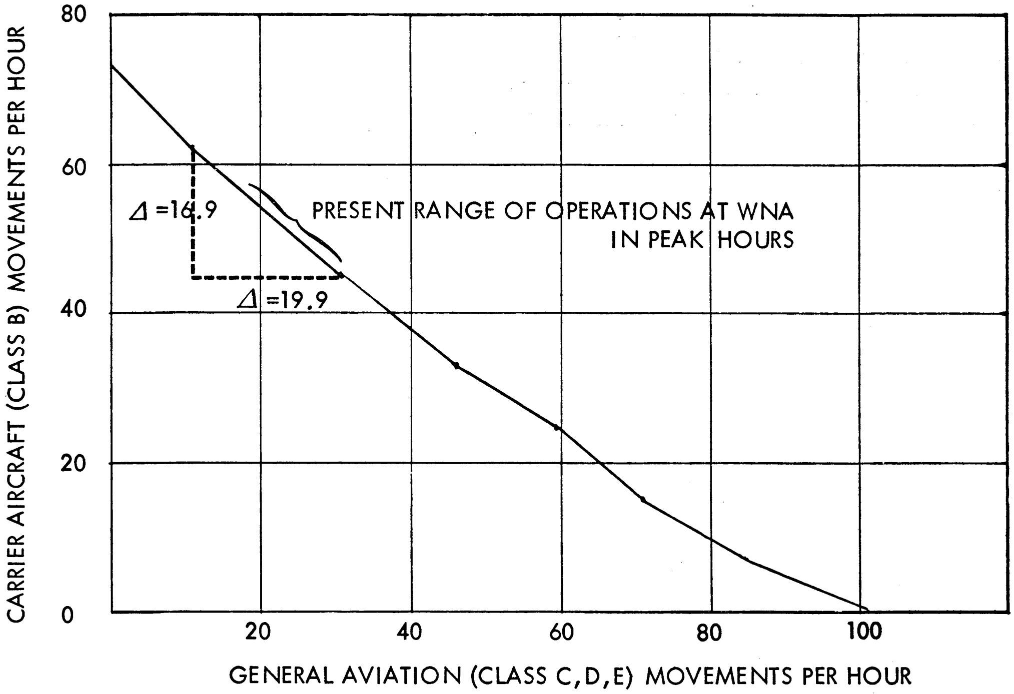
IMPLICATIONS FOR RELATIVE LANDING FEES

The time that a movement takes has an "opportunity cost" in that either (1) an additional aircraft movement increases the average delay for all aircraft or (2), if the average delay is not to be increased, an increase in the movement rate of one type must be accompanied by a decrease in the movement rate of another type. Either definition of opportunity cost is valid. The first has implications for the level of landing fees; the second has implications for the relative landing fees for small *vs.* large planes. For the present, we use the second definition. We are particularly concerned with peak hours, and assume that the carrier fees at such times are the correct ones; the point is discussed in the next section.

Figure 2 Alternative Movement Rates of Class B and Class C, D, E Aircraft at Capacity Operations (Av. Departure Delay = 4 Minutes)

In present Range of Operations:

Slope of Curve = Trade-Off = $\frac{16.9 \text{ Class B}}{19.9 \text{ Class C,D,E}} = 0.85$ Source: Table 1



In the example given above, to increase the movement rate of general aviation aircraft by one movement per hour, keeping the average delay constant, the movement rate of carrier aircraft would have to be reduced by 0.8 aircraft per hour. Thus, the opportunity cost of landing a small plane is 0.8 as much as that of a large plane. The landing fees paid by the small planes are in a much smaller ratio than this to those paid by carriers. Thus, a small plane might weigh 12,000 pounds compared with 100,000 pounds or so for a large piston aircraft, and hence pay landing fees 0.12 of those paid by the carrier. The ratio of landing fees is very different from the relative time demand of 0.8 taken as an example.

To indicate what this implies in terms of dollars, the landing fee rate at Washington National Airport is 14.5¢/1,000 pounds of gross weight for piston aircraft and 32¢/1,000 pounds for jet aircraft, implying a landing fee of about $2 for a small plane, $15 for a large piston aircraft, and $32 for a jet. Or, to look at it another way, the landing fee for the small plane is about $2, compared with an opportunity cost of

$12. At a $12 landing fee for peak hours, a general aviation aircraft owner would probably begin to consider alternative airports or a shift to off-peak hours.

A more dramatic example is New York, where the landing fee at LaGuardia is 95¢/1,000 pounds, so that a small plane of 12,000 pounds pays $11.40. For LaGuardia, since the runway configuration is different from that at WNA (in particular, a special runway has been built for general aviation aircraft to reduce the effect on carrier movement capacity), the relative time demands may also be different; but, if the tradeoff were 0.8, the opportunity cost of carrying out the general aviation movement would be $76. If a new general aviation landing fee of $50, say, were charged at peak hours, a considerable portion of the demand might be shifted to commercial flights or to off-peak hours or to other airports.[5]

Some qualifications have to be made. It may be that landing fees should not be based simply on relative time demands. Smaller aircraft may cause less wear and tear on the runways; the landing fees may cover also certain parking costs which are related to the size of the aircraft. These differences in other costs have to be considered in setting landing fees. It does appear, however, that general aviation aircraft make inordinate time demands on the major airports by comparison with their landing fees.

THE LEVEL OF LANDING FEES

It is of interest to see what guidance economic analysis might provide in determining the correct *level* of landing fees.

The essential feature of congested facilities is that a user imposes costs on others – an external diseconomy. Thus, the marginal highway user imposes an increased travel time on other highway users. The total extra delay caused by an additional aircraft movement includes the delay the user incurs himself, plus that imposed on others. He "pays" the first cost, but not the second. The economic theory of congestion indicates that, if the user is not required to take into account the cost he imposes on others, a facility will be over-used. Efficient use of congested facilities can be brought about, however, by including in the fee a "congestion toll" equal to the cost of the delay that the marginal user imposes on others – the marginal external delay.

Thus, in place of the "trade-off" definition of opportunity cost, we can define opportunity cost in another way, as the costs which vary with an additional aircraft movement – the marginal operating costs and the cost of marginal external delay. At present, landing fees seem generally to be based on the average cost of the landing

[5]Forecasts of general aviation activity, such as those issued by the Port of New York Authority, do not usually contemplate changes in landing fees. Yet, if the cost of providing capacity is actually taken into account and landing fees revised, the forecast increase in general aviation traffic might be substantially affected.

In the WNA study (*Economic Feasibility* . . . Appendix I), the forecast is made that an increase in carrier movements at an airport will result in a decrease in general aviation movements, but no mechanism is suggested to explain why the decrease will occur (increased delay time, increased landing fees?).

area (capital costs, maintenance costs, and overhead), omitting Federal grants for airport construction, local property taxes, and air traffic control costs. For efficient airport use, fees would be equal to the *marginal* cost of operating the landing area (which is likely to be less than the average cost), and would also include the cost of the marginal external delay.

The delay that the marginal user imposes on others varies between small planes and large ones; and – for the moment neglecting operating costs – if landing fees were set equal to the cost of the marginal external delays, they would be in the same ratio as determined above (see Note 2). Since the level of marginal external delays varies with the movement rate, the level of fees would vary between peak and off-peak periods; the ratio of fees for small to those for large planes might become somewhat lower in off-peak hours.

Preliminary analysis suggests that external delay costs during peak hours are substantial, and that, at such times at least, the landing fees for small planes should be raised. In addition, perhaps the level of fees for both large and small planes should be raised at peak hours.

POSTSCRIPT

Since this paper was written in the summer of 1967, landing fees for small planes in three metropolitan areas (Washington, New York and Boston) have been increased by an increase in the minimum landing fee. In Washington and Boston, minimum fees have been increased from $0.05 and $1.50 to $4 and $5 respectively, and apply all the time. In New York, the increase in the minimum landing fee from $5 to $25 applies during peak hours, and is therefore of interest as a step towards a fee based on congestion costs.

In comparison with the fees implied by the trade-off analysis based on AIL graphs, the new minimum fees appear rather modest, but they will probably have some effect. The increase in New York went into effect on 1 August. During July and August delays were particularly severe, because of an air controllers' slowdown. The delays may have discouraged general aviation traffic, so that it is difficult to estimate the separate effect of the higher fee. But it is of interest to note the "private plane traffic had dropped 17 per cent at Kennedy in August, compared with July, and 25 per cent at LaGuardia" (*N.Y. Times*, 25 September 1968).

NOTES

1. The relative time demands can be explained more fully by considering that the AIL results define, for a given runway configuration,

(A.1) $D = f(C, G)$

where D = average departure delay
C = carrier movements per hour
G = general aviation movements per hour.

By setting $D = 4$ minutes, we select a set of points which satisfy

(A.2) $dD = f_C \Delta C + f_G \Delta G = 0$

where dD is the change in average delay, f_C and f_G are partial derivatives. Hence,

(A.3) $$\frac{\Delta C}{\Delta G} = -\frac{f_G}{f_C}$$

Hence the relative time demands as defined in the text by Equation (1) can be thought of as the ratio of partial derivatives f_i, where f_i is the increase in average departure delay caused by an additional movement of type *i*.

2. The opportunity cost of an aircraft movement can also be defined in terms of the increase in the total delay to all aircraft caused by an additional carrier or general aviation movement. Since landing fees cover a landing and a take-off, we calculate the marginal delay caused by two movements.

Delays are assumed to be incurred only by departing aircraft, so the total delay in an hour:

$$\text{Total delay} = P\,D$$

where

$$P = \text{number of departures per hour of any type plane.}$$

Assume a general aviation plane lands and takes off in equally busy hours. Its landing will not change P, but will increase the average delay to the departing aircraft by f_G, causing the extra delay

$$P\,f_G.$$

Without going to a more refined notation, when the G movement is a take-off, $\partial P/\partial G = 1$. The general aviation take-off will therefore cause the marginal delay

$$\frac{\partial}{\partial G}[P\,D] = \frac{\partial P}{\partial G}D + P\,f_G = D + P\,f_G.$$

Hence, the marginal delay caused by an additional general aviation plane landing and taking off[6] is

$$D + 2P\,f_G.$$

Assuming the departure rate P is half the movement rate (M), the marginal delay caused by a general aviation landing and takeoff is

$$D + M\,f_G.$$

By the same reasoning, the marginal delay for a carrier plane is

$$D + M\,f_C.$$

In each case, D is the delay incurred by the aircraft itself when it takes off, and the marginal external delays are $M\,f_G$ and $M\,f_C$ minutes. According to congestion theory, user fees should include the cost of these external delays to the persons and airplanes being delayed. Depending on the mix of aircraft being delayed, the cost of the delay will vary. However, the point of the derivation is that, with a given mix of aircraft being delayed, large planes and small planes will cause external costs in proportion to the derivatives f_C and f_G, and hence would be charged congestion fees in proportion to the derivatives.

Boston University

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[6]Really, the rate at which delay is added per trip, for infinitesimal increases in the number of trips.