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UNITED STATES and EUROPEAN Airport Capacity Assessment using the GMU Macroscopic Capacity Model (MCM)

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Abstract

This paper uses the George Mason University Macroscopic Capacity Model (MCM) to compare capacity factors between United States and European Air Transportation Systems. To limit the complexity of modeling all the airports, 16 airports from both areas are used. For the United States the airports selected represent 7.6 million operations per year in an airspace volume similar to that of Europe. The 16 European airports used represent 4.3 million operations per year. Aircraft separation is the main factor that determines capacity and therefore delay. In the United States, separation in the arrival queue has been observed to be a limiting condition most of the time. These arrival queues can effectively propagate into enroute airspace for hundreds of miles, exacerbating enroute sector loading problems. It is observed that European airports do not seem to be as heavily loaded as in the US, but the enroute delays seem to be comparable.

Background

International air transport is the fastest growing segment of transportation. This can be partially attributed to a combination of market trends and institutional reforms combined with rising incomes and increased leisure time. Air passenger traffic since 1960 has grown worldwide at an average yearly rate of 9 percent with freight and mail traffic growing at 11 percent and 7 percent respectively. In 1995, some 1.3 billion passengers were carried by the world's airlines. For European air passenger traffic growth, the projected annual growth rate is 5.2 percent between 1993 and 2000, 4.2 percent between 2000 and 2005, and 3.8 percent between 2005 and 2010 (ATAG, 1996). This growth is graphically displayed for the top 16 European airports analyzed in this study (representing 78 percent of total European passenger transport) in Figure 1.

In addition to passenger transport, air transportation has become an important form of freight transport. Freight traffic is predicted to grow at 30 percent over the same time. The International Civil Aviation Organization (ICAO) estimates that over 30 percent of world trade by value is transported by air with forecasts of it rising another 400 percent by 2015.

This continued rise in air transport activity has placed enormous pressure on the finite capacity of the air transportation system. In particular, the effect of reaching capacity limits has caused the number and length of air

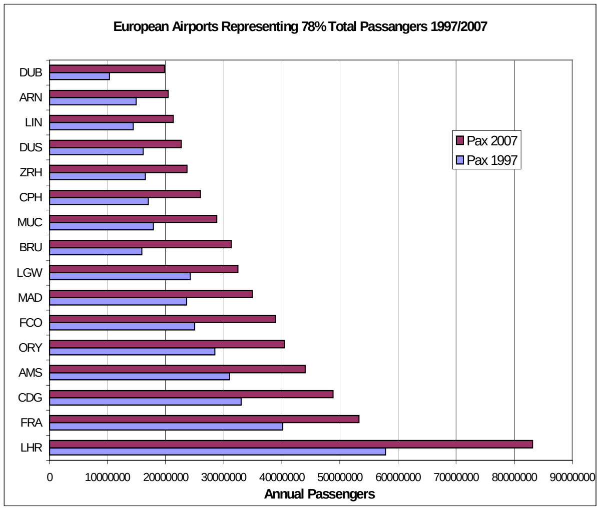

Figure 1. Current and Projected enplanement at the 16 European Airports used in this study.

transportation delays to increase. This could affect future economic growth, especially for export-oriented economies such as Germany (Huttig, Busch, & Gronak, 1994). Therefore, understanding delays and their relationship to capacity becomes very important (Reynolds-Feighan and Button, 1999).

There are a number of high resolution models available[1] that will assist in the understanding of the factors involved with capacity and delays. These models provide a detailed analysis, but require significant amounts of data that are sometimes difficult to obtain. Learning to use these models takes considerable time and effort limiting their use to specialized individuals.

This paper will focus on the Macroscopic Capacity Model (MCM) (Donohue, 1999a), developed at George Mason University, that takes a "simpler" approach to analyze the expected capacity limitations of airports while using aggregate data. Having a reduced "data dependent" model will allow greater access for initial capacity/delay analysis. The work being done on this model will be of benefit to policy makers who are responsible for making national and/or local air transportation systems decisions and for those responsible for measuring the air transportation systems operational capacity.

The remainder of this paper will briefly discuss the methodology used by the MCM. Thirty-two "high-density" United States and European airports will be analyzed and compared using the MCM. The final section concludes with a utility analysis of the European air transportation system compared to the United States air transportation system.

The MCM Approach

The MCM is designed to estimate the maximum capacity of national air transportation regions. The model is based on empirically observed aircraft arrival rates; government published annual operational rate statistics, and analytically derived airport arrival and departure functions. This is a simple model based on aggregating the effects modeled in a number of airport capacity and delay simulation models (Odoni et al., 1997).

The MCM assumes that the air transportation system can be modeled as a network of queues in equilibrium whose maximum capacity is the sum of twice the maximum airport arrival rates[2], less airspace human factors limitations. This underlying theory of modeling the air transportation system as a queuing problem has been incorporated into both the LMI model (Long, et. al., 1999) and the MITRE Decision Policy Analysis Tool (DPAT) model (Wieland, 1999).

The MCM model approach is much like highway engineering and communications theory (Sheffi, 1985).Knowing the maximum capacity has much to offer in gaining theoretical insight into the air transportation problem. The MCM model for system maximum capacity can be expressed as:

$$\mathbf{C_{max} = 2 \text{ x } C_{AR\,MAX}\; S\, \Sigma_i\; (XGR)_i \\ -\; C_{AS\,MAX}\, \Sigma_K\; A_K.}$$

where,

$$\mathbf{A_K = (A/C_{REQUEST} - A/C_{ACCEPT}) \,/\, C_{AS\,MAX.}}$$

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[1] LMINET, DPAT, TAAM, and RAMS models in particular.

[2] In equilibrium the total mix of operations is 2 x arrivals. Arrival rates are typically less than departure rates.

The factor R_i is the number of runways at the i^{th} airport, X_i is an airport runway design efficiency factor, and G_i is the gate utilization factor. The variable S is an aircraft separation factor[3], largely independent of airport.

The second term in this equation represents human factor limitations in the enroute airspace. It will be seen that this term can be significant in high capacity airspace such as Europe and the Northeast Triangle of the United States. The factor A_K is the receptivity factor for the K^{th} sector and ideally should be minimized.

The term $A/C_{REQUEST}$ = number of aircraft requesting sector entry and A/C_{ACCEPT} = number of aircraft granted sector entry (i.e. not restricted via a ground delay program or holding pattern).

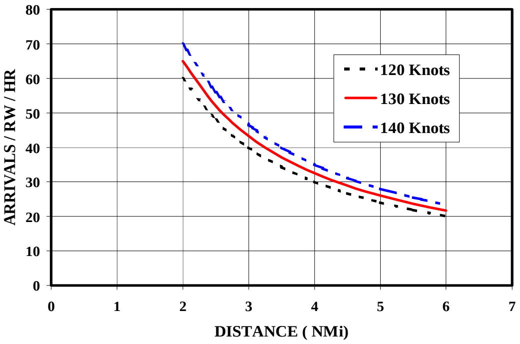

Figure 2. Runway Arrival Rate as a function of aircraft spacing.

The factor $C_{AR\ MAX}$ is estimated to be 64 aircraft arrivals/hour[4] as shown in Figure 2. The factor $C_{AS\ MAX}$ represents the maximum number of aircraft per hour in a sector (approx. 120)[5].

MCM Validation

It is difficult to validate any model. One way of validation is to see how predictions of a model correlate with empirically derived dependent variables and theoretical correlations. To evaluate whether or not this macro-capacity model formulation is reasonable, we examine how well delay is correlated with airport capacity ratio predictions from established models. Comparing the MCM results to that of the DPAT model has provided a preliminary evaluation of the MCM (Donohue & Shaver, 2000). Although different parameters are computed, the results were consistent in predicting delay growth, suggesting that the MCM captures the essence of the ATM system behavior as represented in a more highly detailed model.

MCM Assessment of United States and European Airports

An analysis of the air transportation capacity in the United States and Europe using the MCM has been conducted to compare relative operational efficiency using a common macro capacity model. The data used for the United States came from the ACE plan and 1997 CODAS data. From this data, a sample of 16 airports was selected representing 7.6 million operations per year in an airspace volume similar to that of Europe.

European data came from the ATAG (1996). An equal sample of 16 airports was used representing 4.3 million operations per year (over 78 percent of total European air transportation operations). Annual operational rates were divided by 350 days and 16 hours/day to determine peak hourly operational rates for both United States and European airports (Donohue, 1999b).

Based on this analysis, MCM estimated that the Northeast Triangle[6] of the United States is currently operating at 74 percent of maximum capacity as shown in Table 1 and will be at 89 percent capacity by 2012 (Table 2).

Using this same definition of capacity, European capacity is estimated to be currently at 40 percent of maximum capacity if the average final approach spacing is assumed to be 4 nmi[7] (Table 3). Estimating capacity fraction for 2007 resulted in 55 percent capacity fraction, respectively (Table 4).

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[3] S= 0.5 at 4.0 nmi separation, roughly current technology limit.

[4] This represents approximately 2 nautical mile separation on final approach at 130 kts.

[5] This assumes a 15 second entry and exit acknowledgment without data link.

[6] A 1000 nautical mile triangle from Boston to Minneapolis to Tallahassee, Fl. Donohue, Journal of ATC, June, 1999.

[7] 4 nmi. spacing equates to approximately 32 operations per runway per hour.

Figures 3 and 4 illustrate the relative efficiency of these airports as a function of the number of runways (normalized for runway and gate efficiency). Note that all of these airports are operating at less than maximum capacity. Queuing theory would suggest that the maximum capacity will never be reached for a random access queue but that mean delays will increase hyperbolically above a capacity fraction of 50%.

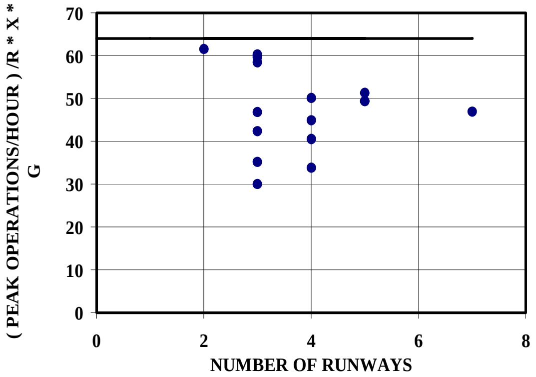

Figure 3. Comparison of 16 US Airports in the utilization of Runway Capacity (OPS/RW/HR) normalized for runway and gate efficiency.

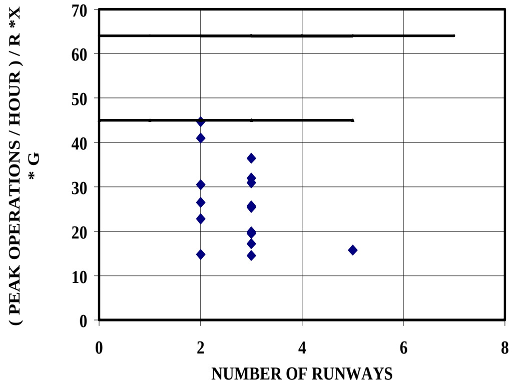

Figure 4. Comparison of 16 European Airports utilization of runway capacity OPS/RW/HR normalized for runway and gate efficiency.

If the Air transportation system can be approximately modeled as the sum of airport queues, then delay at any particular airport would be predicted to grow as:

$$\textbf{Delay} \approx 4\{\%\ AP_{CAP}\ /\ (1 - \%AP_{CAP})\}$$

where $\%AP_{CAP}$ is the predicted airport capacity fraction and 4 is observed to be approximately equal to the mean number of US delays greater than 15 minutes per 1000 operations at 50% capacity fraction. Both the airline reported delays and the model predictions are listed in Table 1 and shown in Figure 5.

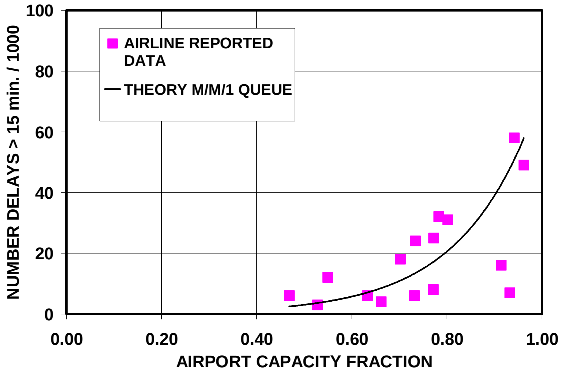

Figure 5. Comparison of Airline reported delays at 16 Major US airports compared to M/M/1 queuing theory prediction.

Similar data are not available for the European airports considered but are available in delay minutes per movement (Eurocontrol, 1999). For that reason US delays in minutes were plotted using CODAS data for 1997 and shown in Figure 6. Since the units of delay are now minutes of delay per movement, the equation becomes:

$$\textbf{Delay} \approx \textbf{1min/mv}\{\%AP_{CAP}\ /(1\%AP_{CAP})\}.$$

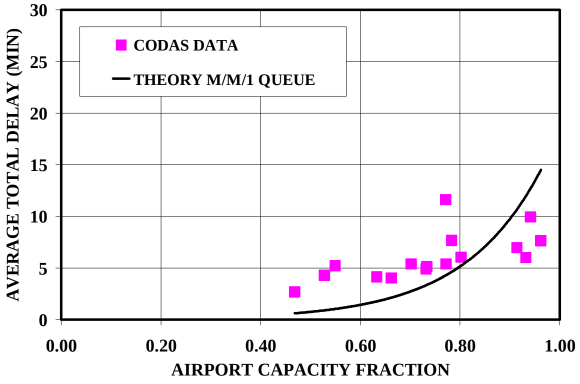

Figure 6. Comparison of CODAS reported delays at 16 Major US airports compared to M/M/1 queuing theory prediction.

Both the EUROCONTROL reported delays and the model predictions are listed in Table 3 and illustrated in Figure 7. Comparing the reported delay to airport M/M/1 queuing predictions show a different outcome than the United States.

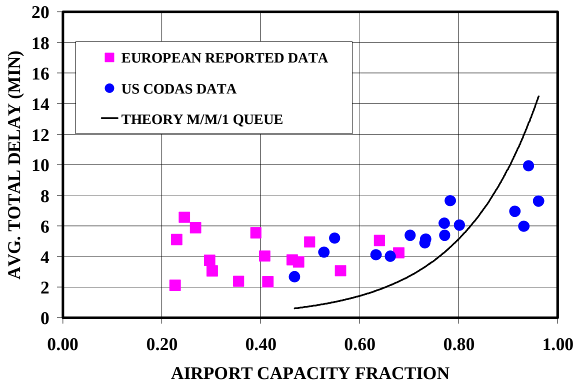

Figure 7. Comparison of reported delays at 16 Major European airports compared to US CODAS data and queuing theory prediction at 4 nmi separation.

MCM Comparisons

From earlier analysis (Donohue and Shaver, 2000) and the data shown in the previous section, a number of observations can be made. For the United States, air transportation system capacity seems to be largely airport queue limited. The 16 airports selected out of the Northeast Triangle also indicate that delays are higher at moderate capacity fractions indicating that congested airspace is also leading to delays in this region of the United States.

Results from the European airports analyzed indicate a different situation. Capacity does not follow the M/M/1 predicted levels. Figure 7 illustrates this showing that delays are significant even at airports that are operating at low capacity fractions. This would suggest that externalities outside of the airport environment are causing delays. To determine with greater precision the factors causing this would require further analysis.

A macroscopic observation may be suggested, however. Due to the historically based random access / random service (i.e. First In First Out – FIFO) nature of air traffic control, delays are very sensitive to demand/capacity ratios above 50 percent. For Europe, with airport capacity remaining constant, it has been observed that a one percent increase in demand generates approximately six percent increase in ATM delays (EUROCONTROL, 1999b). In an earlier paper, Fron (1998) has postulated that a system relationship exists between demand and delays for Europe that show an elasticity of five between demand and delays. Queuing theory would imply that, overall, Europe is operating at 60%[8] of system capacity, compared to 40% as predicted by the model considering airport capacity alone. This would imply that 20% of the potential capacity of the European air transportation system is lost to enroute inefficiencies.

Conclusion

This paper has focused on the MCM and its use as a reliable macro-capacity model to be used as an initial level of air transportation capacity analysis. In the first section of the paper the MCM was described and evaluated as a model able to predict capacity levels using aggregate data. The next section assessed the MCMs' capability by using data from 32 high-density airports in the United States and Europe.

It is observed that the United States is achieving a higher utilization of existing runway infrastructure and possibly enroute airspace than is Europe (i.e. up to 30 aircraft per runway per hour vs. 20 aircraft per runway per hour). Also, it is observed that the United States has constructed more runways at its major airports but has invested in far less gate and terminal infrastructure, which is becoming a limitation at some US airports (i.e. US gate to runway ratio of 26 vs. a European ratio of 42). In addition the European airport designs are in general more efficient that the older US designs found in the Northeast Triangle (i.e. US average X factor equals 0.52 whereas the equivalent European X factor equals 0.73).

For the European airports selected, the MCM indicated an adequate capacity margin at the airports even though overall delays are increasing (EUROCONTROL, 1999a). This result may not be due to the inadequacy of the MCM, but factors external to the airports themselves. These factors are represented in the

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[8] d(Delay)/d(%Cap) = 0.064 at %Capacity = 60%.

model's second term that represents enroute airspace capacity degradation.

Hüttig, et. al. (1994) has stated, "The inconsistent development of air traffic and airport capacity (in Europe) is the reason for the looming capacity crisis..." This is supported in that delays on the ground imposed by the CFMU result from insufficient sector capacity at certain control centers. In 1996, 15 percent of control centers were responsible for 90 percent of ATM related delays (Fron, 1998). EUROCONTROL has stated that a small number of sectors (i.e. fifteen sectors, roughly 3 percent) caused about 45 percent of the ATM delays during the summer of 1998 (EUROCONTROL, 1999a). In 1999, 44 percent of ATM delays originated from a demand/capacity mismatch in 30 sectors out of 468 sectors (EUROCONTROL, 1999b). This may be one cause for reactionary delays, i.e. late departures due to late arrivals, that are the largest single category of departure delay causes (EUROCONTROL, 1999b).

Airport capacity in Europe may be determined more by operational norms than by physical airport runway capacity. These operational norms appear to be more conservative than those used in the US. Overall capacity may possibly be set artificially lower than can actually be safely achieved.

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TABLE 1. Capacity and Delay Parameters for 16 US Airports in the NE Triangle

US NE TRIANGLE MCM ANALYSIS - 4 N.MI. SEPERATION (1997)										
AIRPORT	# R/W	GATES	G	X	TOTAL OPS/YR FAA 1997	MCM MAX EST.@ 4 nmi.	PEAK OPS/HR FAA 1997	CAPACITY FRACTION	PREDICTED DELAY	REPORTED DELAY
CHICAGO (ORD)	7	173	0.97	0.5	892,665	217	159	0.73	11	24
ATLANTA(ATL)	4	180	1	0.7	785,854	179	140	0.78	14	32
DETROIT(DTW)	5	99	0.99	0.4	547,350	127	98	0.77	13	8
ST. LOUIS(STL)	5	86	0.92	0.4	528,746	118	94	0.80	16	31
MINNEAPOLIS(MSP)	3	73	0.9	0.55	496,091	95	89	0.93	55	7
CHARLOTTE (CLT)	3	62	0.86	0.7	473,800	116	85	0.73	11	6
BOSTON(BOS)	5	88	0.95	0.36	473,127	109	84	0.77	14	25
NEWARK(EWR)	3	92	0.97	0.47	461,500	88	82	0.94	64	58
PITTSBURGH(PIT)	4	122	1	0.6	454,259	154	81	0.53	4	3
PHILADELPHIA(PHL)	3	63	0.86	0.5	422,493	83	75	0.91	42	16
CINCINNATI(CVG)	3	120	1	0.7	413,579	134	74	0.55	5	12
NEW YORK(JFK)	4	180	1	0.36	362,305	92	65	0.70	9	18
LA GUARDIA(LGA)	2	60	0.92	0.55	348,854	65	62	0.96	101	49
WASHINGTON DULLES(IAD)	3	78	1	0.67	337,383	129	60	0.47	4	6
WASHINGTON REAGAN(DCA)	3	48	0.93	0.47	311,105	84	56	0.66	8	4
CLEVELAND(CLE)	4	50	0.92	0.36	300,620	85	54	0.63	7	6
TOTAL	61	1574			7,609,731	1873	1359			
AVERAGE				0.52				0.74	24	19
MEDIAN								0.75	12	14
STANDARD DEVIATION								0.15	28	17

TABLE 2. Predicted Delay increases for 16 US Airports using FAA forecast for 2012. Some airports are predicted to be unable to meet forecast demand. The overall Capacity Fraction for this region is predicted to increase to 89% +/- 13%.

US NE TRIANGLE MCM ANALYSIS - 4 N.MI. SEPERATION (2012)										
AIRPORT	# R/W	GATES	G	X	TOTAL OPS/YR FAA 2012	MCM MAX EST.@ 4 nmi.	PEAK OPS/HR FAA 1997	CAPACITY FRACTION	PREDICTED DELAY	REPORTED DELAY
CHICAGO (ORD)	7	173	0.97	0.5	1,110,000	217	198	0.91	42	
ATLANTA(ATL)	4	180	1	0.7	985,000	179	176	0.98	213	
DETROIT(DTW)	5	99	0.99	0.4	700,000	127	125	0.99	291	
ST. LOUIS(STL)	5	86	0.92	0.4	655,000	118	117	0.99	588	
MINNEAPOLIS(MSP)	3	73	0.9	0.55	530,000	95	95	1.00	953	
CHARLOTTE (CLT)	3	62	0.86	0.7	613,000	116	109	0.95	72	
BOSTON(BOS)	5	88	0.95	0.36	527,000	109	94	0.86	25	
NEWARK(EWR)	3	92	0.97	0.47	485,000	88	87	0.99	374	
PITTSBURGH(PIT)	4	122	1	0.6	590,000	154	105	0.69	9	
PHILADELPHIA(PHL)	3	63	0.86	0.5	460,000	83	82	0.99	788	
CINCINNATI(CVG)	3	120	1	0.7	716,000	134	128	0.95	78	
NEW YORK(JFK)	4	180	1	0.36	415,000	92	74	0.80	16	
LA GUARDIA(LGA)	2	60	0.92	0.55	360,000	65	64	0.99	533	
WASHINGTON DULLES(IAD)	3	78	1	0.67	437,000	129	78	0.61	6	
WASHINGTON REAGAN(DCA)	3	48	0.93	0.47	329,000	84	59	0.70	9	
CLEVELAND(CLE)	4	50	0.92	0.36	415,000	85	74	0.87	28	
TOTAL	61	1574			9,327,000	1873	1666			
AVERAGE				0.52				0.89	252	
MEDIAN								0.95	75	
STANDARD DEVIATION								0.13	309	
OFFICIAL FAA OPS/YR REDUCED TO NOT EXCEED PREDICTED MAXIMUM										

TABLE 3. Capacity and Delay Parameters for 16 European Airports at 4 nmi separation.

EUROPEAN MCM ANALYSIS - 4 NMI AND 6 NMI (1997)											
Airport	R/W	Gates	S	G	X	PROJECTED	MCM MAX	PEAK OPS/HR	CAPACITY	PREDICTED	REPORTED
			4nmi			OPS/YR	EST. @ 4 NMI	1997	FRACTION	DELAY	DELAY
						IATA 1997	.		4 NMI	4 NMI	ADM[1]
Heathrow	3	172	0.5	1.00	0.71	428,600	136	77	56%	1	3
Rheim/Main	3	145	0.5	1.00	0.76	389,600	146	70	48%	1	4
Charles De Gaulle	2	193	0.5	1.00	0.77	374,998	99	67	68%	2	4
Schiphol	5	144	0.5	1.00	0.80	353,000	256	63	25%	0	7
Orly	3	103	0.5	1.00	0.77	250,000	148	45	30%	0	3
Leonaro Da Vinci	3	72	0.5	1.00	0.77	245,757	148	44	30%	0	4
Barajas	2	93	0.5	1.00	0.55	252,400	70	45	64%	2	5
Gatwick	2	90	0.5	1.00	0.71	207,679	91	37	41%	1	4
Brussels National	3	107	0.5	1.00	0.66	277,006	127	49	39%	1	6
Munich	2	83	0.5	1.00	0.77	255,948	99	46	46%	1	4
Copenhagen	3	128	0.5	1.00	0.63	280,800	121	50	41%	1	2
Zurich	3	60	0.5	1.00	0.50	268,352	96	48	50%	1	5
Dusseldorf	3	67	0.5	1.00	0.65	187,549	125	33	27%	0	6
Linate	2	35	0.5	1.00	1.00	165,283	128	30	23%	0	5
Arlanda	2	264	0.5	1.00	1.00	255,000	128	46	36%	1	2
Dublin	3	95	0.5	1.00	0.55	134,300	106	24	23%	0	2
TOTAL	44	1851				4,326,272	2022	773		.	.
AVERAGE					0.73				40%	1	4.10
MEDIAN									40%	1	3.91
STANDARD DEVIATION									0.14	0.5	1.3
Note 1. Average Delay per Movement data from EUROCONTROL Annual Report 1998											

Table 4. Predicted Delay increases for 16 European Airports using IATA forecast for 2007.

EUROPEAN MCM ANALYSIS - 4 NMI AND 6 NMI (2007)											
Airport	R/W	Gates	S	G	X	PREDICTED	MCM MAX	PEAK OPS/HR	CAPACITY	PREDICTED	PROJECTED
			4nmi			TOTAL OPS/YF	EST. @ 4 NMI	2007	FRACTION	DELAY	DELAY
						2007	.		4 NMI	4 NMI	(ADM)[1]
Heathrow	3	172	0.5	1.00	0.71	634,433	136	113	83%	5	4.62
Rheim/Main	3	145	0.5	1.00	0.76	461,100	146	82	56%	1	5.48
Charles De Gaulle	2	193	0.5	1.00	0.77	533,739	99	95	97%	29	6.38
Schiphol	5	144	0.5	1.00	0.80	520,056	256	93	36%	1	6.57
Orly	3	103	0.5	1.00	0.77	250,000	148	45	30%	0	4.59
Leonaro Da Vinci	3	72	0.5	1.00	0.77	351,529	148	63	42%	1	5.64
Barajas	2	93	0.5	1.00	0.55	392,487	70	70	100%		8.03
Gatwick	2	90	0.5	1.00	0.71	243,360	91	43	48%	1	6.05
Brussels National	3	107	0.5	1.00	0.66	363,000	127	65	51%	1	8.43
Munich	2	83	0.5	1.00	0.77	357,000	99	64	65%	2	5.69
Copenhagen	3	128	0.5	1.00	0.63	415,653	121	74	61%	2	3.53
Zurich	3	60	0.5	1.00	0.50	397,227	96	71	74%	3	7.43
Dusseldorf	3	67	0.5	1.00	0.65	238,925	125	43	34%	1	8.84
Linate	2	35	0.5	1.00	1.00	244,659	128	44	34%	1	7.67
Arlanda	2	264	0.5	1.00	1.00	298,000	128	53	42%	1	3.57
Dublin	3	95	0.5	1.00	0.55	168,524	106	30	28%	0	3.17
TOTAL	44	1851				5,869,692	2022	1048		.	.
AVERAGE					0.73				55%	3	5.98
MEDIAN									49%	1	5.87
STANDARD DEVIATION									0.23	7.3	1.8
Note 1. Average Delay per Movement data from EUROCONTROL Annual Report 1998											