Operational Evaluation of Traffic Management Advisor Using Statistical Performance Metrics and Simulation Approach

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The Traffic Management Advisor (TMA) is an air traffic management automation tool designed to allow more aircraft to land during the peak arrival periods by increasing the airspace capacity and minimizing delay via better scheduling, spacing, sequencing, and runway allocation of arrival traffic. This paper evaluates the TMA's operational performance at George Bush Intercontinental airport in Houston over three daily selected rush-hour periods in the pre- and post-TMA deployments, using both the conventional and newly proposed performance metrics. The performance metrics used for the statistical analysis include: flight distances flown during transition from en route to terminal airspace, runway arrival distributions, and airport arrival traffic distributions. The results obtained from the analysis show that TMA improves the characteristics of arrival air traffic by better runway balancing, improved airport arrival throughput, and more evenly distributed airport arrivals. In addition to the statistical analysis, a model is developed to simulate aircraft transit between arrival arcs and meter fixes, queuing, and runway arrivals during a selected rush hour period in the post-TMA era.

INTRODUCTION

The current growing air traffic demand in the United States has contributed to increased congestion and costly delays. Airports may

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experience severe congestion when traffic demand exceeds available capacity. In 1991, twenty-three of the country's largest airports reported more than 20,000 hours of annual flight delay. This translates into an average annual loss of $32 million for each of these airports, based on an average airport direct operating cost of $1,600 per hour delay [1]. Due to widespread concerns over delays in the National Airspace System (NAS), the Federal Aviation Administration (FAA) decided to develop automation tools that would help manage and improve the increased flow of traffic. These concerns led to the establishment of the Free Flight Program (FFP) in 1998 [2]. The Free Flight concept, among other benefits, introduced automation tools intended to maintain safe distance between planes while reducing the control workload, without violating safety procedures. The overall goal of the new design is to optimally meet the need of growing air traffic demands via the establishment of an effective airspace structure. The Traffic Management Advisor (TMA), borne out of these design paradigms as one of five basic automation tools, is a decision support tool that allows Traffic Coordinators to efficiently schedule aircraft arrivals.

Prior to the deployment of TMA, the En Route Metering (ERM) program and the Arrival Sequencing Program (ASP) were deployed as the first and second generation time-based metering tools, respectively. The ASP and ERM were developed and deployed at several Air Route Traffic Control Centers (ARTCC) in the western part of the United States, such as the Fort Worth Center, to improve the flow of arrival traffic to the Terminal Radar Approach Control (TRACON) airspace at major airports (e.g. Dallas Fort Worth International Airport). Although the ASP and ERM showed promise of realizing the operational efficiencies that encouraged their development, neither could be successfully transferred to operate in two key facilities, namely the New York and Washington Center airspaces, where the need to minimize congestions and delays was vital for efficient airport operations in these tightly-constrained northeast corridors. TMA was introduced to replace its predecessors and improve the degree of compatibility with the existing National Airspace System (NAS).

With the recorded success of TMA's implementation at Dallas/ Forth Worth, its deployment was effected at many other sites, such as Miami (MIA), Los Angeles (LAX), Oakland (SFO), Minneapolis (MSP), Atlanta (ATL), and Denver (DEN). Since the FAA is in the process of deploying TMA NAS-wide (i.e. to all 20 ARTCCs), the need arises for more research to help capture the performance/benefit of the TMA in measurable terms, and hence create an enabling environment for continuous improvement. To meet the need of TMA assessment, starting from the benchmark paper by Swenson et al. [3], several analysis studies have been reported. The evaluation conducted in [3] includes thirty-nine rush traffic periods during a one-month period in the summer of 1996 at the Fort Worth ARTCC. The paper carefully evaluated TMA's performance during numerous shifts of air traffic operations as well as periods of inclement weather. Lee et al. [4] discussed human factor perspectives in relation to the 1996 TMA operational evaluation. Hoang and Swenson [5] described challenges encountered during various phases of the TMA field evaluation at the Fort Worth Center (ZFW) in the summer of 1996. Harwood and Sanford [6] examined the Denver Center TMA to determine the extent to which TMA could provide decision advisories. The authors' assessment addressed the effectiveness of TMA for supporting various traffic management activities, such as staffing, distributing traffic load, and changing the airport acceptance rate. Finally, Hansen et al. [7] examined the relationship between the performance of the NAS and airline costs.

While air traffic controllers generally confirmed, as cited in evaluation reports, that preliminary tests of the TMA deployment were able to improve arrival throughput and situational awareness, a more quantitative performance measure was desired [8]. Actually, the FFP has established a metric team to interface with the aviation industry stakeholders, to determine appropriate performance measures, and to develop methodologies to assess the effectiveness of the newly introduced automation support tools. The metric plan developed from this collaborative effort has the capability to provide better information that will enable cost effective decision making.

This paper aims to evaluate the performance of the newly deployed TMA tool at Houston's George Bush Intercontinental Airport (IAH). Full capacity operation at IAH commenced as recently as 2004, an era when TMA concepts were still in the early stages of implementation, and this accounted for the few previous studies on TMA deployment reported at the airport. Kim et al. [9, 10] evaluated the operational performance of TMA under partial and full time-based metering at IAH airport. This current paper, which is an extension of the work, introduces new performance metrics intended for better assessment of TMA performance.

IAH LAYOUT AND STATUS

Air Spaces around IAH

IAH is the eighth busiest airport in the U.S. and the eleventh busiest in the world [11], and in 2003, had a regional economic impact of more than $8 billion annually and created more than 90,000 jobs during 2003. Moreover, in 2004, IAH was ranked second among U.S. airports for scheduled non-stop domestic and international destinations, and it increased international destinations by 14 in the first six months of operation. It provides service to 184 destinations, 64 being international destinations in 28 countries.

IAH is one of the 35 Operational Evolutional Plan (OEP) airports [11], which are highly recognized as subject to large demand. Figure 1 shows four major meter fixes geographically located around IAH namely: MARIT, DAYBO, STROS, and BUHOL. These fixes represent the handoff point between the ARTCC and the TRACON (i.e. the final point at which TMA metering constraints can be applied to arrivals). Also shown in Figure 1 are four imaginary circles ("arcs") we draw around IAH for the purpose of analysis on flight distance across the arcs starting from the Extreme Arc (EA), through Outer Arc (OA), Inner Arc (IA), and Meter Arc (MA) to the runways. The radii of the arcs, measured from the outmost runway, are 200, 160, 100, and 40 nautical miles from IAH, respectively.

Runways at IAH

In November 2003, a new runway, 8L/26R, was constructed parallel to the existing runway, 8R/26L, at about 4,500 feet away. Runway 8L/26R is 9,000 feet long and 150 feet wide and it includes high-speed exits to the parallel taxiway which help to ensure speedy flight operations. The new runway is IAH's fifth runway and the third parallel Category III runway, permitting triple, independent, and simultaneous all-weather flight operations. Currently, IAH is one of the three airports in the United States that have the capability to land three airplanes at the same time in the lowest visibility conditions. Since the addition of Runway 8L/26R at IAH, the airport has re-

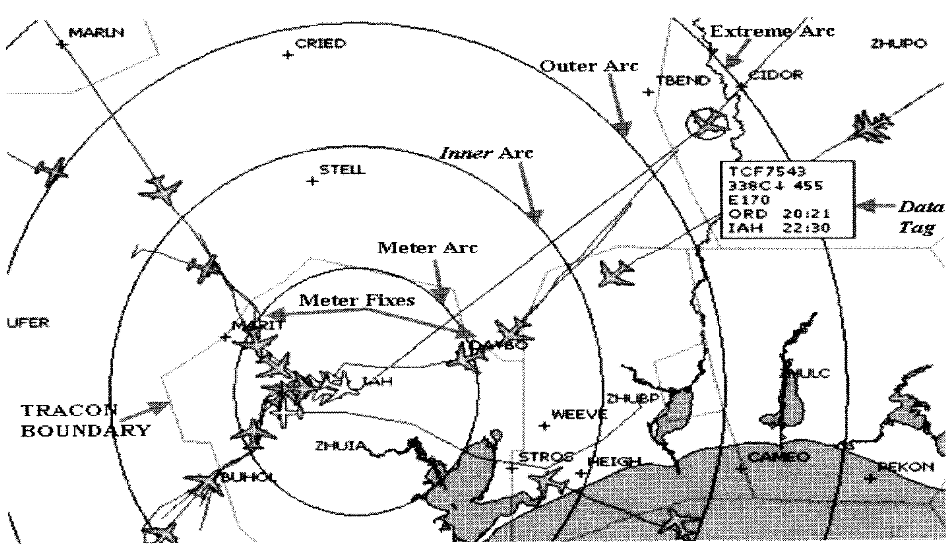

Figure 1. George Bush Intercontinental Airport approach paths, arcs (range mark/ rings), and fixes.

corded reduced flight delays, reduced airborne traffic jams (especially during bad weather), reduced aircraft ground delays (resulting in lower total emissions), and registered 108 arrival operations per hour under normal visibility conditions [12]. In addition to the construction of this new runway at IAH, Runway 15R/33L was extended to 10,000 feet and widened to 150 feet so that it could accommodate arrivals and departures of commercial jets. Figure 2 shows a diagram of the IAH runway configuration.

When Runway 8L/26R was opened in November 2003, the existing Runway 8R/26L was closed for resurfacing until July 2004. Also, work was carried out on Runway 9/27 and its taxiways during the same period. Thus, as a result of all the simultaneous activities and changes, we were only able to analyze flight arrivals on Runways 8L/26R, 9/27, 15L/33R, and 15R/33L, respectively.

ANALYSIS OF IAH ARRIVAL TRAFFIC

IAH Arrival Database Description

This section describes the database this analysis is based on and how each arrival record in the database is grouped together for evaluation purposes. The duration of the investigation is from January to August of year 2003, and January to August of year 2004, respectively. Figure 3 shows a sample of the IAH arrival database received from

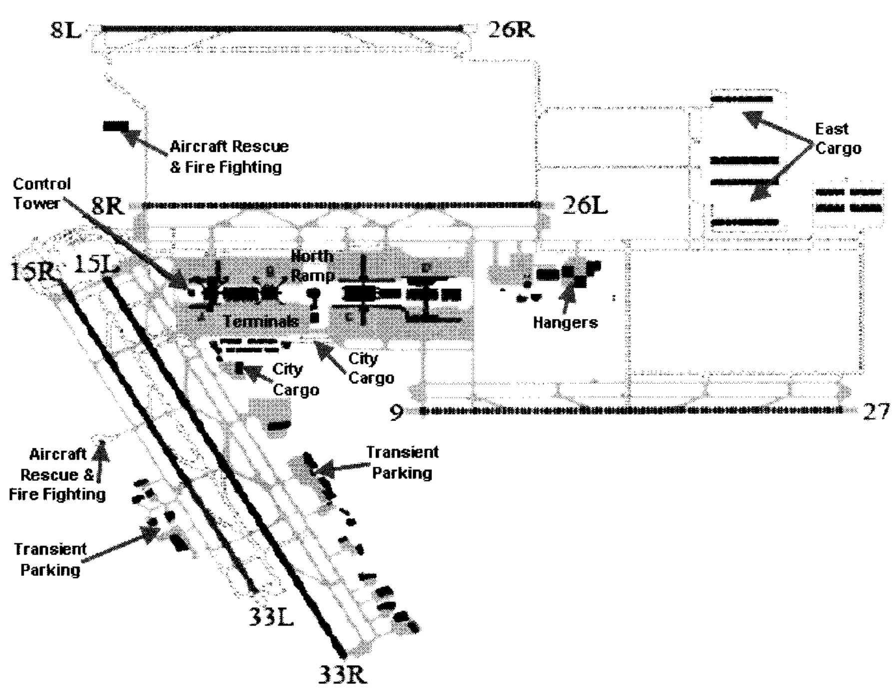

Figure 2. IAH airport runway layouts.

2004_iah_data_no_zero_season_167733 - Microsoft Visual Fox

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Ident	Fltid	Callsign	Ac_type	Ac_model	Dep_arp	Runway
61591	41499511	COA1123	JL	B738	DEN	26
61592	41499536	COA1233	JL	B738	LGA	27
61593	41499544	COA1257	JL	B737	MPTO	27

Figure 3. Sample of IAH Flight Arrival Database for 2004.

the FAA for year 2004, in which there were 165,034 flights (158,299 for year 2003). The same figure also displays several fields, such as flight ID, callsign, runway, aircraft model, and aircraft type. These fields, being part of a complete listing, characterize all the flights that arrived at IAH from departure airports in the pre- and post-TMA era. To ensure correct linking of the data from departure to arrival, the unique identity of each flight had to be established. This was accomplished by using a combination of flight call sign, departure city, departure runway, and month, to uniquely identify arrivals at IAH. The resulting groups of flights are called uniquely identified flights (UIFs). Furthermore, we set a threshold of 4 monthly flight arrivals, to separate regular flights from the lot of the irregular flights. Only those flights that arrived at least four times per month were used in the analysis. Figure 4 shows a view of some of the uniquely identified flights for year 2004 as they appear on Microsoft Visual Fox Pro 8.0.

Overview of Arrival Flights

When daily flight arrivals for both the year of 2003 and 2004 were observed, several peak arrival periods stood out. These peak periods were usually recorded on Monday mornings, Thursday afternoons, Fridays, Saturday mornings, and Sundays. For the analysis, we selected the three rush periods which recorded the highest number of

Iah_2004_uif_data

Callsign	Dep_arp	Month	Cnt_ident	Runway	Avg_tim_e_o
AAL1011	DFW	1	4	26	245.00
AAL1011	DFW	1	1	27	0.00
AAL1191	DFW	1	22	26	150.27
AAL1191	DFW	1	5	27	145.60

Figure 4. Uniquely Identified Flights Database.

flight arrivals, according to the arrival database: 256 hrs to 1356 hrs (rush hour 1), 1557 hrs to 1657 hrs (rush hour 2), and 1857 hrs to 1957 hrs (rush hour 3), local time. There were a total of 12,422, 13,486, and 16,063 flight arrivals in rush hour 1, 2, and 3 respectively, from the 2003 IAH flight arrival database. Similarly, a total of 13,054, 14,879, 16,618 flight arrivals in rush hour 1, 2, and 3, respectively, were obtained from the 2004 IAH flight arrival database. Since rush hour 3 has the largest number of counts for both the pre- and post- TMA era, the period was strategically chosen for the analysis and model simulation.

Performance Metrics

Metrics are developed to assess performance, and Table 1 lists the conventional, well-accepted metrics, as well as the newly proposed ones in this paper. The conventional metrics are self-explanatory so that we do not need to mention each of them. However, the rationale and importance of the newly suggested metrics are to be mentioned. The first new metric is designed to measure the arrival distribution skew-ness using a measure termed "Distortion Distribution Index (DDI)." DDI is defined as a statistical measure of distortion of the actual airport arrival rate distribution from that of an ideal distribution of uniformity. A lower DDI value would indicate a more uniform airport arrival rate distribution, with a consequent reduction in the instances of exceeded airport capacity. The second new metric is related to the FAA's Quality of Service (QoS) by which it is desired to

Table 1. Performance Metric Definitions

Concept		Variable	Description
Conventional Metrics	First	Average arrival delay	Average of the difference between scheduled and actual arrival time over all flights
	Second	Arrival delay variance	Variance of the difference between scheduled and actual arrival time
	Third	Average arrival delay >15 min	Average of excess time delay of flights that have arrival delays greater than 15 minutes
	Fourth	Unreliability	Proportion of flights with arrival delays over 15 minutes
	Fifth	Flight Distance	Distance traveled between the arrival arcs en route to runway
	Sixth	Runway Arrival Distribution	Arrival distribution on runway entry points
Proposed Metrics	First	Arrival Traffic Distribution	Degree of distortion in arrival pattern of flights
	Second	Arrival Quality	Degree of on-time and delayed Arrivals

provide a more consistent and predictable customer service metric than now exists (Average arrival delay >15 min). This would be accomplished by the "Arrival Quality" metric, which measures, not just the delay greater than 15 minutes, but the composition of delays greater than 15 min, 30 min, 45 min, etc.

In applying the metrics listed in Table 1, we faced a few problems. One of the problems is that the departure delay data (from departure airport) and the en route delay data were not available in the FAA database during the study. The lack of departure data prevented us from using several metrics. Instead, we could only apply one conventional metric (i.e. "Flight Distance") and one proposed metric (i.e. "Arrival Traffic Distortion" or DDI) for the TMA evaluation.

Flight Distance Analysis

To determine the effect that the TMA might have on aircraft inbound to IAH, we ran a query on the arrival database using Visual FoxPro database management program for the flight distance flown between the four arcs that are within a radius of 200 nautical miles from IAH (Figure 1). As seen in Figure 5, the mean flight distance between the Extreme Arc (EA) and Outer Arc (OA) is 43.3 nautical miles for the pre-TMA duration, while it is 42.9 nautical miles for post-TMA duration. TMA reduced flight distance traveled by each flight by 0.4 nautical miles. The mean flight distance covered by aircraft between OA and IA is 66.3 nautical miles for pre-TMA and 64.9 nautical miles for post-TMA: TMA yielded an improvement of 1.4 nautical miles per flight. Figure 5 also shows that the mean flight distance covered by aircraft between IA and MA is 64.9 nautical miles for pre-TMA and

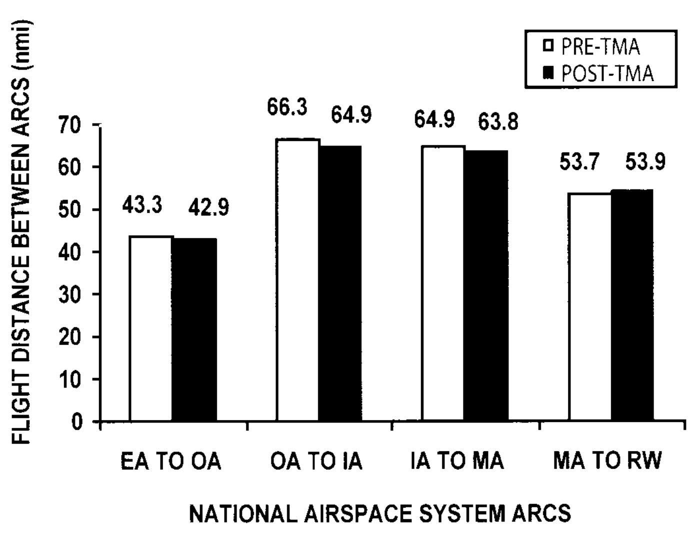

Figure 5. IAH flight distance comparisons for pre- and post-TMA.

63.8 nautical miles for post-TMA, indicating a 1.1 nautical miles flight distance reduction per flight by the TMA operation. However, the MA to RW flight distances for pre- and post-TMA did not show any significant difference. We note that the later analysis has no significant impact on flight times/distances inside the meter arc (i.e. in the TRACON), as TMA is a tool for the ARTCC controllers. In summary, we observed an important reduction, in post-TMA, in the flight distance of arrival aircraft at IAH.

In addition, we performed comparison analysis of flight distance standard deviation as shown in Figure 6. The standard deviation of flight distance for post-TMA is 18.1% less between the EA and OA, and 23.6% less between the IA and the MA. However, the standard deviation of flight distance covered between the Outer Arc and Inner Arc is higher in post-TMA by about 11.5%. The flight distance standard deviation between the MA and RW has no significant difference between pre- and post-TMA durations.

Arrival Traffic Distribution Analysis

In a given day, the number of arriving flights at an airport varies throughout the day. If we divide each 24-hour day into 15-minute time bins and count the number of arriving flight per time bin, we can draw a daily arrival distribution plot. Arrival distribution skewness, or DDI, relates to the daily arrival distribution. A uniform arrival distribution, one that has the same number of arrivals in each 15-minute interval, is ideal and has a uniform distribution (DDI = 0). On the other hand, an extreme case would exist if all arrivals

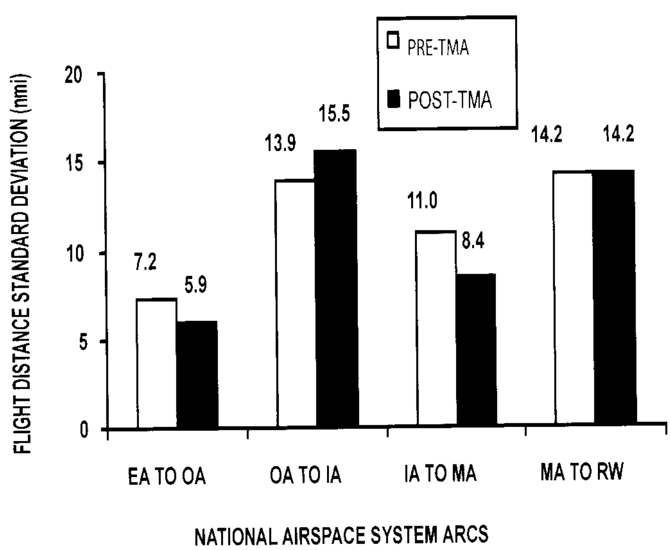

Figure 6. IAH arrival flight distance deviations.

occurred only in a single 15-minute interval, which maximally distorts the ideal uniform distribution (DDI = 1). Lower distortion index values indicate more evenly spread out arrivals, resulting in reduced instances of exceeding the airport capacity. Figure 7 shows arrival distribution distortions for each month of 2003 and 2004. We observe that, over most of their respective intervals, the arrival distribution for post-TMA operations is lower (closer to a uniform distribution) than during pre-TMA operations. This latter observation depicts an era when TMA has come into full operation with time-based metering.

Summarizing from the mean and standard deviation of flight distances in the arcs, we note that, except between OA to IA, both flight distance and the variation of the distance under TMA operation were lowered. In other words, TMA operation had the result that each individual flight that was heading for IAH entered into the Extreme Arc with higher certainty of less flight distance to runway.

SIMULATION OF ARRIVAL TRAFFIC

Simulation of Arrival Traffic using Arena

The arrival traffic model developed and simulated here aims to imitate the real life airport operations and resultant arrival traffic that occurred at IAH during a selected peak arrival period. The model and simulation tool we applied is *Arena*. Arena is a simulation software tool manufactured by Rockwell Automation that has been used to solve numerous intricate problems by mimicking the behavior of actual systems. The software also has the ability to generate true statistically independent and identically distributed normal outputs

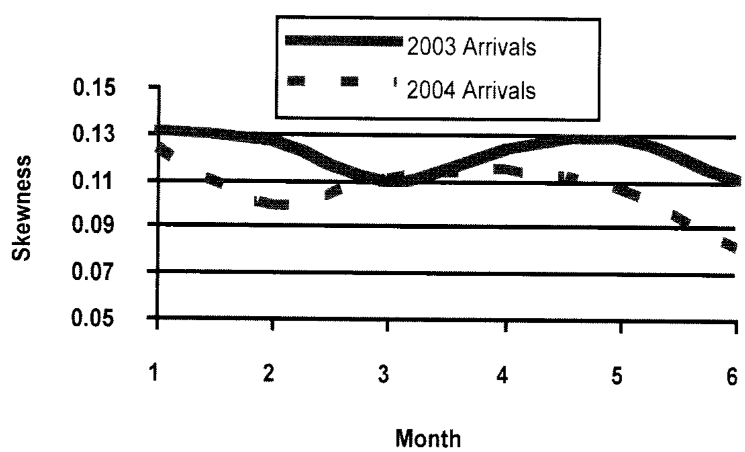

Figure 7. Arrival distribution distortion for rush hour period 3.

(replicates) for the terminating simulation analysis. A terminating simulation [13] is one in which the model dictates specific starting and stopping conditions as a natural reflection of how the target system actually operates. The basic building block of Arena models is called "modules." The modules are sub-divided into the flowchart and data modules and they both define the process to be simulated and are chosen from panels in the Project bar. The flowchart modules describe the dynamic processes of the model; on the other hand, the data modules describe the characteristics of various process elements, like entities, resources, and queues. A typical flowchart module and the necessary connections created for a simulation process in Arena is shown in Figure 8.

The "ARTCC" module simulates flight arrivals at the EA. The inter-arrival time of flights that arrived at IAH during the chosen rush hour period are exported from 2004 IAH database to Arena Input Analyzer, which generates the best arrival distribution that closely defines the inter-arrival characteristics of flights at EA as illustrated in Figure 9. The inter-arrival time is defined as the time duration between an aircraft arrival and that of the next aircraft at specific points, such as across the arrival arcs and runways. In addition, the Input Analyzer also generates a mathematical expression, which will be used as an input for the "Create module." For instance, the expression generated for the distribution in Figure 9 is given as –0.01+EXPO (3.72). This expression defines an exponential distribution of mean equal to 3.72, which is shifted to the left by 0.01.

The same procedure is repeated for the other modules. For instance, during rush hour 3 in January 2004, the mathematical expressions generated by the Arena Input Analyzer for the transition

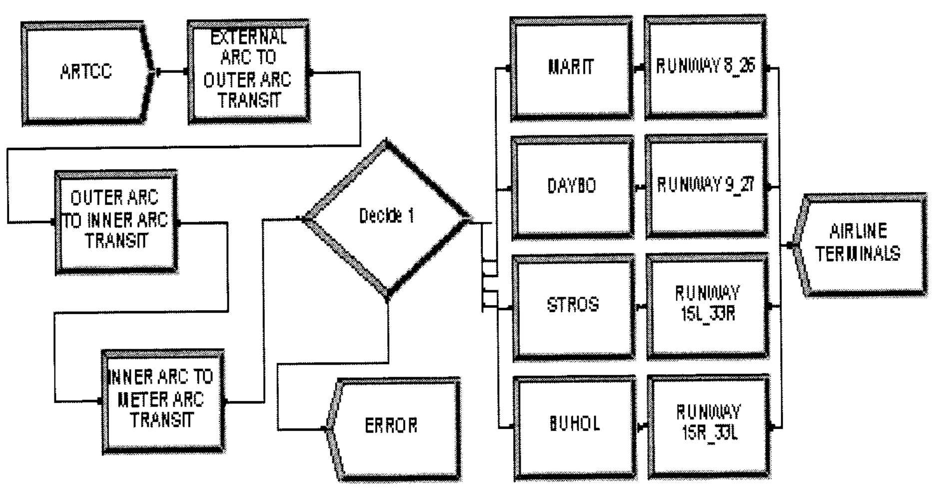

Figure 8. Arena Arrival Traffic Model.

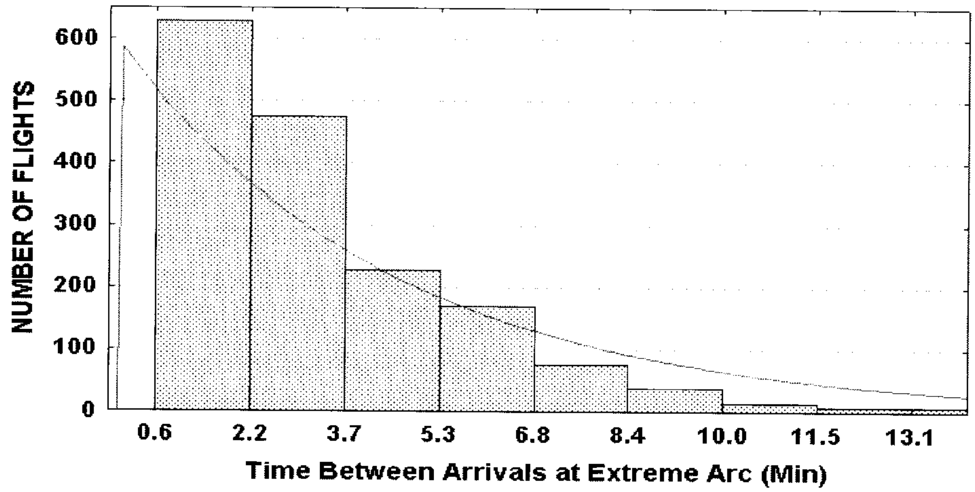

Figure 9. Extreme arc inter-arrival distribution for selected peak time in January 2004.

time of each arrival aircraft between the arcs enroute to IAH are given below:

- Transition Time between EA to OA = NORM (5.57, 2.03)
- Transition Time between OA to IA = NORM (9.12, 2.76)
- Transition Time between IA to MA = 7 + 16 * BETA (6.46, 24.7)
- Transition Time between MA to RW = 7 + LOGN (7.91, 3.6)

The decision module "Decide 1" in the flowchart simulates the sequencing of flights that arrive at IAH from different geographical locations via the meter fixes at the Meter Arc. It also ensures that flights that have been scheduled to land at a particular runway pass through a particular meter fix that enables the aircraft to begin final approach to a runway.

On the other hand, the meter fixes at IAH airport airspace are simulated in the model by the MARIT, DAYBO, STROS, and BUHOL modules. All arrival flights must pass through one of the fixes before final approach to runways. An arrival flight passes through a specific meter fix based on which geographical location (west coast or east coast) it is coming from. A screen shot of the animation of the arrival traffic simulation model is shown in Figure 10. The animation is made possible by the introduction of the transfer modules, such as the Route transfer modules, which allow the transfer of the generated aircraft entities from one station to the other without direct connection between respective stations.

Once the necessary mathematical expressions have been generated and entered into the respective modules, the model is then simulated for the peak period from 1857 hrs to 1957 hrs (converted to minutes) for each of the selected months in 2004. The simulation was

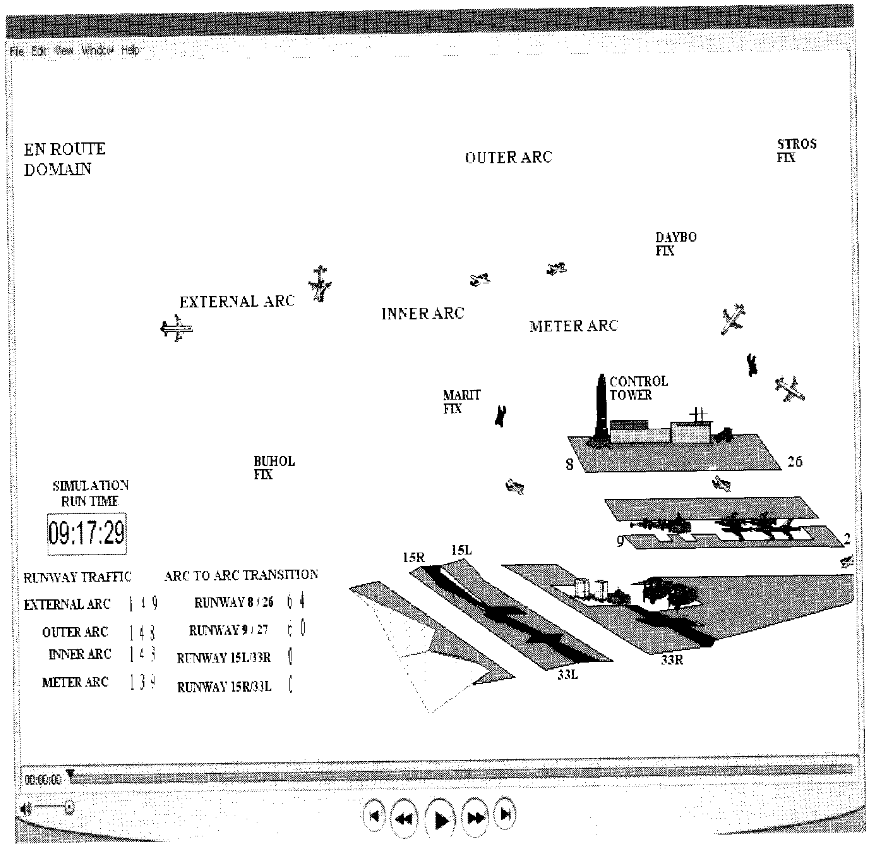

Figure 10. Arrival traffic animation view on Arena window.

repeated, for cumulative inter-arrival time at the EA, for 20,000 replications. This time period was strategically chosen to capture all flights that cross EA. The same procedure is applied to the remaining six months of 2004. Next, we compare the results obtained from the simulation and from the direct analysis of arrival traffic delays from the database.

Comparison of Simulation Analysis vs. Database Analysis

Table 2 displays the comparison analysis between the simulated results and the results obtained from the database. The numerical data entries for the number of flights and arc transit times are almost identical in two analyses, indicating that the Arena modeling based on the distribution of the actual data is very close to reality.

Similarly, the differences in the usage of runways between the database and Arena modeling analyses are almost none or minimal at most, with percentage change of 0.47%, 0.50%, 5.0%, and 2.5%

Table 2. Arc to Arc Transition Cumulative Time Comparison Analysis for 2004

	# of Flights		EA to OA [min]		OA to IA [min]		IA to MA [min]		MA to RW [min]	
	Database	Arena	Database	Arena	Database	Arena	Database	Arena	Database	Arena
January	2067	2056	11510	11512	18856	18823	21215	21265	30806	30666
February	1897	1881	10679	10941	17504	17479	19832	19778	29599	29495
March	2121	2113	11656	11670	19384	19374	21460	21362	33777	33684
April	2009	2000	10831	10771	17965	17946	20451	20329	31794	31670
May	2037	2030	10620	10643	17880	16118	20429	20218	32099	32180
June	1803	1796	9570	9634	16128	16247	18136	17981	26380	26231
July	2189	2180	11323	11289	18348	18315	21186	21029	31976	31877

Table 3. Runway Allocation Comparison Analysis for 2004

	8L/26R		9/27		15L/33R		15R/33L	
	Database	Arena	Database	Arena	Database	Arena	Database	Arena
January	983	978	1074	1068	2	2	8	7
February	931	926	965	960	0	0	1	0
March	1063	1059	1056	1052	0	0	2	1
April	1032	1028	967	963	2	2	8	8
May	984	981	1050	1046	1	1	2	1
June	848	845	942	938	4	4	9	9
July	1145	1140	1036	1032	6	5	2	2

for runway 8L/26R, runway 9/27, runway 15L/33R, and runway 15R/33L, respectively (see Table 3).

The model and simulation presented here could assist air traffic controllers and traffic management coordinators to predict future flight arrivals. It will also provide an alternative means of economically performing contingency analysis on airport arrival operations.

CONCLUSIONS AND FUTURE WORKS

The operational evaluation of the Traffic Management Advisor was performed by statistically analyzing IAH arrival traffic data using a few performance metrics, some conventional and others newly proposed in this paper. One of the new metrics helped to discover another aspect of TMA benefit: a more uniform distribution of flight arrivals. In general, the operational benefit of the Traffic Management Advisor at IAH was apparent in the statistical measurements of the arc-to-arc flight time and distances flown. The modeling and simulation performed compared favorably with actual data analysis, and therefore could potentially assist air traffic controllers and traffic management coordinators to predict the behavior of future flight arrivals at IAH.

As for future work, further studies using departure information could help verify TMA's effectiveness in reducing aircraft delay. Furthermore, the development of a simulation model that relates fuel cost with arc-to-arc flight time and distance would be beneficial for analyzing airline jet fuel expenditure during peak arrival periods.

ACKNOWLEDGMENT

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LIST OF ABBREVIATIONS

ARTCC	Air Route Traffic Control Center
ASP	Arrival Sequencing Program
ATC	Air Traffic Control
DEN	Denver International Airport
DDI	Distribution Distortion Index
DFW	Dallas/Ft. worth International Airport
EA	Extreme Arc
ERM	En Route Metering
FAA	Federal Aviation Administration
FFP	Free Flight Program
IA	Inner Arc
IAH	George Bush Intercontinental Airport
MA	Meter Arc
MIA	Miami International Airport
MSP	Minneapolis/St. Paul Airport
NAS	National Airspace System
OA	Outer Arc
OEP	Operational Evolutional Plan
QoS	Quality of Service
SFO	San Francisco International Airport
TMA	Traffic Management Advisor
TMC	Traffic Management Coordinator
TMU	Traffic Management Unit
TRACON	Traffic Radar Approach Control Facility
UIF	Uniquely Identified Flight

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BIOGRAPHY

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Report:
den Braven, W. (1992), *Design and Evaluation of an Advanced Air-Ground Data-Link System for Air Traffic Control*, NASA TM 103899, NASA Ames, Moffett Field, CA.

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Nolan, M.S. (1990), *Fundamentals of Air Traffic Control*, Wadsworth, Inc., Belmont, CA.

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knot	kn	(not kt)
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