United States Department of Transportation

Report No. VNTSC-DTS20-PDP-001

A Preliminary Design Process for Airspace Systems

Initial Assessment - Chicago Case Study

Final Report

Prepared for:
AATT Program Office at
NASA Ames Research Center

By

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The Boeing Company
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Federal Aviation Administration

October 19, 2000

A Preliminary Design Process for Airspace Systems Initial Assessment, Chicago Case Study Report

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Prepared by the Joint Study Team

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October 19, 2000

This report was prepared for the National Aeronautics and Space Administration, Ames Research Center, Advanced Air Transportation Technologies (AATT) Program Office. The NASA Program Manager was Shahab Hassan.

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Executive Summary

A Preliminary Design of Airspace Systems
Phase 1 Report

NASA has responsibility for directing a substantial research investment to support the air transportation system growth for the National Airspace System (NAS) over the next twenty years and beyond. An assessment capability is needed to help NASA and the FAA identify alternative operational concepts and technologies that best address the needed capacity, safety, environmental and economic goals of the far-term system. This report describes an airspace preliminary design approach, with supporting methods and tools, that provides alternative concept and technology performance assessment data for long-term air transportation policy makers.

This assessment capability addresses multiple interdependent airspace objectives and spans a range from the policy level to the subsystem performance level. Included in the assessment process is an examination of human and technology roles and their performance implications in potential future airspace operational concepts. The process is based on using analytical and simulation methods to enable an assessment of a broad range of future concepts and technology enablers.

This report documents a limited Phase 1 effort, funded by the NASA Advanced Air Transportation Technologies (AATT) Program. This work was performed by a team comprising DOT Volpe Center, FAA, Boeing Commercial Airplane Group, Logistics Management Institute and Flight Transportation Associates. The report addresses requirements for quantification of long-term system performance objectives and traffic demand forecasting, and presents a Case Study approach centered around the Chicago area to derive initial preliminary design process requirements. The study included visits to the Chicago area's primary FAA air traffic control facilities and detailed interviews with FAA air traffic and procedures specialists. The operational information and data gathered during the visits, along with some operational data, were analyzed to identify the primary operational constraints in the Chicago area.

The study conclusions are summarized as follows:

1. Operations at Chicago O'Hare airport and in the surrounding airspace are quite complex and dynamic. A list of ten significant operational issues summarizes the team's findings, based on this preliminary operational assessment, and the issues were mapped against technical, procedural and environmental performance factors in the various operational domains.
2. A large number of operating states can be postulated for Chicago, and due to environmental influences and the nature of the traffic demand, the operation must frequently transition between states.
3. Data are not currently available to validate postulated capacity states for O'Hare, and there is currently insufficient allocation of resources to collect and analyze the needed operational data.

4. The large number of states and frequent transitions at O'Hare call into question the current airport and airspace capacity modeling approaches that represent the system operations for a single steady-state configuration. There is currently no airport and airspace simulation tool that allows an assessment of the dynamic aspects of a complex terminal area, but it is clear from the O'Hare operational assessment that the dynamics of the operation pose a significant challenge for the operational staff.

The study includes a preliminary identification of potential areas of capacity improvements for the Chicago area. These include dynamic flow planning coordination across facilities, with central flow control, in response to dynamically changing weather and outage events; terminal area and en route capacity improvements; and the fundamental limitations on runway system capacity imposed by LAHSO rules and wake vortex spacing. However, given the significant challenges of identifying the relative contributions of performance constraints on overall Chicago area capacity, the report concludes that these suggestions have no supporting quantitative rationale yet.

The report's primary recommendations for continued effort toward improvements in the systems engineering approach for the NAS modernization are:

1. There is a need for a sound engineering approach for the early definition of best options for the long-term NAS, and the Preliminary Design Process proposed in this report is the first step toward defining this approach. Further validation of this process is needed through additional Case Studies and derivation of tools and data requirements.
2. Focused operational data collection is required to help validate a capacity baseline for areas such as Chicago, and for the whole NAS. This data is needed to identify and validate the primary capacity states of the system and must include a correlation with causal state variables such as weather conditions and system outages. Data are also required that quantify the contributions and nature of dynamic transitions between identified states, to assess the significance of transitions on the overall capacity picture.
3. Continued development of benefits, safety and affordability tools is needed to support the Preliminary Design process. The following deficiencies have been noted:
   - The current toolset and operational databases have significant limitations in quantifying regional and overall system performance metrics such as capacity, efficiency and safety.
   - The operational assessment toolset currently does not allow a direct modeling of the effects on C, N, S, ATM and human performance factors on the capacity, safety and efficiency of traffic flow. This is a fundamental requirement for the ability to assess the feasibility and viability of proposed future operational concepts.

Several appendices are contained in a separate Volume II, including detailed operational data and field interview notes compiled as part of the study.

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Volume I

Preliminary Design of Airspace Systems
Initial Findings

October 19, 2000

1.0 Airspace Preliminary Design

1.1 Objectives

The FAA is currently planning the National Airspace System (NAS) architecture through the 2015 time period [1]. This architecture is envisioned in three time periods: the near-, mid- and far-term. Much of the near-term architecture is involved in sustaining the current system's operational capability. Selected enhancements are included where expenditure levels and program risks can be contained, such as in Free Flight Phase 1, which was recommended for near-term implementation by the FAA NAS Modernization Task Force. However, as illustrated in Figure 1-1, there is recognition by the FAA, NASA, airlines, and manufacturers that additional significant decisions are required to deploy advanced communication, navigation, surveillance and air traffic management (CNS/ATM) technology in 2003 and beyond to avoid traffic gridlock [2-6].

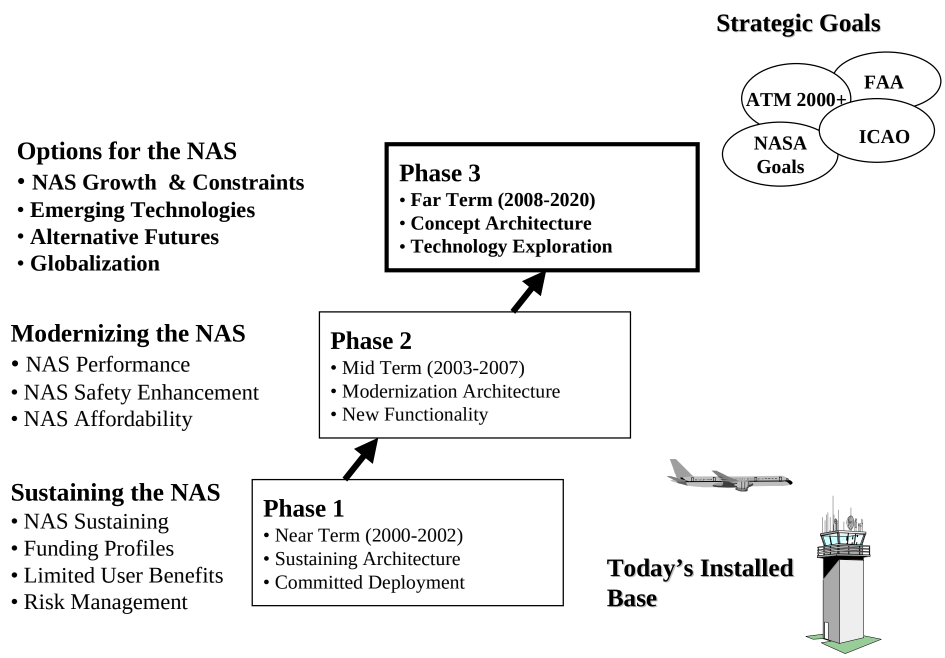

Figure 1-1. US National Airspace System Modernization Phases

NASA has responsibility for directing a substantial research investment to support the air transportation system growth for the National Airspace System (NAS) over the next twenty years and beyond [7]. A systems assessment capability is needed that will help NASA identify alternative operational concepts and technologies that best address the needed capacity, safety, environmental and economic goals of the far-term system. This report describes an airspace definition and assessment approach, with supporting methods and tools, that provides alternative concept and technology performance assessment data for long-term air transportation policy makers.

This assessment capability addresses multiple interdependent airspace objectives, and spans a range from the policy level to the subsystem performance level. Included in the assessment process will be an examination of human and technology roles and their performance implications in potential future airspace operational concepts. The process will be based on analytical and simulation methods to enable an assessment of a broad range of future concepts and technology enablers.

Figure 1-2 shows conceptually the multiple objectives that drive the air transportation system, along with the multiple technology solutions that can potentially be applied to achieve those objectives. A key aspect of the problem is that the system performance objectives are not independent, and the concept and technology trade studies must allow a careful evaluation of alternatives across all the essential performance objectives.

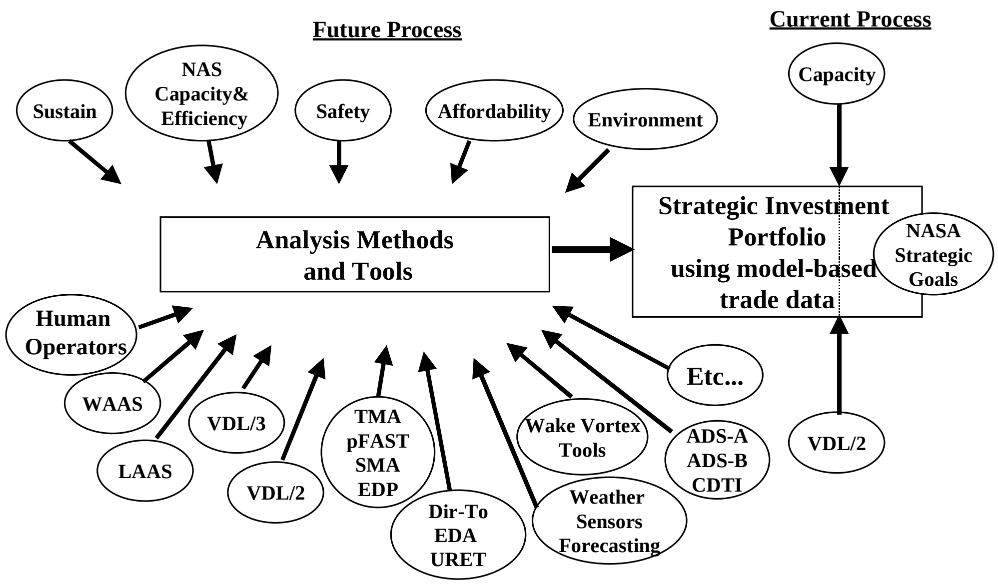

Figure 1-2. Investment Analysis for Multiple Objectives with Multiple Enablers

The investment analysis process used currently as a basis for most industry decision making examines a single technology solution against only one performance objective, e.g. VDL Mode 2 data link for system capacity. The operational concept is only vaguely defined around the single technology change, and the analysis ignores the operational coupling between the multiple system performance aspects. Additionally, the bottom-up technology focus often fails to consider fully the potential of multiple technology enablers to effect a significant change in a number of performance indices. This approach is institutionalized through a segregation of C, N, S and ATM programs and generally ineffective systems engineering approaches in the air traffic management arena. While this structure served the industry well into the 1980s, all indications are that the complexity of the long-term modernization problem requires a much more comprehensive engineering approach.

1.2 Approach – Airspace Preliminary Design Process

Figure 1-3 illustrates the proposed airspace preliminary design (PD) process [8-9] that will quantify long-term air transportation system needs, define new airspace operational concepts consistent with these needs, and translate these concepts into subsystem technical requirements. The PD process is driven by NAS top-level long-term performance objectives such as capacity, safety, affordability and environmental impact, obtained by combining market forecasts with public policy goals in Step 1.

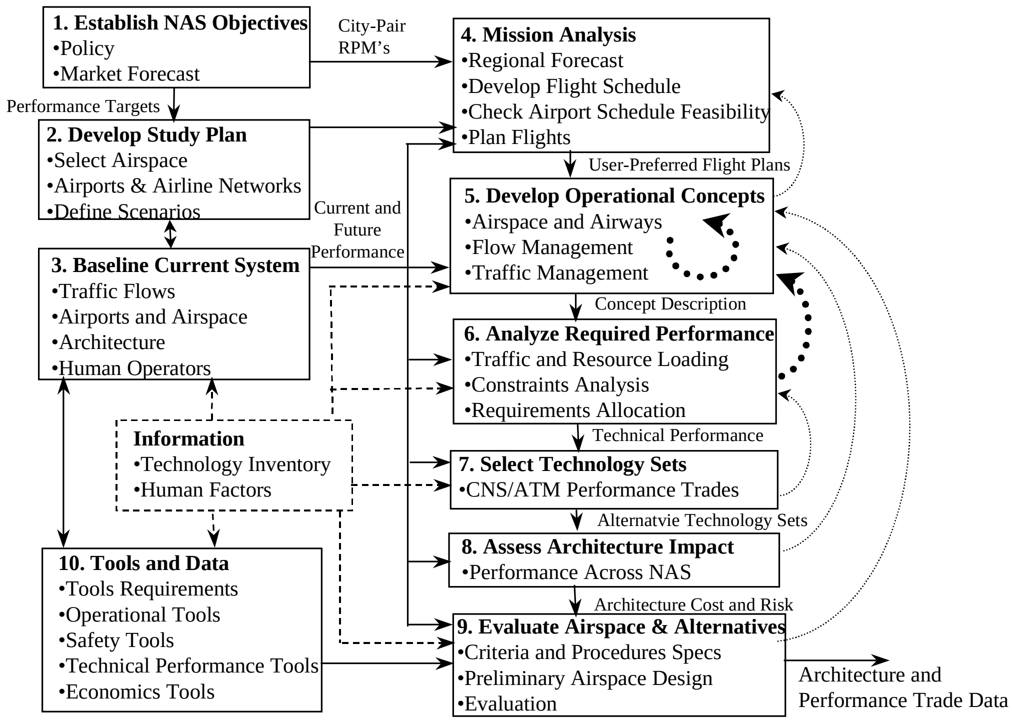

Figure 1-3. Airspace Preliminary Design Process

Step 2 develops a plan for a detailed study of particular airspace regions in the current NAS, selected based on an examination of the primary system performance concerns identified early in Step 3. Step 2 develops assumptions about airport infrastructure plans, airline business strategies and fleet mix for the study timeframe. Alternative future scenarios are defined in this step, to span the range of possible futures upon which traffic demand predictions can be based.

Step 3 evaluates the current system operational performance to provide a baseline against which future improvements can be evaluated. The baseline incorporates the current operational concept and existing system architecture, and describes a set of operational scenarios sufficient to define normal, rare-normal and non-normal behavior. The performance baseline provides the current system performance data needed to select Case Study airspace regions in need of substantial operational improvements.

Step 4 uses the market forecast from Step 1 to perform a mission analysis for the Case Study that takes into account airport infrastructure development plans and airline networking strategies to develop desired operator schedules and a prediction of time-of-day traffic demand on NAS resources. The traffic demand load is developed in terms of user-preferred flight plans that the system is expected to satisfy as closely as possible.

In Step 5, the user-preferred flight plans, the top-level performance objectives and the current system baseline are used to assess the performance shortfalls predicted through the Case Study year of interest, i.e. 2020. This forms the basis for the synthesis of operational concepts that address the needed improvements. The new concepts take into account anticipated new technology in this time frame, along with the associated human performance characteristics, and are selected based on their potential for meeting the quantified system performance objectives.

Step 6 assesses the potential value of the alternative operational concepts selected in Step 5, and develops subsystem performance requirements to achieve the objectives established in Step 1. This step includes an analysis of capacity enhancement and system safety potential for the alternative concepts, and initial analysis of affordability for users and the air traffic service provider.

Step 7 identifies alternative technology sets for implementing the operational concepts subject to the performance requirements established in Step 6. This step includes allocating and developing specific technology requirements to achieve system performance objectives such as the capacity targets. Then, the technology sets are compared based on criteria such as performance, cost and schedule risk to down-select the most promising candidates for achieving the performance requirements.

Step 8 evaluates the impact of the selected technology sets on the NAS architecture for the Case Study region. This analysis includes identifying critical architecture requirements for the operational enhancements, and evaluating timing and transition issues associated with implementation. An initial analysis of life cycle costs is performed to provide a relative cost basis for assessing system enhancement alternatives.

Step 9 addresses the development of criteria for airspace and procedure design (e.g., separation minima, obstacle clearance and traffic handling) to reflect the changes in operational concept and technical/human performance parameters. Based on the changed criteria, a preliminary airspace design for the study region can then be performed, and this design will form the basis for an evaluation of the operational performance of the new system.

The airspace evaluation in Step 9 is performed against a number of reference cases and for a number of proposed new concepts, as illustrated notionally in Figure 1-4. In the figure, "PD Concepts A and B" represent two system alternatives driven by long-term performance improvement objectives that could be available for initial operating capability in 2010. "Current Operational Concept" represents a do-nothing scenario, where the system is operated as it is today, resulting in rapid growth in waste as traffic demand continues to grow. The "NAS V4.0 and V5.0" cases represent current FAA short- to medium-term architecture plans, driven primarily by the need to sustain operational integrity in the short term, thereby not providing substantial performance improvement for the far term.

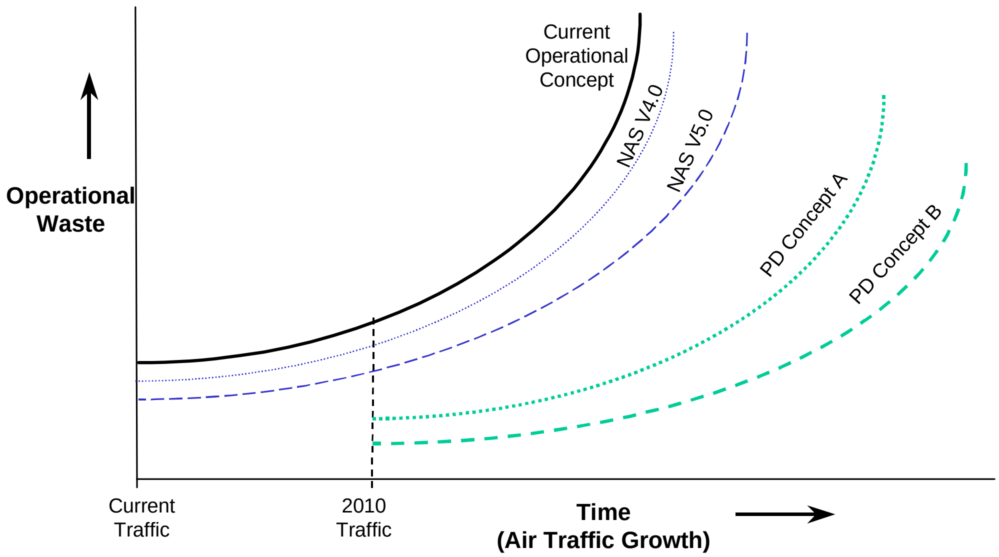

Figure 1-4. Evaluation of NAS Concepts Alternatives

Step 9 includes safety and other operational performance evaluations of the proposed concepts. In addition, it assesses the development risk and cost of the architecture alternatives from Step 8 to enable an integrated investment analysis of the system alternatives. This then forms the basis for decisions on how to go forward with the far-term system architecture.

Step 10 documents the long-term tools and data requirements for the PD process. The tools will span from broad NAS level policy and econometric forecasting tools to detailed subsystem models that provide representation of the subsystem performance factors. The Case Study will illustrate how a federated set of tools, representing various levels of system abstraction, can be applied. Step 10 will develop the long-term plans and requirements for tools and data for a full application of the PD process.

1.3 Phase 1 Case Study Approach

This report documents a limited Phase 1 effort, funded by the NASA Advanced Air Transportation Technologies (AATT) Program. This work was performed by a team comprising DOT Volpe Center, FAA, Boeing Commercial Airplane Group, Logistics Management Institute and Flight Transportation Associates. Due to budget constraints, the effort was limited to preliminary exploration of steps 1, 2, 3, 4, 5 and 10 in the PD process discussed in section 1.2, to set the stage for a more comprehensive PD process and toolset development in follow-on phases.

Section 2 describes the quantification of NAS-level performance objectives, air traffic forecasting methodology and the requirements on methods and tools to support far-term traffic forecasting for concept development and system assessment. Section 3 discusses in detail the selection of a Case Study airspace for Phase 1, and the overall study scope and constraints. Section 4 documents the primary focus of the Phase 1 effort, the approach and requirements for developing a comprehensive baseline of the Case Study airspace system. This baseline includes a demand forecast for the selected airspace region and a discussion of the methodology needed for capacity and affordability baselining. Section 5 documents the tools and data needs discovered in this phase of the PD process development. Section 6 discusses initial indications of airspace constraints and concept development directions for the selected airspace region. Section 7 presents the study conclusions and recommendations for follow-on phases of the PD process development. Several appendices to this report are contained in a separate Volume II, including detailed operational data and field interview notes compiled as part of the Phase 1 study.

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2.0 NAS Objectives and Demand Characterization

2.1 Performance Objectives

The NAS is subjected to a wide variety of performance expectations from the FAA, aircraft operators, and travelers. In this section, we briefly describe some of those performance objectives and discuss how they should be used to support the PD process for evaluating NAS improvements.

The PD process aims to meet four broad objectives: throughput, affordability, safety, and environmental compatibility. For this preliminary analysis, we will only discuss the analysis requirements to address the throughput and affordability objectives. The other objectives are equally important, but are omitted due to time and resource constraints. In addition, safety and environmental issues require different models and analytical methods, which in the case of safety are not as fully developed as in the other areas.

For the year 2010, a reasonable performance objective for throughput is to achieve the increase in air travel predicted by underlying economic and demographic trends. This forecast should NOT be affected by existing or predicted capacity constraints, since one of the aims of the throughput performance objective is to define the desired system performance. This baseline unconstrained forecast should be driven by reasonable assumptions about the price of fuel and other inputs, changes in aircraft operator productivity, and other factors such as economic growth rates. To a large extent, the underlying assumptions are highly uncertain and can support forecasts that vary significantly. To address this concern, we suggest starting with a baseline scenario that is consistent with a broad industry forecast, such as the FAA's Terminal Area Forecast (TAF), and then evaluate other scenarios based on different input assumptions. Alternative scenarios based on airline strategies should also be incorporated into the analysis, as discussed more fully below.

2.2 Demand Characterization

The role of demand modeling in the PD process is to provide a quantitative basis for specifying required air traffic services, both nationally and at the local level. The demand profiles used to estimate the demand for air traffic services also serve as critical inputs for the analyses of constraints and proposed improvements. To meet these objectives, the PD process requires a baseline scenario that depicts demand for air travel in the absence of any capacity constraints. This baseline serves as the primary yardstick to identify existing and predicted system constraints, and evaluate proposed solutions. The baseline scenario provides the initial design objective to meet the overall economic aims of the air transportation system, including industry, aircraft operators, the flying public, and government.

The complete PD process should also use other scenarios to support trade studies and to avoid reliance on an inherently uncertain point forecast. These other scenarios should span the range of plausible outcomes, including demand shifts, airline and passenger strategies, and capacity constraints. The aim of the scenarios is to help assess the robustness of proposed system improvements, and to add credibility to the entire analysis process by incorporating more realistic scenarios than may be reflected in the unconstrained baseline scenario.

To support a credible PD process, the demand characterization must include, at a minimum, city-pair aircraft flights. For higher level analyses, city-pair traffic can be adequately described by an hourly arrival and departure schedule. For more detailed assessments of constraints and solutions, a more detailed flight-by-flight schedule is required, similar to today's OAG schedule or ETMS operational data.

2.3 Demand Forecasting Issues

The objectives of the demand forecast are to provide quantitative information on the volume of future air traffic, along with information on its temporal and geographic distribution. Since forecasting is inherently uncertain, we seek to minimize the degree of uncertainty by employing an evolutionary approach that starts with a characterization of current demand and grows it over time with a minimum of changes in current demand patterns.

While airline schedules will likely change significantly by 2010, our approach relies on the strong tendencies of the airline industry since 1978 for major carriers to construct tightly coupled hub and spoke schedules to obtain economic benefits. These schedules provide opportunities for other airlines in many markets, but the economic benefits from current practices are so great that it is unlikely that significant changes will occur unless operational and capacity constraints become intolerable. Since one of the objectives of the PD process is to identify system performance requirements, the baseline forecast should closely reflect current operational strategies.

This section describes and illustrates a method to construct an air traffic demand profile for 2010. The forecast aims to present a baseline forecast for system-wide aircraft operations, with city-pair flights estimated on an hourly basis. We also describe an approach to construct additional forecast scenarios that could be used to support trade studies of alternatives, although we present only the unconstrained baseline forecast.

Consequently, one of the first demand forecasting issues is to determine a set of minimum assumptions with which to characterize the critical aspects of current demand. For the reasons just described, one set of assumptions to initialize the baseline forecast that maintains current operational strategies is:

1. Construct an industry-wide model instead of one that integrates carrier-specific models. The air transport industry in the United States is an oligopoly, consisting of 10 major carriers with about 90 percent of total domestic operation and three dozen or so affiliated and unaffiliated commuter, cargo, and chartered passenger and cargo carriers.

2. The FAA's TAF will be used as an initial input, so the future schedule we derive must meet the TAF at the airport level. Because of the way the TAF is produced, we assume that airport and ATC service capabilities will grow accordingly, not to constrain the traffic demand. However, the model itself is flexible to take any terminal area forecast as desired by the analyst.

3. The traffic growth rate between two cities must be proportional to the traffic growth rates in both cities, respectively, given that the traffic growth rates are fixed for the rest of the airports.

4. Air carriers’ operational practices will be unchanged. Specifically, we assume that the current air carriers’ operations are rational and will continue to be so in the future. By 'rational', we mean that the air carriers, being commercial companies, will try to maximize their profits by putting their resources or schedules where the demand is. The assumption of rationality of air carriers can be deconstructed into the following:

a. The current OAG schedule is the best schedule available to meet air travel demand. One example is Continental Airlines’ decision in the past few years to cancel its hubs at Denver and Greensboro/High Point, and redeploy the flights to Houston and Newark to get better yields.

b. The air carriers will continue to conduct bank operations in hub airports. Since airline deregulation in 1978, the carriers have had the freedom to design their schedules as they see fit except for the slot-controlled airports. Since then, air carriers have consolidated their operations to concentrate on large hub airports, which are characterized by alternating banks of arrivals and departures. There are two major advantages of bank operations: first, the number of markets, through connection at the hub, is massively expanded—offering travelers choices that cannot be made through point-to-point operations; second, the airline that has the dominant market share at the hub cities commands premium fares.

6. The time-of-day demand pattern will not change. Given the total number of people willing to travel from A to B in a day, research by airlines and Boeing shows that the distribution of that demand across the day depends on the local departure and arrival times and the journey time, where business travelers and leisure travelers may have different demand patterns, and, of course, different demand elasticities. Thus, unless there are new technologies that will drastically reduce the journey time, the travelers’ time-of-day demand patterns will not change.

With these assumptions, we impose no a priori changes to current airline scheduling strategies.

Another major forecast issue is to select growth rates for the baseline air traffic demand profile. In keeping with the objective of estimating unconstrained system performance requirements, growth rates through 2010 should not incorporate constraints other than those that are imposed by law or other restrictions that are considered relatively permanent (such as slot controls or noise restrictions at selected airports). The FAA’s Terminal Area Forecast (TAF) provides a forecast over an extended time period of the FAA’s prediction of enplanements and aircraft operations at hundreds of airports. By design, these forecasts represent unconstrained estimates of air travel based on demographic and economic factors, without regard to potential system capacity constraints. While the FAA forecast has limitations, it is the most detailed forecast available, and it is widely publicized and vetted throughout the industry. The FAA also regularly brings in outside experts to improve its forecasting methods. For the initial baseline forecast, we recommend using the TAF for growth rates in enplanements and operations.

The TAF, published annually by the FAA, has several data tables for the total annual enplanements, operations, and various FAA workload measures for the set of airports and control towers that the FAA tracks. Each table has several columns to give more detailed information (e.g., the enplanements can be domestic or international). For the TAF released in December 1998, the data from 1976 to 1997 are the annual totals reported by the airport control towers, while the data from 1998 to 2015 are the predicted values.

The Airport Council International sponsors the annual FAA Commercial Aviation Forecast Conference every year, and 2000 is its 25th. The FAA not only updates its TAF every year but also improves the forecast's methods constantly. The TAF has become the *de facto* official aviation demand forecast. In this report, we are interested in the TAF of operations for the LMINET airports. LMINET is a queuing network model of the National Airspace System. LMINET links multiple queues at 64 airports in the NAS via queues at en route sectors. As an analytical queuing model and not a simulation, LMINET can be integrated with air transportation economic models of airline cost and air travel demand. This integration provides the ability to incorporate feedback between capacity changes, delays, airline ticket prices, and aircraft operations. This closed-loop modeling approach generates estimates of system throughput and delay for the entire NAS and at each of the 64 airports analyzed in the network.

The FAA makes forecast operations in the TAF in the following way:

1. It forecasts the enplanements based on outputs of socioeconomic models, such as gross domestic product (GDP) and demographic growth rates, with due consideration of originating traffic and connection traffic. Each major airport has its own specific models.

2. It forecasts the load factors to and from each airport based on the demand, fare yield, and airlines cost.

3. It forecasts the average number of seats per aircraft for arrivals and departures at the airport.

4. It divides the forecast enplanement by the forecast load factor and by the forecast average number of seats per aircraft to get forecast operations.

In deriving the forecasts, flight delays due to traffic congestion are never explicitly considered. Implicitly, the TAF assumes that airport and ATC capacities will grow to meet the potential demand. In other words, the forecasts are unconstrained except for JFK, LGA, ORD, and DCA, which are slot-controlled.

Table 2-1 shows, based on the FAA's TAF, the total annual operations for 1997 and 2010 and the growth rates, for each of airport in LMINET. Since our model treats commercial operations represented by OAG and the GA operations differently, the traffic and growth rates are listed separately. We used the total of *air carrier*, *air taxi*, and *itinerant GA* in the TAF as the airport operations measure. Air carrier and air taxi are the operations of scheduled air transport service corresponding to the OAG; air taxi data are for aircraft with less than 60 seats, which are typical of commuter operations. One can see that all the airports will enjoy positive total and commercial operations growth during the period, but there are many airports with negative GA operations growth. This may imply that the commercial traffic growth will be at the expense of GA operations. For all airports reported in FAA's TAF but not included in the 64 LMINET airports, they are aggregated at the first row of the table under the airport designated as "OTR."

Table 2-1. Unconstrained Annual Operations (Thousands) and Growth Rates

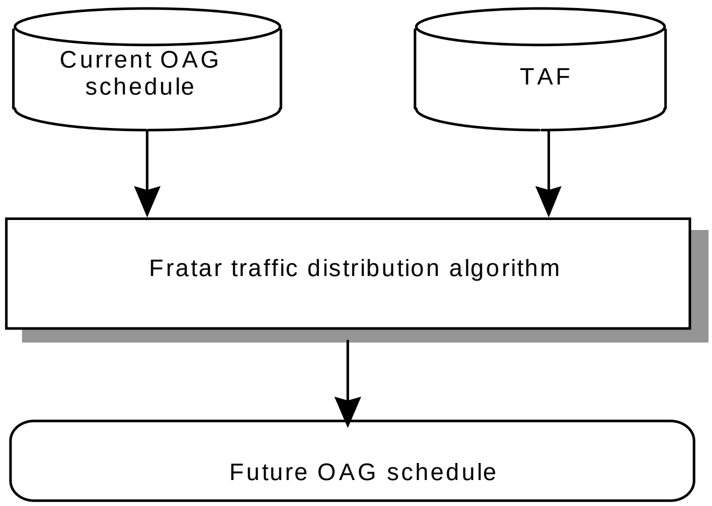
		Commercial			GA		
Airport	Airport	1997	2010		1997	2010	
Index	Code	Ops	Ops	Growth(%)	Ops	Ops	Growth(%)
0	OTR			20.72			7.91
1	BOS	459.5	522.4	13.67	34.0	39.3	15.57
2	BDL	113.4	153.9	35.73	42.0	48.6	15.58
3	HPN	49.1	62.2	26.78	114.1	131.8	15.57
4	ISP	31.2	34.2	9.49	79.0	91.3	15.57
5	TEB	20.6	20.6	0.00	164.4	215.3	30.93
6	LGA	334.8	356.9	6.61	18.6	20.0	7.69
7	JFK	346.6	393.3	13.47	15.3	12.5	-18.13
8	EWR	449.1	556.4	23.89	18.3	18.5	1.57
9	PHL	403.4	563.7	39.72	50.5	58.4	15.57
10	BWI	236.2	331.0	40.13	21.8	21.8	0.00
11	DCA	260.3	274.1	5.29	49.5	49.6	0.21
12	IAD	276.7	382.3	38.19	60.5	75.4	24.59
13	GSO	64.5	108.4	68.09	51.5	57.9	12.48
14	RDU	155.8	193.0	23.88	74.1	81.8	10.40
15	CLT	400.4	473.0	18.12	59.1	55.4	-6.23
16	ATL	749.1	1112.1	48.47	23.2	26.3	13.18
17	MCO	320.3	528.0	64.83	30.9	39.2	26.73
18	PBI	82.8	104.2	25.86	95.0	109.8	15.57
19	FLL	165.4	228.1	37.91	78.5	77.6	-1.19
20	MIA	460.6	647.6	40.61	64.7	67.4	4.16
21	TPA	208.3	279.9	34.35	38.1	26.2	-31.30
22	MSY	136.1	190.6	40.05	23.9	25.8	7.81
23	MEM	301.6	433.3	43.68	59.7	67.3	12.60
24	BNA	141.2	149.3	5.71	65.0	75.2	15.57
25	SDF	140.6	217.7	54.83	34.1	39.4	15.57
26	CVG	395.6	617.1	55.97	15.2	23.5	54.08
27	DAY	96.7	120.1	24.20	42.8	49.5	15.58
28	CMH	154.2	245.7	59.38	39.9	37.4	-6.20
29	IND	179.3	281.7	57.09	51.0	59.0	15.57
30	CLE	279.8	418.2	49.46	30.9	25.3	-18.25
31	DTW	457.1	609.0	33.24	84.0	92.6	10.29
32	PIT	424.9	516.4	21.55	25.6	28.7	12.04
33	SYR	88.4	122.6	38.67	36.2	36.2	0.00
34	MKE	154.3	244.6	58.48	43.3	43.3	0.00
35	ORD	849.8	1020.4	20.08	38.7	32.8	-15.41
36	MDW	171.5	254.9	48.62	88.6	88.7	0.18
37	STL	480.5	579.9	20.70	30.4	26.4	-13.12
38	IAH	382.7	650.6	70.02	26.9	31.1	15.57
39	HOU	140.5	161.0	14.55	118.1	136.4	15.57
40	AUS	94.9	116.1	22.31	101.0	109.0	8.00
41	SAT	122.4	170.0	38.88	115.7	146.0	26.13
42	DAL	127.1	139.9	10.08	99.6	121.2	21.66
43	DFW	837.3	1163.1	38.90	88.4	119.2	34.79
44	MSP	427.8	603.0	40.94	56.0	69.1	23.30
45	MCI	194.8	265.2	36.16	14.0	14.0	0.00
46	DEN	455.8	565.3	24.03	22.6	19.7	-12.99
47	ABQ	118.7	177.9	49.94	59.3	68.6	15.57
48	ELP	68.2	102.6	50.43	45.7	42.9	-6.20
49	PHX	443.5	643.8	45.15	81.6	64.5	-20.89
50	SLC	293.8	445.5	51.63	75.8	68.4	-9.72
51	LAS	350.3	565.3	61.38	92.1	106.5	15.57
52	SAN	201.7	279.2	38.42	16.1	15.1	-6.15
53	SNA	101.4	142.0	40.05	272.0	289.5	6.42
54	LGB	13.7	20.5	49.14	238.1	221.0	-7.15
55	LAX	738.6	1017.2	37.72	25.6	25.6	0.00
56	BUR	96.6	120.7	24.88	78.4	83.2	6.20
57	ONT	127.1	187.5	47.51	27.9	32.2	15.57
58	RNO	104.7	175.7	67.71	46.5	53.7	15.57
59	SMF	119.5	195.6	63.73	24.6	24.6	0.00
60	OAK	222.2	293.4	32.07	160.4	200.6	25.06
61	SFO	402.4	542.7	34.86	26.3	30.4	15.56
62	SJC	134.0	205.7	53.52	91.0	76.5	-15.93
63	PDX	256.5	364.7	42.17	39.6	32.8	-17.15
64	SEA	375.0	518.4	38.23	5.8	5.8	0.00

While airline schedules are a major determinant of air traffic service demand at major airports, we must also account for general aviation (GA) traffic.

The TAF does not provide city-pair forecasts of aircraft operations. Therefore, different methods are required to construct the city-pair aircraft flows. To be consistent with our first constraint - that the schedule reflects current scheduling strategies - the future demand forecast should be consistent with the temporal pattern found in the current OAG, and the geographic growth pattern depicted by the TAF. LMI previously developed such a method, as described in Figure 2-1.

The Fratar algorithm is the most widely used method for generating trip distributions based on the terminal area forecast. Both the DOT and FAA have used it in their transportation planning models, such as NASPAC, an event simulation model of NAS. A schematic diagram of the algorithm is shown in Figure 2-1. Table 2-2 shows an example of the approach applied to departures from Chicago O'Hare to other major airports.

Figure 2–1. The Fratar Traffic Growth Distribution Algorithm



The daily traffic, t_{ij}, from airport i to airport j, total daily departures, d_i, from airport i, and total daily arrivals, a_j, to airport j are related to the schedule, s_{ijkl}, as follows:

$$t_{ij} = \sum_{kl} s_{ijkl}, \quad \text{[Eq-1]}$$

$$d_i = \sum_j t_{ij}, \quad \text{[Eq. -2]}$$

$$a_j = \sum_i t_{ij}. \quad \text{[Eq. -3]}$$

If the schedule is balanced, or the network does not have any sinks, then $d_i = a_i$, $\forall\ i \in I$.

Let D_i, $i \in I$ represent the total number of departures in the target year taken from the forecast. The Fratar method is an iterative algorithm that takes the following steps:

Step 0:

Assign t_{ij}, d_i, a_j, $\forall i, j \in I$, based on the current year schedule.

Step 1:

$$g_i = \frac{D_i}{d_i}, \forall i \in I, \quad \text{[Eq-4]}$$

Step 2:

$$T_{ij} = t_{ij} \times g_i \times g_j \times \frac{1}{2}\left[\frac{d_i}{\sum_m t_{im} \cdot g_m} + \frac{a_j}{\sum_m t_{mj} \cdot g_m}\right], \forall i, j \in I\ . \quad \text{[Eq-5]}$$

Step 3:

If $\sum_m T_{im} = D_i, \forall i \in I$, then go to step 4

else

$t_{ij} = T_{ij}, \forall i, j \in I$, and update $d_i, a_j, \forall i, j \in I$ accordingly; go to step 1

Step 4:

Compute the traffic growth factor, $r_{ij}, \forall i, j \in I$, by dividing the traffic, T_{ij}, in the target year by the one in the current year; compute the schedule, S_{ijkl}, in the target year by multiplying the schedule in the current year by the traffic growth factor, r_{ij}. Stop.

Now let us check that the schedule in the target year made by the Fratar algorithm has the desired properties. First, the schedule always will meet the terminal departure totals predicted in the TAF, which is embedded in the algorithm.

Second, $r_{ij} = r_{ji}$, which means the traffic growth is nondirectional. This is an implicit desired property in a travel network, although not explicitly stated in the previous subsection.

Third, the growth factor is uniform across the entire day, which is a desired property if we assume that the current schedule is rational and the travelers' time-of-day demand pattern will not change.

The fact that the growth factor is uniform across the day implies another property of the schedule in the target year: the airport traffic is dynamically balanced and the bank operations in hub airports are preserved. Let $d_{ik}, a_{ik}, \forall i \in I, \forall k \in K$, be the total departures and arrivals in time k at airport i.

$$d_{ik} = \sum_{jl} s_{ijkl.}$$
$$a_{ik} = \sum_{jl} s_{jilk}.$$

An airport i is said to be dynamically balanced if $d_{ik} = a_{ik}, \forall k \in K$, which means there are no idle aircraft sitting on the ground. In reality, a flight has to spend some time in the terminal before taking off, but we will keep this simple definition, and real operations can be modeled by shifting the time index. Let $D_{ik}, A_{ik}, \forall i \in I, \forall k \in K$ be the total departures and arrivals at airport i at time k in the target year. By the Fratar algorithm,

$$D_{ik} = \sum_{jl} s_{jkl} = \sum_{jl} r_{ij}\, s_{ijkl} = G_i \sum_{jl} u_j\, s_{ijkl}, \qquad \text{[Eq 6]}$$

$$A_{ik} = \sum_{jl} S_{jilk} = \sum_{jl} r_{ji}\, s_{jilk} = \sum_{jl} r_{ij}\, s_{jilk} = G_i \sum_{jl} u_j\, s_{jilk}, \qquad \text{[Eq. 7]}$$

where

$$G_i\, u_j = r_{ij},\ \forall i, j \in I, \textit{ and } \sum_{jl} u_j = 1. \qquad \text{[Eq-8]}$$

The right-hand sides of D_{ik} and A_{ik} resemble the expectations of the product of two discrete random variables. If two random variables are independent, then the expectation of their product is equal to the product of their expectations. If we assume that the traffic growth rate is independent of the current schedule, which is a reasonable assumption, then

$$D_{ik} \cong G_i \left(\sum_{jl} u_j\right)\left(\sum_{jl} s_{ijkl}\right) = G_i d_{ik.}$$

Similarly,

$$A_{ik} \cong G_i a_{ik}.$$

Since $d_{ik} = a_{ik}$, $\forall i \in I$, $\forall k \in K$, then $D_{ik} \cong A_{ik}$. And, interestingly, G_i must be the growth factor implied by the TAF in order to satisfy the binding terminal total departure constraint.

As the case study focuses on the Chicago area, the method was applied to Chicago O'Hare International Airport (ORD).

Table 2-2. Predicted Traffic Growth Rates And Departures From O'Hare.

Airport	Growth ratio 1997-2010	1997 daily departures	Fratar algorithm		Geometric mean	
			Pair growth ratio with ORD	2010 daily departures	Pair growth ratio with ORD	2010 daily departures
	1.239	34	1.167	40	1.220	42
	1.397	30	1.328	40	1.295	39
	1.053	30	0.998	30	1.124	34
	1.485	29	1.425	41	1.335	38
	1.571	22	1.415	31	1.373	30
	1.332	21	1.259	26	1.265	26
	1.207	20	1.136	22	1.204	24
	1.389	32	1.328	42	1.291	41
	1.409	38	1.365	51	1.301	49
	1.24	20	1.161	24	1.220	25
	1.377	37	1.297	48	1.286	47
	1.349	20	1.252	25	1.273	25
Total		1217		1461		1520

Table 2-2 only lists the departure flights for the most important markets. The traffic growth rate for O'Hare from 1997 to 2010 is 20.1 percent. Based on this traffic growth rate, the total number of daily flights from O'Hare is 1,461 in 2010, which the forecasts based on the Fratar algorithm satisfy. Another popular forecasting method is to assume the traffic growth ratio between a city-pair is the geometric mean of the traffic growth ratios of the two cities involved. Although the geometric mean forecasting is appealing, it does not satisfy the terminal area forecast—it implies 1520 daily departures from O'Hare, or a 24.9 percent growth rate.

This approach provides an aggregated unconstrained baseline forecast for the PD process. It gives hour-by-hour aircraft flights between the 64 airports in the network, and RPMs and other measures of throughput. This information is sufficient for the Level 1 analyses. For detailed operational analyses and trade studies, however, we require a more specific schedule that provides minute-by-minute departure and arrival demand, as well as aircraft type. For a 2010 PD study, we require a close approximation to a 2010 OAG, or ETMS operational data. Such information, of course, does not yet exist.

High fidelity operations and capacity models, such as TAAM, require such detailed schedules. A future task for the PD process is to construct a future schedule for the unconstrained baseline, as well as for other forecast scenarios as described below.

To accommodate increasing demand in the face of growing congestion, it is likely that air carriers will alter their current operating strategies. This section lists the possible airline strategies, discusses the methods we used to evaluate each strategy.

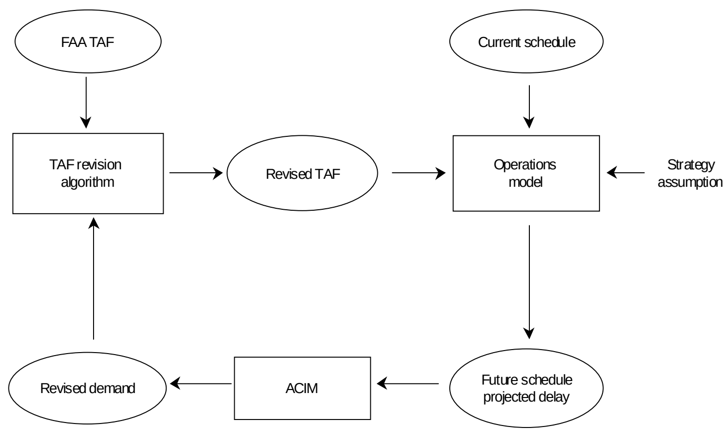
FUTURE OPERATING STRATEGIES

- By increasing fares and rationing demand in the face of scarce capacity (a passive strategy);
- by establishing new hub airports to mitigate congestion at existing hub airports;
- by shifting additional resources toward direct service as opposed to connecting service to mitigate congestion at major hub airports;
- by smoothing the peaks and valleys of typical bank operations to mitigate the growth of delay at major hub airports;
- by shifting additional resources toward nighttime operations;
- by employing larger aircraft, as opposed to growth in frequency; or
- by a combination of the five active strategies.

MODEL SCHEMATIC

Our methodology is adapted from our previous work related to assessing the economic impact of air traffic congestion. The basic approach is to link delay forecasts from the Operations Model, which are driven by traffic projections at the airports, with industry-level supply and demand characteristics imbedded in the Air Carrier Investment Model (ACIM). The impact of various operating strategies to alleviate congestion and its resultant airline delays can be analyzed by modifying parameters of the Operations Model. The result is a revised forecast that can be compared with the unconstrained forecast, e.g., FAA TAF, to measure the success of the proposed strategy in accommodating air travel demand. Figure 2-2 illustrates this approach.

Figure 2–2. General Methodology



As shown in Figure 2-2, the general methodology begins with the Operations Model, which takes projected airport operations growth rates, combined with the current traffic schedule and the operational strategy assumptions, to generate the future traffic schedule and delay estimates. Future demand is forecast based on the Fratar algorithm, while the delay is computed by a queuing network model. Because the Operations Model computes airport delays according to the traffic schedule, delays are amplified by a set of multipliers to account for the rippling delays for the rest of the day. The delay multipliers are derived by American Airlines using real data. In general, the earlier in the day the delay occurs and the longer the delay lasts, the larger the delay multiplier.

Next, the total delays computed from the Operations Model are used to generate the block time changes. Increases in block times increase airline costs, which will generate a revised industry forecast.

The revised RPM forecast from the ACIM is the variable in which we are most interested. The system starts with the unconstrained operations growth rates from FAA's TAF. Our idea is to modify the airport operations growth rates based on the revised RPM forecasts from the ACIM, which is accomplished through the TAF revision algorithm. The system converges when total system traffic (operations or RPMs) from both the Operations Model and the ACIM agree.

Some airports can accommodate the projected demand without generating much additional delay. However, many of the airports are severely constrained by a lack of capacity and generate projections for large increases in delay even as air carriers take steps to mitigate congestion. Therefore, additional methods are required to ration the limited capacity so that demand ultimately matches supply.

One approach to reduce demand to match capacity is to simply eliminate operations at congested airports. Although the Operations Model can implement this approach, the selection of which flights to eliminate is quite arbitrary. Therefore, we developed an alternative approach that uses the ACIM to ration the limited capacity through higher fares.[1] The premise of using the ACIM to evaluate the impact of delay on air travel demand is that increases in air carrier operating costs (due to congestion) are passed along to consumers in the form of higher fare yields, which further slow the growth rate of demand. Thus, an equilibrium is achieved in which the costs of delay are balanced by the passengers' willingness to pay for additional travel. Under this approach, the ACIM produces an estimate of the reduction in aggregate air travel demand due to the increased costs of congestion.

[1] The ACIM consists of four core modules: the U.S. Econometric Module, U.S. Functional Cost Module (FCM), Asian Econometric Module, and European Econometric Module. The U.S. Econometric Module uses an econometric approach to estimate air carrier costs, while the FCM uses activity-based costing. For this study, we employed the FCM exclusively.

3.0 Case Study Selection and Rationale

The objective of the Case Study approach is to select airspace regions which provide a 'rich set' of operational constraints associated with the long-range system objectives under study. For the initial case study, the capacity and affordability objectives are emphasized. The capacity objective of the Case Study dictates certain selection criteria for choosing the initial airspace region. Once the region is selected, the Case Study plan for a particular multi-airport airspace region is detailed.

The Case Study considered the five most congested airports in the NAS: Atlanta's Hartsfield (ATL), Chicago's O'Hare (ORD), Dallas-Fort Worth (DFW), Los Angeles (LAX), or the North-East corridor (centered around LaGuardia (LGA), John F. Kennedy (JFK), Newark (EWR), and Philadelphia (PHL).

For the region selected the intent was to characterize the 'capacity' of the airport and airspace of the region. It was expected that a range of capacities would be observed, given the operating variability of airspace. And it was expected that a characterization of 'good', 'intermediate' and 'bad' days in terms of system capacity could be developed, that there would be a highest throughput/lowest delay day at one of these central airport locations, and that there would be an opportunity to identify at least two non-normal days.

The highest throughput/lowest delay day was intended to cover the central airport(s) itself, in the hope that, with enough sample days, the same condition would exist within the entire larger multi-airport region itself, and hopefully in the entire NAS. The correct method to identify such days, given unconstrained resources, would be to do a thorough statistical analysis of perhaps several years worth of traffic data. Then one might identify those days with better than average (say, 2σ) as 'best' days. For this short study, we used an alternate technique based on identification of days with good conditions to minimize the effort of obtaining and analyzing traffic data.

The project team decided that a visit to the selected central airport(s) would be needed so that operations and available data from its en route facilities, TRACON, and tower(s) could be examined. The examination would provide the following useful information:

1) Additional data from the facilities for specified days that could be compared with an analysis of the Enhanced Traffic Management System (ETMS) archived data on the same days. This might identify shortcomings in each data set. It would also confirm conclusions derived from the ETMS data.
2) The identification of the number of highest throughput/lowest delay days that might be used as a standard against which higher delay days and non-normal days could be compared.
3) Information that might guide the selection of a few non-normal days with prevalent conditions that could be identified by the air traffic personnel in the field.

An integral part of the Case Study plan is the identification of airline business change factors that would be considered for the Case Study. It was recognized that regional and major airlines continuously 'adapt' schedules and operations to respond to changing business needs and system operations factors. However, during this initial phase, simple assumptions were made regarding airline responses to a changing environment, limited to the identification of needed economic and forecasting tools to model such behavior.

This section has five parts:

1. Selecting an airspace region for an initial case study.
2. Characterizing the range of capacity performance of the selected region[1].
3. Performing a field data collection for the region for a specified time period.
4. Performing analysis of the available operational data sources for capacity assessment.
5. Evaluating the field data and assessing the approach.

3.1 Choosing an Airspace Region

This subsection describes the part of the Case Study Plan that began with the assumption that the higher throughputs of a large multi-airport geographical area (e.g., 435 NMi or approximately 500 statute miles, and one to two hours flying time) should be established as a standard for normal operations. Against that standard, lower throughput non-normal operations due to bad weather, high winds, or other causes could be compared in the follow-on full PD project. The analysis to produce a throughput standard for the selected region requires the use of methods that enable it to be extended to other regions, and then the entire NAS, using ETMS archived data and other data sources.

The entire NAS throughput standard was defined as the highest total throughput day or days[2] encountered at the 57 biggest and seven other selected U.S. airports. This occurs when the demand is highest and there are no (or a minimum number of) weather-related delays across the entire nation. The time interval for the existence of the standard is ideally 18 hours[3], but can be shortened (to, say, a decoupled 8-10 hours) if clear weather across the entire nation does not exist for that long. The highest daily demand is defined, for a given year, as the maximum number of ETMS scheduled operations during the busiest days of the week.

For this first phase of the PDP, it was assumed that a major airspace region is an area large enough to show the effects of en route structures, traffic demand patterns, operational procedures, weather variations, and miles-in-trail restrictions around one of

[1] Only a few non-normal days could be chosen due to the limited funds in this first phase of the project.
[2] Hourly throughput rates are also considered.
[3] 18 hours are based on a 15-hour traffic day at a major airport plus three hours for time zone differences.

the five busiest airports in the U.S. A 435 NMi radius was selected[4] to have an area large enough to include many other airports around each of the five busiest airports. As previously stated, the five airports considered were: ORD, LAX, DFW, ATL, and the New York (NYC) metroplex including PHL.

Figures 3-1 and 3-2 illustrate two regions, the first centered at ORD, and the second centered at PHL that include the JFK, LGA, and EWR complex. The two regions are the most difficult to characterize since they contain the highest volumes of traffic and complexities of airspace, airports and runways in the NAS.

Note that in both figures the radius of 435 NMi does not include any of the other four busiest airports. Although it is clear that the entire NAS represents a coupled system, the 435 NMi cut-off is reasonable as the point at which the effect of the key airport in the region becomes predominant. Similarly, smaller circles for a large airport within a region (e.g., around MSP in Figure 3-1), that do not include any other of the larger airports within the area, have been drawn to reflect the ranges of traffic management for these airports. As the circles get smaller (e.g., for PIT, CLE, and DTW in both figures, and, especially, for the New York/ Newark and PHL complex, and the group DCA, IAD, and BWI) the available range for independent traffic management into an airport is decreased, eventually resulting in a tightly coupled set of airports with significant operational interactions.

The PDP team agreed that the LAX, DFW, and ATL areas did not present sufficient traffic loads or airport/airspace complexity to be of interest for this Case Study. On the other hand, the LGA, JFK, and EWR complex might present too much difficulty for this first effort, even though it represents a high degree of technical and operational interest. This latter area would require considerably more extensive field data collection by the project team since:

1. Two **or three** additional towers would have to be visited.
2. The total number of runway configurations at the three **(or four)** airports would be significantly higher.
3. The closely-coupled TRACON airspace and ground operations would require extensive interviews with air traffic operations personnel.

It was therefore agreed that the ORD region should be selected in this first phase of the PDP project.

[4] The 435 NMi radius size and its form (e.g., circle, ellipse, or rectangle) may be modified in a later phase when traffic patterns are more carefully examined. An examination of ETMS traffic patterns around O'Hare did show a relatively uniform radial traffic pattern.

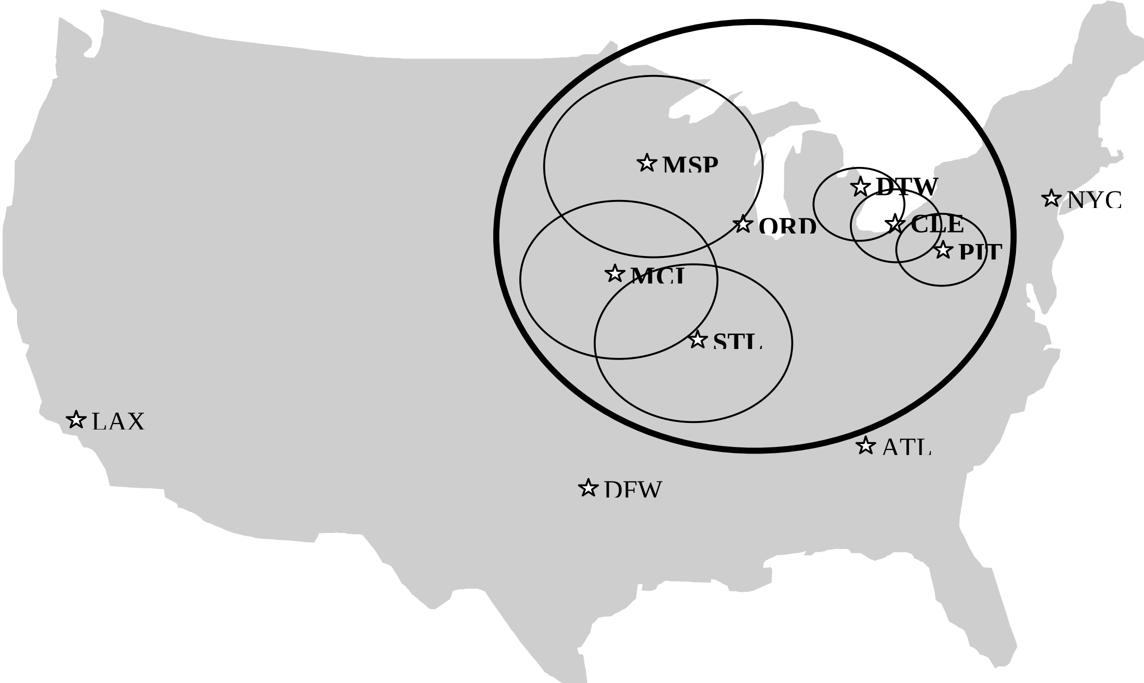


Figure 3-1. O'Hare-centered Region (435 NMi radius)

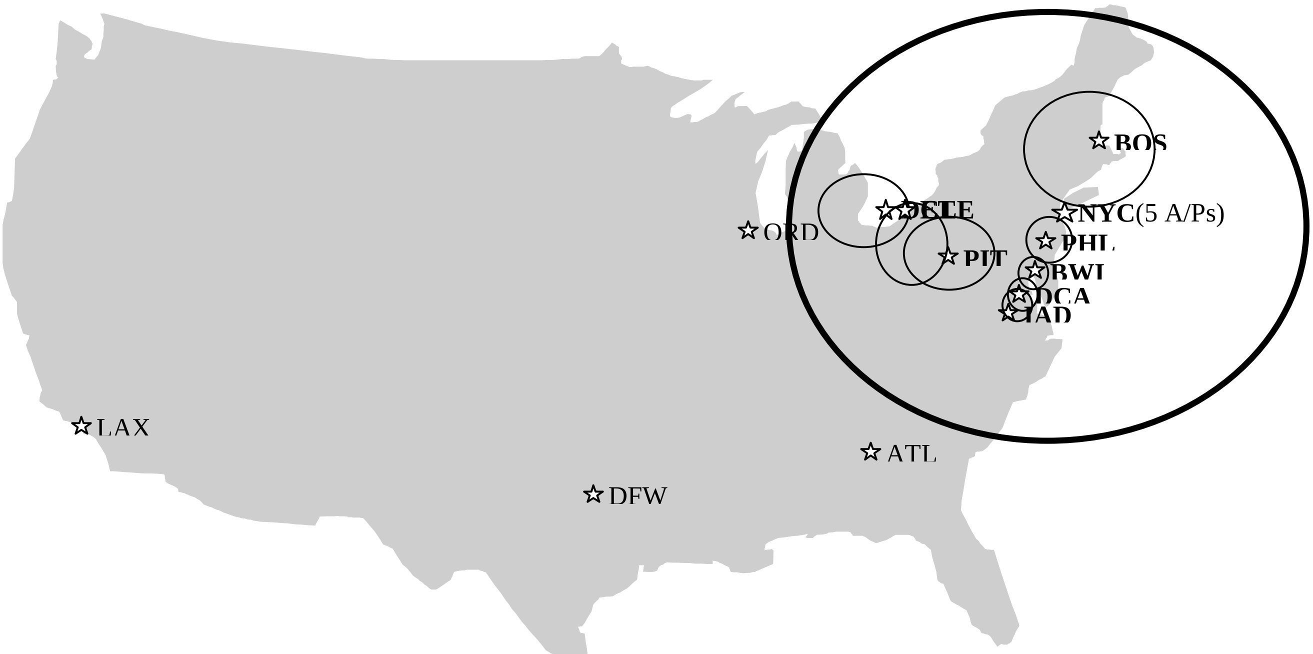


Figure 3-2. JFK, LGA, EWR Complex Region (435 NMi radius)

3.2 Characterizing the Capacity Performance of the Selected Region

After selecting the O'Hare major airport region, the team made a three-day visit on October 25-27, 1999 to the Aurora En Route Center, the Elgin TRACON, the O'Hare

Tower, and to Landrum and Brown's Airport Consulting group in Chicago. Minutes from these visits are contained in Appendix B.

Prior to the O'Hare visit, the team narrowed down the number of candidate days to one or two of the highest throughput days that were to be examined from the ETMS archived data. It was also hoped that a few non-normal days would be found where, even though the O'Hare region had good weather, there would be restrictions and delays caused by air traffic limitations from airports outside of the region. These days would serve as examples of cases where the delays might be partially mitigated by new technology or different operational procedures, both at ORD itself and within the 435 NMi region.

The next step in the selection process was to determine a range of days for which the capacity performance could be examined. First, the period from late April, through May, and June 1999 was selected as the candidate period for examination, considering that traffic demand is generally higher during the summer months.

The next step was to examine National Oceanographic and Atmospheric Administration (NOAA) O'Hare airport surface weather data for the target monthly periods in 1999 to identify twelve days, prior to the visit, that had clear ten NMi visibility and moderate winds (with no thunderstorms or heavy rain) for that day.[5] It was hoped that at least two of these days would have bad weather conditions outside of the 435 NMi radius region that would significantly increase O'Hare's departure delays. These days might serve as examples of cases where the delays might have been partially mitigated by new NAS-wide technology or different operational procedures.

3.3 Capacity Baselining Field Data Collection

Five members of the project team spent two days visiting the Aurora En Route Center, the Elgin TRACON, and the O'Hare tower. The visit was intended to allow the team to get familiar with the operations at these facilities and to request data on the twelve days from each facility. The tower data was hand-written. The TRACON had manually-entered and computer-generated OPSNET data, while the En Route data was mostly computer-generated with a few manual entries. Appendix B provides the descriptions of the data elements from each facility, and the data elements from a third-day visit to Landrum and Brown, Inc.

The prime indicators of total daily operations counts at O'Hare and its secondary airports (e.g., Midway) were requested from the OPSNET data, and the operations delays at O'Hare were obtained from the En Route data. These results were compared to the days obtained from the NOAA O'Hare weather data to make an initial validity of using the

[5] These criteria were derived from NOAA airport data at O'Hare during late April, May, and June 1999, where one, eight, and three days respectively were found to have at least ten NMi visibility, moderate winds, and no heavy rain or thunderstorms over the entire day. This is a total of twelve days. O'Hare had five, six, and nine thunderstorm days respectively in April, May and June 1999.

weather data as the prime source of high throughput day identification. As a second check, the O'Hare arrival and departure delays for a few days were subsequently compared to the same counts obtained from the ETMS archived data.

Due to the limited scope of the initial data assessment, the team picked only one day with the highest throughput/low delay, and two non-normal days, for corroborating the analysis using ETMS archived data.

3.4 Capacity Field Data Initial Analysis

Estimating Current Performance During High Throughput, Low Delay Days and Two Non-normal Days

This subsection reports on the available field information[6] and the findings from the twelve days of data obtained from the visit to the Chicago area. The report focuses on a comparison of two high throughput, low delay days and information on the two worst-delay days.

An analysis of the data for several days in April and May was undertaken. A more comprehensive analysis approach involves the comparison of field-collected data with that from the ETMS archives. This approach is identified in section 4.0 and sample results are provided in Appendix H.

Available Information and Findings from Field Data:

The field data was obtained for the following days:

a. Three Mondays on April 26th, May 5th, and June 7th, 1999
b. Two Wednesdays on May 26th and June 30th, 1999.
c. Thursday, May 27th, 1999.
d. Two Fridays on May 28th and June 25th, 1999.
e. Two Saturdays on May 1st and May 29th, 1999.
f. Two Sundays on May 2nd and May 9th, 1999.

The consistency of airline scheduling was evident from the total number of itinerant operations on each of the days of the week during the sampled days of the Spring and early Summer 1999. The two Wednesdays, the Thursday, and the two Fridays, taken together, had the highest numbers, averaging 2680 ± 1.7%[7] operations. The three Mondays were next highest, closely averaging 2572. The two Sundays were slightly

[6] Full descriptions of the data obtained from the Aurora En Route Center, the Elgin TRACON, and the O'Hare Tower are contained in Appendix B. The data was given to the project team through the superb cooperation of the field personnel at each of these facilities.
[7] Due to the slight non-symmetry of the numerical data, plus and minus percentage ranges are approximate.

lower, averaging 2422; while the two Saturdays were lowest at 2227 and 2118[8] operations.

Highest throughput/lowest delay days

The highest throughput/lowest delay day was selected from an examination of the En Route data by determining the fewest combinations of low aircraft departure and arrival[9] delays charged to air traffic control, and delays (charged to each aircraft) from the Traffic Management System (TMS). Other observation factors in the multi-center airspace were examined since they provided information important in the search for high throughput, low delay days nationwide (where flying conditions outside of the Aurora Center were also good). These factors were:

a. Low numbers of aircraft 'SWAP' routes, to avoid troublesome, mostly poor weather, conditions on the normal preferred routes.

b. Few MIT restrictions at both O'Hare and from O'Hare-bound airports outside of the O'Hare Center boundaries.

c. To a lesser extent, fewer TMS ground stops that are initiated by ATC, or ground delays initiated via ETMS, at O'Hare and from O'Hare-bound aircraft at remote airports outside of the Aurora Center boundaries.

The two high throughput days that best satisfied both of the above delay criteria and the observation factors were May 27th and 28th[10].

May 28th had:
One 30 minute departure delay and 11 arrival delays, averaging 19 minutes with a maximum of 31 minutes;
16 TMS delays (with four at CLE and four at DTW) averaging 27 minutes with a maximum of 53 minutes; resulting in
A total for the above delays of 641 minutes (less than 0.24[11] minutes per operation).

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[8] This result agreed with a comment made by Dave Michalak at the Aurora En Route Center (See Appendix B).

[9] Note that Miles-In-Trail (MIT) arrival delays due to en route centers outside of Aurora Center are not counted by the destination center. **The home center only records delays due to internal holding.**

[10] It is noted that the high throughput day, June 25th, had lower delays (140 minutes total) but had 32 restrictions (15 with the Aurora Center boundaries and 17 outside), making it a poor candidate for a 435 NMi radius or nationwide high throughput, low delay area. The two other high throughput days (5-25 and 6-30) had respectively, higher total delays and a much higher number of restrictions.

[11] The 0.24 minute average delay and low average delays in most of the other days studied were a superb indication of the management of at least 2500 aircraft operations at O'Hare.

May 27th had:
No departure delays and ten arrival delays, averaging 19 minutes with a maximum of 30 minutes;
32 TMS delays (with seven at ZMP and five at CLE) averaging 32 minutes with a maximum of 76 minutes; resulting in
A total for the above delays of 1114 minutes (0.4 minutes per aircraft).

When the SWAP routes, restrictions, and ground stops and ground delays for these days were compared, the following results were found:

May 28th had:
Seven SWAP routes
No restrictions
Two one-hour ground stops (ground delays were not given)

May 27th had:
Eleven SWAP routes
No restrictions
Three ground stops (ground delays were either zero or not given)

Worst-delay days

In spite of the good weather conditions at O'Hare, there were two worst-delay days in the sample of twelve. The analysis of the field data is presented here to provide additional support to the criteria for determining the highest throughput/lowest delays in the 435 NMi radius around O'Hare and throughout the nation. The two days were April 26th and May 10th, both on a Monday, when the total number of operations at O'Hare was still high.

May 10th had[12]:

112 departure delays, averaging 20 minutes and no arrival delays;
72 major TMS delays, averaging 44 minutes, with a maximum of 444 minutes (!) mostly from eastern airports; resulting in
A total for the above delays of 5408 minutes (2.1 minutes per aircraft)[13].

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[12] Both of the two worst-delay days had eleven convective SIGMETS and were the only ones that had them.
[13] The average delay of 2.1 minutes is large when a total of 2531 O'Hare operations are considered.

April 26th had:

No arrival delays[14] and 164 departure delays of 37 minutes average and 190 minutes maximum;
Nine TMS delays, averaging 33 minutes, with a maximum of 162 minutes; resulting in
A total for the above delays of 6365 minutes (2.5 minutes per aircraft).

When the SWAP routes, restrictions and ground stops and ground delays for these high delay days were compared, the following results were found:

May 10th had:

46 aircraft SWAPs (ten to DFW and thirteen to the west coast airports) and eleven SWAP routes
No restriction data was provided.
Three ground stops and one long ground delay.

April 26th had:
42 aircraft SWAPS (eleven to DFW and many to west coast airports) and five SWAP routes
73 restrictions (38 at the Aurora Center, ZAU, and multiple other airports)
Four ground stops and five long ground delays

3.5 Field Data Evaluation and Assessment

The manual basis of the field data generation gave it a limited usefulness for a comprehensive assessment of the capacity situation in the Chicago region. It is clear that when the operational situations become critical, one of the first tasks the controller 'sheds' is data entry of system assessment measures. One recommendation of the research team is that the data collection methods in the field need automation support to provide consistent and complete assessment of the operational situation.

An alternative approach to baselining was developed based on the preliminary assessment of the difficulty of using field data. This approach is outlined in section 4.0. It relies on field observations to guide the statistical data collection, but relies on the automatic traffic and delay reporting mechanisms of the ETMS to achieve the analysis.

[14] The absence of arrival delays on both of the worst-delay days show that the weather around O'Hare was good.

4.0 Chicago Case Study Baseline Findings

The following section discusses the findings of the Chicago case study regarding the development of a 'baseline' of the region of study. The purpose of a baseline is to extrapolate the current system performance (without new technology investment) into the future, with increased demand for air traffic services. Then alternative CNS, ATM and other investments can be postulated to improve airspace operations and affordability, with each alternative quantified against a common baseline.

The performance objectives for airspace operations are discussed in section 1.1 and as a minimum include capacity, efficiency, safety and affordability. The first three we will group as operational objectives. Development of an operational baseline is required to evaluate these objectives for alternative investment scenarios. Affordability assessment is also needed to evaluate the financial aspects of alternative architecture investments. The Preliminary Design process discussed in section 1.2 recognizes the inter-dependencies of these performance objectives and the implicit tradeoffs among them.

Requirements for the development of an operational baseline are discussed in section 4.1. The initial focus of the case study in this effort was on the Chicago system capacity. Most of the emphasis in 4.1 is on capacity baselining, but a discussion of how to broaden the Chicago capacity baseline to include safety and efficiency considerations and to address the total NAS is provided in sections 4.1.8 through 4.1.10.

The other envisioned evaluation of the preliminary design process is the overall impact on NAS architecture and operations and maintenance costs. For this assessment a baseline extrapolation needs to be developed of operations and maintenance costs with no new facilities and equipment expenditures. Section 4.2 identifies the high-level considerations for developing an affordability baseline.

The process described in Section 4.1.1, Operational Baseline Developmental Approach, is the second-tier expansion of step 3 of the Airspace Preliminary Design Process summarized in Figure 1-3 of Section 1.2 of this document.

4.1 Chicago Operational Baseline Requirements

This section deals with the characterization of a capacity baseline for the Preliminary Design process. The discussion of the baselining begins with the findings of the Chicago Case Study reported in sections 6.1-2, and focuses on capacity and affordability (in section 4.2), the two measures selected for the Phase 1 investigation. For the capacity and affordability objectives, requirements for a comprehensive baseline development are stated. The extrapolation of these requirements to a NAS-wide baseline of overall system capacity and affordability are discussed. Finally, consideration of a NAS baseline against the full set of airspace performance objectives envisioned by the Preliminary Design Process is discussed in section 4.3.

One of the issues in the baseline characterization is the boundary of the region of interest. During the analysis, it was recognized that the Chicago airport-airspace system could be considered to encompass the whole of the domestic US, given the extent of traffic interactions. The national flow control system spans, for all Chicago arrivals, from the destination airport to all origin airports. Similarly, ground stops for O'Hare departures may be initiated based on predicted conditions at all destination airports. For the study, a region was selected spanning about 500 miles to and from Chicago O'Hare. This region was found to be a good cut point, maximizing Chicago impacts and minimizing external affects. However, it is realized that on many occasions, constraints at O'Hare may spill into the en route airspace to the first-tier, or even second-tier center.

Standard airport capacity modeling currently assumes the final approach and runway system is the primary constraint and recognizes two factors in the determination of this capacity: ceiling/runway visibility range and wind direction. For these two factors, a runway operational use configuration is established and modeled to assess the overall airport capacity. This assessment is typically for the final approach and runway system performance. Up-stream airspace and down-stream surface constraints are frequently neglected as second-order effects. The adequacy of this approach O'Hare is increasingly questionable for a complex airspace/airport region such as Chicago. The complex coupling of flow control actions, en route and terminal area dynamics, as evidenced by the field interviews and observations of personnel in the center, approach and tower (section 6.1-2 and Appendix B) raise the issue of the sufficiency of such static and local evaluations to predict and diagnose system capacity limitations. Additionally, the number of capacity 'states' of the system needs an analytical and qualitative validation. Finally, rare-normal and non-normal states, while limited in frequency or direct impact, may fundamentally condition aspects of normal operations such as separation minima, thus limiting airport and airspace throughput.

The development of a detailed, second-order capacity model of the airport system, empirically validated, is proposed to assess the adequacy of today's first-order models of the airport capacity and provide insight into potential CNS/ATM system improvements.

4.1.1 Operational Baseline Development Approach

The approach to the development of an operational baseline for Chicago airport and airspace system to support current capacity estimates and future capacity projections is summarized in Figure 4-1. One result of this first case-study application of the Preliminary Design process is the expansion in Figure 4-1 of the "Baseline Current System" process discussed in section 1.0.

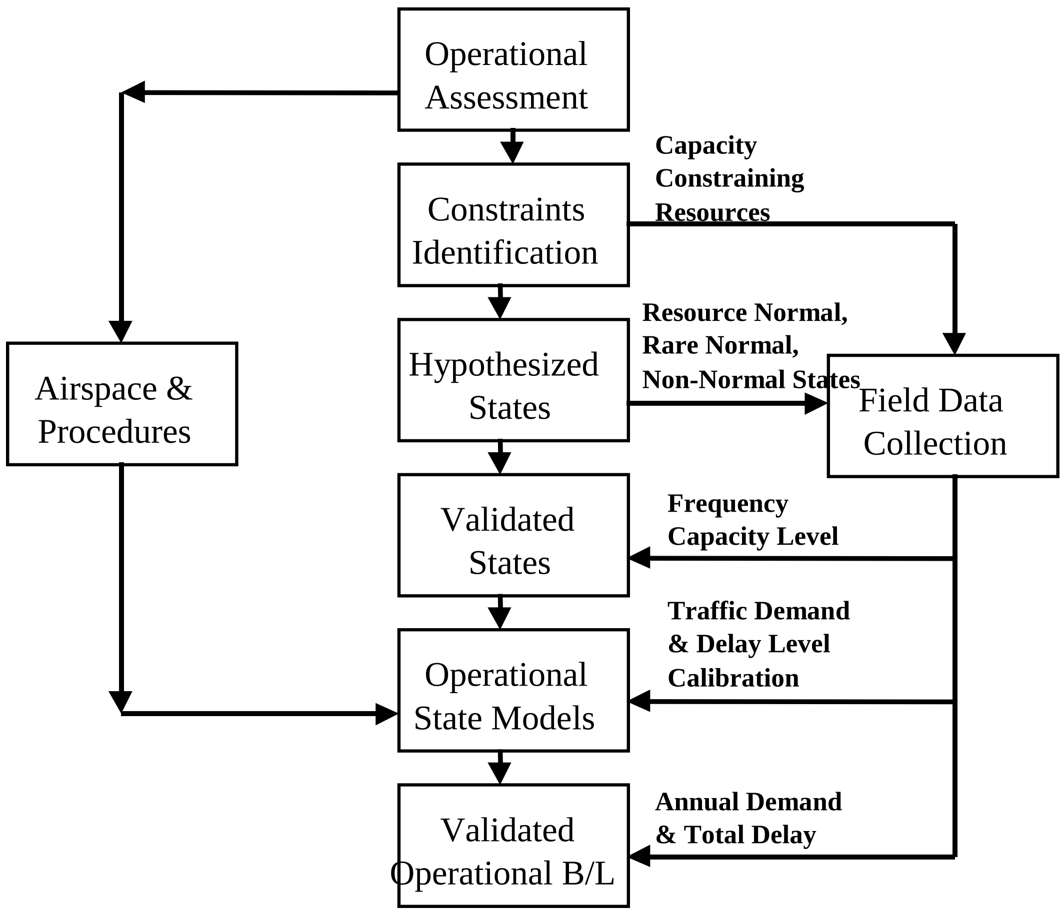


Figure 4-1. Operational Baseline Development Approach

The baselining methodology begins with the identification of the resources which affect the operational capacity of the system, and the associated operating states which have a capacity impact. In the traditional view, the final approach and runway resource is identified as the key capacity constraint. For this constraint, an examination of the usual factors of wind direction, cloud ceiling and runway visibility range (RVR) identifies the operating configurations of the airport and the associated ATC separation rules. Sections 4.1.2 - 4.1.10 describe the baselining process in Figure 4-1 in detail. Sections 4.2 and 4.3 present a discussion of how to extrapolate the NAS capacity findings, incorporating other operational factors and infrastructure change considerations into the capacity assessment.

4.1.2 Chicago Capacity Assessment

The airspace Preliminary Design process is grounded in an in-depth understanding of the current operation, focusing on the quantified performance aspects of the airspace operation. As such, it begins with a systematic definition of the current operation. To do this, it is assumed that the various operators' views are necessary to assemble a comprehensive understanding of how, how well, and why the system works as it does. The 'how well' is tied, for our initial investigation, to system capacity assessment. Capacity is a complex issue that is not directly measurable, but quantified through a calculated operating state, for which a level of demand on the system results in a level of delay.

For the initial phase of study, with limited time and resources, the operational assessment was limited to a series of operational interviews and a qualitative assessment, described in sections 6.1-3. This was felt to be the best way to gain substantial understanding of the complex capacity issues associated with the extended Chicago operating region. The Preliminary Design process requires the system design to begin with an examination of the current operation, its performance, limitations and constraints. Any proposed solutions, whether technology-based or procedurally-based, must address these operational issues.

Appendix B of Volume II reports in some detail the results of the interviewing process. The availability of senior FAA personnel to the study team and their ability to address the wide range of operational questions was key to any significant results to be gleaned from this report. In a full exercise of the Preliminary Design process, the interviewing process shown in section 6.1 would be augmented with discussions with operators, including the full range of airspace users, and an analysis of field data (ETMS, radar, etc.).

The operational assessment activity provides the initial basis of the identification of operational constraints and the suggestion of system states which need to be known to identify the total system capacity level.

4.1.3 Chicago Capacity Constraints Identification

The standard capacity assessment methodology focuses on the final approach and initial departure aspects of the airplane operation and determines the limiting (throughput) or level-of-service (operations per delay level) capacity. This approach assumes that the system capacity is limited by the final approach, initial departure and runway system capacity. This approach further assumes that the predominant system conditions (operational states) involve wind direction, ceiling and RVR.

For a given ceiling, RVR and wind direction, an airport capacity estimate can be determined. For visual operating rules, the associated runway spacing constraint is often assumed to be the runway occupancy performance of the landing aircraft stream. When weather conditions degrade, the constraint tends to shift to the final approach region, where a complex of radar separation rules and wake vortex considerations (based on the weight class of aircraft pairs) limit final approach spacing. Delay is calculated for a given traffic demand and the appropriate set of inter-operation final approach spacing constraints (rules based on weather, runway configurations, etc.).

The assumption that the predominant cause of delay at Chicago was related to final approach spacing and runway operation was not corroborated based on the operational interviews reported in section 6.1. There was significant discussion of corner posts, en route flows, and other conditions which significantly limit the flow of traffic into and out of Chicago O'Hare, as summarized in sections 6.2-3.

A generic airspace constraints model is summarized in Appendix G. This model forms the basis for organizing the complex set of constraints that may limit airport flows under various conditions (see Allen, David L., *The Economic Evaluation of CNS/ATM Transition*, IATA Global Navcom, June 1997). Based on the constraints model, a mapping of Chicago findings is shown in Figure 4-2.

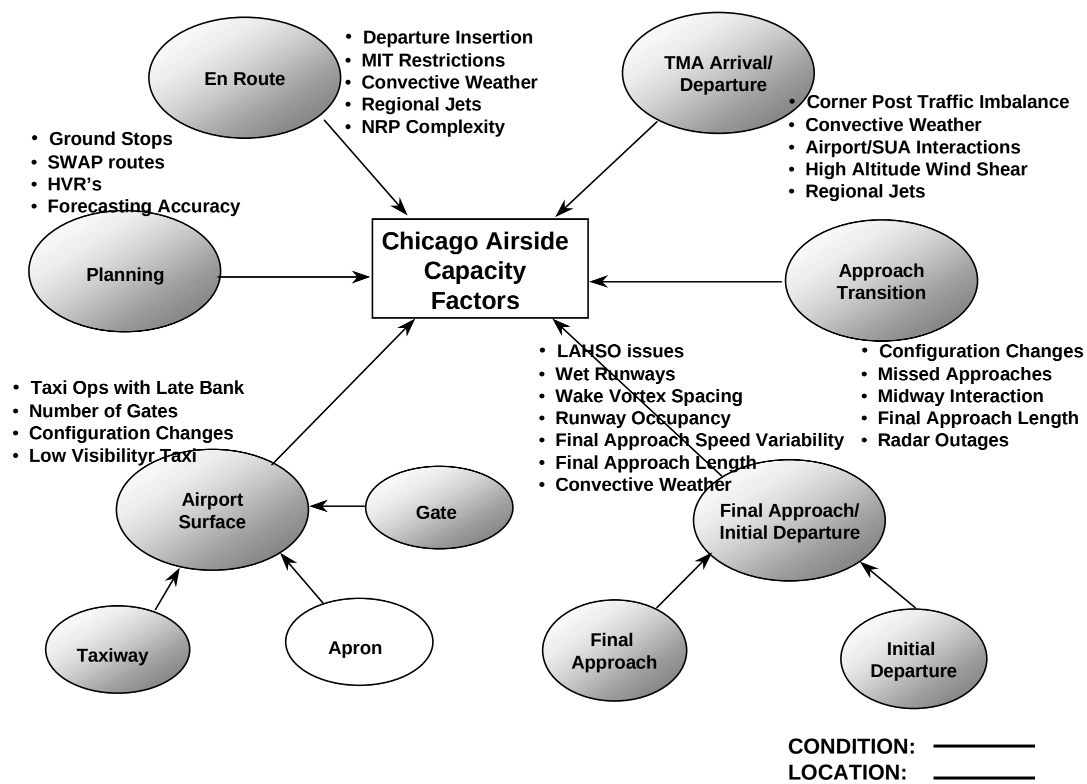


Figure 4-2. Chicago Airside Capacity Constraint Factors

A discussion of a more systematic review of several significant approach flow constraints is presented in sections 6.2 and 6.3. These sections point to the difficulty in isolating, for a given operating condition, which element is flow limiting, given the dynamics of the demand and the constraints.

4.1.4 Hypothesized Chicago Capacity States

Each of the constrained resources identified in section 4.1.3 has, qualitatively, been identified as constraining the system traffic flow under certain conditions. These include gates, taxiway system, final approach and runway system, approach transition (terminal vectoring area), TMA transition (SIDs and STARs including corner posts), en route and planning. The next step of the baselining process is to identify the probable states in which the capacity (or throughput) of a system resource is constrained.

The final approach and runway system is examined first. This element of the system is usually assumed as the capacity bottleneck of the system. The results of a set of runway system capacity states for Chicago O'Hare is illustrated in Figure 4-3.

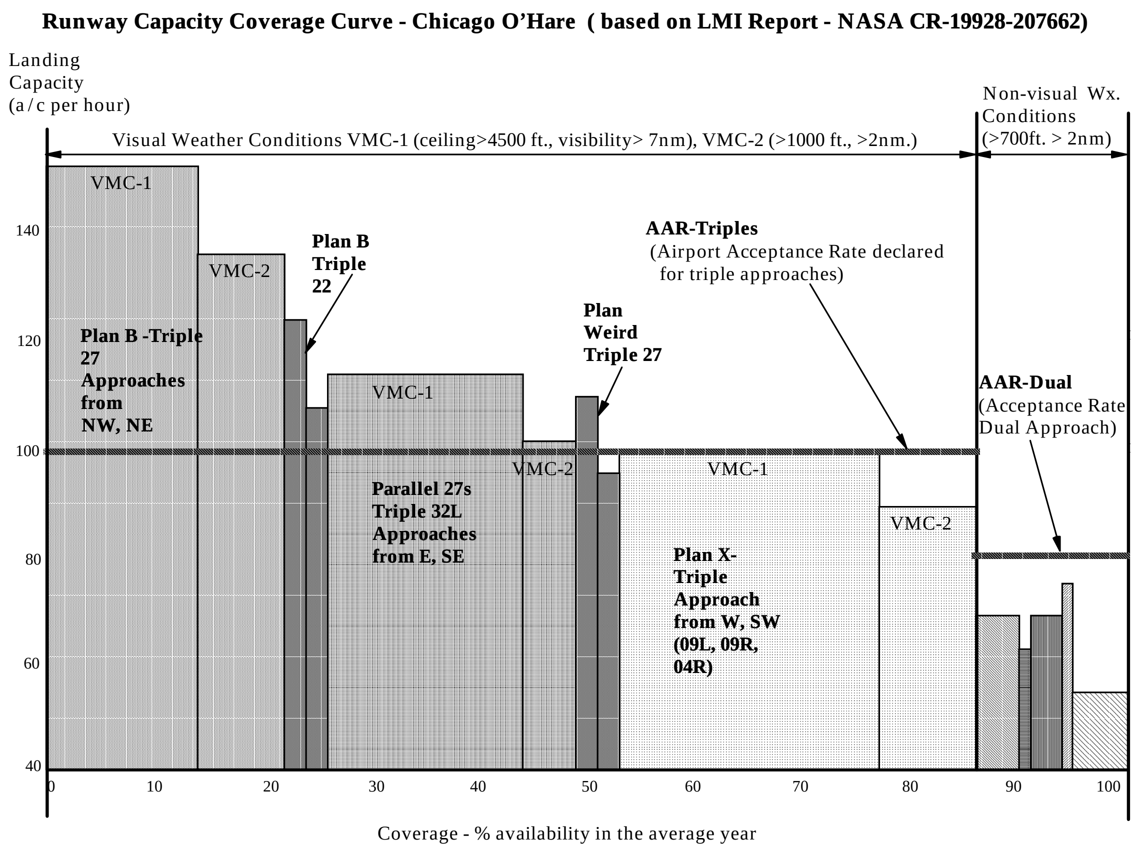


Figure 4-3. O'Hare Airport Runway Capacity States

The figure shows the system capacity in operations per hour for each of the states in the assessment. The width of each of the states indicates the frequency with which the particular state is in use. The evaluation, via simulation or field measurement, for each state provides the basis of the capacity estimate. (See Lee, David, et al, *A Method for*

Making Cross-Comparable Estimates of the Benefits of Decision Support Technologies for Air Traffic Management, Logistics Management Institute, McLean, VA, July 1998, and Long, Dou, et al, *Modeling Air Traffic Management Technologies With a Queuing Network Model of the National Airspace System*, Logistics Management Institute, McLean, VA, January 1999.)

The total airport system capacity is thus derived from the capacity of each state, weighted by the frequency of use of that state. Graphically such a result is presented in Figure 4-3 for the Chicago O'Hare Airport system, based on results from the LMI Chicago model report. In the figure, the system capacity is represented as the area under the curve, with high capacity value for the good-weather conditions and lower capacities as the weather conditions degrade below the most favorable. The LMI study, in the absence of detailed operational data, derived the system configuration states from wind data, using assumptions about what configuration is in use for a given wind and visibility condition. The capacity values are typically validated by using measured throughput values (operations per hour and level of delay experienced) for a given state.

Based on the operational interviews described in Appendix B of Volume II, as illustrated in Figure 4-3 for the final approach and runway region, the standard factors (wind speed and direction, cloud ceiling and runway visibility range) may not be adequate to account for a significant portion of the runway system capacity states. A number of rare-normal and non-normal factors may have a significant impact on runway capacity, such as convective weather in and near the airport, snow removal, aircraft unable to exit the runway, runway configuration changes, etc. Based on these considerations, additional state variables to be investigated for the runway and final approach system include convective weather and runway closure events.

For other regions of operation, such as the taxiway system, normal operations may not produce delay. However, events such as the interaction of an arrival and departure bank and unplanned configuration changes may produce significant problems. Similarly, for the arrival transition (TRACON), outer TMA, en route and planning regions, an identification of performance states and associated throughput is needed. Appendix D describes in detail a conceptual analysis of the overall arrival flow process for O'Hare. Quantifying the frequency and severity and identifying the associated state variables for this complex operation is part of the baselining process.

4.1.5 Field Data Collection Requirements

Data collection is a key element of validating the traditional capacity coverage curve of the runway system. This will verify that the identified capacity states are, in fact, correctly formulated and that the assumed frequency data agree with the experienced frequencies.

The primary performance metric for system capacity is not directly observable in the operational system. What can be observed are various points on the demand versus delay relationship. Figure 4-4 illustrates the basic nature of this relationship, which is a characteristic of all queuing processes. The construction of the curve is based on a measurement of delay for a given level of demand.

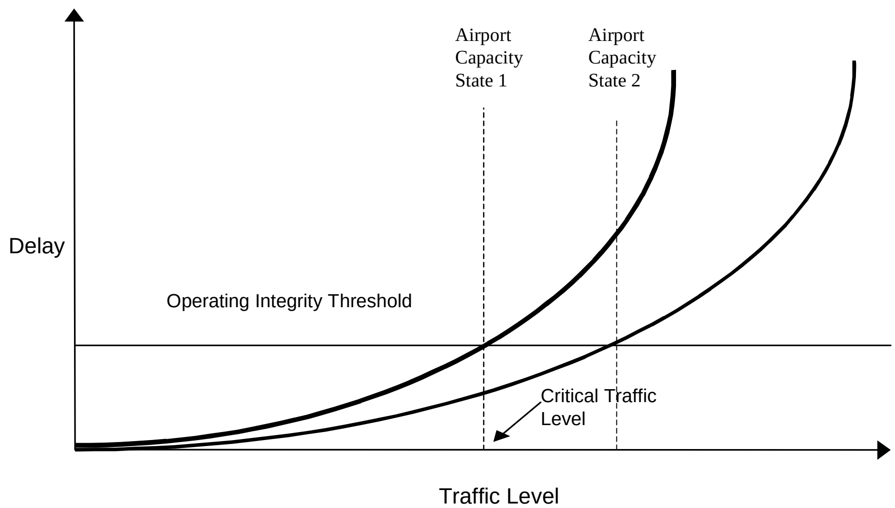


Figure 4-4. Capacity as Demand Versus Delay

Because of the complex nature of capacity, a number of definitions with associated metrics can be formulated. One approach is to define the capacity of a system state as the traffic level associated with the limiting (fully loaded) operation. In Figure 4-4 this is represented by the asymptotic traffic value as the delay becomes infinite. Often, capacity is defined as the traffic level at which an Operating Integrity threshold is reached. In many airport assessments, 'capacity' is declared when average delay reaches 4, 6 or 10 minutes per operation. In the American Airlines study (see Chew, Russ, *Free Flight: Preserving Airline Opportunity*) an average delay per operation was associated with a delay variance value associated with the scheduling integrity of the bank of arrivals at the airline's airport hub. These differing capacity definitions require different measurement definitions.

The basic field data collection problem for the overall airport and airspace system is to determine the number of distinct capacity (delay versus demand) operating curves that the system may exhibit under various operating conditions (states). The hypothesized capacity states of the final approach and runway system each represent one demand/delay curve. Data are needed to insure that each postulated state is, indeed, a distinct capacity state of the system. Statistical tests can be formulated to determine whether a defined state exhibits a distinct capacity level, and to estimate the frequency of occurrence of the state.

Current models typically assume that the observed weather frequencies equate to the operational state use. However, variability in observations of visibility and wind direction often require operators to conservatively pad the ceiling threshold for an operating state, and this can generate substantial differences in actual versus computed frequencies of state use, resulting in generally lower realized system capacity.

For each capacity state validated by the operational data collection, with related total delay (expected delay for the state times frequency in the state), an operational model can be developed to represent the associated performance as influenced by the primary system variables. Developing a statistical basis for characterizing the capacity states of a chosen airport and airspace region is one of the primary requirements for the system baseline.

4.1.6 Chicago Capacity Validated States

Validation of capacity 'states' of the system will involve the measurement of operations over a large period of time to establish the correlation of demand, operations counts and system state factors such as weather and equipment health. These factors are discussed in section 4.1.4. Statistical tests will need to be designed to accept/reject the hypothesized system capacity states. Various measurement parameters are discussed in section 4.1.5.

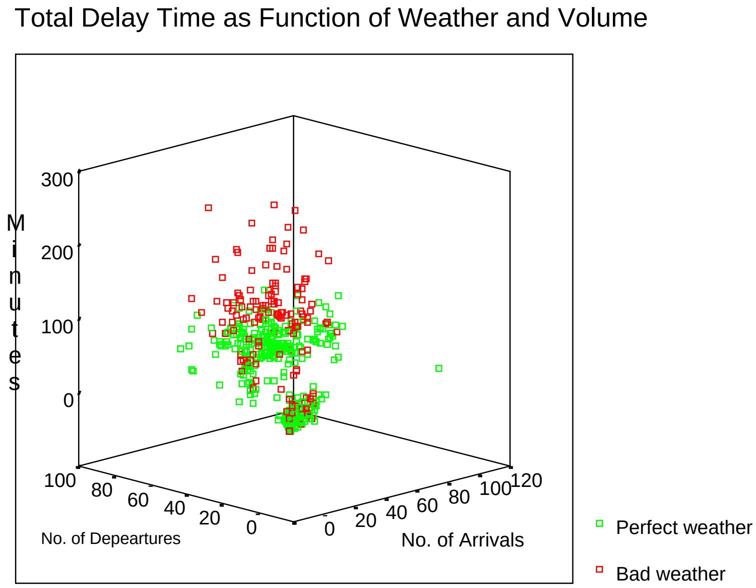


Figure 4-5. Sample ETMS Data Analysis of Capacity State Variables

Data requirements will be compared with available data sources such as the FAA's archived ETMS data discussed in section 5.0 and Appendix E of this document. Appendix H provides an initial assessment of the use of ETMS, OPSNET and CODAS data with weather data to provide a Chicago Capacity Performance Baseline Assessment. Figure 4-5 provides one summary level look at the ETMS data for the purposes of validation of the 'capacity state variables' based on the ETMS data sample.

Measurement of the demand and delay in an airspace region can be used to 'calibrate' an operational simulation of the region of interest. For calibration, this measurement should be taken at time periods when there are not up-stream flow control actions.

Identification of a few 'typical days' for the baselining assessment will be required. These days will represent a sampling of operational states.

4.1.7 Chicago Airspace and Procedures Data

This element of baselining collects the set of reference or nominal procedures data needed to build operational models for the airspace regions of interest, those where resources currently constrain or may in future constrain operations rates and limit system capacity.

The definition of operational models in baselining requires consideration of the following factors:

(1) traffic characterization (hourly arrival and departure patterns)
(2) aircraft class characterization

(3) airport gates and schedules
(4) taxi flow patterns by operational use
(5) runway use for arrivals and departures by operational use
(6) airspace flow patterns

Hourly traffic data for the Chicago O'Hare airport are provided in the Landrum and Brown report on Chicago. One of the problems with demand-delay characterization of the airspace system is the de-coupling of the delay source from the point at which the delay action is imposed. With the advent of the flow control system in the late 1970s, forecast capacity shortfalls at arrival airports triggered ground hold delays at the origin airports. Today, a measurement of demand by counting operations at an airport or airspace region misses the up-stream delay effects of such flow control actions. Delays may be understated, since the delay measured at the region of interest may not reflect the previous flow actions.

The operational modeling will need to identify user classes with potentially differing service expectations and aircraft performance. Among the user classes to be considered are:

Air carrier international operations
Air carrier domestic operations
Air Taxi - Turboprop
Air Taxi – Regional Jet
Cargo Operations
IFR General Aviation
VFR General Aviation
Military Transport

Based on the current Chicago traffic demand, if other potential user classes are identified they will also need to be added to the baseline performance assessment.

Patterns for current and potential future uses of runways will need to be identified. An example of such runway use assumptions is found in the Landrum and Brown analysis of the Chicago O'Hare system, as illustrated in Figure 4-6.

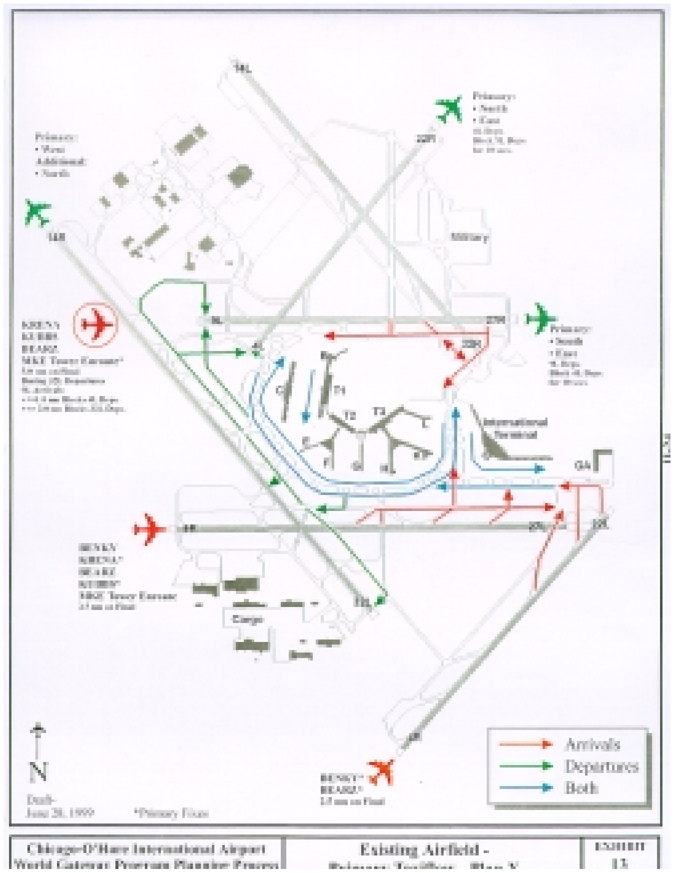
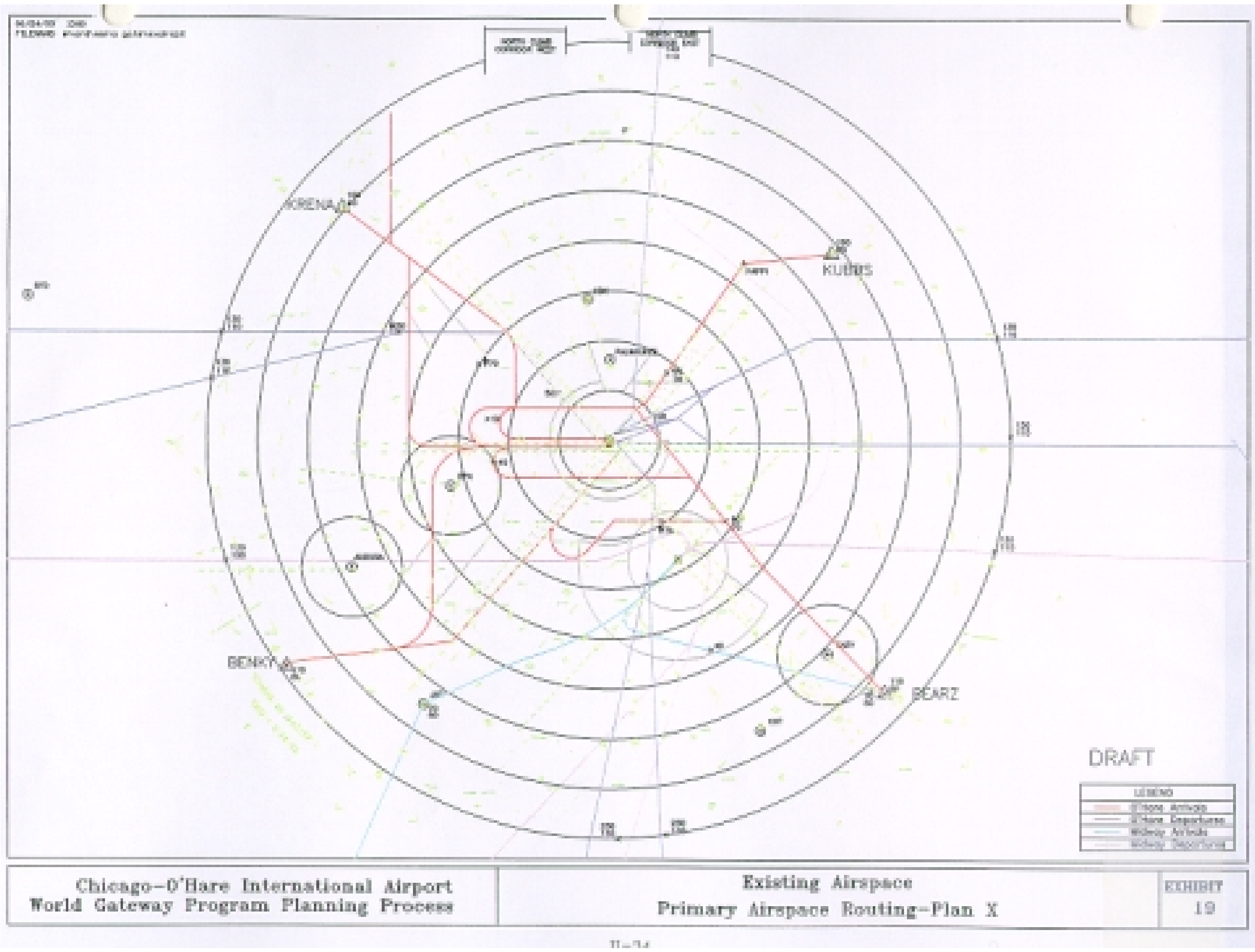


Figure 4-6. Runway Configuration X at Chicago O'Hare

Consideration of gates and scheduling of gates may be required if gate utilization is identified as a significant capacity limitation. Similarly, surface operations modeling may be required for the conditions when surface operations become the capacity-limiting factor. Figure 4-6 also depicts at a high level the taxi flow pattern for Chicago operations for the so-called Plan X operational configuration (courtesy of Landrum and Brown). The development of detailed surface movement models requires substantial effort in terms of defining operational rules and modeling these in a fast-time simulation tool such as TAAM or SIMMOD.

Figure 4-7. Arrival and Departure Paths for O'Hare Configuration X



Airspace use patterns will also be required for some model development. An example of arrival path patterns in the approach transition area is contained in Figure 4-7. Again the Plan X operational configuration is depicted.

A catalogue of data sources related to Chicago O'Hare configurations, runway and airspace patterns, and traffic demand is provided in Volume II, Appendix F.

4.1.8 Operational State Model Development

For the constrained resource area and for each of the 'significant' operating states, a computational model of operations can be constructed. This model provides the basis of extrapolation to future operations scenarios of the airport and airspace system. The current air traffic performance models are fast-time discrete event simulators such as TAAM, SIMMOD or RAMS. Operational data are typically collected to calibrate the model of each operating state. For the observed traffic levels, system delay is measured and compared to the model-computed levels of delay for the same traffic demand.

The above analysis and modeling approach identifies the capacity of the various airspace elements as a function of operating state. There is still a requirement to assemble, at a high level, the various component contributions and model their aggregate capacity effect.   Part of the complexity of the airspace analysis is that a given flight through the system is subjected to a series of queuing processes. The system delay is then the result of the sequence of queues.   It is expected that multiple, dynamically varying, constraints will be applied for flights in the system. Determining average and variable performance will be keys to modeling the system capacity effects.

System resources (FIRs, high sectors, transition sectors, arrival corner posts, departure fixes, vectoring regions, final approach regions, runways, taxiways and gates) will be considered at a high level of representation. For all of these elements, capacity constraints representing current and future operations will be parametrically represented. During the simulations, delay will be accumulated against the system constrained resources to assess the total level of delay for a given set of traffic and resource assumptions, and the allocation of the delay to the resources.

4.1.9 Validation of Capacity Baseline

Collection of the capacity element models into a system level flow model and the validation of this aggregate model against the system level demand and delay measurements collected in section 4.1.5 will be the final activity of the capacity baselining effort. This validation will allow investment analysis practitioners to estimate benefits of technology and procedural initiatives, based on a complete and consistent set of capacity state assumptions for the system under study.

4.1.10 NAS Capacity Baseline Approach

Once the Chicago airport and airways capacity baseline is established, a critical question is the degree to which the Chicago study can be used to infer a NAS capacity baseline. The approach to the development of a NAS baseline involves: (1) a review of recent approaches to the development of a NAS-wide capacity assessment, (2) definition of the requirements to be satisfied by such a data base and model, (3) identification of a likely basis for proceeding. This may seem to be a daunting task as it may appear that we have to collect data and baseline every significant airport and region of controlled airspace in the U.S. system.

Four recent assessments of the NAS capacity are examined: The George Donohue/George Mason University study (see Donohue and Laska), the Boeing Features Strategy assessment of the NAS system delay, the LMI/NASA NAS 'macro' delay modeling and assessment approach, and the large-scale 'micro' modeling approach used by American Airlines and Russ Chew (see Chew, Russell).

The George Donohue approach is founded on an analytic assessment of the ratio of the traffic demand level to the theoretical throughput of the airport system for the 57 busiest airports in the NAS, representing 85% of passenger enplanements and 70% of commercial operations. The Donohue model assumes airspace capacity is much greater than airport capacity and hence can be neglected in the analysis.

Donohue constructs an analytic queuing model for maximum capacity of an airport which is then summed over the airports of interest. Factors in the airport capacity calculation include traffic spacing (a function of 'separation technology', wake vortex and weather). A second factor involves runway configuration, noise and maintenance. A third factor accounts for airport design, gates and taxiways. These factors are combined to calculate the theoretical capacity for each airport and the airports are summed for the NAS. The model appears to account for a single IFR and a VFR operational state for each airport considered, apparently based on the MITRE D-PAT tool (an analytic simulation tool for 'policy level' assessment).

Donohue estimates the growth in maximum capacity of the NAS from the late 1980s extrapolated to 2012. He compares this maximum capacity to the growth in operations and determines the ratio of these two factors. By this calculation, Donohue computes the percentage of maximum capacity utilization to increase from 45% prior to 1990 up to 70% in 2012.

A second approach to a NAS-level capacity assessment is illustrated by the Boeing Terminal Area delay assessment. The Boeing approach uses an airport sampling technique to account for airport 'types' based on high-level consideration of constraints and weather frequencies. The sampling methodology suggested has not been validated, but suggests an approach consistent with the overall direction of the airspace Preliminary Design baseline approach of this chapter.

A recent Boeing study of approach and landing costs in the U.S. system illustrates this process. This study used existing final approach and runway system models for the constituent airport assessments. This methodology needs to be expanded and validated as we have discussed in sections 4.1.1 through 4.1.9 of this report, but much of the extrapolation methodology should still be applicable. The study began by characterizing the major U.S. airports in terms of three criteria: unconstrained, airport constrained (runway system and surface), or airport/airspace constrained. These three categories are matrixed with weather frequency impact (high, medium or low visibility frequency).

For each of the sampled airports, detailed demand versus delay simulations are conducted. These simulation studies are the basis of the Airport Task Force studies that have been conducted at the top 20-30 airports in the NAS. For each airport in the analysis, a capacity coverage curve of the type presented earlier in this chapter is developed. An airport is typically divided into VMC, marginal VMC, IFR Cat I and IFR Cat II/III operations. For IFR operations, wake vortex restrictions are applied. Various airport analysis models have been developed and used. Most are calibrated with interoperation minima measurements for the airport of interest. Primary and alternate wind direction of operation is considered.

Current demand and delay levels are used to calibrate the model; demand is then extrapolated and a 'do-nothing' delay value determined. The cumulative cost of the 'do-nothing' scenario is used as the cost recovery basis of alternate postulated operational changes. Again the en route delay effects have been neglected, although these can be estimated and a term added for their contribution, assuming the en route and airport effects are not coupled. The results of the NAS analysis conducted by the Boeing Features Strategy team can be compared to system-level cost of inefficient operations as well as to system delay metrics. Cost values are determined by weighting the delay value with a cost per minute of delay value (such as the airlines DOC values).

The next approach to a NAS-level assessment of capacity is that employed by the LMI/NASA studies of the benefits of alternative technologies to the NAS through reduced delay and other efficiencies of operation. This approach we will characterize as a system-wide macro-delay analysis.

The LMI approach uses a NAS-level network queue model, LMINET, to represent delay coupling effects of the various NAS elements (airports, TRACON sectors and en route sectors). Each node in the network is represented by a standard analytic queuing computation. For a given day’s conditions, LMINET can represent the system flights and the compounding effects of delays in the flight schedule. The LMI methodology can then grow the traffic and determine the operational and economic impact on the system users.

The most comprehensive approach to capacity baselining is the development of a detailed airspace and airport model which represents 3D trajectories of flights in the system and the various constraints that are imposed: miles in trail due to flow control, sector loading constraints, airway and airspace separation minima, etc. Such an approach to NAS baselining was employed by Russ Chew in the American Airlines study of the U.S.

system capacity longevity. We will characterize this approach as the micro-simulation approach.

The American Airlines study modeled a NAS-wide baseline of airports and other airspace constraints. One limitation to this approach is the number of airports and constraint points which can be evaluated. The link-and-node-based SIMMOD model was used as the basis of the analysis. Delay versus demand was calibrated for a base year and the demand extrapolated. The American study was predicated on 'a good weather day' throughout the system (one that took some searching to find). One can envision repeating the American study over a range of days representing all likely weather conditions in the NAS to develop a comprehensive baseline.

A variant of this approach, based on development of a comprehensive collection of TAAM simulation models, is the National Baselining effort being conducted by the FAA’s Airspace Modeling and Analysis organization.

These analysis and simulation models of the NAS capacity represent various levels of detail and increasing complexity. Requirements for the Preliminary Design of Airspace baseline development follow.   The preferred approach should be the simplest possible, consistent with meeting the requirements of a NAS-level capacity baseline for the airspace preliminary design process. These should include the following:
(1) represent a significant portion of the NAS capacity measurement;
(2) extrapolate from the current performance to future performance with assumed traffic growth scenarios;
(3) relate operational constraints to delay levels;
(4) be maintainable, given constantly changing operations;
(5) address the coupling of constraints; and
(6) adequately represent the complex NAS behavior across system elements.

4.2 Affordability Baseline Considerations

Just as the Preliminary Design Process requires an operational baseline to measure the operational effects (safety, capacity and efficiency) of proposed NAS changes, so an infrastructure baseline is needed to assess the affordability implications on alternative investment scenarios. The affordability baseline needs to support a life-cycle investment analysis of various proposed technology solutions for airspace operations. Operations and maintenance costs are the dominant expenditure of the FAA and other air traffic service providers. The scenario of traffic growth, fixed congressional air traffic expenditures, no new controller decision support functionality and aging equipment is one where escalating operations and maintenance costs threaten capitalization, making investment in infrastructure increasingly difficult.

The Airline CNS/ATM Focused Team (C/AFT) model elements are summarized in Figure 4-8 (illustrated for the air-to-ground data link). The baseline affordability considerations include the establishment of the infrastructure status. Infrastructure here includes the ground architecture elements (FAA, Airline, ARINC, SITA), the airplane architecture elements and the system operational costs. For the current planned investment level, the life cycle cost model can be developed. The airplane fleet equipage model is complex. Many avionics/flight deck configurations are found in the commercial fleet. Adding military transport and general aviation further increases the diversity. Fleet-wide change is thus difficult, expensive and requires considerable time.

The investment model looks at costs, benefits, timing and risk. Timing elements depend on changing constraints of the ground and airplane infrastructure. Costs depend on the new technologies introduced, their operational criticality, and their linkages to other elements of the infrastructure.

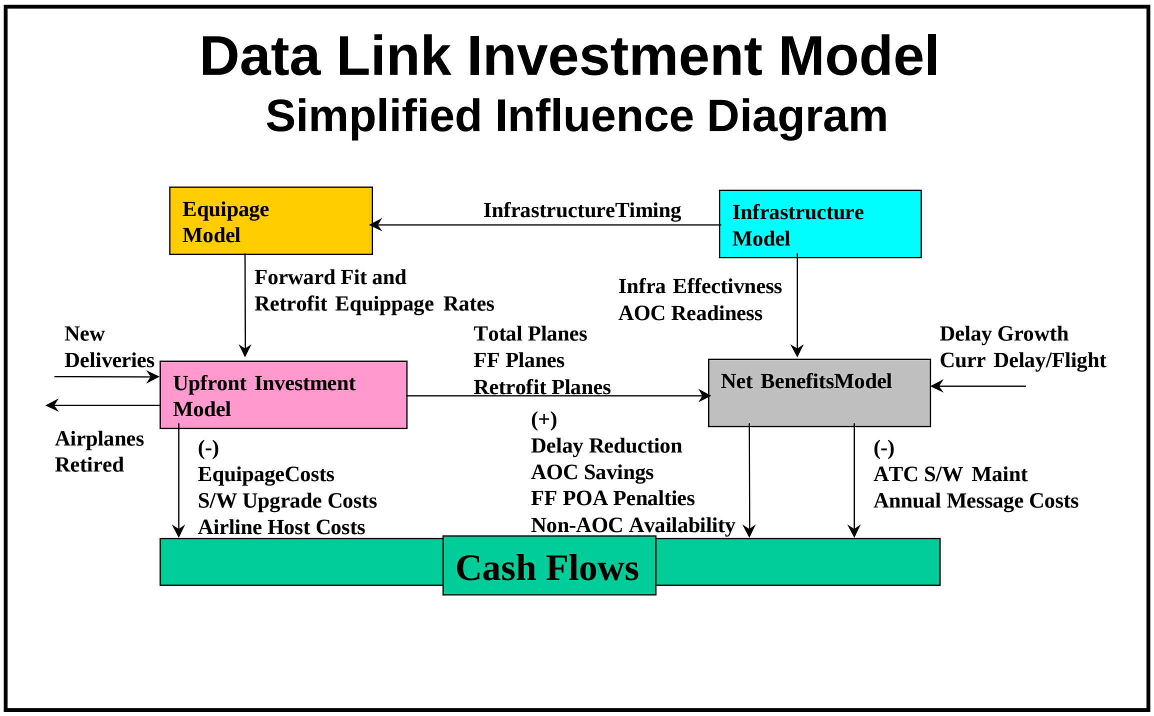


Figure 4-8. Investment Analysis Considerations

4.3 NAS Baseline for Preliminary Design Approach

Section 4.1.10 describes the process of extending the Chicago capacity baseline to a NAS capacity baseline. Other potential operational system measures include efficiency and safety, and the capacity baseline envisioned for the NAS must be integrated into a comprehensive operational baseline addressing safety, capacity and efficiency. The FAA's Airspace Management Program Office (ATA-200) has developed a plan to establish an en route baseline for the NAS, focused primarily on en route and terminal area flight efficiencies. That plan is provided as Volume II, Appendix E of this document. Ultimately, the airspace preliminary design process must merge the various performance objectives and operational domains of the system into an integrated planning methodology.

Similarly, safety assessment methods and tools are needed early in the airspace design process to test concepts and planned technology introductions. Safety assessment methods and tools must address not only the 'normal' operational states of the system, but also the 'rare-normal' and 'non-normal' states. Given failures (loss of radar, communications outages, etc.) the system design must provide back-up systems and/or procedures to ensure fail operational capability. The analysis approach proposed for the Preliminary Design process involves the consideration of Required Total System Performance (RTSP). RTSP can be used to support system safety analysis before a detailed design for the future system architecture is finalized. It can also support performance tradeoffs across navigation, communications, surveillance and controller decision support tools.

The current operational problems in the NAS and the difficulties with insertion of new technologies point to the need for improved system assessment tools and data. We need to integrate various functional, performance and behavioral views of the system. Baselining is the foundation for all of our evaluations. We need to be able to model the current system and to validate that our model represents most of the performance and behavior of the NAS, to establish a basis for identifying operational concepts and technologies that can deliver the needed total system performance.

5.0 Tools and Data Assessment

The PD process is a data-driven approach that requires substantial supporting analysis to provide the required insight into system performance and design alternatives. Numerous models and analytical tools have been applied to ATM questions for the past few decades. However, most of these models were developed and applied to a relatively static system that generally experienced only incremental changes in procedures, systems, and subsystems. As a result, the analytical tools could be fairly rigid and focused on narrowly defined problems with severe limitations on the scope of operational alternatives that could be analyzed. Such restrictions are not acceptable for the analysis toolset supporting the PD process, due to the nature of the design objectives and the extensive time horizon. Significant changes to current operations, such as Distributed Air-Ground Traffic Management (DAG-TM), propose substantial change from current operational paradigms and more powerful analysis tools will be required to assess their feasibility and potential benefits.

This section suggests several analytical tools that could be applied in a Phase 2 PD study of Chicago airspace. It does not present a detailed inventory of all the available models; such inventories have been conducted previously (see Odoni, et al). While an update to this inventory would be useful, the approach taken identifies the specific analysis requirements for a Phase 2 study of high-density complex terminal airspace and suggest available models that could be used in that study with a limited development effort.

The major analytical tool components required for a Preliminary Design study are:

- Demand analysis models
- Aircraft trajectory generators
- Airport and Airspace Capacity models
- Affordability Assessment
- Safety Assessment
- Environmental Assessment
- Infrastructure (subsystems) performance models
- Human agent models
- Dynamic behavior models

5.1 Demand Analysis Tools

As described in section 2, the PD process requires traffic demand profiles to evaluate system performance requirements and to support trade studies. The demand forecast must be national in scope, since Chicago plays a crucial role in the NAS and flights through it must fit into the overall NAS. Second, the demand forecast must include specific information on aircraft type, origin-destination airports, and time of departure. The forecast should reflect unconstrained air travel demand; i.e., demand without physical or economic constraints due to ATM capacity shortfalls.

With some gaps, currently available models can provide forecasts with the desired characteristics. The approach described in section 2 provides a national city-pair hourly forecast that can generate the unconstrained baseline forecast and other scenarios that capture airline strategies. That approach has been applied in several ATM evaluation tasks for NASA, and has been shown to be a powerful, yet flexible analysis tool. The integration of the demand forecast module with other models that analyze system capacity and delay provides NASA with a consistent set of national-level analysis methods to support the PD process.

The hourly demand profile for 2010 generated by this process must be adjusted to add specific aircraft types, and a time-of-day distribution. The final output is an OAG-like schedule for the forecast year, which can be modified to create different forecast scenarios as required. In addition to the models, the methodology requires current data from the OAG, ETMS, and the Terminal Area Forecast.

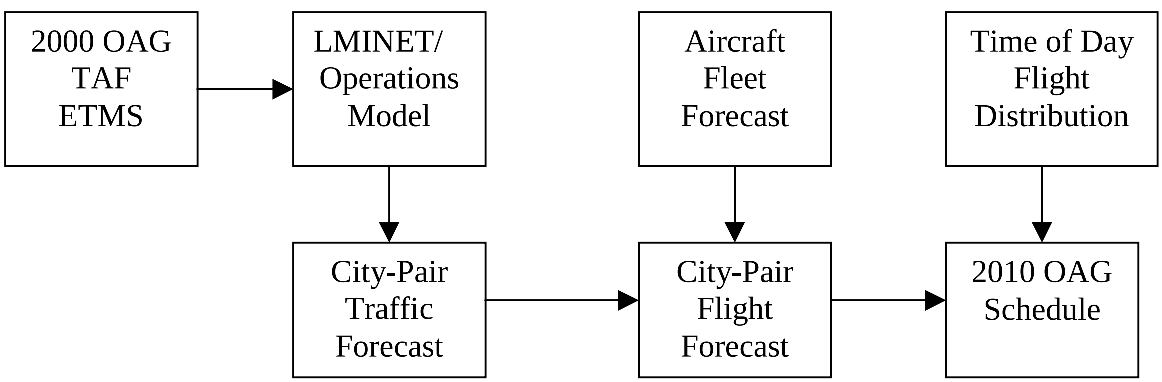


Figure 5-1. Demand Forecast Methodology and Tools

5.2 Aircraft Trajectory Generators

The conversion of the traffic demand into a set of flights to be processed by ATC requires aircraft trajectory generation capability. This capability is provided in some of the capacity analysis tools such as TAAM discussed in the next section. Depending on the airspace assessment to be performed, various precision trajectory generation tools can be employed. These can range from simple great circle representations of the aircraft's flight path, to complex, constrained representations. These can be generated geometrically, or be based on point mass models of the aircraft's performance characteristics, or can employ more sophisticated airplane dynamic models. Ideally, the toolset would support alternative trajectory generation techniques, with the simplest technique used, consistent with the fidelity of the answer needed.

5.3 Airport and Airspace Capacity Analysis Tools

Estimating the capacity of the NAS and its components requires an array of operational models of the air traffic management system. A hierarchical approach to capacity estimation appears to provide the most useful and robust approach to the PD process. Following Odoni, et. al., we used the classification of macroscopic and microscopic models. Macroscopic models operate at a higher level of aggregation and tend to cover a broader geographical area. When used appropriately, they can provide credible analyses of ATM operations and technology investments. Macro models, however, should not generally be used to address detailed operational issues, since they do not provide the required level of detail or time horizon.

Microscopic models provide a much higher level of detail than macro models, typically by focusing on a smaller geographic area and shorter time periods. With the higher level of fidelity comes a need for more detailed data inputs and generally more effort developing and operating the models. Required to evaluate operational changes, especially in high traffic airspace regions, micro models can result in an excess of detail and effort for system-wide investment decisions. Thus, the recommended approach is to apply the micro models to several representative airport and airspace regions, then aggregate the observed performance improvement and apply to similar regions across the NAS in macro models to quantify the potential system-wide performance improvement.

The PD process requires both national capacity models and the high fidelity local simulations. To evaluate proposed operational and technical solutions, a detailed simulation of ORD and the surrounding airports and airspace is required. In addition, a national model is required to capture the interdependence of ORD and the remainder of the NAS. For national models, NASPAC and LMINET provide most of the required coverage, but lack the needed operational detail to assess solutions. TAAM can provide much of the required capacity and operational fidelity called for in a micro model of a particular airport/airspace region, but may prove to be to cumbersome to assess performance on the national scale. In addition, none of the currently available simulation tools allow representation of national and regional traffic flow management strategies. The Phase 1 analysis of ORD identified significant issues with respect to flow management and other dependencies that must be incorporated into the Phase 2 effort. Otherwise, solutions may be proposed that simply move the bottleneck from one region to another without improving overall system throughput or efficiency.

Analyzing the entire NAS with a high fidelity simulation such as TAAM or SIMMOD, with the accompanying large resource drain, should not be necessary to provide the required insight. What is needed is a suite of models that can analyze key airspace and airport regions, as required, and that are linked by a lower fidelity traffic flow model that can represent flow management strategies. The central flow model should also be able to include models of other airports in the system that do not require high fidelity analyses. A potentially productive solution is to explore the integration of a national queuing network model, such as LMINET or NASPAC, with more detailed operational models – TAAM or SIMMOD – for selected airports. Work is currently underway to explore the potential for integrating TAAM airport models with LMINET. If feasible, such an approach enables NASA to select which areas require high fidelity analysis, while maintaining the interdependence among airports and flow management that can be captured with LMINET.

With this approach, resources can be applied where they generate the most insight, rather than in providing an unnecessary degree of detail on non-congested areas. The approach also enables a migration strategy for analyzing national benefits of AATT decision support tools, based on the assessment obtained from a detailed simulation.

Figure 5-2 describes schematically how this integration approach could be achieved. Through the national queuing network model, the demand forecasts could be directly introduced, maintaining the feedback loops developed for the baseline and other forecast scenarios. The national network model should also handle the flow management function, with the ability to explore alternative strategies as well as today's major features. Key airports and airspace could be analyzed in detail with TAAM, providing finer detail on terminal area operations and procedures, and ground operations as required. Other airports can be modeled as part of the national model. Calibration of results between the TAAM airport analysis of the baseline and solutions and the LMINET airport models provides a convenient way to capture national economic and operational benefits without resorting to extrapolations based on limited information.

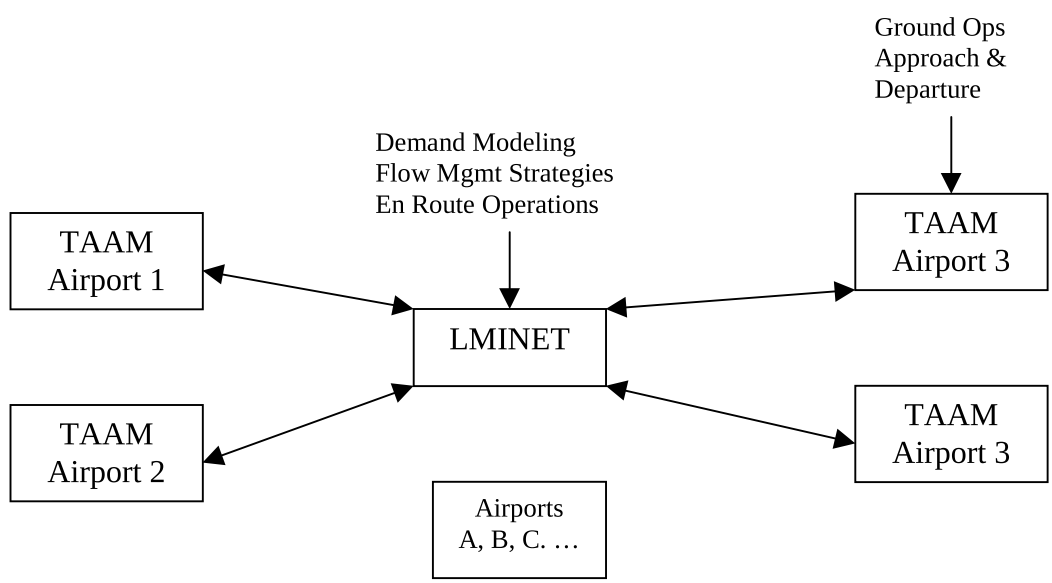


Figure 5-2. Integrating Operational Models

The following section provides brief descriptions of some of the models discussed.

LMINET

In recent years the Logistics Management Institute (LMI) developed and enhanced LMINET, a queuing network model of the National Airspace System. LMINET links multiple queues at 64 airports in the NAS via queues at en route sectors. As an analytical queuing model and not a simulation, LMINET can be integrated with air transportation economic models of airline cost and air travel demand. This integration provides the ability to incorporate feedback between capacity changes, delays, airline ticket prices, and aircraft operations. This closed-loop modeling approach generates estimates of system throughput and delay for the entire NAS and at each of the 64 airports analyzed in the network. The model is useful for identifying bottlenecks throughout the network and can quantify the benefits of capacity-enhancing investments or changes in airline scheduling strategies. The model has been used in recent years to estimate the capacity and throughput effects of the NASA Aviation System Capacity Program.

LMINET currently has little ability to address issues of workload or traffic flow management strategies and tactics. Work is underway to enhance the en route modeling portion of the model, which should improve its ability to analyze flow management questions. As an analytical queuing model, LMINET uses epochs of a given length (generally one hour) to analyze system demand and performance. While this approach is powerful for analyzing system performance under a variety of scenarios and technology assumptions, it is weak at evaluating small operational improvements and changes that affect short time periods.

LMINET source code and data files are available to NASA.

National Airspace System Performance Analysis Capability (NASPAC)

NASPAC is an event simulation model of the NAS that was developed by FAA and MITRE. It covers the entire NAS, including airports and sectors. The FAA Technical Center (ACT-520) operates NASPAC and uses it to conduct policy analyses and delay forecasting studies. NASPAC contains pre-and post-processors to prepare and analyze data files. Analyses using NASPAC can be arranged through the FAA Tech Center, although availability of source code is uncertain.

Total Airspace and Airport Modeler (TAAM)

TAAM provides a powerful application for analyzing a wide array of ATM issues. It supplies excellent detail, with the potential to define and evaluate different operational approaches. Like many high fidelity simulations, TAAM is data-intensive, but extensive data sharing among TAAM users reduces the burden of developing baseline input data files. Because of the voluminous data required to conduct a TAAM analysis, it is difficult to envision how TAAM could be used to analyze large airspace areas or more than a few airports. TAAM employs a number of traffic control rules to represent the current radar control concept, but does not allow the user flexibility in modeling possible new operational concepts. Additionally, like most other currently available ATM simulation tools, it does not have the ability to represent the performance of system agents and technologies such as radar controllers, pilots, communication, navigation and surveillance. Thus, in essence, conflict detection and resolution can be performed perfectly, given sufficient computational horsepower and correctness of the algorithms. The PD process requires the ability to predict the effect of human and technical performance parameters on effective traffic spacing in the system, and it is clear that this is not currently possible using any of the fast-time simulation tools available.

TAAM source code is available at a significant cost, and thus its use has so far been somewhat limited. As a proprietary commercial application, it may prove difficult to encourage changes that incorporate the functionality required by the PD process, given the limited number of users that are involved in research on advanced ATM operational concepts.

Other candidates with similar functionality are SIMMOD and RAMS. SIMMOD does not appear to lend itself well to accurate 3D representation of aircraft trajectories, and thus may not be suited as a basis for the higher-fidelity airspace operational analysis. RAMS currently models only en route airspace operations, but includes some useful functionality representing controller workload as a function of traffic density and complexity. Both RAMS and SIMMOD are available at very moderate cost.

Conclusions for Model Availability

Several potentially useful models for supporting PD capacity and delay analyses exist, although no single model provides all of the required functionality. TAAM provides much of the needed operational analysis capability, but its limitations preclude exclusive reliance on it for PD studies. As discussed in other sections of this report, the Phase 1 PD study for Chicago highlighted the close interaction between airport and TRACON operational constraints and the traffic flow management strategies that are caused by those and other constraints. None of the currently available models analyze properly the interdependence among airport operations and flow management, primarily due to the complex nature of the phenomenon, the large geographical area that must be analyzed, and the time horizons involved. The ability to analyze this interdependence is crucial for the PD process so that an assessment of capacity improvements and flow management strategies can be made at the national level. Furthermore, to assess the potential traffic spacing improvements achievable by a range of operational concepts and associated technologies, a higher-fidelity airport and airspace modeling tool must be available that connects technical and human performance with traffic movement.

5.4 Safety Tools Assessment

Safety analysis tools that support the system design and development process are an area where significant research is needed for ATM applications. While safety analyses accompany all major acquisition efforts, they generally take place after major development is complete and as part of the installation process. For incremental changes to the existing ATM system, this approach is adequate, as demonstrated by the safety record of the commercial air transportation industry. Unfortunately, this approach will not be adequate for the significant changes to the ATM system that are required to meet future demand, nor can it accommodate the analysis required to support DAG-TM and other paradigm shifts. Equally important, safety analysis tools will be needed to support the trade studies of alternatives, coupled with the operational and economic analyses that support system development. The NLR institute in the Netherlands has invested considerable effort in an ATM-oriented safety tool called TOPAZ, and has developed a number of ATM scenarios using the tool. TOPAZ requires very specialized expertise for each new application, and this expertise currently exists only at the NLR. Modeling an analysis process involves significant manual analysis and model development steps, and as such it is not clear how well the tool will be suited to analyzing scenarios that involve more than a pair of human agents and moderate airspace operational complexity.

5.5 Other Tools and Tools Integration

As noted in the opening section of this report, safety is one of the major objectives of the PD process for ATM. Given the interdependence among the objectives and the benefit of analyzing tradeoffs during the design process (rather than after development), the safety analysis tools should be applied concurrently with the operational and economic analyses. If possible, common scenarios and data should be used to support the identification of appropriate design trades. Figure 5-3 shows conceptually how an integrated system analysis process, including safety, can support the PD process.

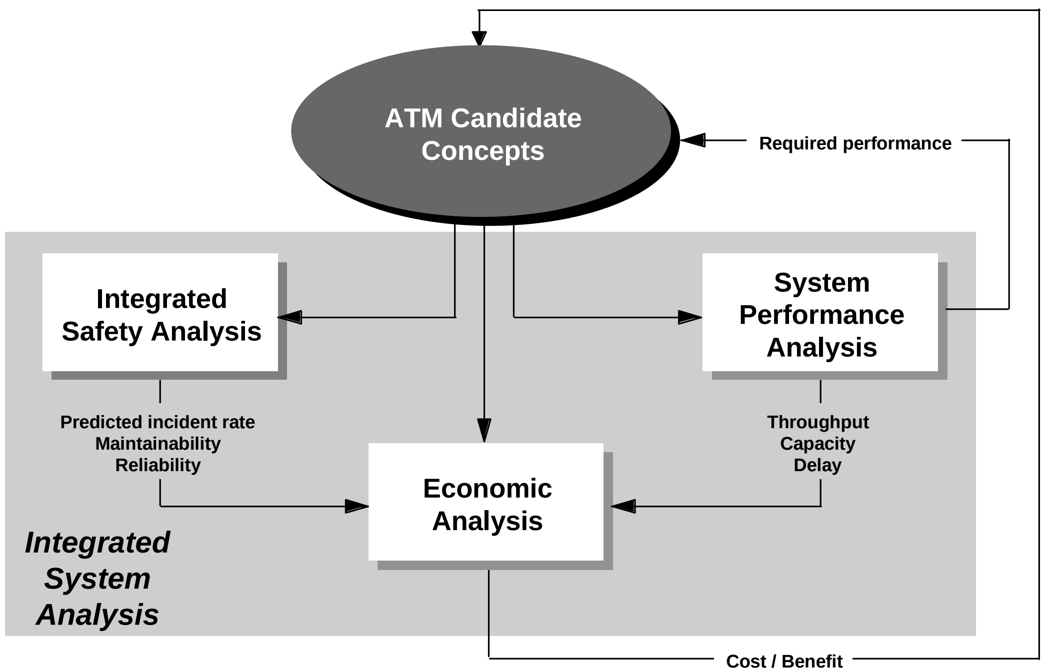


Figure 5-3. Integrated Safety and Operational Analysis Approach

The safety analysis for the PD process requires an integrated systems analysis methodology in which three well-defined activities must take place: 1) development of reliability tools capable of easily assessing a variety of new technologies in a variety of new and existing operational environments; 2) human factors research to determine the impact of human behavior on aircraft and ATC operations; and 3) incorporation of these analytic elements into a dynamic operational simulation. To our knowledge, no single model or collection of models currently meets these requirements.

Our approach to implementing this methodology is to develop an Integrated Systems Analysis Tool (ISAT) with three major parts, each related to one of the three major safety issues described above. This approach is illustrated in Figure 5-4.

Figure 5-4 contrasts the real world of ATM with the parallel analytical world of our methodology as implemented in ISAT. In the real world equipment degrades and fails. In ISAT we employ reliability models to gain quantitative insight into those degradations and failures. In the real world pilots and controllers occasionally operate at less than ideal performance levels. In ISAT the human factors research we have initiated will lead to models providing quantitative insights into degraded human behavior, similar to those that the reliability models provide for degraded equipment operation. Finally, in the real world, both equipment and humans interact with complex operating environments (which include both air traffic dynamics and weather influences) in ways that occasionally result in hazardous situations. In ISAT the data generated by the reliability and human factors models will drive the dynamic simulation to assess, in quantitative terms, the overall impact of these hazardous situations on air traffic throughput and safety.

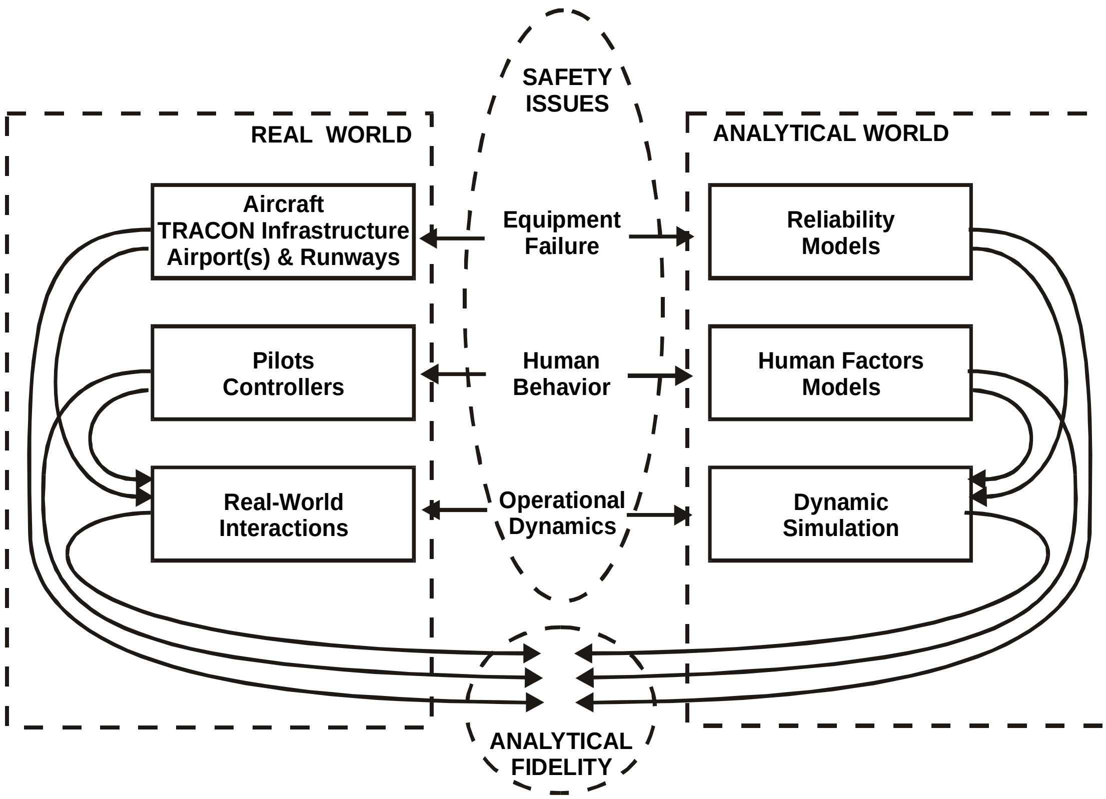


Figure 5-4. Relationship of Integrated Systems Analysis Methodology To Aviation Safety Issues

In previous work for NASA, LMI developed a significant portion of the analytical methods that are described in Figure 5-4. Parallel work at Boeing has focused on constructing reliability models of CNS/ATM systems. With some development, these analysis tools could be applied to the ATM systems to be evaluated in the Phase 2 PD study. Some effort should be devoted to incorporate the learning generated by the TOPAZ researchers at NLR, who appear to be further along than other researchers in evaluating operational procedures. In addition, there is ongoing work by the FAA and Eurocontrol on collision risk modeling and risk assessment that could provide useful algorithms. The key ingredient, however, is to extract suitable system-level insights into human performance that can be incorporated into these models.

Other tools which may also be required for some evaluations include affordability and environmental (noise and emissions) assessment tools which may be linked to the airspace operational tools such as TAAM. Other potential tools, for some analyses, include subsystem performance tools representing communications, navigation, surveillance or air traffic decision support performance and models of human agents as well as dynamic behavioral modeling tools.

6.0 Chicago Operations and Constraints Assessment

6.1 Operational Interviews

The team visited the Air Route Traffic Control Center at Aurora, Illinois, the Chicago TRACON at Elgin, and Chicago O'Hare Tower on October 25th and 26th, 1999. The primary focus of these visits was interviews and discussions with the facilities' managers and air traffic procedures specialists. Additional short visits by one team member were made to the Tower and TRACON on November 10th and December 16th respectively, to observe operations.

The team was very well received by the FAA staff members, who spent several hours at each facility discussing the area's operational issues with team members. In addition to the discussions, the team was furnished with a considerable amount of operational data, which was subsequently analyzed and is discussed in more detail in section 3.1.2. The notes taken by the team during the facility visits are contained in Appendix B. It is apparent from reading the notes that Chicago operations are quite complex and a significant number of operational constraints play a role in overall system performance. The team attempted to parse the interview notes into distinct issues and to group those issues according to primary and secondary characteristics, as shown in the Appendix. The tables presented are sorted on the primary keyword, to assist the reader in identifying groups of related issues. The notes are somewhat repetitive as they are a compilation of several note takers, and many of the issues were discussed for all facilities, but in order to avoid omission it was decided to include all observations with only minimal editing. The notes have been shared with the hosts at each facility, but have not otherwise been reviewed for accuracy so they should be used as overall qualitative indicators of Chicago operations, not as a source of quantitative or accurate data.

6. 2 Operational Assessment

The complexity of Chicago operations poses considerable challenges when analyzing system performance and the primary operational constraints. Appendix D, sections 1 and 2 contain a detailed description of some of the arrival and departure flow processes and issues discovered during the facility visits and through ETMS data examination.

During the interviews a number of issues were identified by the FAA experts as probably contributing the most significant challenges. These issues were as follows:

1. O'Hare airport has been slot-controlled since 1968, with a maximum of 155 operations scheduled each hour. Slot control has limited growth to 2-3% a year for the last 10 years, mostly through filling in between peaks and operating later into the evening. If slot controls are lifted, there will be an immediate need for more gates to accommodate growth as gate utilization is currently very high. Analysis by Landrum and Brown indicates that the runway system is capable of accommodating an increase in demand at least in the short term, in visual conditions.

2. O'Hare airfield complexity. Of the seven runways there are three parallel pairs and most have intersections with other runways. Runway configuration management and the associated interfacility coordination are a significant challenge, further complicated by airspace interactions with Midway Airport. Runway configurations are changed by O'Hare Tower based on three primary factors:
   - Wind direction. A weather prediction system in the Tower is used as the primary anticipation of windshifts, along with phone calls to adjacent facilities. Fronts moving through and lake-effect wind shifts can be difficult to predict and during a departure push a poor prediction can cause significant surface movement difficulties.
   - Traffic demand. Chicago is a hub for two major airlines and this gives rise to a large number of arrival and departure waves throughout the day. To optimize throughput it is best to change configurations between departure and arrival pushes and the timing of these changes has to be just right to avoid queuing on the surface.
   - Runway condition. LAHSO can only be used when runways are dry, and thus certain configurations are not usable for wet and contaminated conditions.
   - Noise mitigation. Configurations are changed regularly to more evenly distribute the noise impact on surrounding neighborhoods.
3. LAHSO rules. The revised LAHSO rules are more restrictive than the hold short operations that were previously practiced at O'Hare. This has resulted in a 10% reduction in arrival rate, down to 90 aircraft/hr from 100 before the rule change. The move from turboprop to turbojet aircraft has further aggravated the impact of the new rules, where previously 15-20% of the arrivals could hold short but currently only 5-10% can. Each pilot makes a decision whether to accept a hold short clearance, and the current controversy over LAHSO rules makes for a more unpredictable traffic flow in the TRACON airspace.
4. Regional flow management. National-level flow management actions are taken in response to major capacity constraint predictions, usually due to weather, at destination airports, resulting in ground delay allocations at origin airports. In addition, ATC facilities are increasingly using more localized short-term flow restrictions to cope with capacity shortfall, and this is accomplished primarily through phone calls between TMU units in each facility. This results in uncoordinated flow regulation and frequent dynamic replanning, which can in itself increase workload and may even result in less than full use of available capacity. O'Hare staff indicated that since only one phone call is needed to O'Hare Tower to stop a large number of aircraft, their departures tend to be penalized unfairly through some of the local flow management actions.
5. En route capacity. Capacity at jet altitudes is increasingly becoming a constraint, influenced by the growth in turbojets (replacing turboprops), by miles-in-trail restrictions in overhead streams to East coast airports and by the national route program. The first of these is simply a growth in demand for jet altitudes, while the others give rise to coordination difficulties and increased controller workload.
6. Congestion at arrival fixes. Arrival flows into O'Hare are frequently heavier on one side than the other, which can result in congestion at one fix and consequently less than maximum runway throughput. Tailwinds above 15000 ft can further aggravate

this problem, where the feeder controllers have to increase spacing during descent to avoid overtakes due to steep wind gradients. Usual spacing at arrival fixes is seven NM, but with tailwind they go up to twelve NM.

7. Severe weather impact. Severe thunderstorms have a significant impact in the summer, and storm cell prediction is difficult, particularly for 'pop-up' storms on hot humid days. Airlines and pilots appear to be increasingly reluctant to fly through severe weather and air traffic controllers often have difficulty predicting what aircraft will need to deviate due to storm cells.
8. Growth at nearby airports. Midway airport is experiencing much higher growth than O'Hare, with Southwest Airlines contributing most, and this trend will continue given the expansion underway at Midway. Pan Am has just started scheduled passenger service into Gary, Indiana and cargo operations at Rockford. Des Moines and Cedar Rapids are growing rapidly, mostly at night when staffing is currently low.
9. Final approach spacing. Single runway arrival capacity in the NAS is currently constrained in VFR by runway occupancy time and in IFR by the wake vortex spacing rules. It would appear that gate constraints and runway system complexity are currently more dominant at O'Hare than final approach spacing, but for the long term this will remain an issue in overall system throughput.
10. Capacity of surrounding facilities to accept O'Hare departures and to deliver O'Hare arrivals appears to be an increasing issue. Cleveland Center is extremely busy with a very complex traffic situation and consequently imposes miles-in-trail restrictions on its inbound traffic flows throughout the day. This has a direct impact on O'Hare departures, but also may result in reduced flow from the east into the Chicago area. This particular issue is further discussed in Appendix D, section 3, by applying an analogy of flow through cascaded buckets to the extended O'Hare arrival stream.

The list of ten issues is derived primarily from the information gathered during the facility visits. It must be kept in mind that additional analysis will be required to derive a more complete performance picture for the short-, medium- and long-term system performance. The issues that are most immediately known to current system operators often do not include an examination of the more fundamental performance limiters such as separation standards, as those must be taken as fixed by the operators. Additionally, the team visited air traffic control facilities, but in follow-on work it will be necessary to include the airborne element and the airline operational control aspect to generate a more complete understanding of the system. To conclude the assessment of current operations, data must be acquired to validate the qualitative operational assessment and discover whether the most important operational issues have been identified.

The validated assessment of current operations, when combined with what is known to CNS/ATM engineering and human factors experts about the potential performance enhancements from emerging technology, becomes the basis for identifying the fundamental performance constraints and potential concept and technology solutions.

6.3 Chicago Constraints Analysis

The issues described in section 6.2 are the primary operational concerns that emerged as a result of the team's visits to the Chicago area facilities. As discussed in section 4.1, a formal data-driven capacity baseline needs to be developed for the area that will identify the most important operational constraints for the current and predicted future traffic demand. To help frame the baselining activity, it is useful to apply the constraints model in Appendix C qualitatively to the list of issues in 6.2, to allow an overall performance and system state picture to emerge. The performance factors depicted in the traffic domains in Appendix C are shaded according to how they contribute to the issues listed in 6.2, with the issue number listed in parenthesis for each affected factor. Following is a short rationale for the mapping of each issue to the constraining factors:

1. Slot Control and Gate Availability. Slot control is a transportation policy issue, and the constraints model excludes non-operational issues. Gate availability is identified under the Gate domain chart in Appendix C, as being the primary constraining factor at O'Hare as far as gate/pushback performance is concerned. Quotas and schedule impact is identified for the Approach Transition.
2. Airfield Complexity. This refers to runway use and complex converging issues. This has an extremely pervasive influence on the constraints mapping, spanning just about every domain from en route to surface.
3. LAHSO rules. This has an impact on runway assignment efficiency in Approach Transition, as it complicates the controller's job and can cause unexpected runway changes when the pilot is unable to accept LAHSO clearance. The primary impact is on Final Approach, giving rise to dependencies with other runways.
4. Regional Flow Management. This is indicated on the En Route and Gate domains, and also has an obvious effect on the Planning region, which is not analyzed in detail in Appendix F.
5. En Route Capacity. This is influenced by several aspects of the Chicago En Route domain, including route complexity, aircraft speed and altitude mix, medium term intent (NRP trajectory prediction) and overall sector workload.
6. Congestion at Arrival Fixes. On the TMA Arrival/Departure domain this is reflected in difficulties with runway load balancing with unbalanced in-bound flows, metering inefficiency with tailwinds at altitude and inaccuracy in aircraft descent and climb performance.
7. Severe Weather. Traffic flow through TMA Arrival Departure can be affected by the need to avoid severe weather cells, and the impact can also be felt on dynamic flight path replanning using VHF voice in Approach Transition.
8. Growth at Nearby Airports. O'Hare departures can be affected by arrivals to Midway airport, and although currently O'Hare usually has priority, with the growth at Midway this will become more of a contention. It is possible that improved navigation using FMS and/or RNP procedures may be part of a solution to such interactions.
9. Final Approach Spacing. This is reflected in several performance factors in the Final Approach domain and upstream in Approach Transition. The number of factors

affecting this issue is significant, along with the difficulty involved in resolving some such as the wake vortex exposure problem.

10. En Route Capacity at Adjacent Facilities. This issue is indicated on the En Route and Gate domains, but the issues were not further explored in this study.

6.4 Initial Concept Directions

A set of initial directions for potential solutions can be identified for the purpose of improving the inbound flow for O'Hare. As will be seen, discussing new operational practices raises new problems in analysis, evaluation, and performance measurement, and may establish requirements for better CNS and ATM performance. The intention here is to provide some example of what Concept Development activities might look like in the Preliminary Design process for CNS/ATM engineering.

The solutions proposed here apply to the objective of increasing traffic flow throughput for the Chicago area, but do not directly address airport infrastructure issues such as additional gates, terminal building, runways and taxiways. It is quite clear that O'Hare airport is gate constrained, and Port Authority has a plan underway to address this shortcoming. It is also clear that passenger and cargo traffic demand in the Chicago area is resulting in air traffic growth at several of the region's airports, thus gradually complicating the airspace traffic flow problem. Most of the improvements proposed here have the potential to enable a higher throughput for the Chicago airport and airspace system.

1. Improved Regional to National Flow Management Coordination. Currently there are a number of flow control regulations practiced at the ATC facility level, in addition to the Ground Delay Program used at the Air Traffic Control System Command Center (ATCSCC) in Herndon, VA. With the exception of publication of Severe Weather Avoidance Program (SWAP) routes and Historically Validated Restrictions (HVRs) through the TMS system, traffic flow managers exercise flow management through phone coordination with nearby facilities and with the ATCSCC on an ad-hoc basis. Better data communications could significantly improve coordination of required constraints, but there is a dire need for an examination of the multitude of possible flow management functions and the proper roles and responsibilities of each flow management agent. This should be done in concert with the Collaborative Decision Making initiative, where the airspace user is allowed appropriate flexibility in optimizing his/her operation within the constraints of system safety.

2. Improved Weather Information. In the NAS, most flow management actions originate in the terminal area and are directly influenced by predictions of low visibility, unfavorable winds or convective weather. There is a considerable number of weather prediction tools in use by the FAA and the airlines, giving different views of impending weather conditions and the users of these tools are not well aware of the inherent inaccuracies of various weather prediction technologies. There is a need for continued data collection, analysis and development to understand and improve the accuracy of weather prediction for aviation users, and weather prediction performance must be taken into account explicitly when designing traffic management functions and decision structures.

3. Dual STAR Streams Over the Arrival Fix with Vertical and Longitudinal Separation. Instead of planning for a single STAR stream over the arrival fix at a common altitude, a dual stream at two altitudes can be established with alternating use of vertical and horizontal separation. Aircraft at the same altitude could be planned to be ten NM apart, and the intervening aircraft would be at the other altitude and also separated from aircraft at its altitude by more than ten NM. The flow rate for the combined flow is again 50 arrivals per hour.

This may be the goal of the current CAP project at Chicago. There often is vertical separation and horizontal separations less than five NM in the STAR streams at the present time, but it is currently the escape mechanism for errors in the STAR metering process. It is quite different to be proposing it as a regular basis for planning the arrival flow, and raises the question of what a new blunder recovery mechanism would be. There are other altitudes, both above and below the two planned altitudes, which seem to be available; but this may require some changes in the current use of airspace around the arrival fixes by piston/turboprop aircraft.

The TRACON would now be receiving aircraft at five NM longitudinal separation and at two alternating altitudes, say 10,000 and 12,000 feet. Upon handoff, its current IFR radar separation standards would allow immediate changes of altitude if desired, since there should be at least five NM between successive arrivals. It requires sufficient airspace in the terminal area on the other side of the arrival fix to handle this higher inflow rate of traffic (i.e., to path stretch, or change altitudes, and re-space such a flow before arriving into the merging and spacing area for final approach). This is generally true (within limits) at O’Hare for most runway configurations, and the inflow separations over the arrival fix for each STAR could vary depending on the runways being fed, if necessary. It would be possible for ATM managers to gradually introduce these new inflow conditions in a series of steps so that every controller has some experience with the new STAR capabilities before being asked to move to the next step.

Since the STAR process is now capable of 'flooding' approach control with aircraft, they will want some assurance that the STAR controllers will be closely monitoring their 'occupancy' and will be capable of reacting in a timely way to manage the flow over the arrival fix to control their occupancy, especially when some unexpected event occurs. This assurance and closer coordination between the STAR controller and the TRACON controller could be provided by some form of interactive computer display of desired rates and spacing which allows quick communication between the two facilities (e.g., a STAR Flow Coordination Display).

4. Reduced Vertical Separation Minima Above 18000 ft. The North Atlantic Minimum Navigation Performance Specification (MNPS) airspace has already transitioned to a minimum vertical separation of 1000 ft, based on proven improvements in modern aircraft altitude keeping. Europe is actively engaged in a plan to take advantage of this potential capacity enabler for domestic European airspace, and there are indications that the FAA may follow suit. On both continents, the aircraft mix is considerably different than that over the North Atlantic, and a significant number of aircraft may still be in service that will require potentially costly altimetry upgrades. Before publishing an implementation plan, care must be taken to assess the actual throughput improvement potential of reduced vertical separation, as it is not immediately clear that in complex domestic airspace the same leverage can be obtained from this aircraft

capability. In addition, there will be a direct impact on en route controllers due to an increase in traffic levels at jet altitudes, and this change may turn out to be very costly to achieve within the current ATC operational paradigm (i.e. without significant improvements in automation support that could mitigate the workload increase).

5. Runway Use Planner. To make good use of all available runways during a directional rush, a Runway Management Advisor could be developed to monitor arrivals and predict their future landing times over the next 15-30 minutes. This would be used to plan 'flipping' and 'back door arrivals' and to ease coordination problems between the Center and TRACON in executing these actions. Its goal would be to improve the balanced use of all landing runways when three or four runways are available during a directional arrival rush. This functionality is similar to what is already developed by NASA Ames in the CTAS automation system, but runway system complexity at O'Hare may pose additional challenges.

6. STAR Advisory Tool. During a directional rush, two of the STARs are working to achieve a uniformly spaced output flow at the arrival fix in order to feed their busy runways at desired rates. At the same time, the two 'Off' arrival fixes are handling lower levels of arrival traffic and are feeding either the same two runways or the third and fourth runways which may not be working at full capacity. At some point, which appears to be around the arrival fix, decisions are made about flipping arriving aircraft, and we see the occasional use of closely spaced arrivals at different altitudes around the fix. When a Runway Use Planner is available, it is possible to create a STAR Advisory Tool which would provide the STAR controllers with desired spacing, speeds, and altitudes for each aircraft in the STAR flow. These will not be uniform, and may require passing and/or the use of altitude separation (as described above) in the flow over the arrival fix for those aircraft which have now been planned for a 'flip' much earlier in their descent along the STAR. Such an Advisory Tool is similar to the Multi-Center adaptation of the current NASA tool called TMA (Traffic Management Advisor, part of CTAS). It might have to send advice outside Chicago Center since the STAR flow management activities are often started by Cleveland, Indianapolis, Minneapolis, and Kansas City.

7. Dynamic Arrival and Departure Flow Planner. To handle the problem of weather blocking STAR/SID flows, it seem necessary to develop a comprehensive method of rapidly reconfiguring the STAR/SID geometry in real time based on forecasts of future weather movements. But this also creates a need to be able to rapidly change the Preferred Arrival Route Structure (PARS), and to transmit flight planning advice on the PARS changes to many other Centers, Airline Operational Control Centers, Flight Service Stations, etc. There would be a schedule for the geometry of flight paths over the next hour or more, and perhaps a need for establishing a computerized form of interactive, online flight planning for inbound flights to O'Hare. This would seem to be immediately applicable to other hub airports around the U.S.

Each Center would require warning times to be able to prepare for the re-routings of the inbound O'Hare flow through new sectors, and the re-routings of their normal flows into yet other sectors without causing overloads anywhere. Controllers in the new sectors might need retraining on merging and in-trail control actions for STAR/SID operations.

Since such a major flow rearrangement will always occur with some aircraft already airborne into O'Hare, it will be necessary to develop methods of achieving interactive replanning of airborne flights throughout all Centers. The existence of some form of data link to aircraft would ease such activities. As PARS is being changed, there are opportunities to consider rebalancing the flows at the arrival fixes in real time. Users would need to understand why the best routing now goes through an arrival fix further from their closest and usual fix.

8. 'North Gate' - Creation of another Diversionary Arrival Fix. Since there are no strong northern departure flows at Chicago, it may be possible to establish a new arrival fix on the northern side of the TRACON to act as a diversionary arrival point for overflows in the PULLMAN and JANESVILLE traffic during their rushes, and to act as an alternate arrival point if weather is blocking the normal STAR flow. There could possibly be similar diversionary arrival points established on the southern perimeter of the TRACON for the two southern STARs if some constraints were placed on the altitudes of southern arrival and departure flows at the same time. The STAR Advisory Tool would be used to divert arriving aircraft over to the North arrival fix whenever advantageous.

9. Reduce IFR Radar Separations for Speed-Controlled Arrival Streams. Current radar separations for encounters between a pair of IFR aircraft at the same altitude make no distinction between the directional nature of the encounter. Whether they are meeting head-on, or crossing, or are in-trail does not affect the legal separation required - if it is outside 40 NM from a radar, there must be at least five NM horizontal separation during the encounter.

Where a single stream of aircraft under radar control have been deliberately put in-trail at controlled, identical airspeeds, it is possible that a safe reduction of this general radar requirement is reasonable. The risk is very small that an aircraft will overtake another when they have been stabilized at three miles in-trail and have been put at a common airspeed, especially when using the modern FMS with its speed control. Any differences in ground speeds will be very small, so that the time to overtake the prior aircraft will be very large. This allows a controller, or pilot using on-board collision avoidance, to safely intervene, and move one aircraft to another altitude.

There are precedents for this type of reduction of a general ATC separation criteria under specific operational conditions. In-trail separations on the North Atlantic Oceanic Track System were reduced in the 1970s with the restriction that aircraft must fly at the same Mach/speed. In the terminal area, the lateral radar spacing of three NM was reduced to 0.5 NM when aircraft were established on parallel ILS centerlines. A reduction of the longitudinal spacing criteria on a STAR to three NM under these conditions (speed-controlled, same speed, in-trail) will allow STAR controllers to achieve average spacing of five NM when needed. This increases the achievable flow rate over the arrival fix to 50 per hour, well above the IFR final approach capacity rate for the runway associated with the arrival fix at O'Hare.

Even though this may seem very simple to accomplish, it may take much study, simulation, and analysis to develop procedures and requirements to satisfy pilots, controllers, and safety analysts that the change can be safely introduced. Failure cases will have to be identified and considered, and resolution maneuvers clearly specified.

10. Lower Minima for Converging Approaches. It is possible that the Chicago area could utilize work that is under way to use RNAV aircraft capability to enable higher precision missed approach paths for operations to converging runways. This may be further assisted by use of a Converging Runway Display Aid for the TRACON operators.

11. Departure Planning Capability. Coordination between Center and Tower is needed to time departures to certain destinations so that they fit in an overhead stream. The timing of this departure release is normally quite tight, and the current coordination tool is a phone call. It is likely that O'Hare could benefit from a departure planning tools to assist with this particular issue, along with potentially other issues such as surface traffic movement for departure rushes.

These example suggestions for operational improvements in the Chicago area require much more thought and development. They are presented here to raise issues about how such ideas would be explored, and what tools are required to analyze the performance of new operational concepts and CNS/ATM technologies. The list is not prioritized in order of potential capacity improvements, nor is there any suggestion as to which might be feasible in the short-, medium- or long-term. There will not be a sufficient basis for prioritizing and phasing a list of operational enhancements and technology enablers until the Preliminary Design Process and the associated toolset and databases are matured.

7.0 Conclusions and Recommendations

7.1 Phase 1 Case Study Summary and Conclusions

This study has discussed the need for a systems engineering approach to the long-term NAS modernization problem, and proposed a Preliminary Design Process to provide the system and architecture performance data that are needed to make long-term investment decisions. The limited effort reported in this document has focused on the early steps in the PDP, involving NAS performance objectives and future traffic demand characterization, along with requirements for system baselining. A Case Study approach was taken, with the high-density complex terminal area around Chicago's O'Hare airport selected for initial application and validation of the Preliminary Design Process and for deriving baselining requirements. The study included visits to the Chicago area's primary FAA air traffic control facilities and detailed interviews with FAA air traffic and procedures specialists. The operational information and data gathered during the visits, along with some ETMS data, were analyzed to identify the primary operational constraints in the complex area, and the study concluded with some preliminary examples suggested for capacity-driven operational improvements.

The study conclusions can be summarized as follows:

1. Operations at Chicago O'Hare airport and in the surrounding airspace are quite complex and dynamic. A list of ten significant operational issues summarizes the team's findings based on this preliminary operational assessment and many of those issues can be mapped against technical, procedural and environmental performance factors in several operational domains.
2. The complexity of the airport and airspace, along with the frequency of operational state changes, lead to considerable challenges in developing a baseline of the current operations. A large number of operating states can be postulated for O'Hare airport and the close-in airspace, and due to environmental (weather and noise) influences and the nature of the traffic demand, the operation must frequently transition between states.
3. Data are not currently available to validate postulated capacity states for O'Hare, given the significant limitations of the current data sources and the insufficient allocation of resources to collect and analyze operational data.
4. The large number of states and frequent transitions at O'Hare call into question the adequacy of the current airport and airspace capacity modeling approaches that represent the system operations for a single steady-state configuration in each model. The Landrum and Brown analysis for the 2012 O'Hare Gateway Program was the most comprehensive performance analysis effort known to the team, and it includes only about 30% of 1997 operations, represented by three distinct runway configurations. It is not clear how much of the overall O'Hare capacity performance shortfall corresponds to these three configurations. There is currently no airport and airspace simulation tool that allows an assessment of the dynamic aspects of a complex terminal area, but it is clear from the O'Hare operational assessment that the

dynamics of their operation pose the biggest current challenge for their operational staff.

5. Initial concept development directions are suggested in the report, as examples of the more creative application of the PD process that must take place to support the overall long-term modernization process. However, given the significant challenges of identifying the relative contributions of performance constraints on overall Chicago area capacity, these suggestions have no supporting quantitative rationale yet.

7.2 Recommendations

This study has discovered a number of NAS long-term modernization areas where significant further effort is needed to establish a sound basis for going forward with concept and technology development decisions. The following are the team's primary recommendations for continued effort toward improvements in the systems engineering approach for the NAS modernization:

1. There is a need for a sound engineering approach to the early definition of best options for the long-term NAS, and the Preliminary Design Process proposed in this report is the first step toward defining this approach. Further validation of this process through additional Case Studies and derivation of tools and data requirements to support the process is needed.
2. Focused operational data collection is required to help validate a capacity baseline for areas such as Chicago, and for the whole NAS. These data are needed to identify and validate the primary capacity states of the system and must include a correlation with state variables such as weather conditions and system outages. Data that quantify the contributions and nature of dynamic transitions between identified states are also required to allow an assessment of the significance of transitions to the overall capacity picture.
3. Continued development of benefits, safety and affordability tools to support the Preliminary Design process is needed.
    - The current toolset and operational databases have significant limitations in quantifying regional and overall system performance metrics such as capacity, efficiency and safety.
    - The operational assessment toolset currently does not allow a direct modeling of the effects on C, N, S, ATM and human performance factors on the capacity, safety and efficiency of traffic flow. This is a fundamental requirement to the ability to assess the feasibility and viability of proposed future operational concepts.

The team discovered a significant number of operational performance issues through facility visits and analysis. When combined with the significant disruptions to air travel in the U.S. that have occurred over the last couple of years, this provides a strong indication that the system is increasingly unable to cope with the traffic demand. There are inadequate data to quantify the performance of the current system and thus there is considerable risk that the current modernization plans will fall well short of delivering the performance improvements that are so clearly needed. A major change in the overall

NAS systems engineering approach is needed and the team believes that a significant effort must be focused in the preliminary design phases of the modernization process.

A Preliminary Design Process for Airspace Systems Initial Assessment, Chicago Case Study Report

Final Report

Volume II - Appendices

October 19, 2000

A. Appendix A

The Performance Triad for ATM Systems

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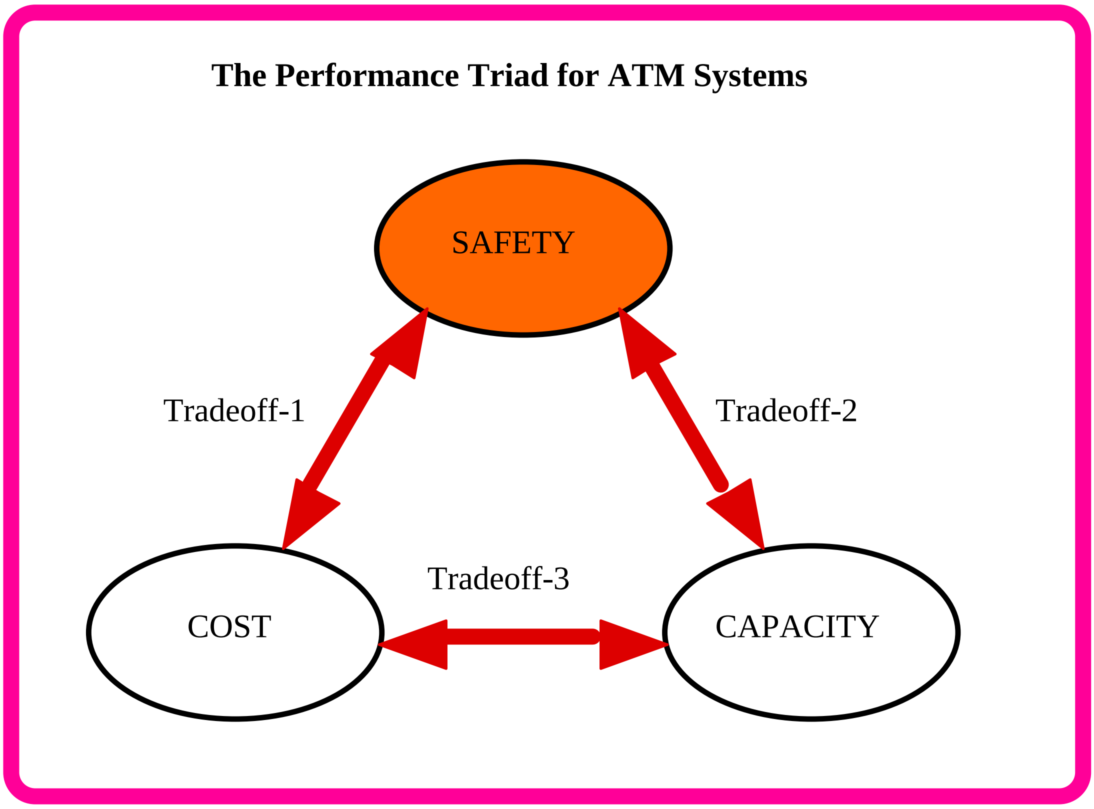
There is a triad of performance measures for ATM systems which have mutual tradeoffs in the engineering of a new system and its new operational procedures. There are multiple measures but they can be organized into three main categories; namely,

1. Safety Measures
2. Capacity Measures
3. Cost Measures



Between these three sets of measures, there are three 'tradeoff' relationships which exist: Tradeoff-1 says that to increase safety there is likely to be an increase in cost; Tradeoff-2 says that to increase the capacity for handling traffic, there is likely to be a reduction in safety; and Tradeoff-3 says that to increase the traffic handling capacity will increase implementation and/or operating costs. The details of these tradeoffs will appear in different ways as any new ATM operational concepts and its procedures are engineered. If safety is 'maintained' at present levels, then the major tradeoff for new or different ATM system is between capacity and cost. As will be discussed, costs will be different for different users and providers for any proposed change in the ATM system. Anyone will favor changes which are perceived to have no personal cost.

1. Safety Measures

Safety is the primary measure of performance for an ATM system since the prime reason for its existence is to provide separation assurance from aircraft (ie., from traffic), terrain, and severe weather. The measures are concerned with the risk of collision (or encounter) as averaged over a long period operation of the ATM system. The expected safety levels have target risks of one in a million or better, but it is difficult, if not impossible, to get sufficient evidence to validate such a level of system performance. This level of risk is achieved by setting separation criteria for various ATC operational situations (eg., horizontal and vertical separation for radar and non-radar environments, longitudinal separations on approach to landing for pairs of aircraft, lateral separations for oceanic tracks and simultaneous parallel approaches) which seem to satisfy ATM managers.

At present, many of these separation criteria do not have a rational basis to relate them to the corresponding risk. It is difficult to set a rational standard for levels of operational risk for ATM systems, but there are two established which serve as a model for further work:

1) A "Target Level of Safety" which has been prescribed for Oceanic Track Systems where the ATM system is very primitive; and
2) Similar risk assessment work to substantiate the reduction of vertical separations.

If a rational method for the design and engineering of new ATM systems and operational procedures is to be developed, then a rational method for assessing risk in a wide variety of situations must be developed, and a method for assessing the risk of human blunders must be established for pilots and controllers when using any innovative set of automated displays and decision support tools. These are long-term research needs.

There is a <u>tradeoff between safety and cost</u>. To improve safety (ie., to reduce safe separation criteria used in ATM), there is a cost in implementing improved and reliable CNS technology and equipment for both aircraft and ATM systems, and implementing and training for pilots and controllers in the new operational procedures which use this CNS equipment. To many people, the ATM system is now 'safe', and nothing should be done to reduce the present levels of safety, even if we can't measure it. With such a view, the present levels of safety become a constraint on the operations of future systems which introduce new operational procedures. This leads to the following approach to innovation in ATM: Before the introduction of any new procedure, it should be shown that current levels of safety are not being reduced.

There is often a <u>direct tradeoff between capacity and safety</u> since to increase capacity, the <u>separation assurance criteria</u> for the current methods of implementing the ATC separation assurance function must be reduced. For example, if the landing and approach capacity at an airport is to be increased under IMC operations, then the longitudinal separations on approach must be reduced. To justify the risks, this requires analysis of the accuracy and reliability of merging and spacing operations, the possible imposition of speed control on final approach, a better method to handle missed approaches, and a much better understanding of wake vortex phenomena than we have at this time. This example shows how research can be defined related to accomplishing an operational goal (i.e., reduce IMC approach separations).

However, there is another type of capacity limit for ATC en route sectors which is based on the peaking of task loads imposed on controllers. We cannot measure sector task load satisfactorily today, although there have been a few attempts. It depends on the sector's traffic complexity and procedures in use, the flow rate through the sector, the instantaneous occupancy, the availability of automation for decision making and communication, etc. The limit comes from a desire to keep task loads less than the workload capacity, but it is clear that individual controllers do not have the same workload capacities and that their capacity may diminish as they tire. As a result, a safe margin must be set between actual average controller capacity and task load limits. Here are more long-term items for research.

With reliable knowledge of incoming traffic to the sector coming from the flight strips of the Flight Data Processing System of the current US NAS, it is possible in a dynamic fashion to reroute traffic into other sectors, or onto additional assistants in the sector, thereby providing protection from short-term peaking in traffic flows. With this protection (it is a form of congestion management which can be called called Dynamic Sector Unloading), US controllers are willing to work at higher workload levels on average and have control over their workload. Here is a different design approach to solving the problem by giving the individual controller some degree of control over the future workload.

This is not the case in Europe where they adopt higher margins of safety against surges in traffic levels by predetermining fixed quotas for allowable traffic flows exiting from adjoining sectors. This is the basis of en route traffic capacities in Europe where fix postings have quotas which limit flight planned departures and cause rerouting or retiming of planned flights based on a 'safe' level of controller workload for an average controller capability. Thus, there can be a tradeoff between en route capacity and safety which is now based on congestion management criteria used by a weak implemention of the congestion management function of ATM.

2. Capacity Measures

There is not just a single ATM capacity but many 'capacities' for the traffic handling capability for various elements of the ATC system. Capacity is measured as a maximum possible traffic flow rate in aircraft per hour (or perhaps over a 15 minute period). Examples of capacities are landing/approach capacity for single or parallel runways, takeoff capacity, departure capacity, oceanic track capacity, aircraft handled per hour in a sector, etc. It is an intrinsic characteristic of any ATM operational concept which usually can be calculated given its procedures and safety criteria, and while it may be a function of several operational parameters (which may cause it to vary over time), capacity represents a theoretical ideal achieved only if the criteria and procedures are applied perfectly.

Actual maximum rates, or 'throughput' rates achieved by controllers, are usually less than capacity rates since they are usually conservative to avoid specific instances of a violation of separation assurance or congestion flow management criteria. Thus throughput rates are less than capacity rates and depend on the skills and aggressiveness of individual controllers and their supervisors.

There is another traffic flow rate called the demand rate which is the rate of arrivals for landing and takeoff in the traffic flow which varies throughout the day. Note that throughput rates cannot exceed the demand rate, so it is necessary to ensure that demand rates are high when observations of throughput rate are being attempted. It is also true that the aggressiveness of controllers (encouraged by their supervisors' tolerance for small violations of criteria) may increase as demand peaks so that observed throughput increases under sustained pressure - they like to move traffic and avoid having it pile up on them, and will work harder and more efficiently when they know even more traffic is coming. Measuring throughput is not simple! Measuring capacity is easier.

There are many locations of the US ATM system and areas of the rest of the world, where actual demand rates are much less than current capacity, so that any improvement in ATM capacity is not necessary or cost-beneficial. Capacity only becomes important as average demand rates exceed perhaps 75 % of capacity when peaking in the traffic arrivals causes short term congestion and increases the frequency of delays. Capacity becomes very important when scheduled rates are established that will exceed even the best capacities for short periods of time.

Since capacity may be decreased due to poor and marginal weather or during equipment failures (perhaps for the whole day), whenever scheduled traffic rates have not been constrained to be below bad weather capacities by predetermined, mutually agreed policies between ATM providers and users, it becomes necessary for ATM systems to introduce some form of real-time congestion management to manage the 'unavoidable' delays. Since congestion management functions are not efficient, their activities usually cause further 'avoidable' delays. If quotas or slots are established for worst-case situations of capacity, it prevents the use of the normal or best capacity for most of the time.

Fixed schedules and variable ATM capacities are simply not compatible - if a slot system is established, some tradeoff should be made to use a normal capacity for slotting which tacitly or explicitly accepts the fact that delays will occur at low capacity times. Delays cannot and should not be totally eliminated by slotting. If slots cannot be established, then the congestion management function of ATM has a major role to play in dynamically determining slots at low capacity times. Airline schedule reliability cannot be maintained when ATM capacities vary with weather conditions from hour to hour, and schedule rates exceed the lowest, bad weather capacities.

When there is surplus capacity (called a 'capacity margin') in system operations, other desirable characteristics ensue. We need to collect and identify these other measures and show how they relate to the capacity margin (such as flexibility, consistency, availability, etc.). With a capacity margin over high traffic levels, the system has a higher probability that it can dynamically and easily offer the surplus capacity to any user; but as demand rates approach capacity, operations must be more carefully planned and execution of the planned operation becomes more rigid or inflexible. Deviations are not easily available, and are not happily tolerated by controllers since they may cause excess coordination work to accommodate, and they may cause continuously changing plans.

3. Cost Measures

Given explicit goals for safety and capacity, the problem in designing a new ATM system using proven CNS technology is to create an ATM system which has low costs for both users and providers. This cost acceptability or affordability must be met around the world since ATM systems meet international standards - any new system must be acceptable to users in other countries as they fly into the US, and providers in other countries as US aircraft fly into their country. Affordability depends on costs and the financial state of users and providers in all these countries.

Thus the costs need to be organized as to who is paying them- different parties pay different costs. First, there are the user classes. They pay user fees and suffer costs in terms of fuel and time delays, and they should be divided into <u>aircraft owners</u> and <u>aircraft operators</u> since these may be different persons paying different costs. The aircraft users are usually classified into general aviation, business jet, military, and regional, domestic, and international airlines. The aircraft owners pay to equip and maintain their aircraft with the airborne CNS elements, and the aircraft operator pays ATM user fees and suffers longer trip time costs.

Another user who has costs is the airline passenger who pays travel time costs for ATM deficiencies through delays and longer trip times, and in the US, they also pay a tax to fund ATM activities. Other users are the providers of ATM services who are the 183 nations of the world and the several oceanic consortia (Eurocontrol, ASECNA, NATSPG, etc.,) since they are the owners and operators of the world's ATM systems, and will pay the costs to equip/implement/train and maintain the ground elements of any new ATM system. These costs are usually passed on to the aircraft users, and indirectly, to the airline passengers. We need to make a matrix of the types of costs and ATM users to show who normally pays for various costs.

The easiest way to handle benefits is to declare them to be a reduction in current costs. In the absence of air traffic, aircraft would fly an optimal route to the destination and would incur a given fuel and time cost. Because of the ATM system, there are extra costs for the aircraft operator due to the routing/altitude/speeds of procedures used by the current ATM system. Any reduction in these traffic costs is a benefit to the aircraft operator. The extra time costs are not delays above current schedule since airlines have adjusted schedule times to get schedule reliability.

As schedules grow longer, the penalties to the airline operator are still real, even if they seem forgotten. Similarly, if ATM is regularly using miles-in-trail, where they put aircraft on a single preferred route into an airport and then control the airspeed and altitude for the last 200 miles or more, the extra fuel for all aircraft operators is not simply the fuel above the average experience for the trip - it is the fuel burn from reserves above the flight planned fuel burn for an optimal trip. Aircraft operators, particularly airlines, have to understand that it is economical to invest in new equipment in order to use new procedures which can save them time and fuel costs, but they must have confidence that they will actually receive these benefits in the new ATM system. When the new procedures actually are in operation with the airline fleet, it will establish an incentive for gradual re-equipment of aircraft in the military, business jet, and general aviation fleets.

As well as classifying cost payers into users and providers, costs should be categorized as to their purpose, and into short term and long term costs. I propose the following:

1) R&D Costs (including certification)
2) Implementation Costs (equipage, training)
3) Operating Cost Changes (positive or negative)

Traditionally, research and development costs are incurred by the governments of leading nations of the world for any new ATM system. They involve paying for the conception, demonstration, testing, and certification of its operational elements, both ground and air. Then, private manufacturers of ATM equipment (both ground and air) are responsible for its design, certification, manufacture, and installation, and they will also incur some R&D costs to improve their products over competitive suppliers. These private sector costs translate to a purchase price and become an investment cost to the owners of airborne and ground equipment. But it is not a free market; the manufacturers have little room to innovate since their products must be accepted and certified by aviation safety regulatory agencies of at least one nation, but particularly the US. These are long-term, overhead costs.

Implementation costs are really one-time, long-term investment costs incurred only by the owners of aircraft and ATM systems. They involve the purchase of new ground and airborne equipment and its installation, and the purchase of maintenance equipment and training of maintenance personnel, and the training of operating personnel (i.e., controllers and pilots).

Operating costs are concerned with the short-term operation and maintenance of aircraft, and the operation and maintenance of the ATM system. It involves fuel and time costs for aircraft including pay for pilots and mechanics applied to the flight hours they produce. Some elements in these costs are annual in nature, and others are very short-term costs. For the ATM system, it includes both long- and short-term costs from purchase of land sites and buildings for facilities, energy to maintain their operation, flight inspection operations by aircraft and pilots, etc. The major short-term component of operations is labor, and includes pay for controllers, their supervisors and managers, and the maintenance technicians and flight inspection personnel.

We need to know these costs in detail for current operations since we are interested in how they might change for a new system. If the new system operational concepts envisage a reduction in the number of controllers (or larger sectors) by using decision support tools, the issues of human capacity and safety arise, and some simulated demonstration of the safe operation and capacity of the new concept and its tools becomes an R&D requirement. If the new concept envisages an increase in capacity through new efficient procedures which use new, high performance CNS technology, there is a tradeoff between capacity benefits and the cost of implementing and operating the new CNS equipment.

A. Appendix B - Chicago Field Interview Notes

Visit to Chicago Center
October 25, 1999

Attendees:
Robert Wiseman, Volpe Center
Robert Simpson, Flight Transportation Associates
Robert W. Schwab, Áslaug Haraldsdóttir and Xiaoling Gu; The Boeing Company

B. Chicago Air Route Traffic Control Center, Aurora, Illinois

Hosts: Ralph Davis, Center Director; David Michalak, Operations Specialist

Description of Topic	Primary Keyword	Secondary Keywords
United has a very long taxi to its gates when the Plan X runway configuration is used.	airfield	airlines, efficiency
O'Hare has no single configuration that is used more than 30% of the time. Configuration management and coordination is a significant challenge.	airfield	configuration management,
Highest throughput configuration is 5 runways active: either 3 arrival and 2 departure or 2 arrival and 3 departure, depending on demand. In that configuration the only possible cause of delay is problems in the airspace.	airfield	maximum throughput configuration
Third Chicago airport, a hotly debated topic politically. The new site that has been proposed is at Piedtone, but it is possible an airport such as Gary will become the third airport.	airfield	new airport
Regional jets are requested to Land-And-Hold-Short (LAHSO). This is now a bigger problem since the turboprops that could do LASHO used to be 15-20% of the total aircraft, but are now only 5-10%. O'Hare airport's maximum arrival rate was 100 ac/hr 2 years ago, but it is now 90 ac/hr due to the operational impact of the new LAHSO order and the increasing portion of turbojets in the arrival flow. The turbojets are rapidly replacing older turboprop aircraft in the short-haul fleet.	airfield	throughput, LAHSO, aircraft types
Many pilots are refusing LAHSO at O'Hare, even though they routinely land on very short runways at airports such as Reagan National (compare Reagan's 5,400 ft runway with 8,500 ft from threshold to intersection at O'Hare). The TRACON notifies the pilot on entry to expect a LAHSO at a given runway. The pilot can refuse, and in that case the aircraft will need to be routed to another runway. Pilot evaluates winds, runway condition and other factors and may not notify controller of refusal until close to FAF. Thus,	airfield, TRACON	LAHSO procedures, runway assignment, flow planning, safety

Description of Topic	**Primary Keyword**	**Secondary Keywords**
traffic flow planning through TRACON and tower is difficult, very dynamic flow with last-minute runway changes.		
Airlines do not want aircraft to be diverted to an alternate, it is very costly and can be difficult to get passengers and aircraft back where they were supposed to go. The very high load factors increase the impact of aircraft cancellations and diversions on the airline operation, and it is now preferable to take long delays and continue traffic flows late into the night on difficult days.	airlines	diversions, cancellations, cost, load factors
Monday is usually the lightest traffic day at O'Hare.	airlines	schedule
Daily logs are kept for the Aurora en route center and 14 specific days requested by the Volpe Center were provided. The logs cover such useful information as: 1. Daily quick looks (arrival and departure delay numbers and average times related to volume, weather, or other causes; the number of TMS and other departure delays from O'Hare and Midway to identified other airports; and the average delay time due to TMS delays over specified time intervals and by air carrier or air taxi type). 2. Daily records of facility operations (ceiling, visibility, winds, precipitation, SIGMETS, and O'Hare runway configurations). 3. O'Hare and Midway delay logs listed by end times for those that are less than 15 minutes or those greater, in 15 minute increments. 4. TMU delays by time period, average and maximum delay, destination airport, cause (i.e., weather, volume, equipment, closed runway, and other), and type (e.g., ground stop, miles-in trail). 5. Identifications of ground delay programs and ground stops and their time intervals. 6. Total number of yellow and red alerts by sector number. 7. Hourly traffic reports (hourly arrival and departure ETMS demands. 8. Arrival transition restrictions, e.g., miles in trail from other centers, their airports and their overflights). 9. Hourly grouped transition fix counts for KRENA, KUBBS, PLANO, and BEARS; and the combined total demand	baseline	TMU logs
Center airspace & sectorization:	Center	airspace design

Description of Topic	Primary Keyword	Secondary Keywords
Center has 48 sectors grouped into 8 control areas. The 8th area was recently established. (1) Center airspace is mostly 10,000 ft and above. Chicago Center boundaries are "fixed in concrete." Airspace divided into four "diagonal" flows with dual departure streams along the cardinal directions. Center may go into holding to accommodate missed approach. Sectors are designed to handle inbounds and overs or outbounds and overs but not all three types.		
Arrival Corner Posts: Three of four corner posts sometimes limit flows due to unbalanced demand. Spacing minima is 7 miles (5 miles plus snitch-patch pad). Corner post operation needs higher flow rates at times: two streams @ 7 miles or one stream @ 3.5 miles. One proposed solution was to "give" SE corner post to approach so they could run 3 mile minimums. Center preferred solution is "Compressed Arrival Streams"; two streams with altitude separation which can be merged into one by approach. Problems for approach to deal with high altitude wind shears, etc. Bradford arrival sector goes from 33,000 to 24,000. Bradford steps down Chicago arrivals at 2000 ft steps to cross Bradford @ 24,000. Jump zone at Ottawa near Bradford reaches to 17,500.	Center	arrival fixes, throughput, traffic spacing, windshear, jump zone
Arrival rushes shift between East and West and if delay is needed it is usually applied to the side that's less busy.	Center	arrival rush, delay allocation
International flights are given priority in a delay situation due to fuel and fatigue status and cost impact of potential missed connection. First-tier flights are impacted by flow restrictions most frequently, both to take delay but also to release when slots open. 3:00 afternoon push for international traffic to ORD.	Center	delay allocation, slots, international flights
All Chicago airports are restricted to the same en route paths, which can cause contention for airspace.	Center	en route capacity
Close-in flows for Indy Center are set up by Chicago's TMU.	Center	flow management
Delays & Holding:	Center	holding,

Description of Topic	Primary Keyword	Secondary Keywords
(2) MIT is accomplished by speed commands, and sometimes by vectoring. A lot of the delay is un-reportable in today's delay reporting system. Much of the delay is taken in en route through vectoring. Occasionally approach will "ask for" 15 MIT out of holding fix. Center will frequently run aircraft to corner post and hold. Center "pulls" aircraft out of holding. Holding is usually set up on the "light side." Most holding due to convective weather or to unexpected wind shifts. RNAV routes are only used occasionally; especially when a VOR is out. The web site for Chicago Center SWAP routes: atcss.faa.gov/uis/ Fix balancing is done with internal traffic. Delays caused by staffing shortages occur 1-2 days a year. East coast hold over top of airport is a potential option for performance improvement.		delays, miles in trail, RNAV, fix balancing, staffing
Center uses close-in holding at Milwaukee.	Center	holding, Milwaukee
Interactions with Milwaukee: flows into Milwaukee can impact a sector that handles O'Hare departures, but usually priority to O'Hare operations.	Center	interactions, Milwaukee
Interactions with Minneapolis: MN arrivals are pushed down to accommodate O'Hare flights.	Center	interactions, Minneapolis
The slowest aircraft control the MIT stream speed.	Center	miles-in-trail, aircraft performance
Newark acceptance rate limitations. Departures from O'Hare destined to Newark are frequently given 30 miles in trail leaving Chicago Center into Cleveland Center. This is due to a rationing of arrival slots at Newark among arrival feeder flows, propagated all they way to Chicago airspace. O'Hare departures have to be timed on a short notice into a timed slot of 2-3 minutes.	Center	Newark AAR, miles-in-trail, timed departure slots
Overflights using the National Route Program (NRP) were difficult this summer with the weather problems and lack of predictability of available airspace and desired paths. The NRP creates a problem for overflights when there is	Center	NRP, weather

Description of Topic	**Primary Keyword**	**Secondary Keywords**
convective weather activity. NRP also causes a loss of knowledge of constriction points, or makes many new ones.		
The Quick Look tool, with the See All snapshot of the current traffic picture, allows the TMU to look at loads in all sectors in the Center. This cannot be done across facilities, and the airlines do not have this (only the TSD display with their own aircraft).	Center	Quick Look tool, TMU, sector loads
Inbound sectors keep aircraft in altitude separation until they are in an in-trail merge at 24,000 to 33,000 feet.	Center	separation, merging
En route operational practice sets a 7 miles-in-trail (MIT) to provide some slack above the 5 MIT minimum, particularly when aircraft are being merged. If there are tail winds at or above 15,000 feet, 12 MIT's are used.	Center	separation, merging, wind
Oshkosh air-show a big burden on Chicago Center; also Chicago air-show.	Center	special events
Overnight operations: 1 sector per area @ midnight; 2 sectors per area @ 3 A.M.	Center	staffing, nighttime
The corresponding increase in the regional jets at altitudes above the turboprop's 8,000 feet to those of the larger airline aircraft has put the regional jet into the larger aircraft altitude regions that are now more congested.	Center	throughput, aircraft types
Center TMU monitors final approach length and when it becomes 20 NM long they will slow the flow into the TRACON to ease the load, even before getting request for relief.	Center	throughput, spacing at arrival fix
It is not well known how much of the delay in this airport/airspace region is due to convective weather. The Chicago Center has a statistician that publishes delay data, but it is often difficult to track the original cause of a delay.	convective weather	delay
Noise exposure in the Chicago area has been mitigated by changing configurations regularly to spread the noise. FMS routes "Fly Quiet Approach" have been designed but are not used until after 11pm because they would reduce throughput.	environment	noise, configurations, FMS procedures, throughput
O'Hare is affected by traffic 500 NMi away.	flow management	
Flow restrictions from Boston, Philadelphia, National and EWR are standard.	flow management	
Center TMU uses ETMS data, through the TMS system, to predict aircraft mix in the arrival flow and make a flow plan for traffic spacing at each of four arrival fixes. The heavies and long hauls peak at 3 pm.	flow management	aircraft mix, spacing at arrival fix
Optimum sequencing activity would need to start 300 NM from the airport, which is outside the boundaries of Chicago	flow management	arrival sequencing,

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Center. The CTAS tool is not yet fully developed for multi-center applications, and may also have additional challenges due to complexity of O'Hare's configuration management.		CTAS
Collaborative Decision Making is making a big difference in improving data reliability for planning purposes.	flow management	CDM, planning data
Coordination across the system is a problem involving airspace access and weather prediction. With dynamic replanning of flows, there is not a coordinated plan to ensure that each airport is treated fairly, it is more or less ad hoc who gets to go. A big airport like O'Hare is easy to shut down with one phone call to get a big effect on flow. Unpredictability of weather causes need for dynamic flow management.	flow management	coordination, weather prediction
ORD off times set by MIT restrictions out of Cleveland (30 to EWR; 30 to JFK).	flow management	departure slots
Historically Validated Restrictions (HVR) is a new name given to flow management restrictions that have a pattern of recurring (although there are examples of HVR's that pop up for the first time but under that name). Using Historically Validated Restrictions (HVR) in place of static restrictions. Chicago does not have any HVR's, theirs are too variable. Roughly 20% of HVR's are due to sector volume, 80% to airport capacity.	flow management	HVR
Swap routes are used to get around capacity restrictions or weather problems in the normally used routes. Roughly 20% of the swap routes are because of sector volume overloads, while the remaining 80% are for overloads at airports. The swap routes for each center are called Historically Validated Restrictions (HVR) and are to specifically designated airports. O'Hare gets separate HVR for the east and the west. HVR for Newark, Philly, NY, Cincinnati and Detroit.	flow management	HVR, swap routes
Chicago places restrictions out to first tier Centers "only for the rushes" every day in peak periods.	flow management	miles in trail
Center with impacted sectors must offer SWAP routes.	flow management	SWAP routes
Cleveland Center is the busiest FAA Center, with its airports at Detroit and Cincinnati growing rapidly. Cleveland Center issues a lot of flow restrictions and the reasons may include staffing levels, but they are not well known by the adjacent facilities.	growth	Center, Cleveland
Growth at Washington Dulles airport is felt throughout the system through flow in/out of Indianapolis and Washington Centers. UAL has added 300 flights a day at Dulles. Dulles is a "new problem" for Indy Center.	growth	Dulles

Description of Topic	Primary Keyword	Secondary Keywords
Chicago operations have been growing at about 2-3% a year. Peaks are not getting bigger, mainly due to slot control, but the growth is in the off-peak times. Midway growth will be a lot higher, particularly with expanded operations by Southwest Airlines, lots of airport constructions going on to accommodate it. Pan Am has just started scheduled passenger service into Gary, Indiana.	growth	slot control, reliever airports
This past summer the Chicago area suffered through a larger-than normal number of severe thunderstorms, which caused congestion even in en route airspace.	severe weather	throughput
80% of delay is airport-caused and 20% is en route sectors.	throughput	delay, cause
O'Hare's acceptance rates set miles-in-trail separations for remote en route centers. For Chicago operations, the AARs are converted to Miles In-Trail (MIT).	throughput	miles-in-trail
OAG as "marketing tool" needs updating for delays and cancellations.	throughput	OAG, delay, cancellations
Airlines push for efficiency on their flights, but ATC would rather ensure that all slots are used even if paths are not optimized.	throughput vs. efficiency	
Midway airport arrival streams only from the SE and SW, procedurally separated below O'Hare traffic. They get penalized more on East bound rush. SWA complains about their delays at Midway, caused by interactions with O'Hare. It is difficult to coordinate between the two towers to mix departures.	TRACON	interactions, Midway, coordination between towers
Interactions with Midway airport: the stream straight into 13C can cause departure interaction with O'Hare. Usually O'Hare gets priority, but during a push at Midway they may shut an O'Hare departure flow off for a while.	TRACON, Center	interactions, Midway
Weather picture on ARTS and on-board don't seem to track very well.	weather	airborne, ground picture
National Routes Program (NRP) makes impact assessment of convective weather more difficult.	weather	convective, NPR
O'Hare departure delays increase 30-40% due to downstream convective weather.	weather	delay
Departure delays are not a big problem at O'Hare, only when they are down to 2 runways, then they have to slow departures as well as arrivals. Another departure delay problem is convective weather forcing an arrival stream through a sector that normally handles only departures.	weather	departure delays
Airlines and their pilots are becoming more reluctant to fly through severe weather or turbulence. When pilots want to deviate due to weather or turbulence, ATC almost always accepts due to aircraft safety, but this causes difficulty in	weather	deviations, safety, throughput

Description of Topic	Primary Keyword	Secondary Keywords
maintaining spacing in traffic streams.		
Weather predictions are improving; but about three times each summer there are major un-forecast weather events.	weather	prediction performance
The ground delay program is operating at about a 70% reliability with respect to prediction and appropriateness of delay allocation. Storm systems (fronts) travelling through Chicago are fairly predictable as they move through from the West, but on very hot humid days "pop-up" storms can blow up in an hour. Ceiling and visibility can fluctuate and are not always easy to predict. The FAA facilities get weather predictions by FAX from UAL and AA and if they are not in agreement with NWS there is a telecon to decide on needed actions.	weather prediction accuracy	ground delay program

Working session with David Michalak. David provided copies of maps including high altitude Center sectors, arrival airways and fixes.

Description of Topic	Primary Keyword	Secondary Keywords
De-icing operations are performed at the gate and then the aircraft must take off within 15 minutes. They are therefore excempted from ground hold program and MIT restrictions due to difficulty in coordination.	airfield	de-icing, ground hold, miles-in-trail
Noise issue prevents having a third airport in Chicago area.	airfield	new airport, noise
Growth in region's cargo traffic has averaged 30-40% annual until recently. Cargo traffic into Rockford, Indy, Wilmington and Dayton.	airlines, cargo	growth
Rockford, Des Moins and Cedar Rapids have cargo operations, late night mostly. Wilmington and Dayton departures get route restrictions on the midnight shift, all occur about 3 am when there are fewer controllers on shift so flow has to be organized to handle the load. Cargo operations start after 12 and peak at 3 A.M.	airlines, cargo	midnight shift, restrictions
The CTAP initiative proposed to delegate additional airspace to the TRACON around each arrival fix so that streams could be merged using the 3 NM separation minimum. This plan has been abandoned in favor of CAPS, which involves stacking streams vertically to deliver to TRACON at the fix, the TRACON can then apply 3 NM separation to route aircraft to separate runways.	airspace design	CAPS, dual streams, separation minima, CTAP, airspace structure
CTAP airspace redesign effort collected a lot of operational data to base their analysis on. Bob Everson and Annette Davis in the Regional Office were the primary airspace	baseline	CTAP, data

Description of Topic	Primary Keyword	Secondary Keywords
design specialists.		
Data sources include ETMS data and we are looking for some good weather days and some bad days also. Using ETMS only can be difficult to correlate delay situations with actual weather causes. TMU daily file, hard copy several inches thick for the year, but it includes reasons for delay and restrictions, and all weather information including Faxes from airlines with their weather forecasts.	baseline	ETMS data, TMU daily file, delay data,
VFR flights in the Chicago area generally file IFR flight plans to get access to airspace, and then they are captured in the ETMS data stream.	baseline	ETMS data, VFR flights
Herndon Command Center log is a clearance house for all restrictions along with severe weather reports. There log should give a picture of overall system activity during a day.	baseline	Herndon log, system-wide data
OPSNET records delay data. TMU logs record causes and some of the data log is kept beyond 15 days. June 8th shows convective activity in Cleveland so it is not a good day. There were HVR including Cleveland for sector volume and West into Albuquerque.	baseline	OPSNET, TMU logs
Southbound flights have to be vectored around regional jets until they are above regional jet's preferred altitude.	Center	aircraft types
Arrival fix load balancing can be achieved by routing 1st tier traffic to the more lightly loaded side to get them in.	Center	arrival fix load balancing, 1st tier traffic
Bradford fix used to be a difficult sector due to complexity of traffic. This has been fixed by reducing streams from 3, mixed arrival departure, to 2, mostly arrivals, into the fix, and doing a merge upstream in Kansas Center airspace instead. Also the low altitude crossing is restricted to prioritize Eastbound departures.	Center	Bradford fix, merging, sector complexity, structure
The Bradford High sector is between FL 330 and 240, arrivals cross Bradford fix at FL 240. When there is strong tail-wind from the West the trailing aircraft at FL 330 will start to overtake the descending aircraft and they have to impose MIT spacing upstream to prevent the overtaking. West controllers must deal with tail-wind compression of spacing.	Center	Bradford fix, tailwind, overtaking, miles-in-trail
Aircraft climb performance is difficult to predict and therefore controllers are very conservative by blocking a large chunk of airspace for every climbing aircraft. Intent look-ahead could help make better predictions and therefore better use of airspace.	Center	climb performance, intent, airspace use
In O'Hare runway configuration management, the impact on Center operations when configurations change is that	Center	configuration management,

Description of Topic	Primary Keyword	Secondary Keywords
departures arrive at different altitudes in Center airspace. This is well coordinated by phone prior to configuration changes, and the Center can also monitor O'Hare localizer data to see how their operation in doing.		en route impact
Timed departure slots are used to fit aircraft into streams that have restrictions. This can be difficult to time accurately and sometimes they let departures go and hold for a while to fit them into the stream.	Center	departure slots, holding
Dynamic sectors are a big topic and the primary issue with those is controller proficiency and strategies for solving problems. Hard to see how this can be achieved without taking the controller out of the loop.	Center	dynamic sectors, human factors, automation
CENTER personnel mentioned that there can be restrictions on TER (Terminal Enroute) IFR flights at lower levels to the east of Chicago due to problems in handling arrivals and departures in that area during surges.	Center	en route restrictions
Over-reactions sometime cause a shut off of departures at O'Hare. Good anticipating tool will help.	Center	flow management, coordination
Center makes the call on which plane to hold when speed and path adjustment is not sufficient.	Center	holding, arrival planning
The Center is now looking at possibly using the airspace directly overhead O'Hare airport to hold aircraft that are affected by restrictions from the East (Cleveland).	Center	holding, overhead O'Hare
There is a jump zone over Ottawa, which can interfere with an O'Hare arrival stream. The jumpers want to go as high as 17,500 ft and they try to coordinate with the operator, but there is sometimes interference. Activity mostly in summer and in good weather.	Center	Interference, jump zone
Military activity. Howard military base exercise operations stay below FL 290 with traffic overhead at FL 330. Hilltop in the SE also can have an impact. Wisconsin Air National Guard stays at low altitude and does not interfere.	Center	interference, military activity
At arrival fixes, flight speed 250 knot, in-trail separation 7 nm. Before fixes, aircraft were separated vertically. Sometime due to jet stream at high altitude, separation at fixes are set at 12-15 nm.	Center	miles-in-trail, wind
Monitor-alert parameters are based on the complexity of a sector. Complexity takes into account outbounds, inbounds and overflights, no longer mix all three in any one sector. The Bradford High sector used to work all three. The monitor-alert parameter is then set by the Center given the complexity of the sector and what the workforce is comfortable with.	Center	monitor-alert, sector complexity, workload

Description of Topic	Primary Keyword	Secondary Keywords
NRP has changed the system tremendously, much less predictability now. Prior to it the problems were very predictable and solutions were known and ready. With NRP the confliction points are variable and with different wind conditions each one is different from the last, which causes much more workload. NRP into EWR was cancelled during the spool-up of DSR this summer and as a result Chicago Center recorded much less delays. The program was then opened up again. There is not enough baseline data to really evaluate the overall effect of the NRP.	Center	NRP, conflict points, winds, workload, baseline
Over flights with NRP can cause significant delays because of overhead stream congestion.	Center	NRP, delay
NRP operations can cause everyone to file over the same fix during a rush and then it would be good to stack the stream vertically and use the 3 NMi in the TRACON to compress the flow.	Center	NRP, dual streams, vertical stacking
Chicago ARTCC has 9 radars feeding its systems.	Center	radars
SUA and military activity is coordinated through a military specialist position in Chicago Center. He coordinates directly with the military side, then discusses with Center supervisors.	Center	SUA, military coordination
Staffing delays sometimes restrict sector capacity.	Center	throughput, staffing
Chicago has to reroute traffic en route that is bound for EWR. They use the TSD with a filter on EWR, put range rings on a fix that's a bottleneck to spot aircraft that will be contending for a slot at that fix, and then either apply speed control, vector or hold to adjust spacing. The TSD allows them to write scripts to filter on a number of items in the records: fix, airport, aircraft types, etc.	Center	TSD, en route metering and spacing, en route restrictions
Canadian response to "off loading" traffic peaks is variable.	flow management	Canada
Chicago is placed with the Western states in Herndon flow management, which is not the best arrangement due to its interactions with Eastern flows.	flow management	East and West flow management
EWR traffic streams, can see zigzags in their paths in Chicago airspace. EWR has no arrival holding stacks due to airspace limitations and ground holds are not effective enough to meter flow. Speed control is used if there is enough time to achieve effect. Cleveland Center is too busy to apply these adjustments.	flow management	EWR, flow metering, path stretching, speed control
FSM (Flight Schedule Monitor) is part of CDM, the airlines use to swap flights for available slots and also to allow schedule compression in case of cancellations.	flow management	FSM, CDM, slot swapping, schedule

Description of Topic	Primary Keyword	Secondary Keywords
		compression
Cleveland Center imposes most of the MIT spacing on Chicago Center, with 50% of Eastbound Chicago traffic getting MIT out of Chicago.	flow management	miles-in-trail
MIT restrictions are coordinated by taking arrival rate, then depending where the traffic load is coming from, allocate MIT spacing to particular arrival fixes, and propagate this back as far as needed.	flow management	miles-in-trail, propagation
Miles-in-trail restrictions are applied into Chicago Center during rushes every day.	flow management	miles-in-trail, rush
O'Hare tower does not have a TSD display to see what flow problems they are releasing departures into.	flow management	TSD, tower, departure planning
Thunderstorm activity is characterized using metrics such as the level of the storm top, and the severity of storm cells. Then individual pilots make decisions on whether they need to deviate. ATC has to set up spacing to plan for the worst case scenario to avoid safety problems.	severe weather	deviations, flow planning
Chicago Center airspace is 10,000 ft and above, with a few spots where they cover to the ground. Tower-En Route operation is defined as Approach Control to Approach Control and therefore has to stay below 10,000 ft.	TRACON	Tower-En Route
Thunderstorms within 500 miles can have a major traffic impact.	weather	convective

Visit to Chicago TRACON
October 26, 1999

Attendees:
Robert Wiseman, Volpe Center
Robert Simpson, Flight Transportation Associates
Robert W. Schwab, Áslaug Haraldsdóttir and Xiaoling Gu; The Boeing Company

Hosts: Olivet L. Smith, Operations Manager, Joan Linnane, Acting Assistant Manager, Bob Flynn, Traffic Manager, Dave Schuler, QA, Regional Office.

Description of Topic	Primary Keyword	Secondary Keyword
Plan X is the 100 AAR: 4R, 9L, 9R, and can be used with wind from 340 to 150 (northerly). Now keep using this configuration for a larger range of wind directions, with light winds, to stay at 100 AAR. Plan B is 14R, 22L, 22R which is also good. SW and W winds are not the best for throughput.	airfield	AAR, runway configurations, wind direction
Configuration changes are usually known well in advance to	airfield	configuration

Description of Topic	Primary Keyword	Secondary Keyword
plan for, but about one in every 25 times they have to be done suddenly due to change in winds. Try to watch wind directions at nearby airports to anticipate wind changes due to lake effect. These wind changes can happen up to 3 times a day due to lake effect. This causes difficulty getting departures lined up correctly for the runway system.		management, departure planning, wind
LAHSO issues are significant right now after the release of the new FAA order. Previously such operations were routinely conducted under the term Simultaneous Operations on Interacting Runways (SOIR). The new LAHSO order is much more restrictive and complex with 5 groups of airplanes defined each with required runway length for dry and wet conditions. The impact is worst with prevailing westerly winds such as this time of year. The order was 15 years in preparation.	airfield	LAHSO
The LAHSO effect on O'Hare is effectively a loss of 2 runways. 14L hold short of 27R is lost, this cuts departure rate in half. In addition, 27L hold short of 32L, could do for all except aircraft group 5 in the past but now only some can and others won't (AA MD 80's demand 8000 ft now). CRDA position predictor might help with these operations, but that has not been positively determined.	airfield	LAHSO, airline and pilot refusal, ac groups
TRACON controller notifies the pilot on entry 20-40 NM out to expect LAHSO clearance to a runway, and sometimes the pilot will wait until 4-5 NM out to refuse the clearance. This causes traffic exposure in close-in airspace that is difficult to handle and may reduce safety.	airfield	LAHSO, pilot refusal, traffic exposure, safety
Noise abatement calls for changing configuration every 8 hours if winds allow.	airfield	noise abatement, configuration
When there is snow, the TRACON sets new airport acceptance rates.	airfield	snow
CAPS is the new concept to achieve higher throughput at the arrival fixes. They do not have the budget to program the training simulators to demonstrate how the concept would work to the controllers. Increased TRACON airspace (CTAP) would be preferable for the 3 cornerposts because that would give controllers more options to handle the traffic using the 3 NMi separation.	airspace design	CAPS, CTAP, separation standards, airspace structure. budget issues
Limited coverage of their two ASR-9 radars, mentioned attempts to get radar coverage to achieve 3 nm separations within 40 nm.	automation	radar coverage
The TRACON operates 2 ASR 9's with different coverage. The QXM radar does not cover the NE and NW cornerposts	automation	radar coverage, radar outage

Description of Topic	Primary Keyword	Secondary Keyword
and when they use it, it affects the operations. Had upgrades over the summer but winters have been tough with radar outages. They have lost their ASR 7 and then must use QXM as the backup. Now sensors don't seem to be a problem anymore.		
RADAR Issues: RADAR coverage by terminal ARTS IIIE with ASR 9s with 2.6 second updates. ASR 9s have unplanned outage history (recently upgraded, hopefully problem fixed). Second radar (back up) for NW and NE coverage of Tracon airspace. Reflectivity sometimes a problem: targets drifting off the data block. Frequency interference a marginal issue (loss of full performance). CTAP would have necessitated 3-5new RADARs. Chicago TRACON's ARTS-IIIE can only accommodate 7 sensor inputs, which they presently have. QXM as back up, limited in effectiveness. NASA AMES may have ARTS IIIE tapes.	automation	radar coverage, radar outage
Baselining, before or after LAHSO, before/after regional jet growth. The flow has changed significantly since the CTAP analysis was done by ATAC, that data was 1993 and is probably no longer relevant for baselining purposes.	baseline	baselining, CTAP data
Automated TRACON OPSNET data for the same 14 days specified by the Volpe Center were provided. The data covers such useful information as: 1. Total daily itinerant operations at the tower. 2. Total IFR air carrier, air taxi, general aviation, and military operations at O'Hare, Midway, and over flights. Ditto for VFR (which is roughly 5% of the IFR) and the grand total of the two. 3. Hourly arrivals and departures at O'Hare and Midway and total TRACON operations, including over flights. 4. O'Hare peak arrival hour, peak departure hour, peak total hour. Ditto for Midway. 5. TMU Briefing Log containing the airport, its runway configurations, each listed by time of day, AAR, weather conditions (e.g., clouds, calm, VFR). 6. Delay Worksheet with initial times, causes (e.g., eastbound restrictions, Midway or O'Hare or en route) and number, average, and maximum delays	baseline	OPSNET data

Description of Topic	Primary Keyword	Secondary Keyword
over the time interval to the next condition. Totals for the entire day are also provided. 7. TMU restrictions by time started and cancelled, by facility, airport, direction fix, type of restriction (e.g., MIT ceiling) and reason (e.g., volume at identified en route center, debris on runway, weather). 8. TMU shift log of unusual, but not necessarily delay causing situations.		
OPSNET does not capture most of the added delay due to the LAHSO order because it is taken in several places each less than 15 minutes.	baseline	OPSNET, 15 minute delay, LAHSO
Frequency interference is a problem at times. With CTAP they would have needed 5 more positions and frequencies to go with those. Currently have 13-14 positions usually when busy, up to 20 maximum number of sectors. They still use handwritten strips, need them when the radar goes out.	communications	no of sectors, flight strips, CTAP
TSD is used for TMC to TMC coordination to anticipate the dynamic load. Center puts aircraft in holding to time correctly to pack in at the correct spacing on the less busy side. This is the managed arrival reservoirs (MAR), which users were in favor of rather than managing all the load by the ground hold program.	flow management	holding, MAR, throughput
Regional jets are further aggravating the delay situation: American Eagle ATR 42s and 43s could be pulled out of jet flow.	throughput	aircraft types
Land and Hold Short: Reduced LAHSO use has cut capacity from 103 to 90 (best rate). Order has made things worse than a year ago, and uncertainty of pilot acceptance of clearances further compounds the issue. Many American Eagle turboprops refuse LAHSO. Order out of Jeff Griffith's (ATO) shop with support from Flight Standards. Order has significantly reduced the effectiveness of several crossing configurations at ORD. The order has led to significantly altering the historical runway use frequencies. Uncertainty as to daily acceptance and from pilot to pilot. Refusals occur anytime from corner post (where clearance is typically granted) to 5-6 miles from final. Can't give LASHO to general aviation.	throughput	LAHSO
Because the longer haul directional arrival traffic flows have	TRACON	arrival fixes,

Description of Topic	**Primary Keyword**	**Secondary Keyword**
been subjected to MIT spacing for the last 200-300 miles (as explained later), the short haul traffic originating from cities nearby to O'Hare and on the same side as the directional surge is often diverted within CENTER airspace around to the "OFF" fixes for a "back door arrival" rather than disturb the long MIT stream in the last 200 miles before the entry fix.		aircraft types
All arrivals come off corner posts 20 miles from airport and “direct to O’Hare”. Aircraft come over far fixes at 300 kts and over close fixes at 250 (or 240) kts. Two corner posts sequence to one arrival runway and two to the second arrival runway. The en route 7 miles typically “compresses” to 5 mile.	TRACON	arrival fixes, vectoring, merging, speed control
They described a "normal" length of the lineup on the final approach centerline as being 10-15 nm, or 5-6 aircraft.	TRACON	final approach segment, spacing
VMC: 2.5-3 NMi separation at out marker. IMC: 4 nm separation.	TRACON	final approach spacing
Final approach operations: Typically visual separations are not used. Choice of controller is maintaining speed control or granting visual. Speed control to the outer marker is standard operating procedure. Handoff to tower at the outer marker. Compression effects range from 20 knot tail wind to 50 knot headwind on some approaches.	TRACON	final approach spacing
There could also be a need for visual conditions so that the Tower could monitor the lateral separations on final during parallel approaches.	TRACON	final approach spacing, Tower monitoring
Windshear on final approach (4R) can have a big effect on closing rate so they have to adjust spacing at the Outer Marker to ensure separation on final.	TRACON	final approach spacing, wind shear
When the arrival rush is unbalanced they need to send some aircraft around to the 3rd runway, do this dynamically around either side depending on conditions.	TRACON	flow balance, runway balancing
Some configurations require extra spacing on arrivals to fit departures in on crossing runways.	TRACON	interactions, departures and arrivals
Midway 13C interacts with O’Hare departures on ORD 22L because the turn-on to final is 7 NM south of O’Hare. They have to take turns by shutting down one and letting the other run and so on. Possibility to operate simultaneously with RNP-equipped aircraft if they had a special operational	TRACON	interactions, Midway, RNP, monitoring, growth

Description of Topic	**Primary Keyword**	**Secondary Keyword**
position monitoring path conformance on the 2 streams. This is being done at Dallas Ft. Worth and Love Field, but no budget available for that at Chicago currently. Midway is growing by the week and this problem is increasing.		
Minima for dual approaches in marginal visibility: Plan X used down to (1000,3). For (700,2) use a different configuration. Both conditions can use regular in-trail spacing. Tower must see the aircraft to give the visual clearance and that requires 4 NM spacing at the OM because the tower can't see them before that.	TRACON	marginal visibility, dual approaches
Marginal VMC: 700 ceiling & 2 nm RVR.	TRACON	marginal VMC
Missed approach operations: Tower coordinates downstream operations and gives the aircraft back to departure. Departure will pick the aircraft up 3 miles out. Typically they put the aircraft on a vector at the edge of the arrival/departure zone. (3) Try to get aircraft back into arrival stream ASAP, but it's good if he can be re-sequenced in arrivals within 15 miles. 1 miss can be typically absorbed easily.	TRACON	missed approach, merging
Missed approaches: the TRACON tries to work the aircraft back into the stream and because the Center feeds in at 7 NM usually they have room using some S-turns to slow someone down. A rough rule of thumb was quoted that the lineup at the Outer Marker got 4nm longer when this occurred.	TRACON	missed approach, merging
Missed approach: system (TRACON) usually can absorb 1 missed at a time. Missed approach will be absorbed by TRACON or be treated as departures.	TRACON	missed approach, merging
Overflow operations can be "given" to overflow third runway when the two primaries are too busy.	TRACON	runway balancing
TRACON controllers use speed control to the outer marker to ensure spacing on final. On visual approach the spacing is allowed to reduce on final.	TRACON	speed control, final approach spacing
Simultaneous parallel approach operations add two controllers.	TRACON	staffing, simultaneous approaches
There are no SIDs with fixed departure patterns for either O'Hare or Midway so that DEPARTURE positions always use radar vectoring to direct aircraft to the first en route navaid using ad-hoc patterns and altitudes which avoid the arrival patterns.	TRACON	vectoring
Chapters 9 and 10 of the Operations Manual were provided	TRACON	vectoring

Description of Topic	Primary Keyword	Secondary Keyword
to the team, version dated Dec. 1996, new version to be available after endorsement by Union in January 2000. This includes a copy of Plan X, B, and W TRACON vectoring patterns, both horizontal and vertical paths, those 3 configurations represent about 75% of their total operations.		patterns, operations manual
TRACON vectoring patterns are needed for baseline modeling purposes. Most are defined in the Special Ops document but figures are available also for horizontal and vertical paths.	TRACON	vectoring, definitions of paths
They always use Wake Vortex spacing behind a heavy jet.	TRACON	wake vortex, final approach spacing
Tower takes the handoff at the Outer Marker.	TRACON, Tower	handoff, outer marker
Weather shifts are the biggest source of uncertainty and therefore throughput impact. Convective weather number one, then wind shift. Ground and air see different weather information and pilots responses are unpredictable, some fly through weather that others do not. Cornerposts can be blocked during stormy weather even when it's sunny over the airport.	weather	convective weather, winds, throughput,
Departures may be delayed due to weather when they need to move arrivals to departure sectors.	weather	departure delays, arrival and departure interactions

Visit to O'Hare Tower
October 26, 1999

Attendees:
Robert Wiseman, Volpe Center
Robert Simpson, Flight Transportation Associates
Robert W. Schwab, Áslaug Haraldsdóttir and Xiaoling Gu; The Boeing Company

Hosts: Kevin Markwell, Manager and Pat Burke, Operations Specialist.

Description of Topic	Primary Keyword	Secondary Keyword
The growth in regional jets is also having a negative impact because they have replaced turboprops that operated on different runways.	aircraft types	regional jets, throughput
Data Link Delivery of Expected Taxi Clearance (DDTC) report Oct. 22, 99 by ARINC (we got a copy) for UAL. This is being tried in Detroit with NW airlines, using current	airfield	aircraft turnaround, data link, taxi

Description of Topic	**Primary Keyword**	**Secondary Keyword**
ACARS data link. This will give a heads-up on turn-around status from an aircraft at the gate. The prediction of aircraft readiness for pushback was discussed; this isn't known yet but the trials in Detroit should provide data on this.		clearance
Low visibility operations, in CAT II and III the AAR goes down to 60 and they cannot use LAHSO.	airfield	CAT II and III, AAR
Runway change operations: TRACON will typically pick a "last airplane." Usually planned so capacity impact is minimal. Sometime "Lake effect" and "Alberta wind" boundary region near O'Hare, causing big uncertainty in wind direction. Frequency 3 times a day or 1 time in 25 days.	airfield	configuration changes
De-icing operations are done at the gate, then aircraft need to take off within 15 minutes. In this situation they have to slow down arrival stream to make room for departures.	airfield	de-icing, departure priority
When there is a departure stop due to overload at other airports they have to fit O'Hare departures for those airports into timed slots of 2-3 minutes. This makes surface traffic management tricky because they have to be careful how they line up the aircraft for departure.	airfield	departure slots, surface management
TRACON confirmed Center's statement that LAHSO has reduced airport throughput from 100 AAR to 90 AAR.	airfield	LAHSO
Modeling & analysis is being done for the 2012 O'Hare World Gateway Program. Landrum & Brown is modeling Chicago airfield operations using SIMMOD.	airfield	modeling, baseline
Any discussions about a new runway where the railyard is now located is a City of Chicago political issue, not FAA. Tower staff work with what they're given by the City.	airfield	new runway
Ramp control is handled by each airline at each terminal building, 4 ramp controls: International, AA, UAL, others. Yellow-blue line marks boundary between ramp and taxiways, ramp control handles inside, when aircraft show up at the exit points from ramps they call tower to ask for taxi clearance.	airfield	ramp control, coordination
Tower makes decisions about runway configuration changes, based on maximum efficiency for arrival and departure mix. The TRACON is much more concerned about arrivals than departures and there is often tension between them over the balance of arrivals vs. departures.	airfield	runway configuration, arrival-departure balance
Any runway maintenance work is done on the midnight shift to reduce the impact.	airfield	runway maintenance
Daily demand starts at 7 A.M. with east push, followed by westerly departures; then at 10 A.M. a west push. First rush	airfield	rush, delays, hours of

Description of Topic	Primary Keyword	Secondary Keyword
out at 6:00 A.M.; last rush out at 11:00 P.M. Sometimes traffic runs to 3:00 A.M when there are delays accumulated.		operation
Usually UAL and AA have rushes going different directions, which helps with load balancing, but the 5pm and 8 pm rushes they both go same direction.	airfield	rush, load balancing
Surface movement is occasionally a problem, particularly when the tail end of a departure rush stretches into the next arrival rush. This can cause departure delays and is sometimes caused by difficulty fitting departures into slots in Center airspace. Holding areas in several places near runways to handle surface traffic (penalty boxes).	airfield	surface congestion, departure delays, penalty boxes
Surface surveillance radar issues include an area on the surface blocked from Tower near the hotel and hanger area. There is ASDE RADAR echo on 9L/27R near a holding region. The trouble is that it does not show aircraft ID tags and that is a difficult problem technically to solve. Without that they must continue with paper strips for ID purposes. May need GPS with position broadcast to solve this problem.	airfield	surface surveillance, aircraft ID
Taxiways in certain areas are too close where the 747-400 can't pass on parallel taxiways without violating spacing rules.	airfield	taxiway spacing
Taxiway Operations: (4) Surface operations have 20-30 minutes lead time. (5) Each airline has its own ramp control. At ramp exit position the aircraft calls the tower. For ground hold times, airplane is taken away from the gate. Hold pads are located close to runways. Sometimes need to re-sequence departures by moving them down a runway. (6) Arrival and departure pushes alternate. Taxiway pattern is still circular. Little taxiway congestion as long as departure and arrival banks remain separated. Strong head/tail winds can shift directional banks, causing overlap. Penalty box is used when gates are not available. 4-5 large “holding regions” on ground for ground holds.	airfield	taxiways
There are "Coded" Taxi routes for departures published by O'Hare with a different "color" for each runway end and with the numbers indicating a start from various taxiway	airfield	taxiways

Description of Topic	**Primary Keyword**	**Secondary Keyword**
intersections near the ramps. This simplifies the issuance by radio of taxi instructions for pilots if they have their published codesheet out in the cockpit.		
Overall operational goal: balance runway load and avoid crossing paths in the airspace. Try to separate departures and arrivals on dedicated runways. A tool like CTAS could help organize the arrival stream to achieve these objectives.	airfield, TRACON	runway balancing, separate paths
Tower would prefer to use the 3 primary configurations all the time, but there are 4 configurations used most frequently. A couple more for weather, another couple more for certain rushes. The rest are almost never used, maybe for heavy crosswind and other rare conditions. Always try to include one free-roll runway for departures if at all possible.	airfield	runway configuration, frequency, weather, departures
Delays always go up after change in daylight savings time, airlines have to re-tune their schedule after the time change.	airlines	time change, delay
Airport information system from Atlanta Scientific is very useful, are considering giving the airlines access to that system. Includes configurations in use and restrictions.	automation	airport information system
AMASS was supposed to come to O'Hare, but there are problems with false alarm rate on the runway incursion prediction. If the rate is too high the controllers will not use the tool.	automation	AMASS, runway incursion, false alarm rate
Technology: Ground tags on the RADAR would be a big help. Data link delivery of taxiway clearances would be helpful. (7) Detroit Wayne has "silent" push back for ramp control. AMASS might help, but there is a high false alarm rate at SFO. FMS departures are used for noise abatement, but at a capacity cost. CRDA could help with LAHSO: could enable triple misses, but it does not help accommodate departures. CRDA is available on DBRITE.	automation	CRDA, FMS, AMASS, DDLC
CRDA, the airlines want to get this installed here but there are issues with how to use at O'Hare, low visibility and FMS, MAP and pilot reaction time. CRDA would be used to set up arrivals so that missed approach spacing is ok. Need it in TRACON and Tower so that they can verify and monitor correct spacing.	automation	CRDA, low visibility, missed approach
FDIO could provide lots of good performance data but there are concerns that it could get corrupted, it is not robust but operationally very important.	automation	FDIO

Description of Topic	Primary Keyword	Secondary Keyword
Hand-written O'Hare Tower Logs for the same 14 days specified by the Volpe Center were provided. The Logs will have to be associated with ETMS archived data and the en route and TRACON data to unravel the daily situation, but they do contain such useful information as: 1. A few hand written O'Hare delays listed by end times for those that are less than 15 minutes or those greater, 15 minutes increments. Each time entry contains the cause the number of aircraft affected and the average and maximum delay. 2. The initial and cancellation times of restrictions, their direction fix (e.g., origin airport or major compass direction) and, sometimes, the reason for the restriction (e.g., volume). 3. Occasional indications of the runways in use and their time intervals.	baseline	Tower logs
Center capacity is often limited and there is difficulty accepting traffic from O'Hare due to a variety of issues that the Tower does not have visibility into. They can include the NRP, which really is not working well East of Mississippi and that whole situation should be revisited. NRP results in a more chaotic traffic picture and may not be as safe as it should be. There has been no improvement in automation aids to help manage the unstructured traffic patterns. Also EWR problems occur that back up and often stop O'Hare departures.	Center	en route capacity, NRP, Eastern US, automation, EWR capacity
When there is a stop on Southbound departures, they are not allowed to re-file to get around the restriction.	flow management	departure stop
SWAP routes are coordinated through Herndon, which takes a long time and frequently there are no SWAP routes offered through Cleveland and Indiana. Mis-match between SWAP routes and runway configuration causes difficulties in surface planning and runway load balancing.	flow management	SWAP routes, coordination, surface planning, load balance
The O'Hare World Gateway Program, involving a SIMMOD Airspace and Airfield study, involves changing gate operations so that international flights can use any terminal building. That will alleviate traffic around terminals when aircraft have to be moved from international terminal over to their domestic base to continue flights. Analysis indicates that growth from 900,000 to 1,000,000 operations a year is possible. That is assuming VFR, but weather problems will become more significant. The plans have looked at a new terminal building with lots of new gates and additional gates on the international terminal.	growth	gate operations, international arrivals, VFR

Description of Topic	**Primary Keyword**	**Secondary Keyword**
There has been rapid growth in traffic to Europe and Asia. There is a race on to Tokyo that causes a departure push in the middle of an arrival rush and complicates traffic handling.	growth	interactions departure and arrival rush
Slot control program was instituted at O'Hare airport in 1968, which limits operations to 155 per hour maximum. This is what constrains growth at O'Hare, the runways could handle more. Quotas have limited annual growth in operations to 2-3% per year for the last 10 years. There is discussion about lifting slot control and it may happen as early as next year. Then gate capacity will be a constraint to growth.	growth	slot control, runway capacity, gate capacity
Operation numbers: around 100 ops/hr; without landing & hold short 90 ops/hr; without Turboprop (5% currently) 80 ops/hr.	throughput	AAR
Chicago arrival rates of 80 for duals, 90 for duals with third prop runway, 100+for three full runways before LAHSO, 126 for two hours at one time with full third runway.	throughput	AAR
IFR weather: below 1000 ceiling, RVR less than 1 NMi. Airport capacity: 70 ops/hr. Dual approach minimums range from 1000/3 to 700/2.	throughput	AAR, dual approaches
Takeoff rates are usually not limited by the available runways, nor by taxiway capacities, but rather by restrictions from departure and en route airspace operations.	throughput	departure, miles-in-trail
Three factors affecting capacity at the airport: changing policy on Landing & Hold Short, increased regional jets and severe weather. VFR flights don't have much impact on throughput at O'Hare.	throughput	LAHSO, aircraft types, weather
There are about a dozen main operating configurations for the runways at O'Hare with their availability at any point in time subject to wind strength and direction, visibility, and ceiling, etc. A runway configuration is defined by the assignment of takeoff and landing operations of a type of aircraft (e.g., prop or jet). Given the expected mix of aircraft using each runway, each configuration has a known capacity rate for landings (and another for takeoffs, and another for combined operations - takeoffs and landings). These runway capacities are usually expressed as an average hourly value and represent an upper limit on average traffic throughput.	throughput	runway configurations, AAR, weather, aircraft types
The arrival "dump zones" are after passing over departures at 7000 ft. Dump Zone arrival region defined for each arrival runway (turn and climb for departures permitted outside dump zone).	TRACON	arrival dump zone
CASTWIG (new arrival procedures for FMS-equipped	TRACON	CASTWIG,

Description of Topic	Primary Keyword	Secondary Keyword
aircraft) proposed to use 3 arrival runways, triple FMS precision missed approaches, this would be ok but there is no room to put departures.		FMS procedures, departure slots
FMS procedures are useful for noise abatement but currently cannot be used well for sequencing and throughput. A noise abatement FMS departure procedure does not allow fanning of departures so they must be spaced 7 NMi apart, which reduces throughput.	TRACON	FMS procedures, noise, throughput
Last minute missed approaches cause problems, not enough time to arrange paths.	TRACON	missed approach
Diverging (fanning) departures are separated by 1 NMi.	TRACON	throughput, departures
Non-normal events, can be airborne problems and cause disruption, biggest problem if an aircraft can't get off the runway. Weather changes are the biggest cause of disruptions.	weather	non-normal events, runway closure
Pop-up thunderstorms over the Mississippi, they are unpredictable and cannot be put in a coordinated program.	weather	pop-up storms, predictability, program
Hard to predict AAR going from 62/72 to 80.	weather	prediction
To increase the reliability of the weather prediction they sometimes use yesterday's weather pattern (time of day) to predict changes in ceiling/RVR.	weather	prediction, ceiling, visibility
Low visibility ops: 27 L/R full Cat II/III. Arrival rate drops to 60-80 in low visibility.	weather	throughput
The biggest impact of wind shift is on departures on the surface. Wind shift requires a change in runway configuration and during transient departures are held, preferably at gates, until close-in arrivals have been handled. An unpredicted wind change that forces a configuration change can leave lots of departures lined up at the wrong runway endsthat have to be taxied across to the new runway entry points, either while or after arrivals have reached their gates.	weather	wind, runway configuration change, departures, delay

B. Meeting with Landrum and Brown, Chicago
October 27, 1999

Hosts: Doug Goldberg, Vice President, Rich Kula, Senior Consultant
Visitors: Bob Schwab, Aslaug Haraldsdotir and Xiaoling Gu, Boeing.

No new runways are assumed in the capacity improvement program.	airfield	new runways
Surface movement is more difficult because of frequent	airfield	surface

transfer of aircraft between in International terminal and the others as aircraft switch between international and domestic flight segments.		movement, aircraft transfer
With respect to airspace activity and runways, O'Hare cannot handle well an overlap between arrivals and departures due to runway and surface movement logistics. There is a proposed taxiway addition south of Terminal 5 to enable departures on runway 27. The problem is spacing between the taxiways, may need accurate surface guidance to get an exception to the spacing rules.	airfield	surface movement, arrival-departure mix, taxiway spacing, surface guidance
The Capacity Improvement Plan needs an Environmental Impact Study and for financing arrangements they need simulation studies showing airfield and airspace operations improvements to support investment. A Simulation Working Group was established to develop the modeling assumptions, including representatives from Tower, TRACON and Center, UAL and AAL. A workbook documenting the analysis development is kept up-dated for each monthly meeting, with full detail on all analysis assumptions for the operational model. The model includes traffic handling from the arrival fixes to the gates, with a focus on surface movement. O'Hare and Midway airports are modeled. Landrum and Brown will conclude the analysis by the end of Dec 1999. Will request that Boeing be invited to join the Working Group and give a presentation of the Preliminary Design Process; next meeting on November 10th. The Capacity Improvement Plan has a fairly high political profile in Chicago.	airspace design	capacity improvement plan, SIMMOD analysis, TRACON airspace, runways, surface
CASTWIG had a lot of momentum, Boeing participated with simulation capability, then the project ran into serious stumbling blocks in actual implementation.	airspace design	CASTWIG, simulation, criteria, implementation
They are working the CTAP project for the FAA, with 5 Centers. Boeing received a copy of a detailed presentation of the project.	airspace design	CTAP
Criteria for airspace and procedure design: The analytical basis for the LAHSO order is not that clear; what involvement if any did Boeing have in establishing the performance parameters for aircraft stopping distance?	airspace design	LAHSO, stopping performance, criteria development
O'Hare World Gateway analysis is using a 1999 arrival and departure schedule for the SIMMOD baseline.	baseline	airspace analysis, baseline
Landrum and Brown use SIMMOD for their current analysis projects, but have used their own tools in the past, Gatesim and Airsim. Those tools have not been updated and the user	baseline	SIMMOD, Gatesim, Airsim

interface is not adequate anymore.		
Noise analysis and potential of FMS procedures for noise abatement is of considerable interest.	environment	noise, FMS procedures
Chicago is suffering a delay situation that the City is very keen on finding successful solutions to.	growth	delay
Growth predictions assume only marginal growth during peak hours, rather a redistribution of traffic load into lower activity times of day. Big increase in international flights into O'Hare	growth	growth,
O'Hare World Gateway study proposes the following terminal building developments, potential budget $4 billion: Add international arrival facilities to terminal buildings used by hub operators (AAL, UAL). Set up gate operations per airline "alliance". Terminal 1. UAL, reduce constraints on wide body gate space Terminal 2. Non-hub operators. Terminal 3. AAL. Terminal 4. New building for AAL alliance partners Terminal 5. International terminal Terminal 6. New addition to internation terminal.	growth	O'Hare World Gateway, added gate capacity, international operations, alliance partners
Traffic forecast (we received a copy of it) assumes that slot control will be lifted next year. The current slot control rule ends at 9:45pm, and that has caused more growth in late night operations.	growth	slot control, traffic forecast

Visit to Chicago-Elgin TRACON Operations Floor
December 16, 1999

Preamble: Flight from Seattle to Chicago on UAL 1758, Dec. 15th, ATC communications on IFE Channel 9. The flight departed 2 hours late from SeaTac because a ground hold program was put in effect for O'Hare due to a predicted snow storm. The following is whatever the undersigned was able to catch off the in-flight ATC channel, many gaps due to fast speech. Starting in Minneapolis Center airspace, at FL 330:

ATC-1	UAL 1758, slow down to …, sector in Chicago Center closed, if you slow down we might avoid holding
ATC–1	contact Minneapolis Center at …, FL 330
UAL 1758	to ATC-2, can we speed up now?
ATC-2	UAL 1758 standby on that; go ahead and resume normal airspeed (and we feel the engines rev up)
ATC-2	contact Chicago Center at …
	several turns and slowdowns for spacing
	UAL 1758 and 1768 on the same frequency, confusion between the two flights on a speed clearance, after that controller exaggerated pronunciation for both

	flights
	UAL 657 and 667 on the same frequency also, confusion on clearances for those two flights
ATC-3	UAL 1758, descend and maintain FL 240
ATC-3	contact Chicago Center at …
ATC-4	UAL 1758, cleared direct O'Hare
ATC-4	UAL 1758, reduce speed ..., set altimeter …
ATC-4	UAL 1758, cross KRENA at 10000 ft, 250 knots
ATC-4	contact Chicago Approach at …
UAL 1758	checking in at 10000 ft
ATC-5	UAL 1758, expect runway 22R, descend and maintain 7000
	flight attendants on channel going through updates of connecting gate assignments because the flight was 2 hrs late leaving Seattle
	feel aircraft turning left
ATC-5	UAL 1758, reduce speed to 180
ATC-5	UAL 1758, descend and maintain 5000
ATC-5	UAL 1758, turn right heading …, slow to 140
ATC-5	UAL 1758, turn right heading 200
ATC-5	UAL 1758, maintain 2000 till on final, ILS 22R
ATC-5	UAL 1758, contact tower at …
ATC-6	(Tower controller) cleared to land, wind …
ATC-6	(after we turned off the runway) UAL 1758, you crossed 9L, what gate did you get?
	Very fast taxi to the gate. No snow falling yet.

Elgin TRACON Host: Ray Heustis, TMU, coordinated by Bob Flynn.

Attendee: Áslaug Haraldsdóttir, The Boeing Company

Arrived around 1:30 pm on December 16th, O'Hare was running arrivals on 27L and 27R, duals only. Wet runways (a sprinkling of snow fell overnight), no LAHSO when wet. This is not one of the Plan X,W, or B configurations, they were using it because of wet runways and it allows them easy handling of departures going East (off 32L), they turn them right heading 90 to stay north of 27R.

Several positions were working on the right side of the room, working North Satellite, which consists of miscellaneous small airports to the North of O'Hare.

Three positions were working South Satellite, including Midway Airport. One controller on each position, but they can add a handoff position for each next to him. Each seat has a scope and strip bay so the handoff position has its own scope to look at. They always have all positions in each cluster sitting next to each other for easy coordination.

Looked in detail at arrivals on 27L and 27R. They are spaced far enough apart to operate independently, but they staff a controller on a PRM screen to watch for blunders. There was an arrival push from the East, both SE and NE fixes, with a few stragglers from NW and SW. The arrival dump zones start after the extended runway centerline of active departure runways, have to keep arrivals at or above 7000 ft until they pass that line.

One arrival control position working each arrival runway with a handoff position that primarily writes on paper strips. They don't use the strip printer at all, the handoff position writes down on a strip the flight number and aircraft type as the aircraft checks in from Center at the feeder fix, along with the altitude he's been cleared to. Ray told me that the controller then lines up the strips in the sequence he plans them on final and cycles through the sequence with altitude, heading and speed clearances to stay in sync with the flow and not forget anyone (we were sitting at a separate scope to watch the display without interrupting the controllers).

Controller working 27R was taking the handoffs from Center over NE fix, but a "feeder position" controller was taking the handoffs over the NW fix and delivering them to the 27R approach position when established on down-wind at 7000 ft. Mirror image on 27L. Ray said that they limit the number of aircraft for each controller to eight, and use the feeder position to offload the primary final controller.

They use 1000 ft vertical separation at turnon to the localizers for independent dual operations, high side at 5000 (27L), low side at 4000 (27R). Using IFR spacing, looked like about 4 nmi for most aircraft pairs and very regular.

After a while they changed configurations to 22R and 27L for arrivals, departure push finished and arrival push from NE starting. This is better for TRACON because they don't need the PRM position. This configuration change means moving the 27R stream to 22R. They call out the last aircraft that's committed to 27R and start vectoring the following aircraft from both directions toward 22R. Center put a couple of aircraft in hold (visible on our screen) just outside the NE feeder fix. The last aircraft for 27R must land before the first lands on 22R because they intersect. Aircraft coming in from NW fix were vectored back out along downwind for 22R to start merging in with stream from NE. A batch of heavy internationals were now flowing in from the NE.

Listened on the SE, SW (27L) approach control frequency for a while. One interesting pair of aircraft (one from SE the other from SW) were merged on top of each other, 4000ft and 5000 ft, couldn't read the data block, then the lower one was turned left to capture the localizer, then the other a minute later, ended up magically with 4 nmi spacing on final. Controller told each pilot not to worry, they'd each level off 1000 ft apart.

The final approach segment on 27L and 27R was consistently about 20-25 nmi long. When they get less busy they try to shorten the final and specially when not running duals then they can turn them closer and lower. The frequency on the 27L approach was being used almost constantly (guess 95%) by the controller and pilot readbacks. They use a silent handoff from the Center – aircraft symbol blinks on the controllers screen until he points and clicks, then stops blinking also on Center controller's screen.

To balance runway loads they may need to send aircraft from one side over to the other, easier in some configurations than others. They often bring them around the less busy side, maybe straight over the airport. Not much room to do this because of interactions with departures and other airspace restrictions.

Missed approaches are not a big deal, first they go to the departure position that is closest, then get mixed in with departures, then handed back over to the approach that fits them into the stream ASAP. Do this by making some aircraft go further out on the downwind and that results in a longer final approach segment for a while.

The day before they had declared AAR of 80 and there was a ground hold program put in (remember, we were 2 hrs late leaving Seattle). The airlines, through CDM, apparently swapped in mostly their heavies and the mix was very unfavorable on the arrival rushes with lots of heavies and some smalls. They ran only 66 arrivals/hr for 2 hrs due to this mix, had lots of delays and holding (remember, we were getting slowed and turned way over Minnesota) and complaints from central flow that they were not performing according to plan. CDM allows swapping but the AAR assumes an average mix for that airport.

Postlude: Heading back to Seattle from Chicago, departure on UAL 337, 8 pm schedule, 45 min delay in push back due to connecting passengers apparently.

	Taxiing for quite a while from Terminal 1 toward the south-east corner of the airfield, past the International Terminal. On the frequency we hear arrivals on 14R, departures on 27L, no clearances for us even though we are actively taxiing.
ATC-1	UAL 337, go to the right frequency, …
UAL 337	UAL 337 checking in, sorry, we were on the wrong frequency
ATC-2	you should have heard what we were all saying about you! Follow the commuter …
ATC-3	UAL 337, take position and hold
ATC-3	UAL 337, cleared for takeoff, turn left heading … off the runway
ATC-3	UAL 337, contact Chicago departure on …
ATC-4	UAL 337, maintain 5000, what's your heading?
ATC-4	UAL 337, climb and maintain 13000 (we're now over the lake heading east, must have departed 22L heading SE, we've been turning left)
ATC-4	UAL 337, turn left heading 020
ATC-4	UAL 337, turn left heading 340
ATC-4	contact Chicago Center on …, tell them your heading when you check in
UAL 337	UAL 337 checking in, at 11000 for 13000, heading 340
	and so on, not much excitement after that, once we're at altitude there is almost no traffic on the frequency.

Visit to O'Hare Tower Operations Floor
November 10, 1999

Preamble: Flight from Seattle to Chicago on UAL 1564, Nov. 9th, ATC communications on IFE Channel 9.

Starting in Chicago Center airspace, at FL 240:

ATC-1:	UAL 1564, descend and maintain 15000 ft
ATC-1:	UAL 1564, descend and maintain 13000 ft
ATC-1:	UAL 1564, cross fix … at 9000 ft
ATC-1:	to a VFR aircraft on approach to another airport: radar services terminated…
ATC-1:	UAL 1564, expect runway 14R localizer clearance, contact Chicago Approach at …
UAL 1564:	UAL 1564, checking in, passing 9700 for 9000 (on TRACON frequency)
ATC-2:	UAL 1564, descend and maintain 7000
UAL 1564:	maintain 7000 (if that's how you feel tonight!)
ATC-2:	UAL 1564, reduce speed to 210 knots
ATC-2:	UAL 1564, descend and maintain 5000
ATC-2:	UAL 1564, 1.5 miles from …, ILS … for 14R, follow traffic to a visual approach
ATC-2:	UAL 1564, reduce speed to 210 knots
ATC-2:	UAL 1564, reduce speed to 170 knots, contact tower at …., expect hold short of runway 27R - no 27 left
UAL 1564:	UAL 1564 with you (on Tower frequency)
ATC-3:	UAL 1564, hold short of other runway, wind 220 and 12, …

Comments:

Tower controller was also handling departures, presumably on the intersecting Runway 27L. The "hold short" clearance was not mentioned until on handoff to tower; later information from TRACON staff indicated that this information with wind field is on the ATIS and pilots are expected to notify TRACON controller if they don't want to hold short as soon as they have listened to the ATIS (which is not included on the passenger channel).

In all sectors there were several UAL flights with similar 4-digit flight numbers, which caused occasional confusion about whom a clearance was for. All seemed to be caught before anyone took the wrong clearance.

O'Hare Tower Host: Kevin Markwell, Manager.

Attendee: Áslaug Haraldsdóttir, The Boeing Company

Arrived at O'Hare Tower at 1:15pm on November 10th. Plan W was in operation at the time with SW winds of 10 knots, VMC. A departure push was starting.

Memphis Center was not accepting any traffic due to equipment outage. Saw on the TSD the empty Memphis airspace with O'Hare inbounds hugging the edges of their airspace. On and off ground stops on all southbounds from O'Hare, departures waiting for reroutes. Observed 2 aircraft in the 90R penalty box for more than an hour, then finally got reroutes and departed. Inbounds to EWR, LGA and JFK and others were subject to "normal" MIT restrictions.

As I arrived they showed me a weather display where a weather front was moving in from the NE with NE winds (180 degree wind shift), expected to reach O'Hare in 10 min, they decided to move to Plan X based on this and do it immediately because they needed to start moving all the departures out and once they're all taxiing it's difficult to send them to different runways.

For the next 10 min they were landing those aircraft that were already committed to Plan W. The TRACON picks last aircraft for each runway in current use and starts vectoring the other to new plan; in some cases the Center may put a few in holds to ease workload in TRACON. Departures were being sent out using an ad-hoc runway selection – no overall plan was identified.

They then called out "Plan X in force". The wind was still from the SW, clear from watching the bank of flags by the Hilton Hotel, thus operations had a tailwind of up to 10 knots.

During the transition departures were being lined up for 9L, 4L and 32L, a considerable number of them forming queues. A UAL 747 needed 32L but longer than rest, had to be routed around the queue to get behind the others, taxiways very tight in that area and he was told to go slow and careful.

Windshear alarms sounded now and then from the weather sensors. Missed approaches started to happen, one after another, on 9R and 4R. Controllers call across the room when they have a missed on their hands, asking others where to send them to avoid departures. Someone asks what's happening, controller says I don't know, I'm not flying this airplane. Maybe it's wind shear, maybe the tailwind.

I'd estimate that Plan X was in operation for 30 minutes before the wind finally shifted according to the forecast, and that at least 4 missed approaches occurred during this period. On one occasion there were simultaneous misses on 9R and 4R (converging), causing quite a lot of coordination on the Tower floor and by phone with the TRACON.

The configuration change and subsequent missed approach coordination caused considerable queuing on the taxiways by departures, at least 10 aircraft in line for each departure runway, in addition to a significant number in the gate/apron areas.

Wind shifts to NE as the front approaches, dark clouds closing in from the NE. Call to Milwaukee, they're in IMC already, expecting IMC at O'Hare before too long. Still in Plan X, departure queues start to get shorter. Still another missed approach on 9R.

Just before 2:30 pm, time to leave for my own flight (left request to please expedite the 3:30pm to Seattle…). Yet another missed approach on 9R, controller called across the room to the departure controller on 9L, his departure is fanning right into the missed approach aircraft's path (fanning is used to increase departure throughput on a runway). 9L departure controller immediately instructs the departure to turn left to runway heading to avoid the missed approach.

I estimated that at least 6 missed approaches occurred during the 1.5 hours I was observing in the Tower. In a later conversation with Kevin Markwell he estimated there is on the average 1 missed approach an hour and that if they were to reduce that rate they would have to increase spacing and thus reduce throughput.

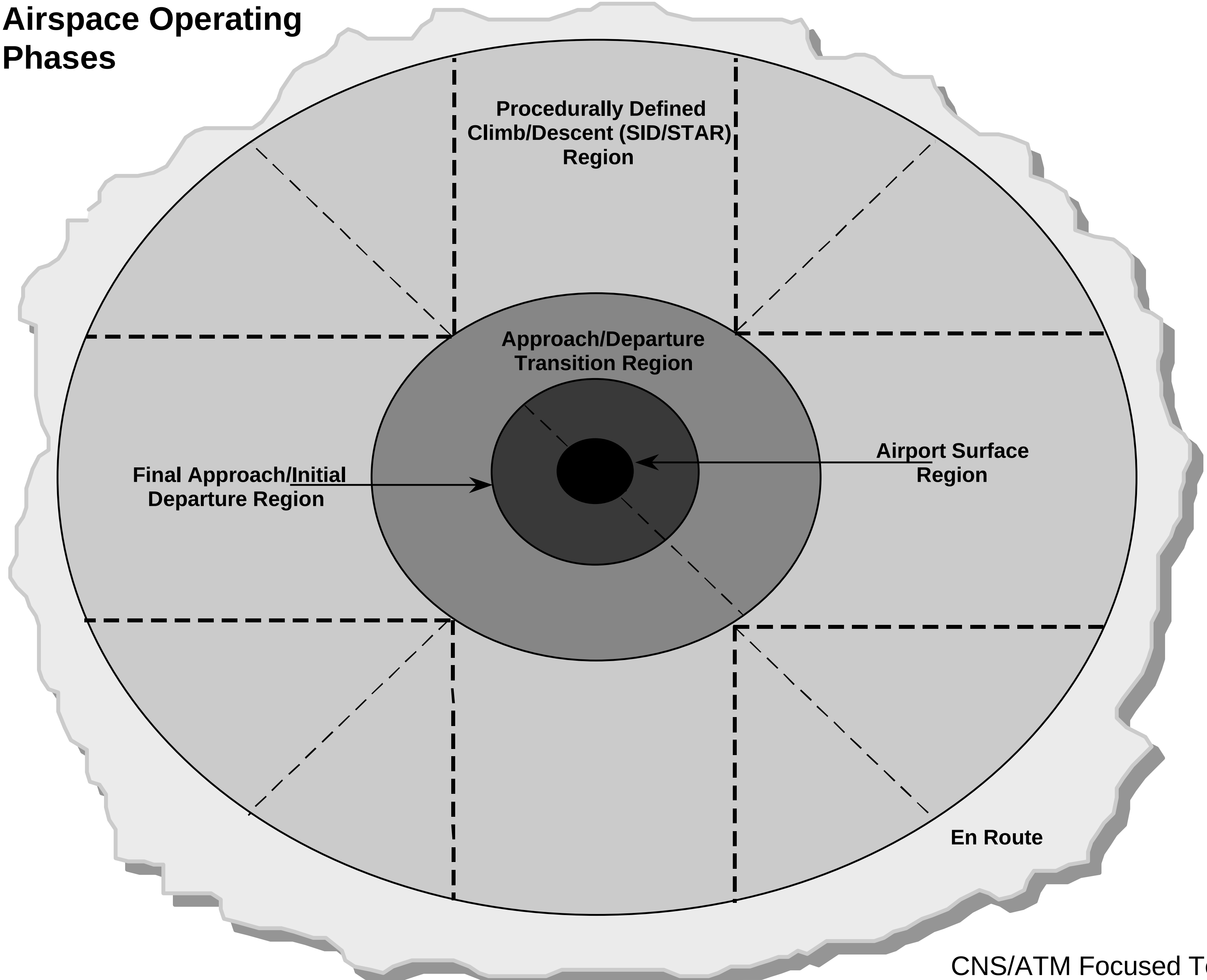
While observing the operations I talked with Bob Keyes, who was operating a flight strip data entry position for coordination with the TRACON. This was for departures off 32L, for each aircraft he called up the data by entering the flight number, then entered the cleared departure heading written on the paper strip by the departure controller. Added the paper strip to a stack, threw the holder into a bucket. He told me that when the TRACON was in the basement of the Tower building, they just threw the strip in the holder into a chute and someone then picked it up and carried over to receiving TRACON controller. He lead the team that brought this system on line after the move, was able to have the basic features put in but the budget was too small to really solve the interface problem and thus they have to staff a separate position just for this data entry job. The complete solution would have involved electronic flight data flowing through each position in the Tower and then on to the TRACON; instead they still hand carry strips across the Tower floor and then have to enter the data in this system for the TRACON coordination.
One of the problems they had with this project, which he sees as a common problem throughout FAA automation efforts, was frequent changes in management during the design and implementation period, changes are made in requirements, then they eventually run out of time and money and end up with an incomplete solution.

Coordination with other facilities is also a big problem in general, all done through phone calls. Example: call a stop on departures to airport X, have to start rerouting everyone on the taxiways to get the X's into a penalty box, then 5 min later another call says let them go we changed our mind; causes a lot of difficulty on a busy taxiway system, not so easy to move a bunch of aircraft around each other on the ground.

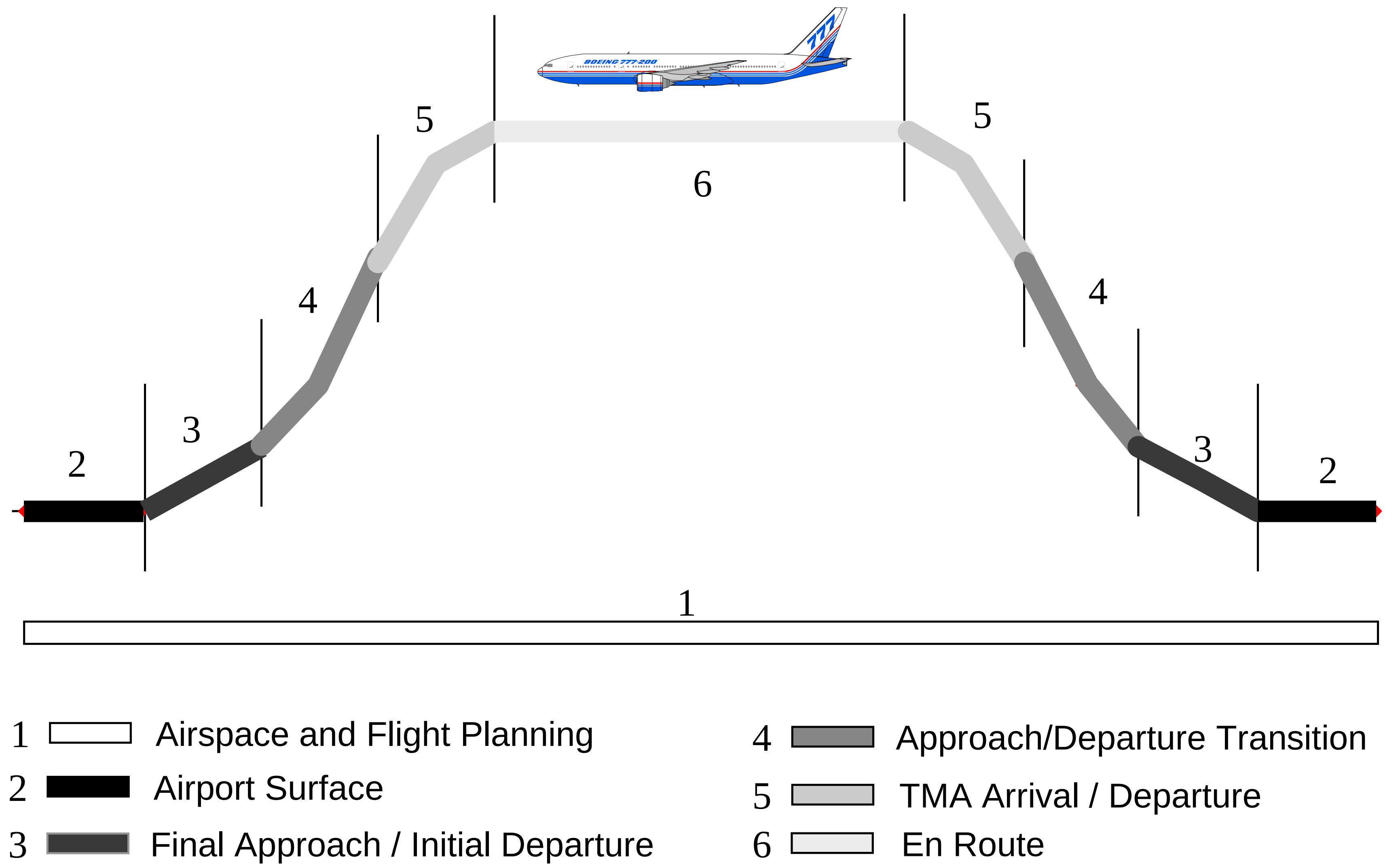
Configuration changes can be difficult also if they already have a bunch of aircraft lined up for one departure runway and then have to change to another unexpectedly. Must give a long taxi clearance, usually give to the leading aircraft and tell everyone to follow him, then sometimes the first aircraft gets confused and the next time you look at them the whole string is heading straight for the boonies!

Postlude: departed for Seattle on the 3:30 pm flight, on time, very expeditious taxi and takeoff.

Airspace Operating Phases



CNS/ATM Focused Team



5
5
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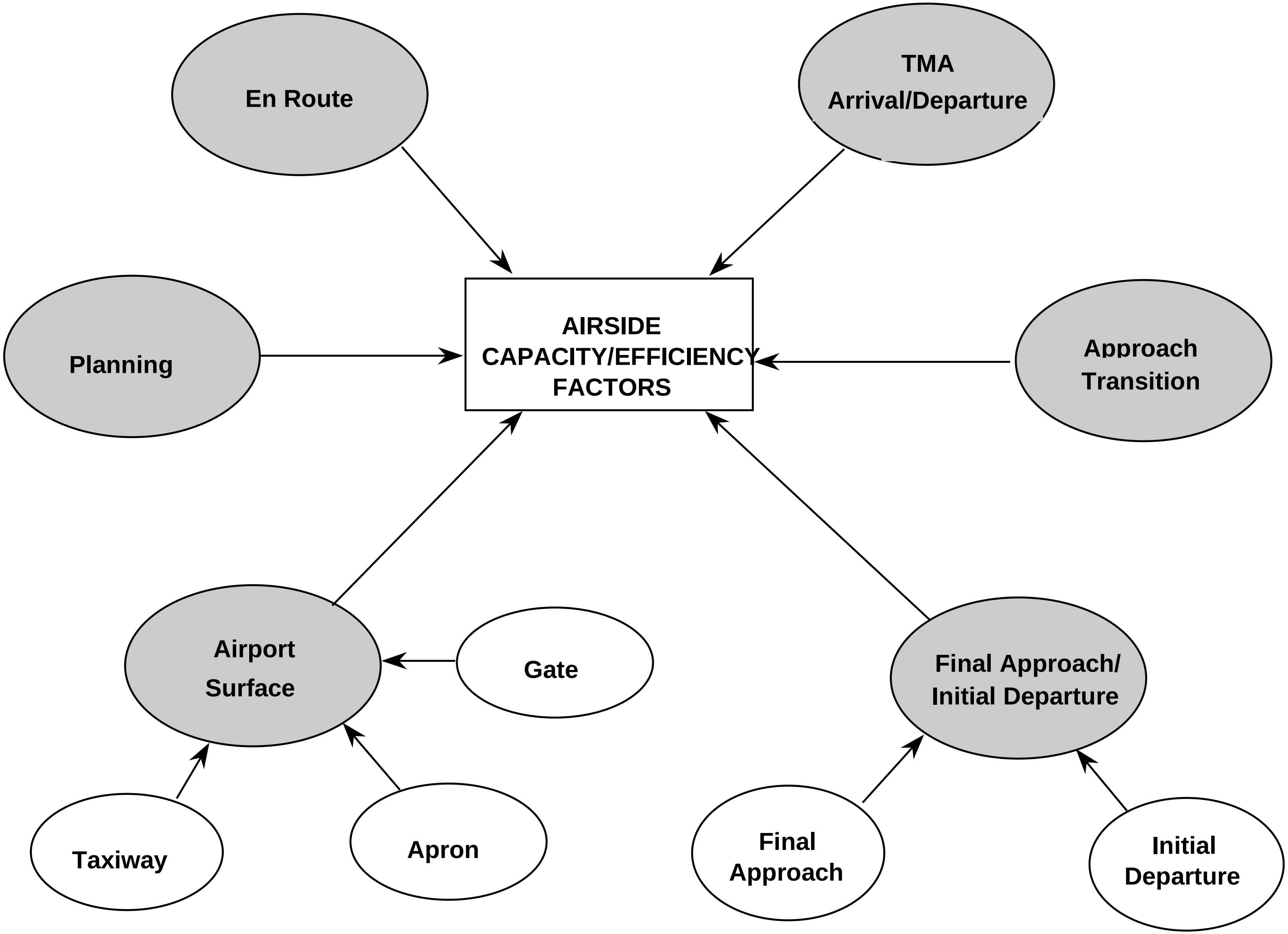
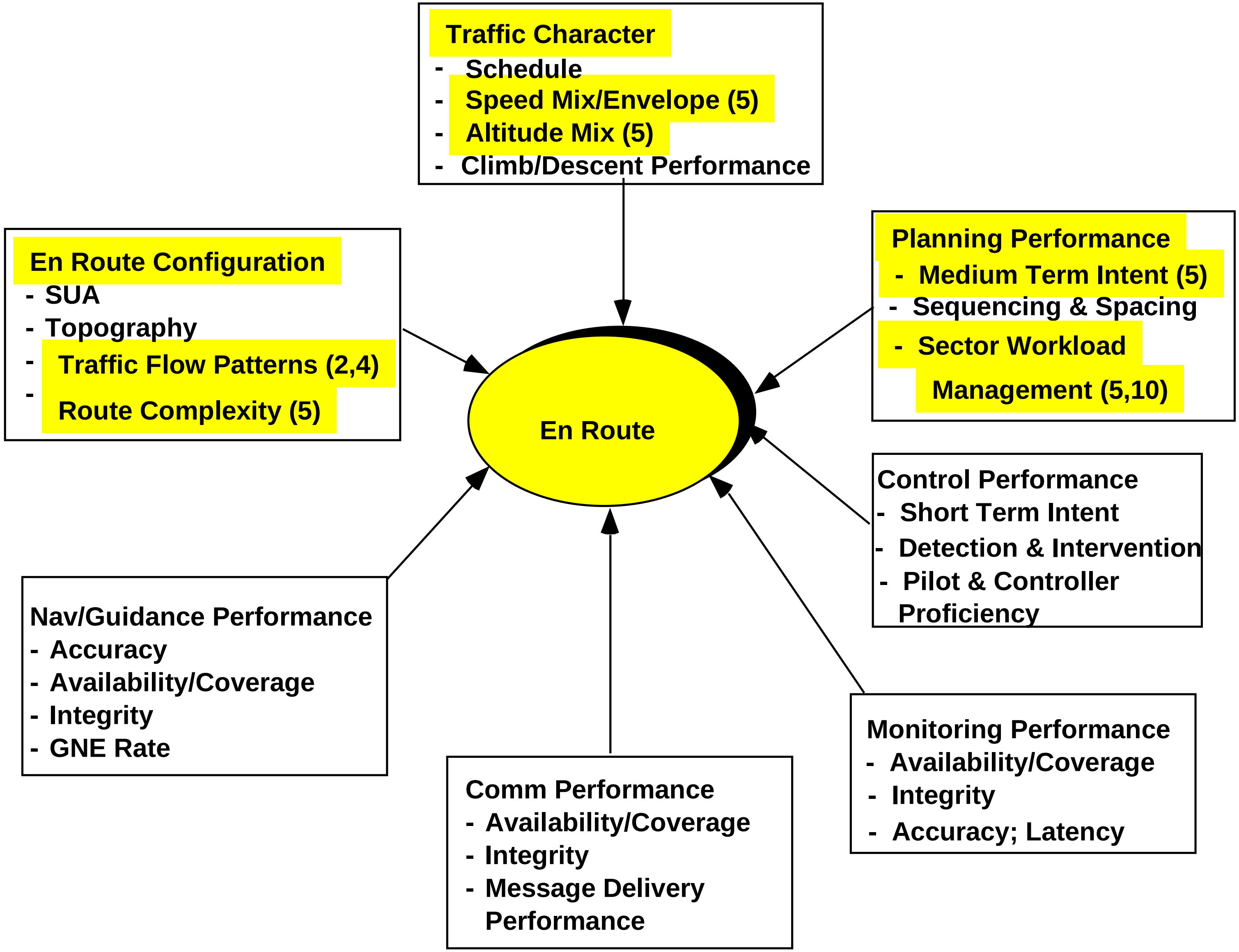
1 Airspace and Flight Planning
2 Airport Surface
3 Final Approach / Initial Departure
4 Approach/Departure Transition
5 TMA Arrival / Departure
6 En Route



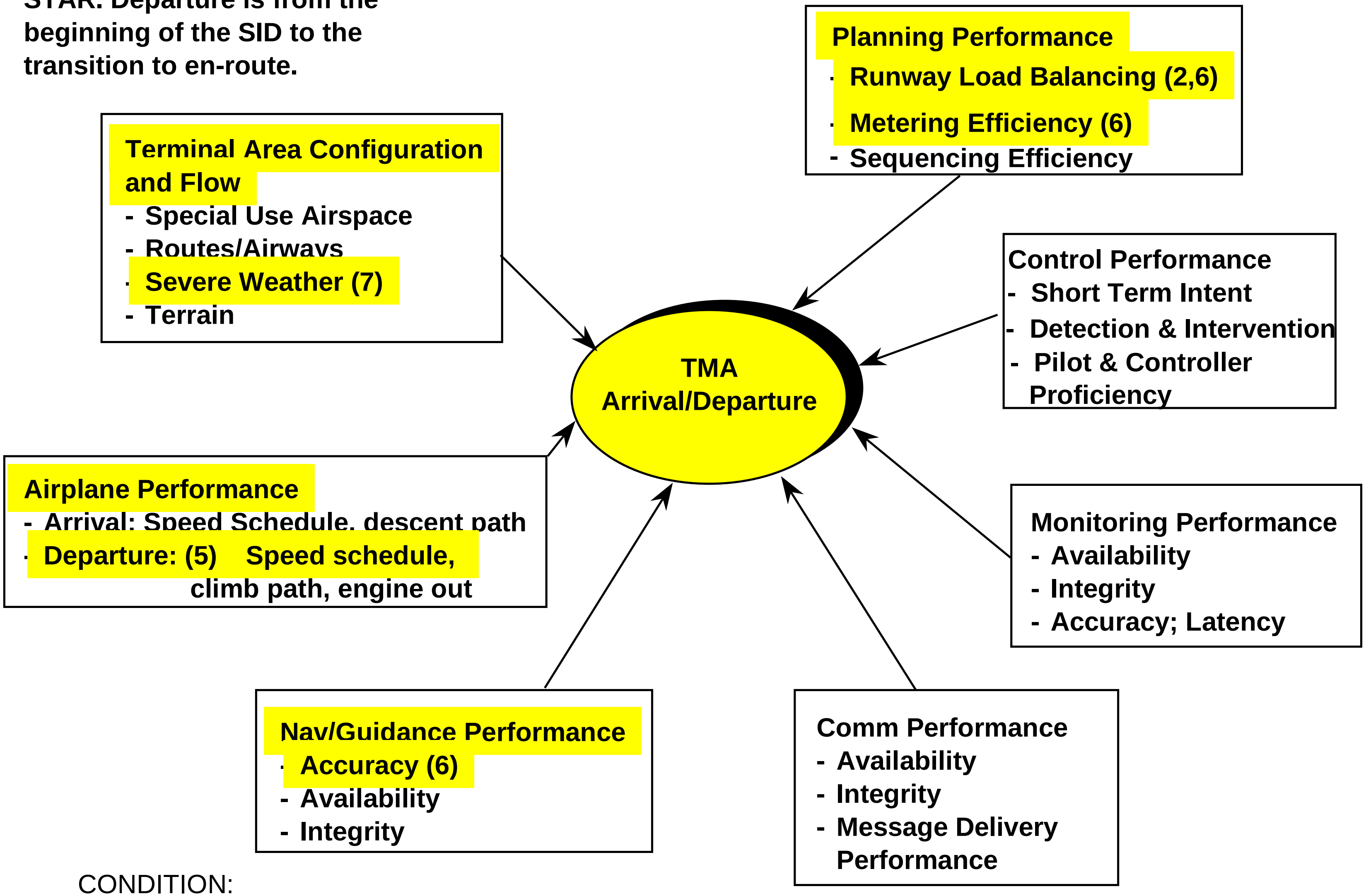
CONDITION: <u>**All Weather**</u>
LOCATION: <u>**Chicago and O'Hare**</u>



CONDITION:
LOCATION: Chicago Center

Definition

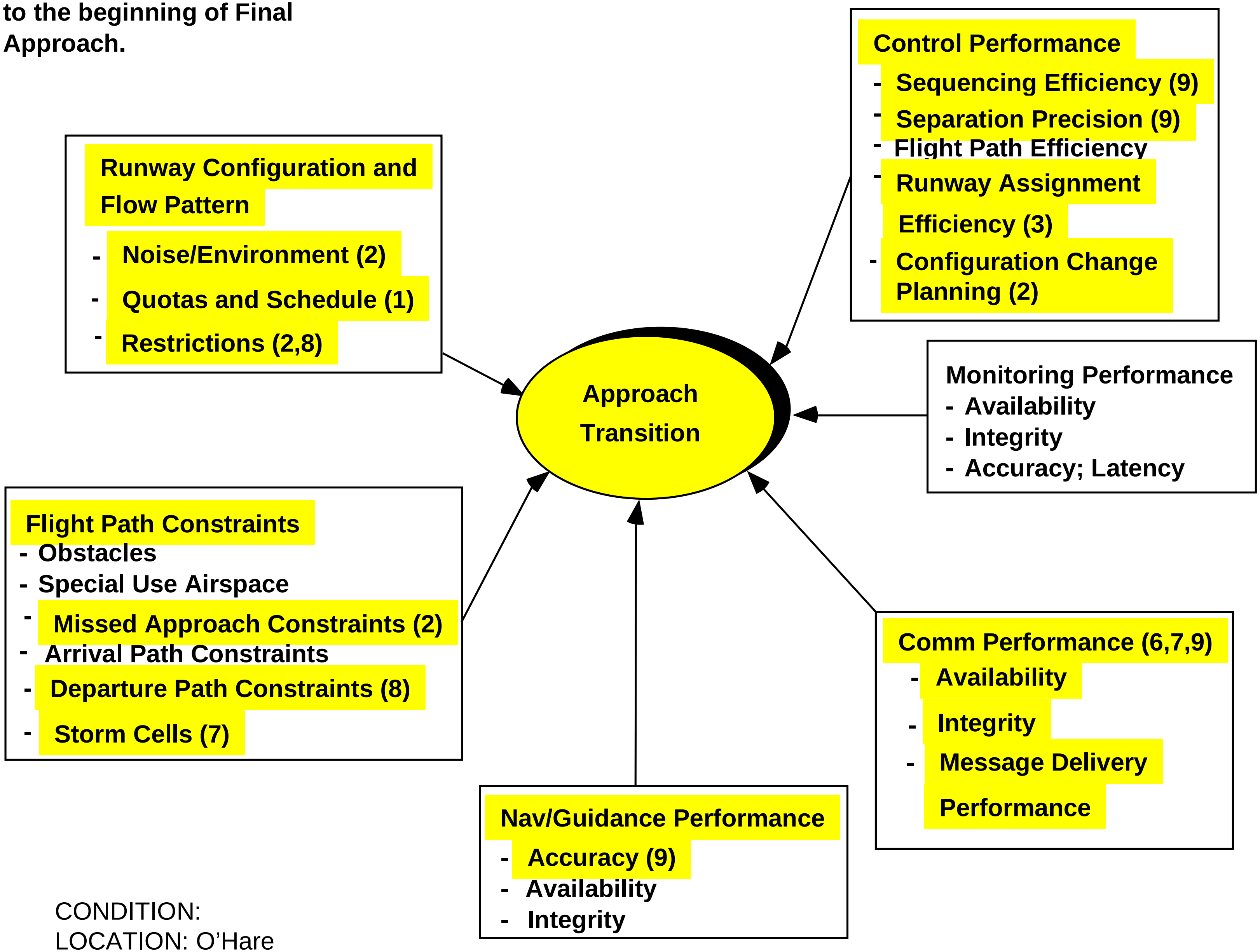
Arrival is from the beginning of the STAR to the end of the STAR. Departure is from the beginning of the SID to the transition to en-route.



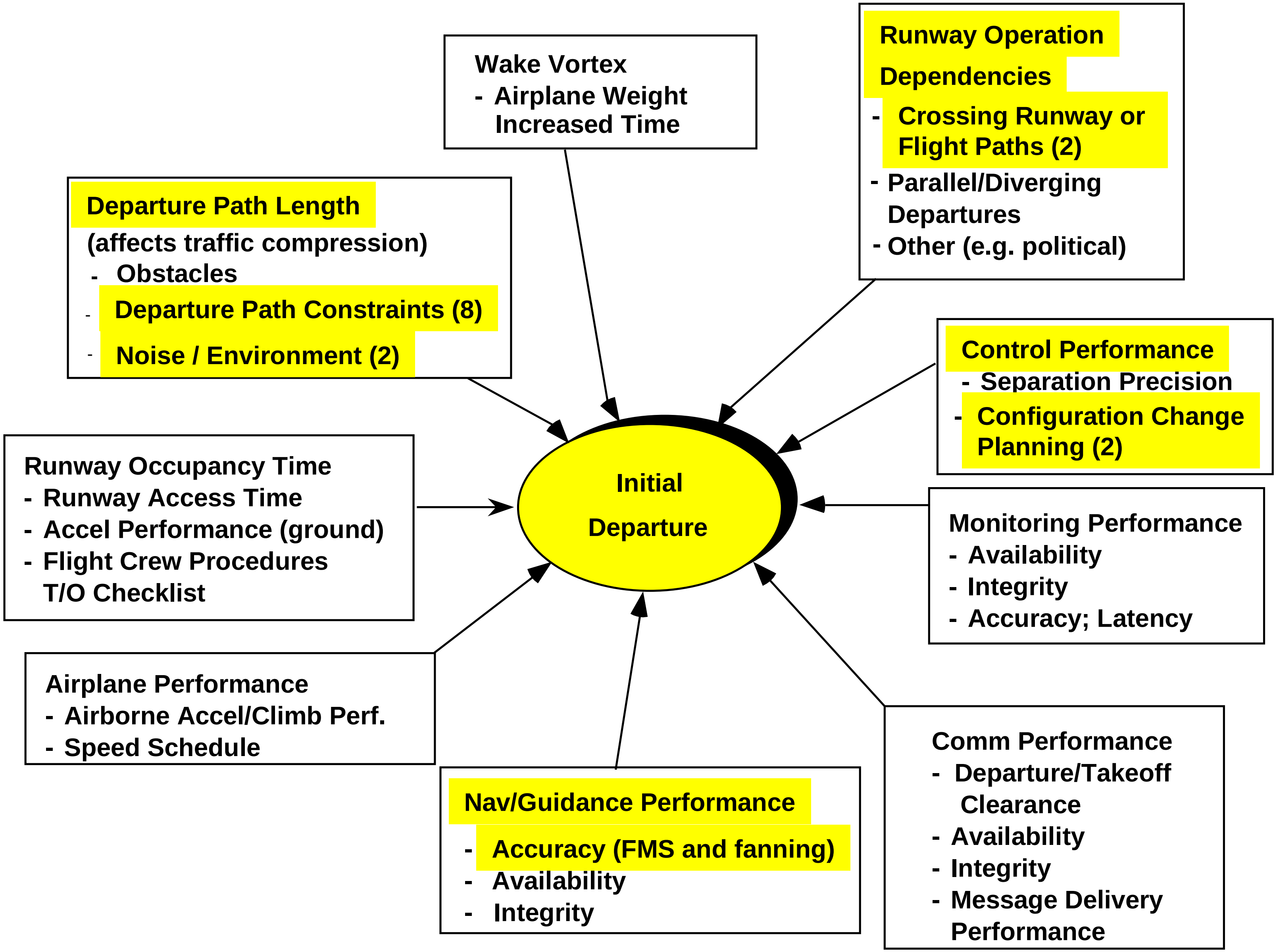
CONDITION:
LOCATION: Chicago Center

Definition

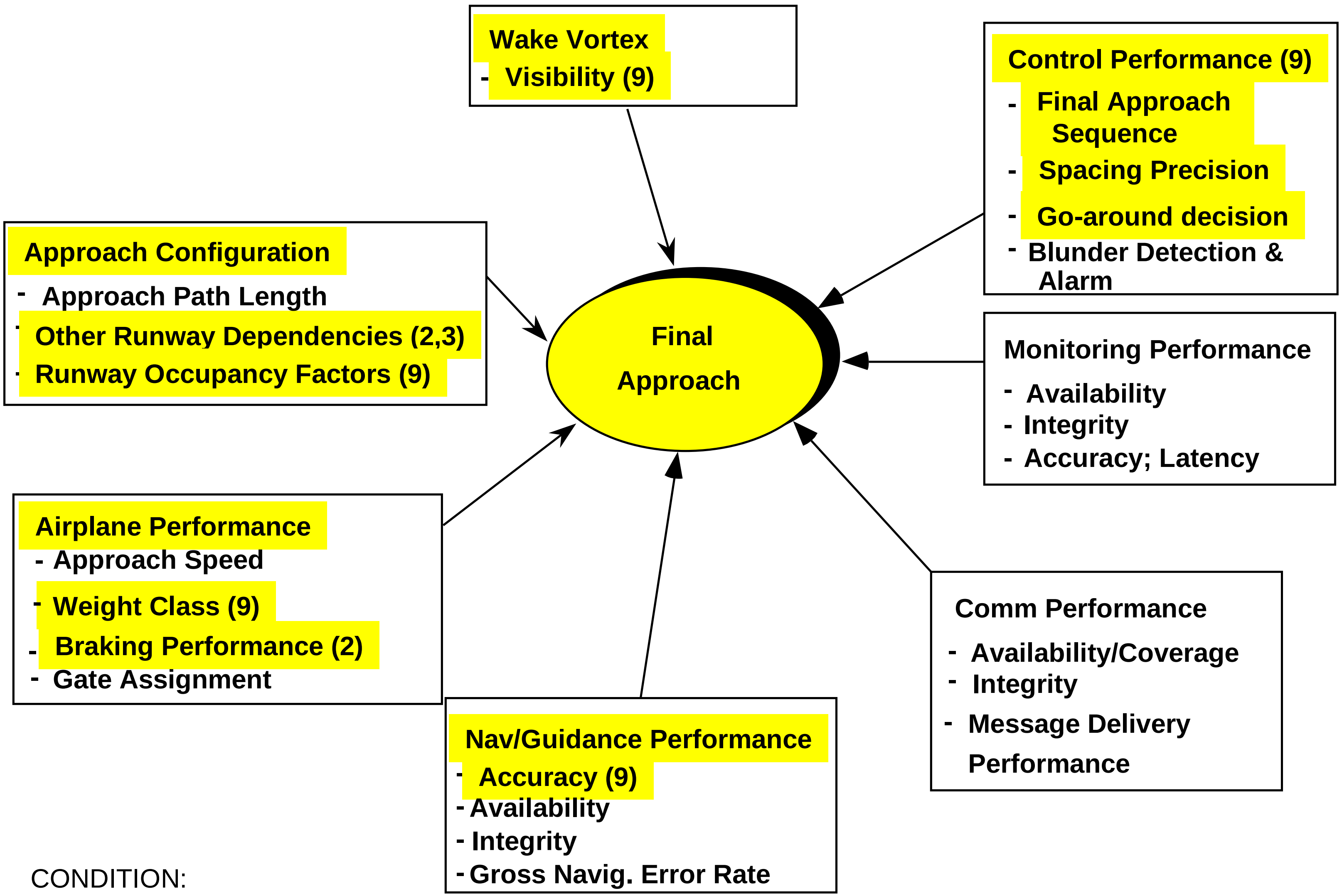
From the end of the STAR to the beginning of Final Approach.



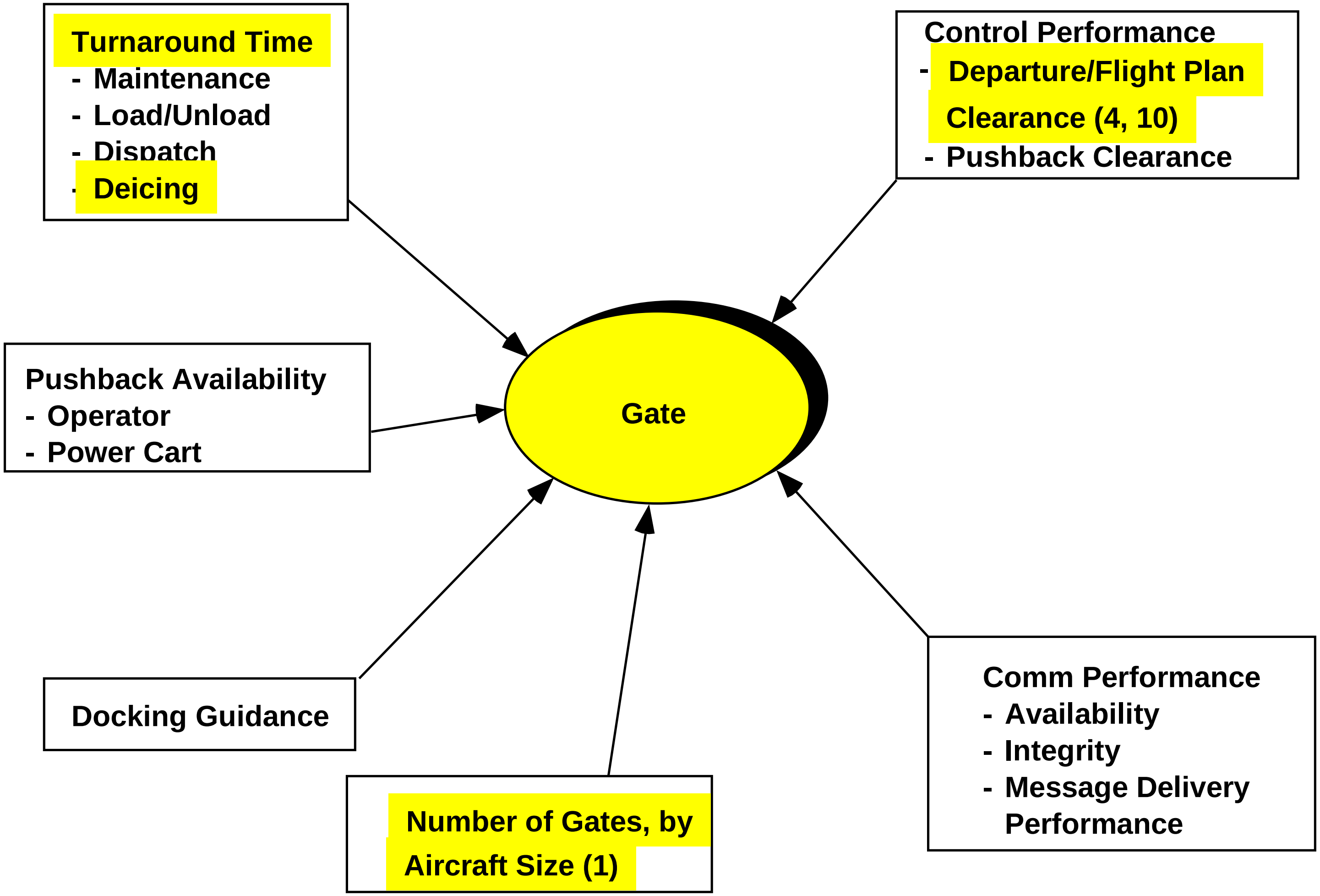
CONDITION:
LOCATION: O'Hare



CONDITION:
LOCATION: O'Hare



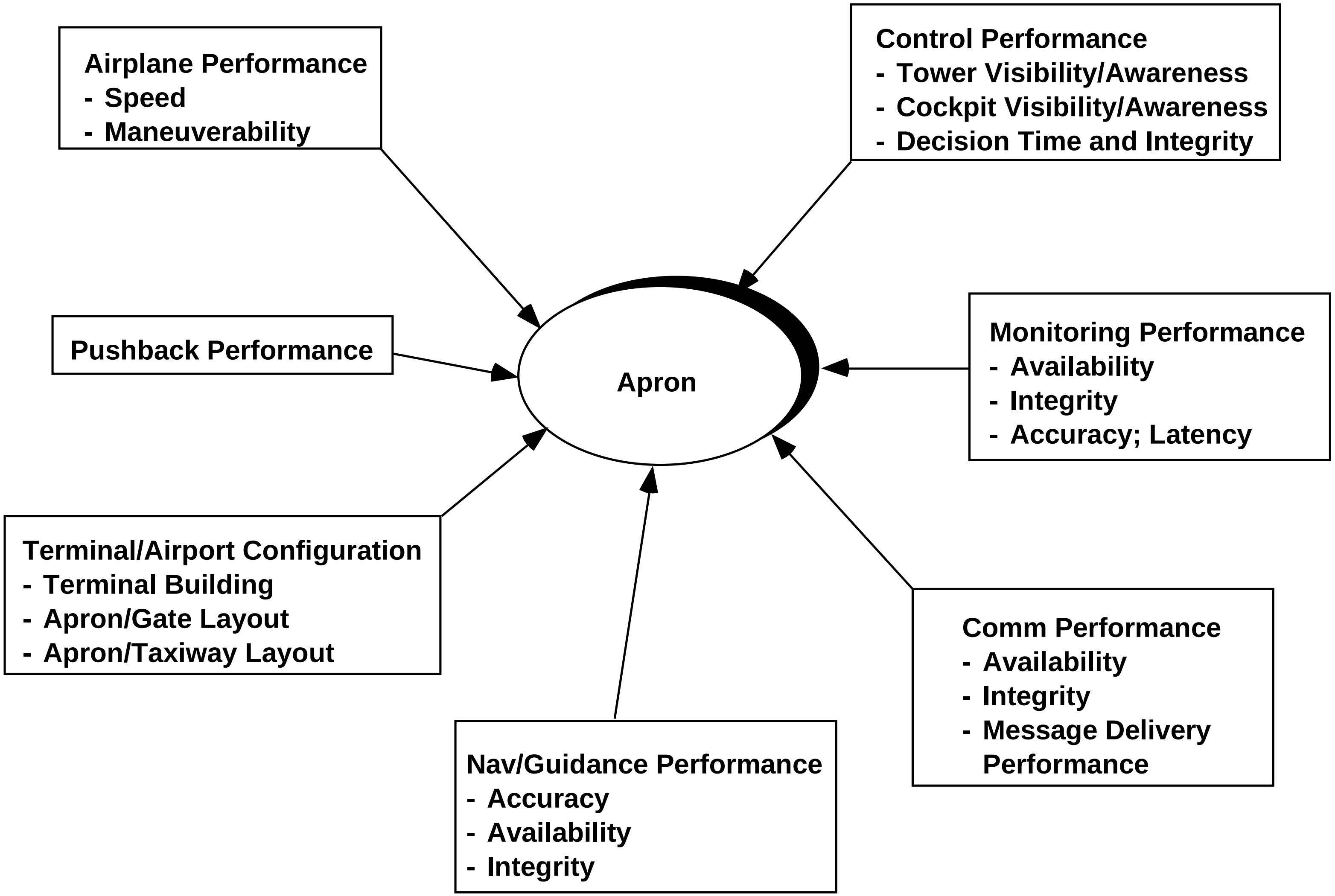
CONDITION:
LOCATION: O'Hare



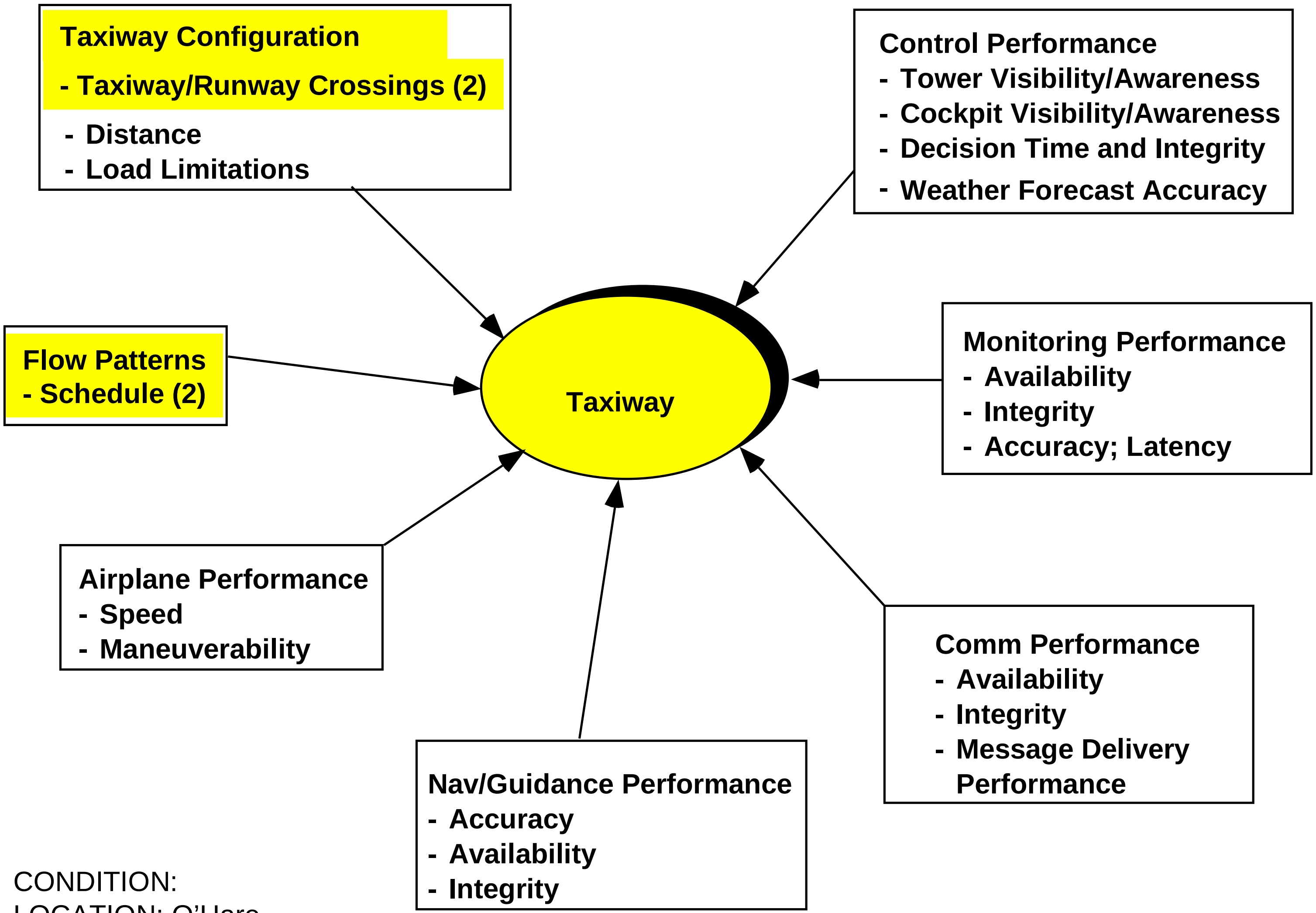
CONDITION:
LOCATION: O'Hare

Definition

End of taxiway to gate.



CONDITION:
LOCATION:



CONDITION:
LOCATION: O'Hare

D. Appendix D

A Description of ATM Operations in the Chicago Area
By Robert Simpson

Introduction

As part of studies for NASA by Volpe TSC, Boeing, LMI, and Flight Transportation Associates, a recent visit was made to the ARTCC, TRACON, and O'Hare Tower to review the current operations for air traffic in the Chicago region. This appendix is an attempt to document a written description of these operations and their interrelationships, and thus to provide a basis for developing a more complete understanding. It is an analytical description with various comments and observation added since it will be used by the PD study team for uncovering more detailed questions and problems, and for directing further investigations. This description is organized into two sections describing:

1) the 'inbound traffic flow' into O'Hare; and
2) the 'outbound traffic flow' from O'Hare.

These two flows were described by controllers during our visit as dominating traffic management considerations in the TRACON and ARTCC of the Chicago region; but other traffic flows (e.g., inbound and outbound to other Chicago airports, and overflights, GA activity, etc.,) will be mentioned as they impinge on these O'Hare flows.

1A - Inbound Flow - Tower

There are about a dozen main operating configurations for the runways at O'Hare with their availability at any point in time subject to wind strength and direction, visibility, and ceiling, etc. A runway configuration is defined by the assignment of takeoff and landing operations of a type of aircraft (e.g., prop, or jet). Given the expected mix of aircraft using each runway, each configuration has a known capacity rate for landings (and another for takeoffs, and another for combined operations - takeoffs and landings). Since the runways are mainly independent at O'Hare, the sum of the constituent runway landing capacities is used to set the AAR, Airport Acceptance Rate, for the runway configuration currently in use. Following usual practice, the AAR is expressed as an average hourly value and represents an upper limit on average hourly traffic throughput.

However, the ATM managers also expressed runway landing capacities in quarter hour periods, presumably to match the shorter term rushes in demand at O'Hare. To simplify the discussion, they classified the various runway configurations into: 'duals' where the AAR (Airport Acceptance Rate) was set at 80 landings per hour (or 20 per quarter); 'duals with a third runway for props' where the AAR was set at 90 landings per hour; and 'triples' where the AAR was set at 100 landings per hour. There was mention also of the possibility of a configuration with four landing runways and an AAR of 126 per hour, accompanied by the statement that they didn't often count on achieving this high value.

These AAR values are much less than the more detailed capacity estimates for the specific runway configurations given in the LMI report (Hemm, et al). Since these are the AAR values that they declare for flow management purposes, they will (and should) be set lower than the runway capacity values since: 1) there may be bottlenecks (i.e., capacity limits) elsewhere on the arrival flows (as discussed later); and since 2), they are wise enough, as managers, to plan on having a small capacity margin to ensure that the ATM elements handling arrivals can perform continuously at the declared AAR level (this allows them to recover from short term upsets, etc.). Still, these AAR values declared for O'Hare are extremely high compared to any other airport (except DFW).

However, two traffic problems at O'Hare are: 1) due to the arrival banks currently scheduled for airlines at O'Hare, peak arrival rates substantially exceed even such high AAR values when 15 minute periods are examined; and 2) the arrival traffic is directionally concentrated during those periods onto eastern or western ATM elements.

This short term peaking is shown in Figure 1 below. Note that at 1945-2000 local time there is a scheduled demand of 60 aircraft in 15 minutes, equivalent to a demand for 240 landings per hour! The actual number of landings in that period was 25, which agrees with an AAR of 100 per hour.

This short term, directional peaking in makes it difficult to use all the available arrival capacity since it would require sending arrival aircraft to the other side of the airport, and it probably explains the ATM manager's comment about not being able to count on using the peak capacities.

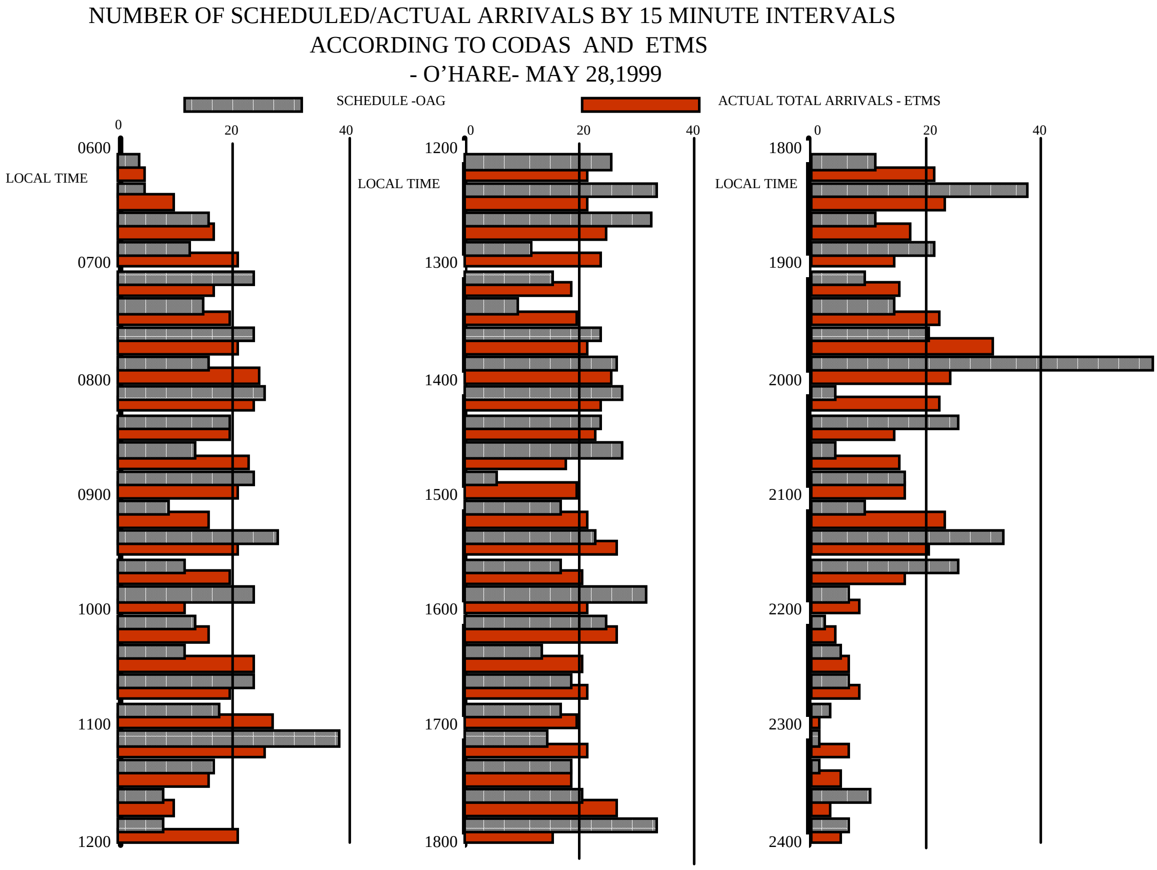


Figure 1 - Scheduled and Actual Arrivals at O'Hare, May 28, 1999

In choosing runway configurations to operate at various times throughout the day, the ATM managers stated that there is a preference to isolating types of operations on a single runway (i.e., assign either takeoffs or landings to the runway, but not both; and to isolate by type of aircraft, i.e., prop or jet). This seems quite easy to accomplish at O'Hare, and since it avoids various inter-relationships in handling aircraft, it simplifies the assignment of portions of the Tower operations to individual controllers. In this context, the statement was made that the takeoff rates were usually not limited by the available runways, nor by taxiway capacities, but rather by restrictions from departure and en route airspace operations.

The ATM managers also said that, unlike some other airports, there was no dominant runway configuration, with the highest usage runway configuration being used around 30% of the year. They said there was an approved noise management plan to rotate the runways every 8 hours (although that statement was made by Center personnel who didn't seem too sure of the number or the current status of this plan). It appears easy to change runways (especially to accommodate the next arrival bank from the opposite direction) and observations of O'Hare operations using the TSD (Traffic Situation Display) on various days during this study indicated frequent changes normally occurred throughout the day. This seems to negate a real impact of the noise constraint on O'Hare.

At other airports, the bottleneck, or limit on the maximum landing throughput rate, is usually established by TRACON activities as controllers merge and space aircraft just outside the outer markers of the final approach to each runway - but that usual situation seems to be in question at O'Hare. The ATM managers briefly mentioned CAP and CTAP projects aimed at increasing the arrival flow rates into the TRACON which seem to indicate that the flow rates at the entry fixes are thought to be a capacity problem. This will be discussed later in the section on TRACON activities.

The Tower was said to be monitoring the arrival spacing inside the outer marker after arrivals have been handed off to them. They described the Tower as "compensating" for "compression" as aircraft reduced their airspeeds from the typical 160-170 knot indicated airspeeds at the outer marker to the typical 130-140 knot indicated airspeeds before landing. Note that this typical speed reduction will reduce a 3nm separation to 2.5 nm. The actual separations outside the outer marker were often observed on the TSD during a rush to be greater than 3 nm (of the order of 5-7nm). The TSD has one minute updates from the ASR-9 at O'Hare.

As usual, while monitoring the landing arrivals, visually or with radar, the Tower is reduced to controlling only the release of takeoffs from the runways; i.e., it does not 'control' the landing times. Those have been established by the Final Approach controllers in the TRACON. Based on their expectations for landing operations, the Tower controllers do issue multiple, simultaneous landing clearances to arriving aircraft as they arrive at the outer marker. They also indicated that the loss of the ability to conduct visual approaches (and the resulting loss of landing capacity) was not a serious capacity impact at O'Hare. It would appear that the Terminal Area traffic flows are too well organized and too busy, and all of their runways are usually independently available, even in poor visibility. Other airports often bring secondary runways into use in good/marginal visibility by using approaches to runways out of use as a landing runway to become visual, and have aircraft circling visually to land on other runways, or stepping over to close parallels, etc. However, it would seem to be important from the LMI report, which somehow computes higher runway capacities for the same configuration under better visibility conditions.

The ATM managers said that the Tower, TRACON, and Center were usually very efficient in coordinating a change of runways. They said they usually had some expectation of the need for a change before it happened; but that if surprised, they could accomplish a change on short notice - an event that might happen perhaps once per month. They did admit that there might be holding at one of more entry fixes during the change, and indicated that they usually could control the release from the fix so that the new runways were started up just as the old ones ceased operations. They made the point that since the daily mode of operations at O'Hare was a series of east-west arrival surges they would, if possible, time the runway changes to occur with the end of one of the surges, or the beginning of a takeoff surge.

It was mentioned by Tower personnel that while there was no taxiway capacity problem in getting aircraft to the departure runways, there could be delays to both arriving and departing aircraft if the departure bank was late in departing, and/or if the arrival surge started before the departure surge had ended. This occurs for runway configurations where arrival and departure operations are not independent, causing the Tower to ask for increased landing spacings to get the departures out. The increased landing spacings to allow departure capacity will delay arrivals by increasing downwind legs in the Terminal Area; and if prolonged, may cause impacts in the en route areas such as temporary holding at the entry fixes, or, slower speeds further out on the arrival routes. We would need information on what spacings the Tower asked for (and for how long) to assess any delay impact of such a situation. Hopefully, that would be in the Tower and TRACON logs.

1B - Inbound Flow - TRACON

The TRACON always accepts the inbound traffic flows destined for O'Hare from the ARTCC at four Arrival Fixes (or 'Corner Posts') called KUBBS, BEARZ, PLANO, and KRENA which are on the periphery of the Class B airspace of the Terminal Area. These are the end points for the five STARs (Standard Terminal Arrival Routes) defined for O'Hare as described in the next section. But because of the directionality of the arrival surges throughout the day, there are usually only two Arrival Fixes busy at a given time. The other two are called the 'OFF' fixes, and continue to have traffic from non-hubbing, non-scheduled, and international flights, and to have short haul flights (dominated by regional airlines and turboprop aircraft) from nearby cities redirected to them (see discussion below). The TRACON has other Arrival Fixes for Midway airport and other General Aviation airports whose entry and patterns of flight inside the TRACON are segregated horizontally and vertically from the O'Hare traffic flows.

The TRACON controllers said that the normal strategy is to direct all the major arrival flow which passes through one entry fix during an 'arrival rush' to a single runway. During and arrival rush from the east, KUBBS and BEARZ are busy, and each feeds its assigned runway: and when the rush is from the west, PLANO and KRENA are busy feeding their arrival flows to their runways. So there are two busy entry fixes and two busy runways dedicated to handling the east/west directional arrival rushes (which usually consist predominantly of aircraft from one airline).

However, when a third or fourth runway is available, they will handle non-bank traffic from the other direction through the OFF arrival fixes, and usually these fixes/runways have spare arrival capacity. Thus, there is a relief valve for errors in en route metering of the arrival flows at the busy fixes by sending them through the Terminal area around to another runway. This is called 'flipping' selected aircraft as they enter at the busy fixes and requires coordinating this move with the other radar controllers within the TRACON.

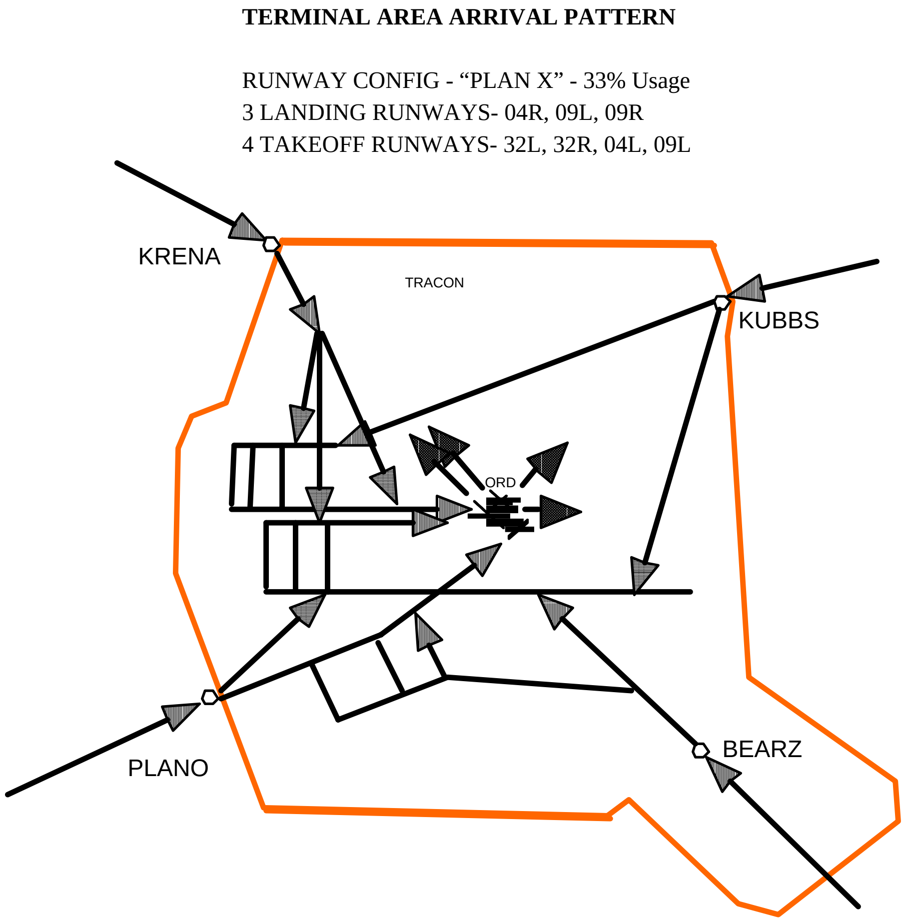


Figure 2. Typical Terminal Area Patterns - O’Hare

Also, because the longer haul directional arrival traffic flows have been subjected to in-trail spacings in the metering processes of the STARs for the last 200-300 miles (as explained later), the short haul traffic climbing out from cities nearby to O'Hare and on the same side as the directional surge is difficult to merge into the already established, descending, arrival flow. While remaining within Center airspace, such local traffic may be rerouted around to the OFF fixes.

The ATM managers stated that the ARTCC will normally deliver arriving traffic at the entry fix spaced at 7nm at a speed of 250 knots, and will usually hand over arrivals at altitudes above 10,000 feet. The 7-nm is the nominal 5-nm required for longitudinal radar separation in Center airspace plus a 2-nm margin to avoid random violations of the radar separation requirement. When only two runways are available, or when AAR is low, the TRACON may ask for greater spacings at the Arrival Fixes. It was explained that this may cause the ARTCC to slow aircraft down; or 'spin' (put aircraft into a 360 turn); or to initiate holding at the several holding points along the arrival routes; or to initiate holding at the OFF entry fixes to allow directional aircraft to be flipped inside the terminal airspace; or to increase the enroute miles-in-trail spacings along the preferred arrival routes; or all of the above. The ATM managers volunteered the point that there is always a beginning time and an ending time for such requests, indicating some sensitivity on this point.

In the absence of winds, this 7-nm spacing and 250 knot speed gives an average throughput rate at a single Arrival Fix of 36 per hour which matches the typical IFR final approach capacity of the assigned single runway (35 per hour assuming approach ground speeds of 120-140 knots and a typical mixture of aircraft in the Small, Large, and Heavy classes). However, it would be below the IFR approach capacity rate for a homogeneous set of arrivals (say all large aircraft) spaced at 2.5 to 3nm which would be 40 to 45 per hour. Because of the flipping and back-door arrivals of small aircraft, the mix headed towards a given runway during a rush often seems very homogeneous consisting mostly of large aircraft, although O'Hare does have rushes when a spaced stream of several Trans-Atlantic arrivals of the heavy class must be inserted. Since the runway approach capacity and Arrival Fix capacity are so close in value, it will be necessary to examine the mix of aircraft passing through each busy fix within a rush to determine whether the Arrival Fixes are limiting the arrival flow to its associated runway.

For the two busy fixes, the total arrival throughput rate into the TRACON is only 72 per hour to handle the directional arrival rush, which would seem to be just able to keep the two associated landing runways working at capacity if there is the usual mix of landing aircraft in the rush. While the AAR for the complete airport may be declared at 100 aircraft per hour based on the runway approach capacities, the capacity to handle the directional rush is limited to a value around 72. This situation seems to explain why the ATM managers are looking to increase the flow rates provided by the ARTCC at the Arrival fixes in their CAPS and CTAP projects. These projects were described as examining the use of lateral or altitude separation in the flow over the Arrival Fixes rather than just longitudinal separation. But note that if increases were actually achieved for flow rates at the Arrival Fixes, the TRACON would then be doing a lot more flipping inside its airspace to make use of the third and fourth runways.

It is important to determine exactly where there is a limit (or bottleneck) on the landing flow rates - this is not a simple determination when there are time-varying rates of arrival and capacity.

Inside the TRACON airspace, aircraft are radar-vectored from the entry fix to the outer marker of its runway along typical (but not fixed) patterns as shown for one of the major runway configurations in Figure 2. The radar approach controllers use the turns in these patterns to adjust spacings, and reduce aircraft altitudes in discrete steps after reaching certain 'dump' areas. They also make ad-hoc use of speed control to get the desired spacings. Apparently there is no regular point for the speed reductions at O'Hare as at other airports. In the terminal area, speeds are often reduced from 250 knots to (say) 210 knots to help in the merging of arrival traffic at some point in the terminal area, and then again to a common arrival airspeed of (say) 170 knots to be maintained in the final, spaced landing lineup that is established on the runway centerline beyond the outer marker. At most major US airports, the Final Approach radar controllers use a substantial speed reduction to a common indicated airspeed on the final centerline as final control in accurately achieving the desired spacings. Essentially, they drive arrivals up to the end of this landing lineup and cut their speed by 30-40 knots (e.g., from 210 knots to 170 knots) when aircraft reach the desired 3, 4, or 5-nm approach spacing for IFR just beyond the outer marker of the ILS. At O'Hare, the ATM managers described a normal length of this lineup on the centerline as being 10-15 nm, or 5-6 aircraft. It was observed on the TSD to reach 20 nm on occasion, and this situation might be accompanied by switches in the approach sequence achieved by extending the downwind legs of certain aircraft to put them behind later arrivals for landing.

Center personnel said they monitored the length of these final approach lineups on their radar to see when the arrival flows might need to be slowed up, and intimated that they might act before the TRACON asked for a slowup. This information feedback is common at many major airports - the arrival controllers and supervisors in the Center are able to meter their arrival flows by monitoring the length of the final lineups on their radar, and make small slowdowns to the arrival flows without coordinating with TRACON personnel.

In the event of a missed approach, ATM managers said the Tower usually returns the aircraft to the TRACON within a few miles at 4000 feet, and since the initial missed approach paths are compatible (and similar to) the departure paths currently in effect, this is easy to accomplish. Tower managers said that if a missed approach aircraft announced beyond 2 miles out it would be easy to handle. Any problems are with 'balked landings' since their unexpected nature requires faster coordination with the TRACON. Such aircraft are usually returned to the arrival flow while remaining within the TRACON airspace, but occasionally may go back to the ARTCC. A rough rule of thumb was quoted to the effect that the lineup at the outer marker got 4nm longer when a missed approach was inserted.

The TRACON and Center managers said that many pilots are currently refusing to accept LAHSO clearances, and that this has greatly reduced the number of runway configurations that can now be used at O'Hare. Given the arrival vectoring described above, the LAHSO acceptance/non-acceptance must be established early by the TRACON as aircraft arrive at the entry fix. A late refusal may prevent flipping that particular aircraft which could give relief to a directional arrival flow, or may cause it to be flipped to an acceptable runway.

TRACON managers mentioned the impact of 'lake effect' winds, which could cause quite different wind directions at some low altitude in the TRACON airspace. These may suddenly occur during the afternoon and disappear in the evening, although they said that they have changed as much as three times in one day! If these wind shears are strong, they could affect the accuracy of spacing aircraft on final approach by controllers, and supposedly cause a conservative behavior by controllers in applying greater margins to ensure safe separations. They could also cause unwanted and sudden changes of runways at awkward times.

These managers confirmed that the ARTCC was responsible for holding aircraft in its airspace outside the terminal area; i.e., the TRACON did not do holding; and that under holding, the TRACON would continue to simply specify a value for the desired mile-in-trail at the Arrival Fix, leaving the job of achieving this spacing out of the holding stack(s) to the Center controllers. The result is that the TRACON doesn't worry about holding, and the arrival flow into the TRACON airspace should remain a continuous stream of spaced traffic whether holding is occurring or not. The ARTCC must be efficient in handling the holding stacks to maintain the quality of the landing stream. There are 2-3 (or more) stacks available along the last 200 miles of each STAR before its Arrival Fix, and there is a high workload for en route controllers along the STAR in keeping the flow well spaced if it is going through the sequential stacks. The ATM managers seemed to say that if the TRACON cleared its traffic problems and asked for higher arrival rates, then the ARTCC could have a delay in getting the arrival rates up (but this may have been just for the case when holding was in effect).

The short term responses by Tower, TRACON, and ARTCC to sudden changes in the AAR should be examined.

The ATM managers indicated that Midway traffic patterns were segregated from O'Hare operations using two STARs of its own and different Arrival Fixes. As a result, there was minimal interference between the arrival flows of O’Hare and Midway. But there was interference in the O’Hare departure flows when runway 13C was in use at Midway for landings. Then, there were times that departure traffic at O'Hare might have to be slowed or stopped to allow some Midway arrivals, and vice versa. While the TRACON airspace has been structured to achieve this segregation, there are always costs in such restructuring, and it is likely that Midway operations suffer some penalties in terms of longer and lower paths in its arrival or departure paths. Currently, operational activity at Midway is growing faster (5-7%) than at O'Hare (2-3%) so that these costs may become more important in future years.

The costs of segregating arrival and departure flows for Midway from O'Hare flows should be examined, and are a factor in designing new procedures for the Chicago area.

TRACON personnel made three or four references (Oshkosh, Pullman, and CTAP project) to the limited coverage of their two ASR-9 radars, and mentioned attempts to get more extensive and redundant radar coverage so as to allow 3 nm separations over a wider area. They must perceive some benefits to this in designing new airspace procedures in the CAP and CTAP projects.

1C - Inbound Flow - ARTCCs

STARs for O'Hare in Chicago Center

As shown in Figure 3, there are five STARs which feed the descending O'Hare traffic into the TRACON: namely, 1) PULLMAN for the north and northeast arrivals from North Atlantic and Canada, and origin points in Boston and New York Centers; 2, 3) KNOX and KOKOMA for the south and southeast arrivals via Indianapolis and Cleveland Centers; 4) BRADFORD for the south and southwest arrivals via Kansas City Center; and 5) JANESVILLE for the arrivals from the west and northwest via Minneapolis Center. STARs are the current US method by which certain sectors within one ARTCC (in this case, Chicago Center) are organized to work together in providing a metered arrival flow into a TRACON.

STARs, and STAR Transitions into ORD

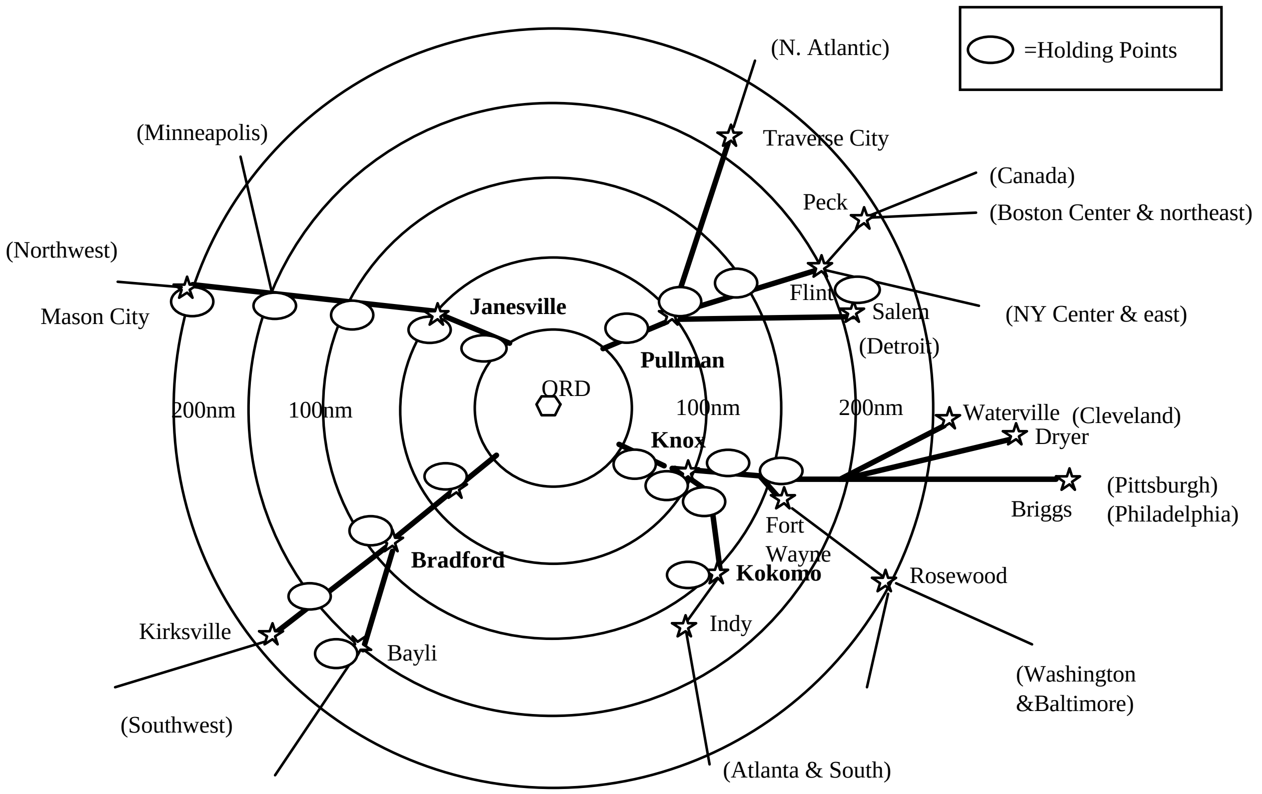


Figure 3 - STARs into Chicago O'Hare

The STARs all have various merging points during descent as arrival flows from different directions join the STAR along transition routes. These points are distributed among sectors to ease the merging problems and may be adjusted in the longer term by ATM managers as traffic flows change in volume. For example, for the Pullman STAR from the northeast, the traffic flows from eastern Canada and Boston Center are merged at Peck VOR, and are then merged with the arrival flow originating from points in New York Center at Flint VOR (this merging is actually being done by sectors in Cleveland Center); the traffic from Detroit and Grand Rapids are sent directly to Pullman since they are climbing under an established flow on the STAR; and the Polar North Atlantic flows arrive from Canada at very high altitude and 80 mile, 10 minute, same-Mach/speed, procedural spacings over Sault Ste. Marie into Minneapolis Center and transition via Traverse City, Michigan, descending directly into the STAR at Pullman.

Figure 3 also shows the published Holding Stacks along each STAR which will be used when there is a stoppage at O'Hare. For example, there are four along the Pullman STAR with the earliest just beyond Flint, at high altitudes in the upper airspace, and more than 200 nm from O'Hare. In the event of an O'Hare closure, the traffic flow along the STAR is collected into them as in-trail arriving aircraft reach the next one ahead. There are a total of 18 such STAR Stacks for O'Hare to accommodate the flows in the STARs. The normal value for aircraft simultaneously inbound to O'Hare today is 150-180, but not all of these are within the STAR and can be held in other Centers as explained below. Since there is a very large buffer airspace reserved around every holding stack (especially at high altitude), it is very desirable to minimize the number of Stacks, and distribute their locations since they can block considerable amounts of en route airspace. En route controllers in surrounding Centers need to know when they are forming so that their traffic crossing the STAR can be rerouted around them, and also when they will be emptied so that they can plan on using the airspace once again. Bad weather (severe turbulence, icing) may make it necessary to shift them to ad-hoc locations: but, of course, an area of such severe weather may also disrupt the operation of the STAR when pilots individually exercise their prerogative (for flight safety) to change altitudes/directions/speeds. This will be discussed later.

<u>Preferred Arrival Routes for O'Hare Enroute Traffic from Adjacent Centers</u>

There is a dynamic, or tactical, method of flow management called M-I-T (Miles-In Trail) being practiced by the Chicago Center (and its adjacent Centers) to manage the rate of arrivals into the STARs for O'Hare. It requires the establishment of a Preferred Arrival Route Structure (PARS) for traffic originating at airports which are major sources of O'Hare traffic. This arrival route structure is shown in Figure 4.

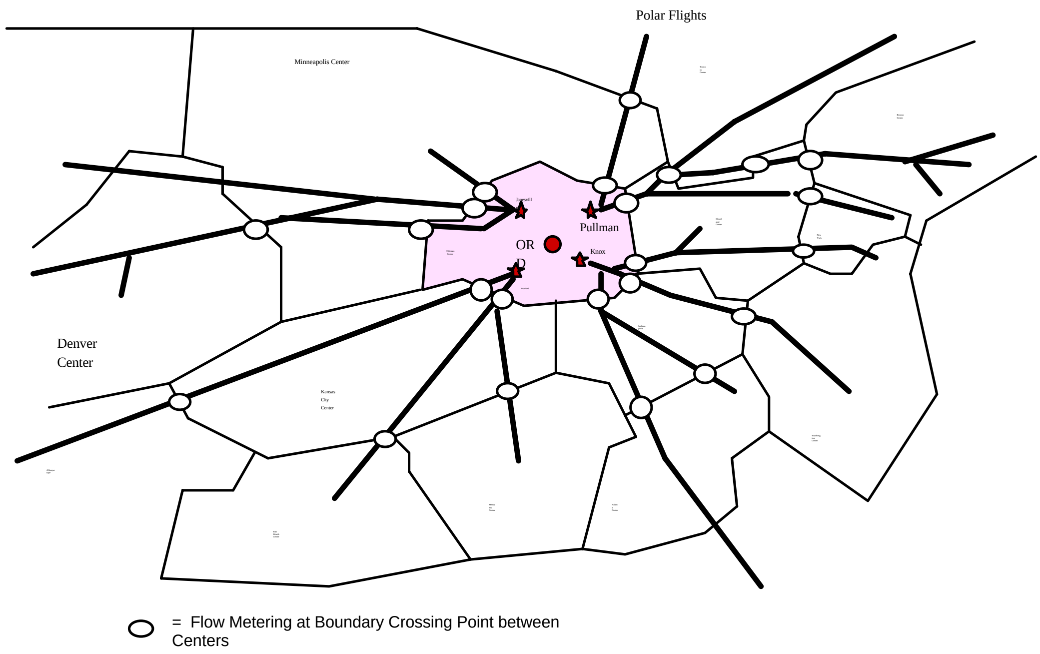


Figure 4 - Preferred Arrival Routes for O'Hare

The published set of one-way routings are used exclusively by traffic inbound to O'Hare, and these routings join together at merging points to form a root-like arrival route structure. The sectors in each Center along this arrival structure may have been freed from opposite direction traffic, and have the responsibility for executing the desired M-I-T values declared by downstream sectors throughout the day. The PARS is the current US method of organizing Centers to handle the flow management problems of traffic arriving into the STARs of a busy airport, similar to the organizational role that STARs play for sectors involved in feeding a TRACON within a Center.

Figure 4 shows the various handover points between Centers along the PARS for O'Hare. There are 23 such handover points in the O'Hare PARS where there is continuous coordination between Centers about M-I-T spacings for the inbound O'Hare flows.

For example, Boston Center will route all its traffic inbound to O'Hare so that it enters Cleveland Center through a single handover point near Syracuse, and may agree to provide M-I-T spacings of perhaps 30 nm or more, regardless of altitude. Cleveland Center does not care how that is accomplished by Boston Center, but all traffic must be handed over at Syracuse in a traffic stream. The Traffic Management Unit for Boston will work with its sectors, its TRACONs, and its airports to deliver on its commitment to Cleveland Center. Currently, for flights into hub airports, it is participating in a national program called the Departure Spacing Program (DSP). In this example, Cleveland Center hands these aircraft off to Toronto Center at Niagara Falls (which merges it with any O'Hare-bound traffic originating in the Toronto area), and then gets them back as the traffic flows back across Lake Huron into yet another Cleveland sector north of Detroit which contains the Peck VOR. In the area around the Flint VOR, two Cleveland sectors will merge this Boston/Canada traffic with all the O'Hare traffic from New York Center which has also flowed through Cleveland. Cleveland then hands over the combined traffic stream to Chicago Center and it becomes the major flow streaming into the Pullman STAR. During an arrival surge from the northeast, there is often a 200-300 nm long stream consisting of 20-30 aircraft, already regularly spaced at spacings which are gradually being reduced from 20 nm towards 10 nm as the altitude and speeds are reduced. No other traffic is in this stream, and all these arrivals are pointed at one runway (e.g., 27R) at O'Hare.

1D - The Impact of Severe Weather on the Inbound Flow Management Processes

Consider now what can happen to this distributed flow management process when there is a weather front with a long line of thunderstorms with reported severe turbulence between O'Hare and the east coast (say, across the full length of Cleveland Center with tops above 40,000 feet, and over 1000 miles in extent - which is not uncommon). At the same time, all departure airports and O'Hare are VMC and operating at full capacity. Since this line of bad weather reaches to cruising altitudes, the traffic inbound to O'Hare on the preferred route structure may now start requesting lateral, altitude, and speed deviations to avoid their perceived turbulence ahead as pilots exercise their prerogatives concerning flight safety to overrule controllers' desires. These deviations may destroy their M-I-T process (i.e., the gradual buildup of the spaced inbound flow to O'Hare coming from the east coast) preventing Chicago Center from receiving a spaced flow and from delivering the desired spaced flow streaming into Chicago TRACON at the desired arrival rates.

This weather disruption of the M-I-T processes results in increased workloads by various Cleveland/Chicago/Toronto sectors as they attempt to reconstruct the inbound flow. This causes slowdowns, en route vectoring, altitude changes, and ad hoc '360 spins' of O'Hare traffic as other sectors try to get the traffic back on the preferred routes and into the proper sectors; or perhaps it may cause the formation of holding stacks around Chicago (even though O'Hare is VMC). Chicago Center Flow Managers may then request a slow-down by increasing the M-I-T values for adjacent Centers, even though O'Hare and the East Coast airports are enjoying good weather. The problem is that the extensive, distributed M-I-T processes for ensuring that there are no surges in the arrival flow to the O'Hare runways have been destroyed (or wounded), and it is not easy to re-establish it. The distributed flow management system works if en route conditions are normal, but Flow Managers have difficulty telling themselves and the collection of controllers in other sectors and Centers what is best done when abnormal conditions prevail such as moving fronts with variable severity and location over time.

Apparently, there has been a predetermined set of alternate arrival structures (which has recently been called a 'playbook') which can attempt to handle severe weather by dynamically reconstructing the STARs and their preferred arrival routings as such weather moves through a STAR area. It would not seem to be an easy task to coordinate all the sectors and Centers involved when there is fast moving, or fast developing, weather. The ATCSCC (System Command Center) has now taken the responsibility for being the 'quarterback' with the 'playbook'.

Since this has all been organized since our visit to Chicago, we need to visit the Command Center to determine how this new Flow Management Activity will be handled, particularly for O’Hare. ATM is not a static operational system - it is constantly changing!

It would seem that we now have identified a weather situation where the bottleneck is definitely in the airspace as the Centers struggle to recover the desired spaced inbound flows along the preferred routes. The bottleneck now is not the final approaches or runways at O’Hare (which actually might be starved at times during this recovery from the passage of severe weather). But note that the basic purpose of the PARS and STARs is to meter the arrival flow to feed the TRACON a flow which matches the approach capacities, and their existence is based on the assumption that they will be the bottleneck capacities.

1E - The View from a User's Perspective

This discussion of the inbound flow for O'Hare concludes by summarizing what this current arrival process looks like from the aircraft operator's viewpoint. For an inbound O'Hare trip, the pilot must flight-plan along a preferred routing, and may be subject to departure delays imposed by the local TRACON/Center to achieve departure spacings or an exact departure time. Once airborne, the O'Hare-bound aircraft may be vectored for traffic spacing to achieve a certain M-I-T spacing from other O'Hare traffic (e.g., "turn 90 degrees right to achieve 20 nm spacing on company traffic 8 nm ahead"). Or they may be subject to airspeed controls (both speedups and speed downs - "reduce airspeed now to 290 knots", "reduce altitude to FL290", "resume speed of 310 knots") as the en route controllers merge aircraft into a 300 mile-long stream to achieve the M-I-T spacing values currently imposed on them. For the last hour into O'Hare, the arriving aircraft will be operating at gradually reducing airspeeds and altitudes as it follows the same aircraft ahead all the way to the runway.

It is hard for many people to realize (or believe!) that the root cause of these actions hundreds of miles from O'Hare is the AAR that is declared by the O'Hare Tower and TRACON. And, if they do understand it, perhaps difficult to accept that these distributed actions can result in an effective use of the AAR. While it seems to work most of the time, there can be inefficiencies with this distributed decision-making, M-I-T Flow Management process. Remember that the root cause is not in the en route airspace where these M-I-T actions actually take place, - there is no en route traffic problem, or lack of en route capacity for all aircraft. Rather, the root problem is the real excesses of the scheduled landing rate over the total runway/approach landing rate during a short period during the arrival bank of one of the airlines, and ATC's desire to ensure protection from extreme arrival surges in such periods. ATM managers want real-time control over this congestion by controlling the arrival rates at the TRACON boundary - they are not going to leave it to chance!

2A - Outbound Flow - Tower

There are various Ramp Control Centers operated by airlines at O'Hare (e.g., UAL has at least four) where individual airlines control the various ramp activities (loading/unloading, refueling, catering, etc.) for their flights, and their pushback/arrival movements. It is not clear exactly what they are doing at O'Hare to initiate taxiing (different aircraft operators may be doing things differently). It would appear that when they are ready to pushback, the pilots (or airline Ramp Control?) will contact the control position in the Tower which handles both 'pushback clearances' and also delivers 'departure clearances. Due to possibility of CDTs (Controlled Departure Times) of a National Ground Delay Program or a ground stop, and also due to possible short-term taxiway congestion, these two clearances may be delayed. Ramp Control does not want aircraft arriving at the ramp exit and then being told they cannot exit the ramp area by Ground Control in the Tower, so some prior coordination is necessary.

The Departure Clearance can be delivered verbally directly to the pilots, but today there is often and automated message system for delivering a hard copy or digital version to the cockpit. Note that if the trip is being delayed, the details of its departure clearance may be changing. It should not be delivered until it is fairly certain that the takeoff is imminent, especially when the Center is dealing with M-I-T restrictions among departures from all airports and overhead flights (see later).

During winter operations, there is often a need for further coordination to release the aircraft for de-icing activities, and a need to have the Tower commit to getting the aircraft off the ground within 20 minutes of completing the de-icing. To honor this commitment, Tower personnel said they might slow down arrivals! De-icing can be done at the gates, but there are also de-icing spots on the larger holding pads out near the runways where aircraft may be sent during a National Ground Hold Program when long departure delays prevent them from remaining on the gates.

If the airline wants to vacate the gate, (moving to another gate or to the holding areas on the airfield to await later departure) someone will explain what is happening to the Tower and get approval to make this 'non-departure' taxi movement. With such approval, Ramp Control can then control the timing of all the pushbacks to avoid local congestion on the ramp and at exits from the ramp, and to avoid congestion with arrivals into the ramp which it does not control. As aircraft move toward the exit of the ramp, it appears that the pilots will then establish radio contact with Ground Control in the Tower to get taxi clearance.

There are three large holding pads at O'Hare, at the ends of runway 09R (about 6 aircraft?) and 27L (4 aircraft?), and a "SCENIC" pad out near the UAL maintenance area. Aircraft can be held there while other aircraft taxi past for takeoff, and the departure sequence can be changed (within limits) by releasing aircraft from their parked positions as desired. Aircraft may be held there for 2 hours or more awaiting a CDT with engines running (while meals are delivered and movies are showing above the roar of nearby takeoffs!). Near the UAL ramp, there is a 'Penalty Box' which can hold 2-3 arriving aircraft (no Heavies) for a short time awaiting gates. We didn't ask the Tower during our visit what they did when the prior departure bank was delayed so much that the next arrival bank started to arrive resulting in a very large number of aircraft waiting for gates. They can store them in the maintenance area, or on a taxiway or runway not in use.

The Tower managers said that there were overlapping banks (both arrival and departure) by United and American only about 3 times per day (i.e., 5 and 8 PM), but observations using the TSD would seem to show this happening much more often, but perhaps with only a partial overlap.

There are 'coded' taxi routes for departures published by O'Hare with a different color for each runway end and with the numbers indicating a start from various taxiway intersections near the ramps. This simplifies the issuance by radio of taxi instructions for pilots if they have their published codesheet out in the cockpit.

It is not clear how they assign aircraft to runways for departure, but they did say their strategy was to avoid crossing traffic in the airspace (not the taxiways?) which would give preference to certain runways depending on the direction of the destination. However, they also said that their strategy was to balance the workload in TRACON, which could conflict with the first strategy at times. Remember that their east-west directional hubbing places a departure rush going out directly against the inbound rush.

After takeoff, it looks like the Tower will hand off aircraft to the appropriate departure sector in the TRACON (there are three such sectors- see later) while aircraft are climbing to an initial altitude of 4-5000 feet. It is not clear what initial departure headings from the runway are commonly used. I expect it is the runway heading, but there was a comment about fanning (by 15 degrees or more) successive departures on the same or parallel runways to use a reduced 1 nm initial radar separation criteria.

If the runway is solely devoted to takeoffs, and this initial diverging technique is used, its demonstrated takeoff capacity is over 80 takeoffs per hour per runway, and O'Hare usually has two such runways. Such operations are sometimes called 'accelerated takeoffs where aircraft are cleared to the centerline and hold as the prior takeoff aircraft is released, and are cleared for takeoff as the prior aircraft lifts its nosewheel off the runway since this action commits it to the takeoff. But giving aircraft at such high rates to the departure sectors in the TRACON and Center for any prolonged time usually exceeds their capacity, so that some other airspace factor limits the use of accelerated takeoffs.

There are time or distance restrictions placed on the Tower for successive departures to the same destination when the Center has received M-I-T restrictions for that destination, presumably under the DSP as practiced at Chicago. They would make use of the holding pads at the runway ends to resequence and hold aircraft for such takeoff spacings; but note that they may not have all such aircraft assigned to the same runway which then requires some coordination between LOCAL controllers.

2B - Outbound Flow - TRACON Departure Sectors

There are three azimuthal departure sectors at Chicago fanning out from the O'Hare VOR (- a northeast sector 330 to 120 degrees, - a south sector from 120 to 220 degrees, and a west sector from 220 to 330 degrees). There are no SIDs with fixed departure patterns for either O'Hare or Midway so that these DEPARTURE positions always use radar vectoring and 'directs' to a departure fix to guide aircraft to the first en route navaid, perhaps using ad-hoc patterns and altitudes which avoid the arrival patterns. Before reaching the first en route navaid, aircraft will be handed off while climbing into the departure sector in Chicago Center. From observing the departure flows on the TSD, it seems unlikely that there is much vectoring done in the TRACON airspace to assist the Center in establishing outbound merging and in-trail spacing, and there is not much room or time to maneuver. Center personnel mentioned an incident where they were given four departures for Newark out of O'Hare and Midway which ended up flying side by side as they approached one of the eastern navaids (GIPER or KEELER) when M-I-T constraints from Cleveland Center were in effect on Newark aircraft.

2C - Outbound Flows - Center

Center personnel accept aircraft climbing out of the TRACON from whatever runways are in use at O'Hare and Midway, and the other airports. The runways in use apparently will affect the timing and altitude of arrivals, and thus the workload in different sectors of the Center - so they are interested in knowing about any changes in takeoff runways.

The Center personnel mentioned the slower speeds of the regional jets as a factor in handling the outbounds. The speeds in climb and the climb rates might be slower for some RJ aircraft, but we should check where this is true. Certainly, the turboprops are already different.

It was mentioned that the inability to predict climb profiles with any precision was a continuing problem for handling departure aircraft and I inferred that this means that more conservative practices are necessary. Whenever M-I-T constraints are in effect, they are in the position of trying to merge and space climbing aircraft whose horizontal and vertical speeds are changing with altitudes, changing winds, and changing temperatures (and subject to no constraints on selection of climb profiles by the pilots - in fact, they are without any knowledge of what the pilot may be intending in changes in climb profile).

Center personnel mentioned that there can be restrictions on TER (Terminal En Route) IFR flights at lower levels to the east of Chicago due to problems in handling arrivals and departures in that area during surges.

At the same time that the inbound flow into O'Hare is imposing M-I-T restrictions on certain inbound sectors in Chicago Center, there may also be M-I-T restrictions arising from other airports which are imposing restrictions on Chicago TRACON, and on other outbound sectors in Chicago Center which are on the preferred routes into those congested airports. For example, the AAR for Newark will be translated into M-I-T restrictions for all Newark traffic flowing into Cleveland Center from Chicago Center, and then back into sectors in the Chicago Center. It was stated that there can be as many as seven different airports simultaneously placing flow restrictions on certain sectors in Chicago Center when it is a bad day on the east coast. If this multiple restriction situation is placed on the same sector simultaneously, then it is difficult (if not impossible) for that sector controller to keep track and apply such a variety of restrictions between the pairs of successive aircraft bound for these several airports amongst all the sector traffic flowing through his/her sector.

It was also stated that there are times when Chicago Center will go into holding traffic destined for Newark at its western boundaries (specifically Davenport, Iowa!) in order to ease these complex flow management problems within the Center, and that they have been considering holding such traffic directly overhead O'Hare at high altitude!

It was pointed out that Chicago Center somehow belonged to a western group of Centers as determined by the System Command Center at Herndon, but is a coordinator with all of the eastern Centers. It is not clear what the implications of this statement might be.

Like other airports under an overhead M-I-T flow, the Tower at O'Hare (and presumably Midway) may be given 'time-windows' by Chicago Center for departures to the other congested airports (e.g., Newark) using a Departure Spacing Program. This assists the Center in fitting such aircraft in the overhead flow of Newark traffic from the west of O'Hare which already has (or will soon encounter) M-I-T restrictions; but also helps it establish the flow of originating Newark traffic departing from O'Hare, Midway, Milwaukee, Indianapolis, etc. These must flow from Chicago Center into Cleveland Center with M-I-T restrictions at the boundary.

It seems clear that Chicago Center (not the Tower or TRACON) has a problem in flow management for the flows into congested eastern airports when weather is bad along the east coast causing multiple M-I-T restrictions to be in effect. It must handle the overhead, high speed, high altitude, flows from the west; and at the same time, merge numerous climbing aircraft at slower and changing speeds from several airports in its region (as well as from adjacent regions) into those multiple overhead flows. An effective DSP for the Chicago region will involve a number of Centers, and will probably require some re-arrangement of arrival route structures and merging points in both Chicago and Cleveland Centers. Again, it should be noted that the reason for this problem in Chicago Center is the lack of runway/approach capacity (and, in some cases, airspace for radar vectoring in the terminal area) of the eastern airports - it is not the lack of airspace or en route capacity problems around Chicago. It is a certainly a current problem for Chicago Center, but its best solution may be found with changes in Cleveland Center or on the east coast, not by introducing new procedures or technology in the Chicago area.

3 Chicago Operations – Analysis and Constraints Assessment

A more detailed description of current ATM operations for the Chicago area wass given in sections 1 and 2 in this Appendix. A very brief and preliminary analysis will be provided in this section of only the inbound arrival traffic handling processes to provide an example of what is meant by Analysis and Constraint Assessment in the preliminary design process.

These Analysis and Constraints Assessment activities of the PD process are undertaken:

1) to document an understanding of the current ATM processes and performance:
2) to define operational problem areas with an adequate level of statistical detail; and
3) to describe and quantify the operational constraints on current ATM performance,
4) to explore the potential of new operational concepts for improving ATM performance.

<u>Preliminary Identification of Problem Areas for ATM in the Chicago Area</u>

Before we concentrate on the problems of the inbound flows to O'Hare, a more comprehensive (but not complete) listing of what appears to be some of the current problem areas for ATM operations in the Chicago area will be presented very briefly to remind us that some of these may interact with each other, e.g., solving inbound flow problems may affect outbound traffic handling. Each problem area needs more study effort than this project was able to provide, including their interactions. Further visits with ATM managers to be able to verify these problems and ask follow-up questions, further observation using the TSD over a wider set of weather and operating conditions is needed, and then a well-designed data gathering effort would be undertaken by the complete PDP process to document the severity and extent and inter-activity of these problems. The listing reflects our concentration on the O'Hare traffic flows, but Midway and the other airports would also be studied.

<u>Inbound Traffic Flow Problems</u>

1. It would appear that they are not making full use of the capacity of third and fourth runways at O'Hare during good wind/weather periods when they are available (about 40% of the year). Further study is needed of the potential shifting from one runway configuration to one of higher capacity that is available, and increased use of "flipping" and "back door" arrivals for directional flows during busy periods.

Constraint Identified: The directionality of arrival flow peaks makes it difficult to use third and fourth runways to their full potential even when they are available.

2. The peaking in the directionality of traffic, and peaking over short time periods (15 minutes) causes, at times, a short term traffic load on the two busy Arrival Fixes which is above their handling capacity. As a result, there are delays in the STARs and PARS as they work to avoid congestion over these fixes, and the regular, well-spaced steady flow which is achieved masks the overload and resulting delay problem at the Arrival Fix. It is very difficult to define and measure these "Fix" delays, and to determine whether or not they exceed what would have been incurred in the terminal area anyway.

Constraint Identified: Since the CENTER flows most of the traffic in a directional arrival rush over the two busy Arrival Fixes at 250 knots at similar altitudes and an average of 7 nm longitudinal spacings, the Fix output flow rates seem to be limited to about 36 aircraft per hour. The flow rates of O'Hare arrivals being fed into each STAR are predetermined by its fixed assignment into the PARS (Preferred Arrival Route Structure); and, with the usual day-to-day variations in traffic arrival patterns, the input flow rates to a particular STAR can easily exceed this value. Simultaneously, Arrival Fix flow capacity can be available at other Arrival Fixes.

3. The existence, or passage, of severe weather in the region of a STAR can disrupt its ability to deliver a regular, well-spaced flow into the TRACON.

Constraint Identified: The "miles-in-trail" method for metering a long (200-300 nm) stream of arrival flows cannot function reliably when there is severe weather/turbulence along the STAR. For safety of flight reasons, pilots/controllers may reroute some portion of the arrival streams in the STAR (or in the PARS which feeds it). The uncertainty in predicting the severity and the future location of this weather makes the planning, re-planning, and coordination for the reroutes very difficult.

4. There may be transient losses in STAR/PARS arrival throughput as runway configurations are changed to one of higher capacity (or after a temporary slowdown or stop), especially when holding stacks have been instituted along the STAR and PARS.

Constraint Identified: Once stacks have been formed in different sectors along the STAR/PARS, it is necessary to quickly coordinate the timing of releases of aircraft from these stacks. Pilots have difficulty in executing a timely exit from the stack after clearance.

5. There are only two, rather inefficient, east-west, STARs for Midway airport, and if it continues to grow faster than O'Hare, or if Midway starts to develop more north-south traffic, this arrival structure will become a source of arrival delay for Midway, it will create pressures for airspace adjustments that affect O'Hare arrival and departures.

Constraint Identified: The proximity of Midway and O'Hare airports makes the operation of multiple STAR arrival structures difficult as traffic volumes continue to grow.

<u>Outbound Traffic Flow Problems</u>

1. When there are several East Coast airports which are congested, and have placed m-i-t restrictions into their PARS, Chicago CENTER has problems with organizing its Handovers to Cleveland CENTER. It must merge climbing aircraft departing from originating airports in its region (at slower and accelerating speeds, at uncertain climb rates, and with changing windspeeds at higher altitudes) with the higher speed, higher altitude, overhead flow of cruising aircraft arriving from the west destined for these same several, congested airports. Some of the Chicago departures have not reached cruising altitude before reaching the Handover point, and high level holding in Chicago airspace is being imposed on some western arrivals.

Constraint Identified: This is a handling problem for Chicago CENTER currently, but the true source of the constraint is inadequate arrival capacity and terminal airspace for the congested eastern airports. For Chicago CENTER, the constraint is their ability to plan/coordinate the departing flows from various airports, and predict the climb trajectories/wind for departing traffic so that an efficient insertion of the departing traffic into the overhead flows can be accomplished.

<u>Preliminary Analysis and Constraint Assessment</u>

There are other problems that can be listed. All of these deserve further exploration and description in a full PDP effort. But we shall now select one problem area to give a preliminary and specific example of problem analysis and initial concept development for the ATM/ PDP process. Because they are inter-related, the example really deals with the first three problems mentioned for the inbound STAR flows. In particular, the discussion will concentrate on the problem of determining the constraints to maximum throughput performance of the inbound arrival flows to O'Hare.

It is clear from the interviews at Chicago and from the detailed description given in White Paper No. 2 that the primary focus in the handling of arrival traffic flows into O'Hare is on providing congestion management - it is vitally important to controllers and flow managers that real time control be in place to prevent congestion around the periphery of the Chicago terminal area in all situations, but especially for non-normal and unexpected situations. The prevention of congestion in a sector ensures an acceptable level of workload and a safe operating situation, which then ensures that the critical ATC function of separation assurance will be safely executed. Thus, considerations of Flow Management, probably based on experience with past congestion events, seems to have dominated the evolutionary design of the current arrival processes for Chicago.

It should be noted that the "Normal" situation for traffic at O'Hare is alternating arrival rushes from the east and then from the west, lasting about one hour; and that when the next arrival rush is starting (say from the west), there is departure rush from O'Hare climbing out in the opposite direction (say westbound) against that arrival flow. Today, the general pattern is two heavy inbound, descending arrival flows through the northern and southern Arrival Fixes on one side of O'Hare; and simultaneously, heavy flows along a small set of east or west climbing, departure streams between the two arrival flows. While these rushes do concentrate the traffic causing congestion on the east or west side of the airport, it is not true that there is no traffic operating on the other side of O'Hare during a rush - it is still reasonably busy with traffic from those airlines that are not "hubbing" at O'Hare. And there is always a reasonably busy southbound departure flow as well. The northern sector has light traffic, and northern arrivals are directed into the east or west STAR flows.

First we shall present a model aimed at creating a better understanding of the relationships between sequential processes in handling arrival traffic. While it is an analogy drawn from fluid flows, it shows that any analysis and problem identification must be based on a correct understanding of traffic flow relationships.

<u>An Analogy for the Overall Arrival Flow Handling Process - Cascaded Arrival Buckets Model</u>

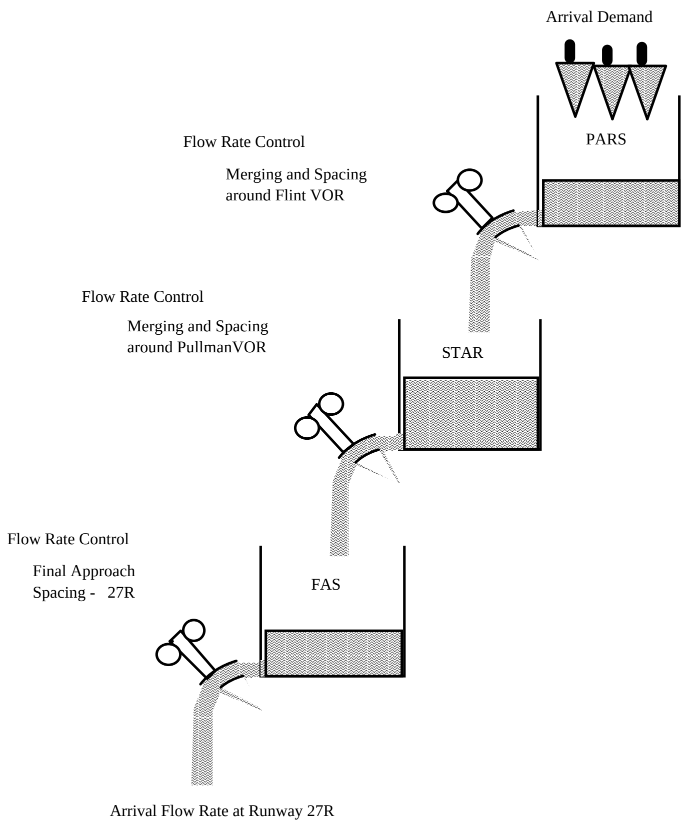
An attempt to summarize an explanation of the sequential processes of current arrival flow handling on the PARS and STARs is presented here using an analogy of a fluid flow through a series of cascaded buckets. This analogy demonstrates that it is important to have a correct basis for understanding the detailed traffic flow handling described in WP No. 2 in order to understand how the sequential arrival elements relate to each other, and to explain what the <u>true</u> goals of each element are in providing the input flow of traffic to the next element. Otherwise, a misguided set of ideas may exist about how to measure the performance of various elements in the sequential flow processing. For example, it was initially thought, in our preliminary analyses, that each process was trying to deliver a regular, uniformly spaced, flow to the next element.

That certainly was the situation in our Case Study efforts when an attempt was made using data from the ETMS to identify where the bottleneck element might be on the flow through the Pullman STAR inbound to ORD. The understanding that was provided by this CAB model turned out to be essential to studying and analyzing current O'Hare arrival traffic flows, and to re-defining our data analysis problems. Creating this simple model changed our ideas about what we were looking to measure.

The CAB (Cascaded Arrival Bucket) model is shown in Figure 1. The output flow rate of fluid from each bucket can be controlled with a spigot. The three buckets in Figure 1 are associated with the three main traffic handling processes described in WP No. 2: namely, 1) the enroute flow handling on the PARS (Preferred Arrival Route Structure) by CENTERs (and also other TRACONs, and originating TOWERs); 2) the descent flow handling in the STARs by sectors in Chicago CENTER; and 3) the approach handling and final spacing by for O'Hare landings by Chicago. The final output flow is the landing flow on a given runway at O'Hare. In reality, there may be multiple input flows into each bucket, or multiple buckets and multiple runways, but that complexity can be ignored here to make the basic observation about the flow relationships of these sequential elements.

The goals of the control process for each spigot are: 1) to keep the next bucket from becoming empty; and 2) to prevent the next bucket from overflowing. It can accomplish this by observing the level of the fluid in the next bucket and then increasing its output in a timely way when that level gets lower, and decreasing it when it is getting too full. It will only be able to guarantee that it can do this if: 1) the maximum output flow rate (called its capacity flow rate) of any spigot exceeds the capacity flow rate of the next spigot (assume that all the spigots can be shut off); and 2) it has an ample level of fluid available in its bucket (that depends on the performance of the preceding spigots, and the continued inflow of fluid arriving at the top bucket).

Cascaded Buckets Analogy for Arrival Traffic Flows



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Now suppose we are interested in measuring the maximum output rate for this system of buckets. We turn the final spigot to its full capacity flow rate and observe what happens. If there is sufficient level of fluid in the final bucket we get a steady flow of fluid at its capacity rate. As the level starts to decrease in the final bucket, the prior spigot reacts and increases it flow rate --

but here is the important observation about the control logic of that prior spigot - it is not necessary to try to match the capacity flow rate of the final spigot as quickly as possible since there is a reserve of fluid in the final bucket.

The next spigot can react slowly, building up its input flow over gradually, and perhaps only exceeding the capacity flow rate of the final spigot after some time - so that the level in the final bucket will decrease before it begins to increase. When that now increasing level reaches some suitable value (it might be higher than the original level, and now selected to be appropriate for the current final flow rate), the next spigot can safely reduce its flow rate below the capacity value for short periods if it wishes. Its short-term goal is not to match the flow rate of the final bucket instantly and continuously. There will be no degradation of the maximum final flow rate as long as it is able to keep the final bucket filled between some minimum level (it might not be zero) and a maximum desired level (to prevent overflow). That is its goal, and if we observe its flow rate we will see short term variations above and below the final flow rate.

This situation means that it is not possible to observe a below-capacity output flow rate in the upper spigots at any point in time, and then to reach a conclusion that it is the cause of a decreased final flow rate at a some subsequent time. Since the deviations are covered by the reserve of fluid present in the final bucket, any degradation or deviation in the final bucket is <u>independent</u> of any prior deviations in the upper spigots as long as the final bucket is kept filled. Those upper spigots will simply match the final flow rate over a longer period of time, i.e., as a longer-term average value. A measure of performance for the upper spigots could be the deviation of the level of the bucket it is filling around some desired level, but that measure is not really critical to the final flow capacity.

What happens if the capacity flow rate of the final bucket exceeds the capacity flow rate of the prior bucket? After some time, the level of the final bucket goes to zero, and the final flow rate will match the capacity of the prior spigot. To find the "bottleneck" spigot, we simply observe empty buckets in a longer-term steady state operation - the spigot now filling the last empty bucket is our bottleneck. But to do that, we need to ensure that there is a steady demand input flow over the longer term. If there are surges in the demand input flow, then there is a transient response in the flow rates of all spigots including the final one.

Consider a case where, starting from empty buckets and zero flows, there is a surge in the form of a step function in the demand input flows to the top bucket. At startup, the fluid flows rapidly through all the spigots at the input rate to reach the bottleneck spigot, whose bucket begins to fill. This filling to some level will cause the prior spigot to slow down; and indeed, all prior spigots may have also started to slow down when they were able to fill their buckets to various levels. This filling is equivalent to a "delay" in that bucket since a unit of fluid remains in that bucket for some period rather than proceeding immediately down to the bottleneck bucket. But it makes no difference to the final delay incurred by that unit - the delay has simply been moved to a higher bucket, and the total delay in getting through the system of buckets is identical under any transient variation of upper levels and upper spigot flows. Controlling the upper spigots will simply be transferring delay from one bucket to another, which can be done without incurring any extra (or unnecessary) delay as long as the bottleneck bucket is not allowed to become empty at any time. If there is an instant step reduction to zero demand, the top bucket will empty first, negating its ability to keep the next bucket filled, and so on down to the bottleneck bucket.

Now consider a step reduction in the input flow to a value less than the bottleneck capacity rather than a complete cessation of flow. After some time, the top bucket will empty, and its flow rate to the next bucket becomes the reduced input rate; and this repeats, cascading down to the bottleneck bucket which will finally empty, and then reduce its spigot output flow rate to the value of low input flow rate.

One can see that a varying demand rate will cause a very complex variation in the flow rates and bucket levels that depends on the dynamics of the control logic for all the spigots. Such a transient input situation makes it difficult to find the bottleneck spigot by simply observing the spigot flow rates. One must observe the maximum flow rate of all spigots over some longer period of time, and find what appears to be the minimum of the maximum values observed for all spigots.

This is a long (and perhaps indirect explanation) for why it has not been possible to gather data that shows that the STAR and PARS traffic handling processes at Chicago might be bottleneck elements for the inbound flow. Constraint identification and assessment in ATM, even with good data tools like the ETMS, will not be easy!

Maximum Observed Throughput Data

Note that, in relating the CAB analogy model to the air traffic processes, there is an issue in defining or measuring the level of traffic occupancy in each process (e.g., the level of fluid in each bucket). Consider the final approach process, or third bucket. If it were observed when it was operating in steady state well below its capacity rate and without delays, one might observe that its handling of an aircraft “normally” took 12 minutes as the time to reach touchdown after passing the Arrival Fix. If the capacity rate of the final approach process were 30 landings per hour (i.e., one landing every 2 minutes), this minimum occupancy time would indicate that there should be a “normal occupancy” in the final approach process of 6 aircraft whenever the final approach process was operating at its capacity rates. This would seem to indicate that observing less occupancy (say 5 aircraft) means that final approach process is “empty”, and that the landing flow rate will be (or soon be) less than its capacity rate. A difference in occupancy below 6 takes the pressure off the final approach controller to work at the capacity rate.

A difference in occupancy above 6 would be the level of “surplus “ aircraft in the final approach process; and would mean that the final approach process can and should be operating at its capacity rate. An increasing value of this surplus will put increasing pressure on the final approach controllers to perform at (or as close to the capacity flow rate as they can) since their “buckets” are filling up. If we are attempting to measure maximum throughput rates of a final approach process by observing its actual performance, the measurements should only be done when such surplus conditions prevail. In fact, we will probably see higher throughput rates (i.e., with values closer to the theoretical capacity rates) at higher values of surplus.

Note that, for any arrival sector, to define “surplus”, we have to first guess, or calculate, or estimate, the value for the capacity rate; and then estimate the value for “normal” occupancy before we can gather data on maximum observed throughput performance. Unfortunately, winds and flying speeds vary so that there is a statistical variation around the “normal” flying time; and consequently, also for the “normal” occupancy. However, maximum observed throughput performance data can be gathered initially only at higher estimates of occupancy values until the maximum flow rate and normal occupancy can be determined. Then data can be gathered at a lower level of occupancy.

Given these discussions, we can now give a preliminary example of the analysis involved in making an assessment of constraints on the inbound arrival flow rate at Chicago

A Critical Analysis of ATM Operations for Inbound O’Hare Traffic

1. - Analysis of Runway Operating Configurations

There are a dozen or more operating configurations for the runways at O’Hare, each with different operational capacity to handle takeoffs and landings. Typically, there are three independent landing runways in operation at O’Hare, and two or more other runways in use for takeoffs. There will be a set of controllers operating these several elements at any point in time. Usually, each landing runway can operate at throughput rate that is limited by the capacity rate of Final Approach operations that feed that runway (and not the runway capacity itself as defined by runway occupancy times). Similarly, each takeoff runway can usually only operate at throughput rates that are limited by the capacity rates of the initial Departure sectors that it feeds.

The value for Final Approach Capacity is a theoretical upper bound for the maximum observed landing throughput rates, and both these values have usually been expressed as an average hourly value (or as an equivalent hourly value for shorter periods). The theoretical capacity value is determined primarily by the IFR longitudinal radar separations that can be safely used on the final approach path to that runway in non-visual weather conditions (although they may still be in use during IFR operations in visual conditions). Since these IFR separations depend on the types of aircraft in each successive pair of the landing stream, it also depends on the actual, or expected, or average hourly mix of aircraft types using the runway. This value can vary throughout the day as the landing mix changes. Typical values for the non-visual Approach Capacity of a single landing runway in IMC conditions is 30-35 aircraft per hour depending on the aircraft mix. But if the types of aircraft using the runway are similar (say all Large jet transports), and if visual conditions exist where the pilots, not ATC controllers, are responsible for controlling separations after the Outer Marker of the ILS, typical Approach Capacity rates can theoretically be 40-45 landings per hour.

Since the three landing runways typically available at O’Hare usually operate independently of each other, the overall landing capacity rates are typically over 100 landings per hour, but can be potentially as high as 150 landings per hour (see Reference xxx) when a fourth landing runway is available. For purposes of congestion management, ATM managers declare the total Airport Acceptance Rate (AAR) for O’Hare to generally be 100 landings per hour if 3 landing runways are available, and 80 landings per hour if 2 landing runways are available. But in times of bad weather and poor runway configurations, AAR can be declared as low as 60 landings per hour. These last two values are well below current scheduled arrival rates for O’Hare (see WP No. 2), and cause severe delays and cancellation of flights if they are in effect for periods longer than a few hours of a day. The AAR value declared for O’Hare is a key value currently used to drive all the various Flow Management activities across the complete US ATC system that are designed to prevent congestion in the O’Hare inbound flows. At any point in the daytime hours, there is more than 160 airborne aircraft inbound to O’Hare.

The demand for landings at O’Hare is predominantly (99%) scheduled airline service. Currently, scheduled landing rates for O’Hare always exceed 60 per hour, and often exceed 80 per hour in 60-minute intervals throughout the day. But the equivalent hourly rate in a dozen or more 15 minute periods throughout the day exceeds 100 - peaking at 120. Given these traffic loadings and available landing capacities, the ATM managers at O’Hare are vitally interested in being able to control congestion in traffic about to arrive at the airport, especially if weather is about to lower the AAR value. It must be possible to safely and quickly stop some or all of the 160 or more aircraft already in the STARs and PARS whenever there is an unexpected closure of O’Hare, or one of its runways; and then to efficiently and easily resume the inbound flows. These considerations are important factors in establishing the operational practices for handling the inbound traffic flows for O’Hare, and help to explain the current form of special handling of the inbound traffic to O’Hare over extended distances by all elements of the US NAS.

2 - Analysis of Merging and Spacing Operations - Arrival Vectoring in the Chicago Terminal Area

The spacing of landing aircraft on the extended centerlines of O’Hare runways is accomplished by Final Approach radar controllers in Chicago TRACON, usually one for each landing runway. The TRACON accepts four spaced streams of aircraft from Chicago CENTER at four Arrival Fixes, or “Corner Posts” (KUBBS, BEARZ, PLANO, KRENA) that are about 45 nm from O’Hare. They then use radar vectoring to guide these aircraft towards the runway final approach area where they are merged to achieve a single stream of landing aircraft with the desired longitudinal spacings and a common airspeed on the extended runway centerline at distances of 10-20 nm from touchdown.

The radar vectoring controls the speed, altitude, and heading of these aircraft in to ensure separation while maximizing flow, and there are various patterns for the flexible paths that lead from the Arrival Fix to the runway for every runway operating configuration. The arrival and departure patterns organize the

Terminal Area so that teams of radar controllers can work independently in handling the inbound and outbound streams to and from O'Hare, Midway (and other airports). These patterns define geographic and altitude limitations on the airspace which must contain all paths of each pattern to ensure separations from other patterns. By controlling the path using magnetic headings and airspeeds (not track over the ground or groundspeeds), the radar controller for the final approach path attempts to achieve exactly the minimum IFR spacings allowed for each pair of landing aircraft. If this could be done perfectly, the observed throughput landing rate would equal the theoretical Approach Capacity Rate.

The actual observed landing throughput should always be less that this value, and it is always stated by ATM supervisors in a TRACON to be strongly dependent on the skills of the particular radar controller doing the approach spacing, but also on other factors such as weather, winds, pilot conformance, mix of landing traffic, etc. There is a statistical variation in the observed "maximum" throughput rates, and the data may even show a few values higher than the theoretical upper bound over some short period depending on: 1) how that bound is calculated; and 2) whether some final approach spacings have been violated, or relaxed to visual separations by pilots during the period. It is possible to establish a data gathering process for O'Hare using the TSD to record final approach spacings and groundspeeds (from radar tracking) just outside the Outer marker at busy times (i.e., following the above discussion based on the CAB model, whenever the "occupancy" exceeds some value).

The general practice at O'Hare is that all aircraft over a given Arrival Fix will land on the same runway, but there are exceptions: if the STAR process fails to provide sufficient metering over the Arrival Fix over short periods, some excess arrivals will be "flipped" and transferred to another approach controller and into the approach flow to another runway. If this can be foreseen (in some unknown way) by the enroute controllers, especially for very short haul traffic climbing out of nearby airports (e.g., Grand Rapids, Michigan) some traffic may be re-directed within CENTER airspace around to another, non-busy Arrival fix, which can be called the "back door". Both of these actions place delay on these particular arrivals, presumably for the benefit of reductions in delay for the traffic in the established flow over the Arrival Fix. Hopefully there is a net benefit. The occurrence of "flipping" and going around to the "back door" would have to be observed in studying arrival capacity problems at O'Hare, and means that all Arrival Fix /Runway operations must be observed simultaneously. One of the tools which might reduce arrival delays at O'Hare would be a decision support tool to assist ATM supervisors and Flow Managers in flipping and back door operations so that better use could be made of the third and fourth runways.

Normally, a well-metered flow will be handed off over the Arrival Fix, and vectored into the final approach operations for its runway. As long as the output capacity rate of the STAR process exceeds that of its Final Approach process, there is no capacity penalty - delays are simply being transferred to the STAR process from the Final Approach process, and no extra or unnecessary delays are being incurred. But, it seems that the approach process and STAR process at O'Hare may have similar values for capacity flow rates; and that, at times, the STAR may be limiting the landing throughput.

To gather data on traffic rates with the purpose of determining whether the STAR process is causing unnecessary delays from time to time requires data gathering on the flows through each of the STAR/runway combinations when it is busy. Because of the problems described above in the CAB model, it is a difficult data-gathering and analytical task involving a determination that the approach merging and spacing process has been allowed to become "empty" (or "starved" as it is sometimes called) for some short period.

3. - Analysis of Merging and Metering Operations in the STARs for O'Hare

Each of the four Corner Posts for O'Hare is the end of a STAR arrival process, roughly 200 nm in length, during which aircraft are slowed down and descended into the Terminal Area. Successive controllers along the STAR control the descents to lower altitudes and the indicated airspeeds, to accomplish the merging and metering of the various arrival traffic flows from the PARS (Preferred Arrival Route Structure). It is not critical if planned spacings are not exactly achieved after the merge between any single-pair of aircraft, as long as the double-pair and triple-pair distances for the sequence of aircraft that includes the single-pair have values which are close to their desired spacings. By controlling the reductions of indicated airspeed when the in-trail traffic pairs are at a common altitude and wind, controllers can get control over groundspeed to open and close gaps, thereby correcting spacing errors and maintaining desired spacings.

The strong deceleration of true airspeeds associated with jet aircraft descending into denser air makes it possible for controllers to open up and close the spacings between successive aircraft by controlling the points for a step-down to common intermediate altitudes, and points at which reduction to a common indicated airspeed will occur to maintain the desired spacing. Spacings are gradually reduced as various merging (or transition) points along the STAR are passed.

There are actually five published STARs for O'Hare: PULLMAN which feeds the northeast Corner Post, KUBBS; KNOX and KOKOMO STARs which both feed the southeast Corner Post, BEARZ (and seem to really be just one STAR with a major merge area before KNOX); BRADFORD which feeds the southwest Corner Post, PLANO; and JANESVILLE which feeds the northwest Corner Post, KRENA. The east/west directional arrival rushes mean that PULLMAN and KNOX are busy simultaneously when BRADFORD and JANESVILLE are not busy: and vice versa.

When the arrival rush is occurring from the east, there is also a strong set of climbing eastbound departure flows between PULLMAN and KNOX/KOKOMO, and a strong southern departure flow between KOKOMO and BRADFORD (which when reaching cruising levels may begin to turn southeast across the inbound flows). When BRADFORD and JANESVILLE are busy with arrivals there is a strong western departure flow between them. Of course, there is some level of departure flow in all directions at all times throughout the day.

The stated goal of each STAR process is to handoff a stream of aircraft in level flight over the Arrival Fix around 10,000 feet, 250 knots, with some desired spacing that must exceed the 5 nm enroute radar spacings required for IFR. The desired spacings are controlled by the STAR controller to match the desired handoff rate into the TRACON. In practice, the average of the minimum observed spacings was said to be 7 nm since controllers need a buffer of 2 nm to avoid violations of the 5 nm IFR radar separation standard; and, if this is true, it would correspond to an arrival rate capacity of 36 aircraft per hour (in zero wind). This roughly is equal to the IFR capacity of the runway approach associated with the STAR.

But in viewing the flows over the STARs for roughly 25 hours over several days using the TSD (and collecting hundreds of 1 minute snapshots of STAR flows for subsequent study), the Arrival Fix spacings during rushes seem to be averaging more like 10-12 nm over the last 25 nm into the Arrival Fix. But aircraft are often at higher speeds, and are not always in level flight at the same altitude. As well, there are late transitions into the STAR from local flights, (or from a stream of several North Atlantic flights of Heavy aircraft arriving at PULLMAN, for example) that may often cause a brief flurry of arrivals late in the STAR which are then handed off to the TRACON at different altitudes (which seems to be able to handle the flurry by flipping aircraft, or using path stretching or speed control inside the TRACON). As the CAB model shows, the observation of such 10-12 nm spacings during a rush does not necessarily mean that it will restrict the final approach throughput, and the flurries (which the STAR controllers can anticipate) rapidly replenish the number of aircraft inside the TRACON. It requires a major data gathering exercise to really understand and measure the performance of each STAR, and to determine when and where the STAR output has actually starved the Final Approach rate.

4. - Analysis of the PARS for O'Hare

Each of the STARs at O'Hare is fed by a preferred arrival route structure that is defined by combining all the published preferred routes from most major airports that originate O'Hare traffic. These are shown in WP No. 2, which also shows the points where CENTERs have agreed to handover O'Hare traffic to the next CENTER with m-i-t spacings which can be varied throughout the day as required. Each CENTER can free-flow the aircraft as it desires within its airspace (e.g., there might be severe weather, or equipment failures), but it will normally be required to provide a metered flow of all O'Hare traffic to the next CENTER at these Handover points. As a result, right from takeoff, all inbound O'Hare traffic is marked for special handling by all CENTERs (and TRACONs within that CENTER), and may be subject to Flow Management actions from the beginning of its trip.

Note that as a result of the PARS, there is a pre-determined Arrival Fix for all traffic from every origin airport. These are assigned strategically to "balance" the inbound flows in a very rough way, and can be changed from year to year. But it may be that the balance does not maintain itself in the various rushes throughout the day, and it could be desirable to re-balance on a much shorter time frame depending on weather and other delays in the ATC system.

While there may be some timed intervals for aircraft departing for O'Hare from a given airport, generally aircraft are spaced in level, cruising flight at high speeds as they near the Handover points. This is initiated by spacing advisories given to various sector controllers by Traffic Flow Managers in that CENTER's Traffic Management Unit. Controllers may use speed reductions, or may call for a brief off-course turn, or "dog-leg," to get spacing on preceding O'Hare aircraft in their sector. They may have to resort to a "spin", or 360 degree turn at cruising altitude and speed, to put an aircraft back 2 minutes, or about 15 nm.

Initially, what may seem to be very large, in-trail spacings (say, 60-100 nm) can be imposed in the PARS. These spacings are set at large values out of the same (or nearby) airports to be able to accommodate several merge points later along the route when traffic from other airports (trying to make the same arrival bank at O'Hare) joins the arrival rush on the PARS. . An initial spacing of 100 nm would be reduced to 50, and then 25, and then 12.5 nm, as other traffic joins the main trunk route of the PARS at only three merge points. The large initial gaps for PARS are designed to leave room for merges along the way - otherwise O'Hare departures would have to wait for the end of the line to fly past their airport (and Grand Rapids departures might never get into O'Hare through Pullman!).

This may seem to be wasteful since there is some probability that this merging traffic will not appear. But as the CAB model shows, as long as there is a long lineup (say 15-20 aircraft over the last 200 nm) of descending traffic in the STAR moving at slower speeds, any gaps in the PARS are usually closed. PARS traffic that has been delayed by large spacings, will be able to remain longer at its higher cruising speeds when it arrives at the STAR. Cleveland CENTER now has something called HVRs (Historically Validated Restrictions) which must attempt to tighten up the in-trail separations based on actual experience. If we are to study the performance of Cleveland CENTER in handling aircraft along the PARS, we will have to know where (and when) the HVRs are being applied. The same statement is true for studying the "baseline" performance of any other CENTER. If we see "wasteful" gaps in feeding a STAR occurring at some point, it will be very difficult to trace back the cause. In fact, we first have to go forward to see if they were not subsequently eliminated in the STAR, or in the Final Approach spacing.

While the PARS and STAR may be able to correct any spacing errors for the arrival flows so that there are no overall delay penalties, the question of fuel penalties will also arise in assessing ATM performance. Most jet transport aircraft plan to cruise above their best fuel consumption speeds, so that slowing them down in cruise below their best mileage speed may actually save fuel for the initial slowdown in their enroute progress. We have the paradox that some small delays during cruising flight may actually reduce trip fuel! To determine fuel penalties we would have to know winds, temperatures, and weights and other performance data about each particular aircraft.

Appendix ‘x’: Establishing a Performance Baseline for the National Airspace System

The mission of the FAA’s Air Traffic Airspace Management Program Office is “to ensure that the physical and human assets of the National Airspace System (NAS) are configured most effectively to provide for the safe, orderly, and expeditious operation of air traffic.” One of the major initiatives of the office is the National Airspace Redesign project. Its mission is “to design and engineer the NAS to optimize the flow of air traffic, commensurate with the efficient use of airspace, the complexity and workload of the Air Traffic Control specialists, and the impending technological changes in air traffic management.”

Any time one speaks of optimizing operations or designing and implementing changes in a system, the first step is to understand what the initial state is; that is, how the system is configured and performing now. Generically, we call this baselining the system. The more complex a system is, the more likely that changes in the system will have unintended consequences.

This is particularly true for the NAS. It has been our experience that identifying and modifying one specific congested “trouble spot” invariably leads to the propagation of congestion spots somewhere else. Case in point: the “East Coast Phase II” design change implemented in 1986. This program was designed to facilitate the flow of traffic into the New York metropolitan area airports by establishing three parallel arrival corridors over the northern tier of Washington Center’s airspace. Increased flow led to reduced restrictions nation-wide. It was not long before traffic management personnel in Albuquerque Center imposed delays on traffic from southern California bound for New York because the ATC specialists there were being inundated.

As a result of this outcome, we have come to depict the NAS as a “complex adaptive system.” That is, a system of agents or components that are governed by theories of “self-organization (the formation of regularities in the patterns of interaction)” and “selection (through system constraints).” Because the interactions between the individual agents are (in general) nonlinear, from a mathematical point of view such systems are often intractable.

Part of baselining, then, is achieving an understanding of these complex interactions, because of the unintended consequences issue, which in turn leads to a requirement to precisely define what one is measuring when constructing a baseline. That is, to reduce the apparent intractability and complexity to some quantifiable and sensible set of measurements. One could approach the question from many different angles: are we baselining affordability? Predictability? Accessibility? Efficiency as measured by operations that experienced delay? Efficiency as measured by operations completed without delay? Ability of the ATC workforce to provide accustomed level of service? Or potential capacity of the system to meet demand, regardless of the needs ATC workforce? When Airspace Management quotes its mission, what is meant by “safe”, “orderly”, or “expeditious”?

To prevent iterative discussions having no conclusion, the Planning and Analysis Division of the Airspace Management Program Office (ATA-200) has very narrowly defined its baseline as an aggregate of complexity factors that are discernible directly from the movement of operations through a volume of airspace. These factors are:

- Number of aircraft in a time interval in a volume of airspace (“traffic density”);
- Number of aircraft changing altitudes by a user-selectable increment;
- Number of aircraft changing speed by a user-selectable increment;
- Number of aircraft changing heading (course or trajectory) by a user-selectable increment;
- Mileage and time required to transit a volume of airspace (observed);

- Great circle mileage from airspace volume point of entry to point of exit (an approximation of optimal distance);
- Number of aircraft on converging courses (conflict prediction);
- Closest points of approach between converging aircraft;
- Number of aircraft whose closest points of approach are less than 5 miles;
- Number of aircraft whose closest points of approach are between 5 and 10 miles.

The last three are intended to give some measurement to the imposition of complexity caused by potential conflicting trajectories. These factors are among those being discussed by many organizations within and outside the FAA under the rubric “Dynamic Density”. Current work is underway to correlate these factors with complexity and workload from the perspective of the ATC specialists. That is, to survey ATC specialists for their knowledge and opinion as to what constitutes being “busy” and to validate these factors with those surveys. Meanwhile, analysts and statisticians are attempting to combine these factors, assigning a weight to each factor based on its contribution to complexity, and derive an aggregate “score” for the volume of airspace under study.

The ATA Lab intends to use these scores as the fundamental metric of its operational performance baseline. Metrics are the quantifiable measurements of various aspects of operations that lead to indicators of system capability. The FAA has determined that specific indicators shall be the objectives of the major system initiatives in progress: predictability, accessibility, flexibility, efficiency, safety, capacity, and environmental impact. The “Dynamic Density” composite metric represents the performance of the system in terms of the predictability, efficiency, and safety indicators and should be a sufficient basis for prioritizing and measuring the value of airspace redesign projects.

These factors and the weighted composite metric will be derived from the ATA Lab database of operational track data and from filed flight plan data using trajectory synthesis algorithms. Actual tracks are compared to projected trajectories, with the intent being to quantify the action of ATC on a planned trajectory in a volume of airspace.

The lab’s computers will calculate the characteristic volume score, taken as an average over a large sample set of different days, and create a baseline of system performance. Using these metrics, computational modeling will create a profile of the behavior of airspace volumes based on the observed operation of traffic through those volumes. This basic information - what is called the “operational characteristic” of the volume of airspace - is the foundation of executing airspace design changes. The baseline will not be a single score, however; analysis shows that operational behavior tends to clearly distribute into three modes. The baseline, then, will consist of operational characteristic scores for each of the modes for the specific volume of airspace.

It is expected that volumes of airspace sharing the same characteristics would be grouped and averaged to establish a nominal volume loading score. Ultra-high sectors, for example, would be grouped, and the performance of that group would be treated as a single entity. Changes made in a specific sector of ultra-high airspace would then be able to be compared to other sectors to indicate the effect of the change.

When changes are proposed for a volume of airspace - changes enabled by the implementation of new technology or new procedures - they must be modeled and simulated. New metrics derived from the affected dynamic density factors will be derived and compared to the baseline metrics. If a performance improvement is detected, then the proposed change can be considered by the investment analysis elements for acquisition and implementation.

One of the associated objectives to establishing a baseline founded upon dynamic density factors is the possibility that it could be used as a predictive traffic flow management tool. That is, once an average score is obtained for a specific type of volume (ultra-high, for example), projected traffic situations in a volume caused by weather or congestion are indicated by a higher than normal score for that volume. Decomposition of the metric into its factors could indicate which factor is the leading cause of the alert. Weather-induced re-routes may have caused the projected traffic density of a volume to exceed its normal levels. By organizing this traffic into an in-trail flow, the other factors (convergence, altitude changes, heading changes, potential conflicts) could be reduced sufficiently to off-set the rise in traffic density, and re-establish a normal composite score for the volume.

Other possibilities include being able to establish natural segregation areas where free flight type operations could be conducted under conditions of minimum ATC constraint; for example, in airspace where Distributed Air/Ground Traffic Management concepts could be implemented. By determining the complexity factors that constrain the operations in a volume of airspace, reasonable estimates of the risks associated with a new technology or procedure could be derived and considered in the proposal.

In summary, by rigorous measurements of efficiency and performance derived from analysis, modeling, and simulation, an operational baseline can be created that will facilitate the National Airspace Redesign project. New traffic flow patterns, new procedures, and new standards for emerging communication, navigation, and surveillance technologies will result from mathematically describing and measuring the operational performance of the NAS.

Appendix F

Chicago Area Airports Database

<u>O'Hare 2012 World Gateway Program</u>

Landrum and Brown have, on behalf of the City of Chicago and the Chicago Department of Aviation, collected and analyzed a considerable volume of airport and operational data for the Chicago Airport System. This includes a Chicago Airport System traffic forecast published in 1998, for a 15 year period through 2012, and a simulation (SIMMOD) analysis of forecast operations at O'Hare as enabled by an increased number of gates and additional customs and immigrations handling facilities in O'Hare terminal buildings. The data assembled by Landrum and Brown to support the O'Hare 2012 World Gateway Program is available on request in the following reports:

Landrum & Brown, *Chicago Airport System Forecast*, prepared for the City of Chicago Department of Aviation by Landrum & Brown, Cincinnati, OH, June 1998.

Landrum & Brown, *O'Hare World Gateway Program Planning Process, Airside Simulation Modeling Analysis,* prepared for the City of Chicago Department of Aviation by Landrum & Brown, Cincinnati, OH, December 16, 1999.

<u>TAAM-Based Simulation Model of O'Hare</u>

The Preston Group, developer of the Total Airport and Airspace Modeler (TAAM), developed a model of O'Hare operations in 1998. The model represents one operational configuration, and is only partially validated. The data comprising this model is available on request from The Preston Group. There is currently additional TAAM modeling work under way for United Airlines to analyze potential improvements in converging runway operations, to be completed in late summer 2000.

The 1998 TAAM model includes the following data:

- Landrum and Brown traffic data for O'Hare for 1997, based on ETMS data.
- "Plan X" runway configuration.
- High traffic load, good weather and visibility operations.
- Terminal area airspace is the primary focus.
- Ground movement model exists but is not validated.
- SID/STAR procedures include a representation of radar vectoring procedures in the TRACON.
- Holding patterns are represented.

Air Traffic Operational Data:

Acquisition, Quality Control, Access, and Storage

The Planning and Analysis Division of the FAA's Air Traffic Airspace Management Program Office (ATA-200) in 1995 was tasked to develop a laboratory to review and analyze the operational performance of the National Airspace System (NAS). The laboratory decided to use the Enhanced Traffic Management System (ETMS) data stream as the only "global" level collection of air traffic operational data.

Initial program direction at that time was concentrated on delivering a near-real-time capability for examining NAS performance by airspace volume, through an idea known as "Flow Monitor Manager" or "FM-squared". This idea faced many technical hurdles, the least of which was the high expense of commercially available computer power that could accept a continuous stream of input data while simultaneously producing an operational database. By the Spring of 1996, ATA-200 realized that the construction of the database could best be accomplished independent of the input and display of traffic data. That is, the requirements of a near-real-time traffic display system did not permit the "luxury" of examining the data, correcting errors and filling in gaps and otherwise preparing the data for analytical purposes. New technical management of the program decided to conclude "FM-squared" and concentrate exclusively on developing a robust and complete database for analytic use, rather than the display of traffic information.

The first step was to identify the appropriate source of data to populate the database. The ETMS processing permits interception at several points:

1. Near-real-time processing, such as that used in FM-squared, Aircraft Situation Display to Industry (ASDI), or Traffic Situation Display (TSD) used for Traffic Flow Management specialists, use the ETMS "map" files that are produced by the (approximately) four minute refresh cycle.

2. Each hour, the system transmits a "orig" binary file that contains all the previous hour's "map" files in compressed format.

3. At the ETMS hub site at the Volpe National Transportation Safety Center, the incoming data files from each of the Air Route Traffic Control Center's Host Computer Systems are preserved as "raw" files, from which data can be retrieved.

The lab decided to use the hourly "orig" files, modifying their current parser program to recognize and appropriately interpret the binary stream. The parser is able to examine the message header that contains, among other things, the number and type of messages in the coming packet. The parser separates out all these different message types and puts them in the proper format, ready to be inserted into the database by another program, the "inserter".

The ATA Lab had experimented with several different database software programs, finally choosing Oracle Relational Database Management Systems. Each night, pre-established scripts create Oracle tables designed to hold specific data based on the type of messages from the parsed ETMS string. The tables are based on a "GMT day" - for Greenwich Mean Time, also known as

"Zulu" - since this is the basis for all time coordination events in air traffic services. The messages from the parsed ETMS string contain a field, "activation date", which tells the inserter algorithm which daily group of tables to place the message in. Messages coming from the Host computers around the country may contain data for flights that are already in operation, or flights that are being proposed for the coming day. So, Oracle must present a three-day "vertical view"; that is, tables from yesterday, today, and tomorrow all must be active and open for insertion. After the receipt of a certain number of "orig" files that have no activation dates in "yesterday", that day's tables are closed and prepared for post-processing.

Finally, each day's data is cast into seven different tables, among which are the ones the lab analysts use most frequently - the route table (containing flight plan and plan amendment information) and the position table (containing all reported positions of a flight during its operation, from whatever source). The position table, as one might imagine, is the largest of all seven. The ETMS has a four-minute update cycle in general, but also displays one-minute updates from several major terminal facilities: Chicago, the New York metroplex, Atlanta, Dallas, Denver, and the Southern California metroplex. Position information can be obtained from radar replies from the Host or terminal tracking computers, from data link messages, or from radio position reports that are transmitted by oceanic communications operators, such as ARINC.

Although the database is built on an hourly data file, for analytic purposes it is decomposed into fifteen-minute increments. Processing, whether for quality control or for production of mission critical metrics, is performed on these fifteen-minute bins. The first stage for a closed set of daily tables is to determine whether the data are sufficient for analyses. A quality control metric is constructed from a "best-fit curve" derived from a least-squares algorithm compared against the position table, as shown in Figure 1. Noticeable drops in the quantity of data records in fifteen-minute bins indicate that the data stream from ETMS had experienced some interruption in the processing between the ATC computers and the ETMS hub site. Since the lab was not constrained by having to follow a near-real-time processing schedule, it could request a re-processing of the "raw" files and re-transmission of the resulting "orig" file from the hub site. Figure 2 shows a typical result of this re-processing quality control phase.

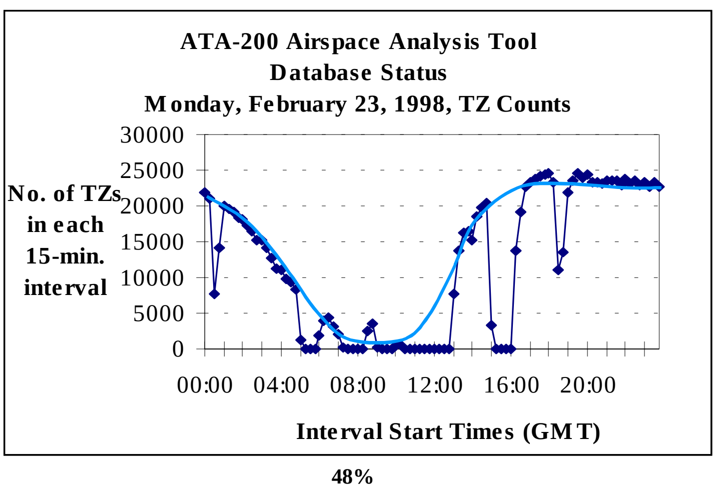
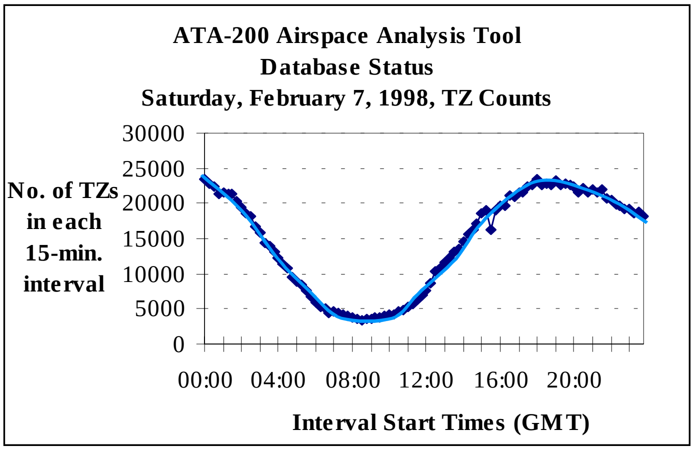


Figure 1: Data Quality Compared to Best-fit Curve



88%

Figure 2: Example of Fill-in Post-processing

In each figure above, the percentage number is a "quality score" for the day. After examining a few months using this quality control metric, the ATA Lab decided that an 82% day would be considered acceptable. Throughout late 1996 and 1997, processes for requesting data re-transmissions from Volpe were established with the target being to have every day reach 82%. Once new computer and communications hardware was installed for the ETMS, much of the data quantity failure was corrected and the minimum acceptable score has since gone up.

Once analysis shows that the database contains a minimum acceptable quantity of data, the next stage can begin: an examination of the flight quality itself. The ATA Lab database creates a unique index to identify each flight based on the flight identity, the ETMS-created index, and the record activation date. Analysis showed that the ETMS-created indexes were sources of inaccurate information about a flight. At certain times of the day, local maintenance of the Host computer might interrupt ETMS processing from that center. A flight transiting that center would be assumed by ETMS to have terminated in the center after a set time interval. Once the flight entered the next center's airspace, and its computer began processing it, the ETMS would assign a new index to this flight and treat it as a new object. Figure 3 shows how the analysts link multiple indexes into a single complete flight with algorithms developed using geo-spatial information systems (GIS) software.

For analytic purposes, a flight had to be clearly defined as a complete record of an operation. From the route table, a flight plan must contain a departure airport, an arrival airport, an aircraft call-sign or identity, an aircraft type, and a route of flight. The position table should contain a departure message, at least one position report, and an arrival message. Figure 4 shows a typical flight record in the database. This record is one of the better flights. Figure 5 shows a flight that has bad position points, which the analysts in the ATA Lab have developed GIS routines to remove from a flight record. Note that these bad points are "flagged" and not really deleted; the original data is preserved to the extent possible in the database for later quality checking and verification.

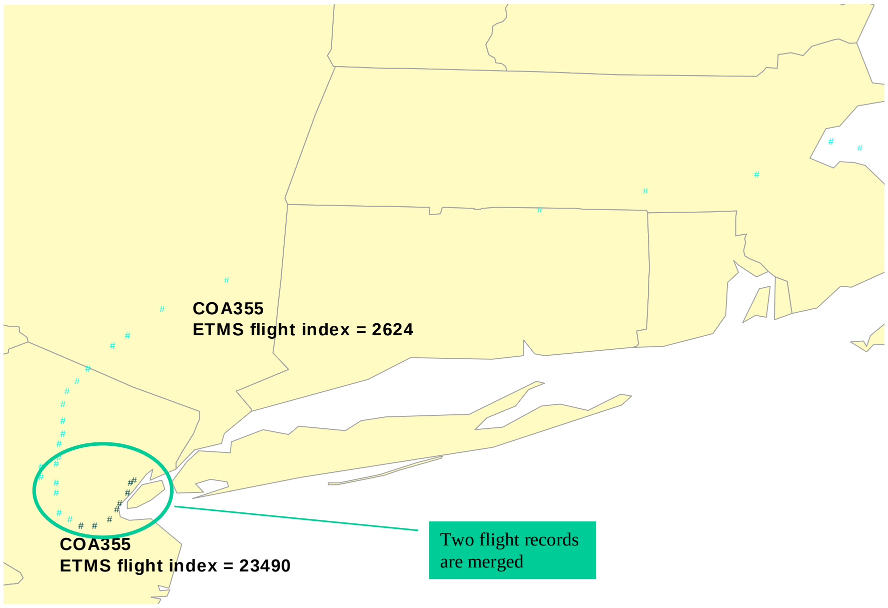


Figure 3: Resolving Multiple Indexes in Flight Record

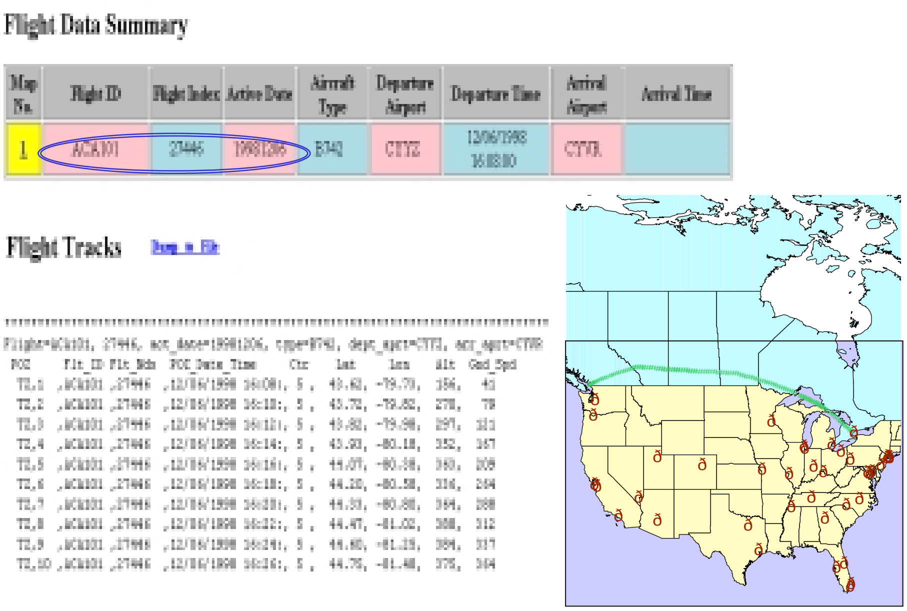


Figure 4: Typical Flight Record

(Note: there is an error in the tabular columns headed “Alt” and “Gnd_Spd”. They are reversed.)

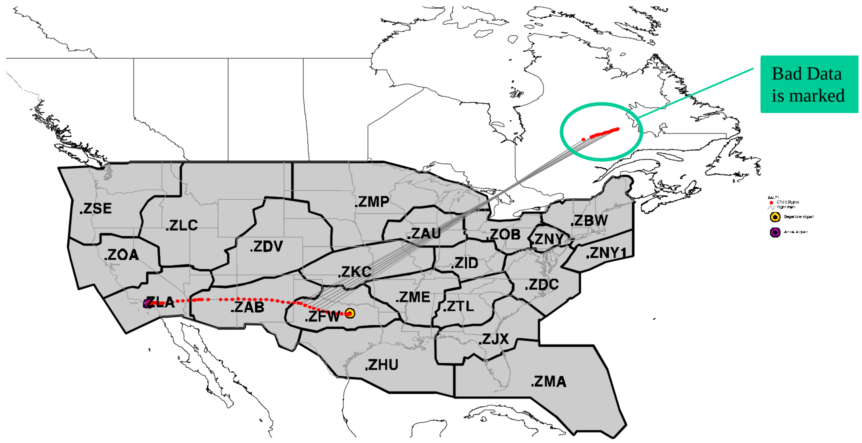


Figure 5: Bad Position Data Yields Bad Flight Metrics

Many times in the ETMS data stream, certain messages will contain information about a flight that should have been included in a previous message of the proper type, but for some reason was not. The ATA Lab uses the entire assortment of messages coming from ETMS to fill in as much flight information as possible, as shown in figure 6.

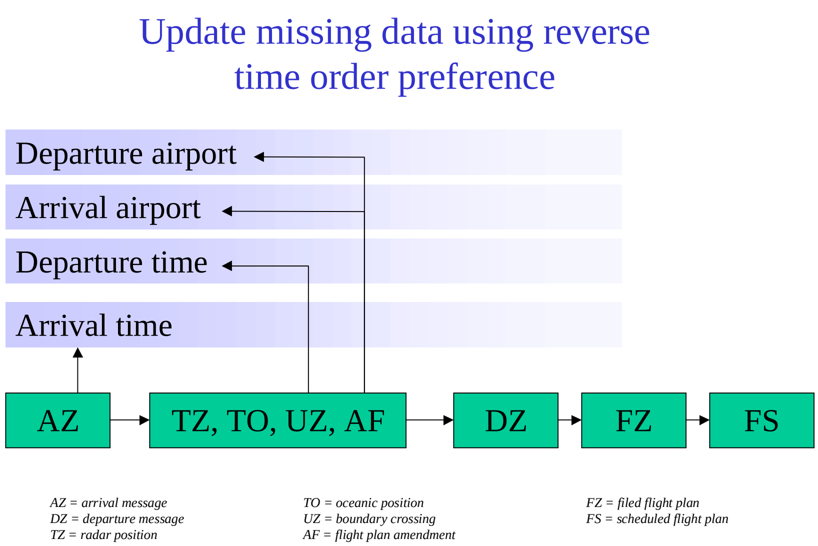


Figure 6: Using Later Messages to Fill in Missing Flight Data

In September 1996, the ATA Lab database was stable enough to begin looking at products that could be derived from the operational data. At that time, the lead office for the Overflight Billing effort approached us and asked whether the data were sufficient to identify aircraft flying through US-delegated airspace but not landing or departing from US terminals for billing of air traffic services. Analysis indicated that the lab could reasonably support this function, but would need to examine more critically the data sources ETMS uses to produce its traffic files. Since the need was greatest in the Oceanic domain, the analysts began there.

Traffic information - flight plans and position reports - enter into the ETMS data stream through the Dynamic Ocean Tracking System (DOTS) programs located at the New York and Oakland Centers. DOTS incorporates its own database of oceanic fixes, usually established at the required reporting points along the oceanic tracks. Each day, the ATC System Command Center works with air traffic service providers in the UK and Far East to set up the day's wind-based tracks and schedule. As flight plans are entered, DOTS converts their route/fix elements into the corresponding track components. Later, as the aircraft depart and enter the oceanic track, the position reports dispatched through ARINC or transmitted by data link are converted to match the fixes recognized by DOTS. DOTS then feeds this information to the interface device at the Host computer, which then sends it to the ETMS hub site.

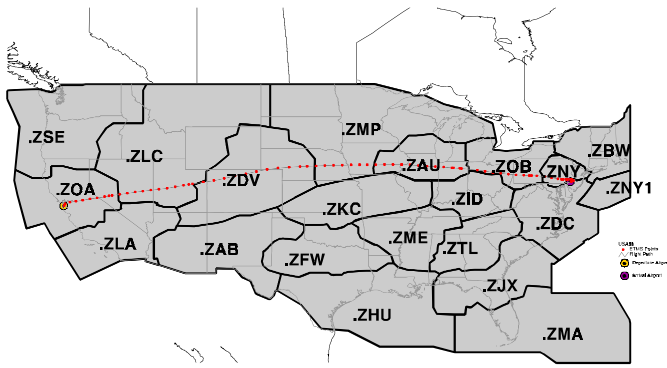
During analysis of the oceanic traffic, the ATA Lab determined that there was a significant amount of oceanic traffic that DOTS recognized but did not appear in the ETMS files. DOTS had been implemented several years prior, and the company that developed and maintained the algorithms had gone out of business. The programs continued to operate well enough for the major US-bound tracks that ATS did not notice the discrepancies. However, in trying to capture revenue from flights operating, for example from Rome to Bogota, ETMS had no data on the flight. ATS knew the flight was there, because they (in this example, the New York Oceanic sector controllers) provided services to those aircraft. But there was no analytical data for these operations.

Since DOTS was an unknown, a second system was examined for possible use. The Oceanic Display and Processing System (ODAPS) was a prototype developed to give a graphic visualization on the movement of traffic through the oceanic sectors. ODAPS had been fielded with an interface to ETMS, but that interface had never been connected due to lack of funds and the absence of a system requirement to do so. ODAPS incorporates a database of oceanic fixes, similar to DOTS, but one that could be easily adapted to match the ETMS fix database. Analysis indicated that matching ODAPS-provided flight plan and position information with ETMS would realize approximately $20 million a year in overflight revenues. The ATA Lab established routine processes whereby automation specialists at New York and Oakland Centers would perform a daily extraction of the ODAPS data files and send them to the Lab. A second set of tables would be created and the flight records in the ODAPS tables integrated with the normal ETMS-generated records.

The ATA Lab's success at using operational data to support the Overflight Billing and Collection System drew the attention of other FAA lines of business. The Office of Aviation Policy had been considering the development of a capability to track operations and delays based on a Eurocontrol program. By integrating airline quality service data from the Bureau of Transportation Statistics with the ATA operational database, the daily production of the Consolidated Operations and Delay Analysis System (CODAS) began in mid-1998.

One of the products the ATA Lab provided to CODAS was the measurement of en-route system performance in terms of delay. That is, using the operational database and GIS software, analysts could measure the time an aircraft crossed a sector boundary, how long and how many miles it flew in that sector, and the time it left that sector. Comparisons then could be made between those measurements and the expected measurements in an effort to identify where aircraft were being delayed en-route. In return, absent or erroneous departure or arrival time data in the ETMS stream could be corrected using the airline reported information in the analytical database.

In turn, this boundary-crossing algorithm became the basis for calculating the service cost metrics - the cost by mile by operation of providing air traffic services in a specific volume of airspace. Figure 7 shows a sample output file of the boundary-crossing program.



Airspace	Time in	Time out	Mins	Distance	Distance-True
USDomestic-.ZOA	1998-03-25 20:17:00	1998-03-25 20:51:00	34	248.286	251.806
USDomestic-.ZLC	1998-03-25 20:51:00	1998-03-25 21:31:00	40	356.359	356.753
USDomestic-.ZDV	1998-03-25 21:31:00	1998-03-25 22:24:00	53	496.995	497.907
USDomestic-.ZMP	1998-03-25 22:24:00	1998-03-25 22:52:00	28	248.934	249.250
USDomestic-.ZAU	1998-03-25 22:52:00	1998-03-25 23:38:00	46	397.593	397.789
USDomestic-.ZOB	1998-03-25 23:38:00	1998-03-26 00:15:00	37	313.325	314.039
USDomestic-.ZNY	1998-03-26 00:15:00	1998-03-26 00:36:00	21	125.632	126.479
USDomestic-.ZDC	1998-03-26 00:36:00	1998-03-26 00:45:00	9	13.376	28.050

Figure 7: Boundary Crossing File

The most recent product created from the ATA Lab database and archive is the Post Operation Evaluation Tool (POET), a set of analytical programs and visualization tools developed for the Free Flight/Collaborative Decision Making team. POET uses the ATA Lab database with CODAS outputs to perform analyses of new flight scheduling and enhanced traffic flow management concepts.

As recognition of the value of ETMS data for analyses has grown, the engineers and programmers at Volpe have begun improving their processes. Work is now underway to reduce the refresh cycle rate from its current 4 minutes to a planned 1 minute. This is intended to prepare the system for the inclusion of operational data transmitted by terminal radar tracking computers. The ATA Lab database already incorporates the data from the previously mentioned six major terminals, who all have direct interface to the ETMS, as well as terminals being equipped with the Surface Movement Advisor decision support tool. As more terminals come on line, data processing and quality control will become more demanding.

Access to the information in the database is through Structured Query Language (SQL) programs. Figure 4 above was created by using SQL statements through a web-enabled interface and limiting selections to a few major elements. The magnitude of the database typically means that more complex queries need to be written by analysts familiar with its construction. There are plans being considered for an eventual re-engineering of the database to take advantage of advanced data mining tools, thereby making access simpler and easier. However, until then, requests for information from the ATA Lab database and archive need to be individually written by the analysts, and usually require several iterations to extract the correct information.

Finally, the question of availability and storage of this information is one of the most valuable aspects of the use of ETMS-based data. The ATA Lab maintains a “near-line” database containing about two weeks’ worth of operational data. The tables are also copied to long-term storage off-line, a large array of optical disk. This array, the “jukebox”, holds the archived tables back to January 1, 1997. The database grows at approximately 650 megabytes per day, near-line storage holds about 8 gigabytes, and the jukebox holds 1 terabyte. Overall, the ATA Lab has slightly over a terabyte of operational data available for analytical purposes. There is also a digital tape copy preserved in another location for risk management purposes.

Although the database goes back that far, analysts requesting such information are warned that the evolutionary nature of the data quality control processes makes this older information less valuable. In spite of this warning, organizations have been able to perform useful analyses of seasonal and annual variations in ATC system behavior. For example, the Oak Ridge Energy Labs were approached by the Free Flight/Collaborative Decision Making team for a longitudinal analysis of Summer peak delays and route variations. They were able to use the ATA Lab data from August 1997 and August 1999 to compare the en-route delays and evaluate possible causes of the increase experienced in 1999.

In conclusion, a significant effort and investment has been made in obtaining, correcting, and storing air traffic operational data based on ETMS. It needed to be done to provide quality data for analytical purposes, and the return on that investment is demonstrated by the growing number of organizations using the database for analyses. Prototype capabilities are being developed for web-enabled data mining and executive information systems, for near-real-time display of flight plan and traffic information for Open Skies (Overflight Security) initiatives, and for evaluation of new technologies supporting the Free Flight operational concept.

H. APPENDIX H

Chicago Baseline Performance Data Collection Initial Assessment -

By Suzanne Chen

As described in Section 4 the next generation airspace systems design should be grounded in an in-depth understanding of the current operations. This section provides a preliminary analysis of the performance of Chicago Airport operations related to the baseline development, in order to provide an example of a typical baseline data collection approach. This preliminary baseline assessment focuses on the issue of capacity, a serious national concern. Once the technique used in this case study is agreed upon, a NAS-wide performance baseline can be established. The empirical data collected from performance baseline would also serve the purpose of validating the simulation models to ensure fidelity of representation of current systems operation. Above all, operational needs should drive the requirements for a new design.

Traffic operations are complex with many parameters interplayed, such as airport environment, controller skills, management decisions, etc. This initial baseline approach focuses on understanding how well the operations performed and what key factors have influenced the Chicago Airport. This provides an example on possible techniques to be used for NAS performance baseline. Should other emerging technology become applicable, like data mining technique to discover knowledge from databases, it would also be used in analyzing the complex aviation environment.

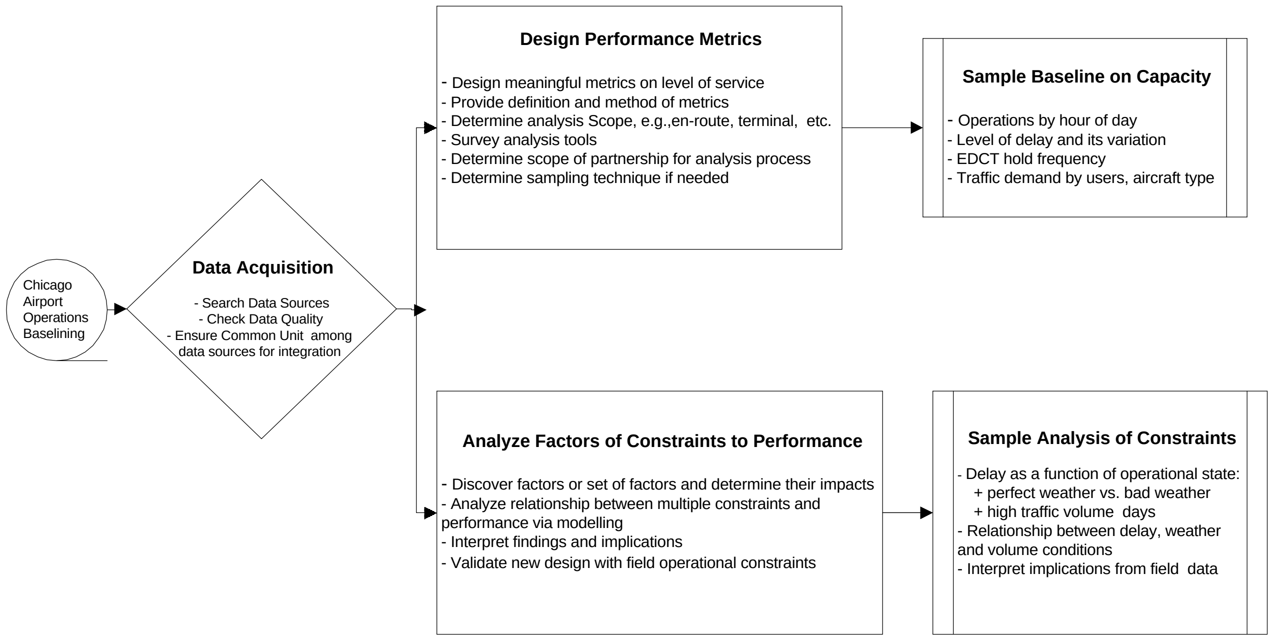
In examining the ORD capacity, two areas are analyzed to meet airspace Preliminary Design requirements discussed in Sec. 4.1.

- Performance metrics on level of service: establish average service level and its variation
    - Number of departures per hour throughout the day, and by day of week
    - Number of arrivals per hour throughout the day, and by day of week
    - Number of EDCT hold per hour
    - Demand by type of aircraft, users
    - Demand of operations at Center and at Tower
    - Delay per flight for total delay, gate delay, arrival delay, taxi-out delay and taxi-in delay

- Capacity constraints: examine delay situation under operational states of:
    - Weather condition: perfect vs. bad weather
    - Volume: high vs. low volume under above weather conditions
    - Relationship between delay, weather, and volume conditions

Performance Baseline Process on Chicago Airport - A Case Study

Some of the necessary steps to conduct an in-depth performance baseline are outlined below. The output of this case study on Chicago Airport is also briefly mentioned below as an example.



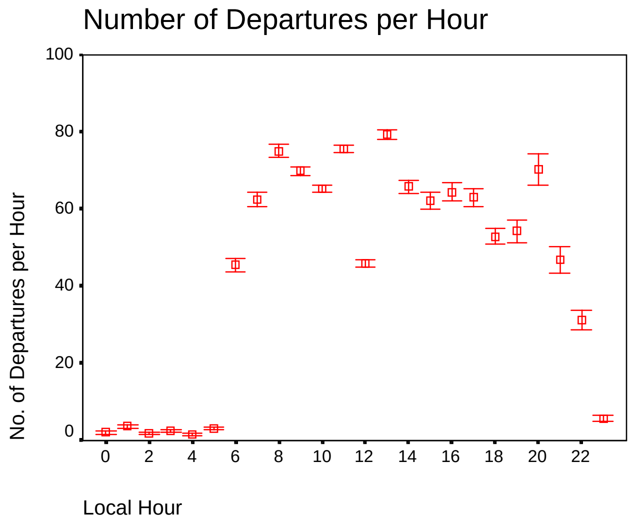
Data Source and Process

Several data sources captured pieces of air traffic operations, and ATA-200 has developed a comprehensive database of CODAS (Consolidated Operations and Delay Analysis System), based on ETMS data, airline schedule, OPSNET delay data, weather data, etc. In this preliminary performance baseline, three month worth of April to June 1999 data were extracted from CODAS on an hourly basis. Here, only three-month of data under normal weather condition was selected to eliminate winter and summer extremes. Also, NOAA weather data was available for these three months in order to distinguish operational state of perfect weather from bad weather.

Example Capacity Performance Metrics

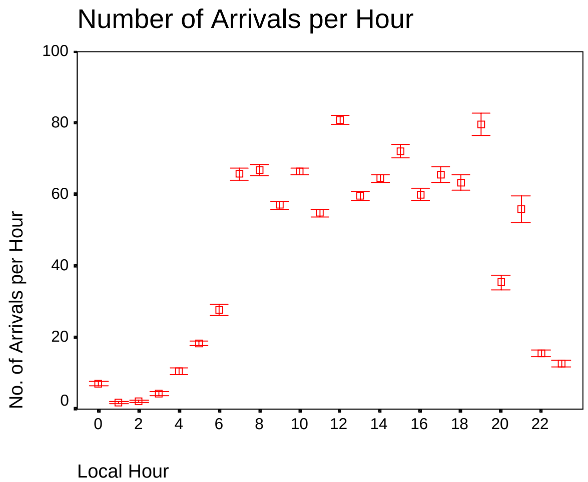
Capacity measured in term of volume of departures and arrivals and their delay situation are presented as examples of performance metrics. To show the variation of a performance metric, its average value and the spread of this average value within 95% confidence level are presented as a bar with the average value indicated in the middle as shown below.

Number of departures per hour



Observation: peak demand for departure occurred around 8am, 1pm, and 8pm, when an average of 80 departures has been reached. Maximum departure per hour reached 91 flights.

Number of Arrivals per Hour

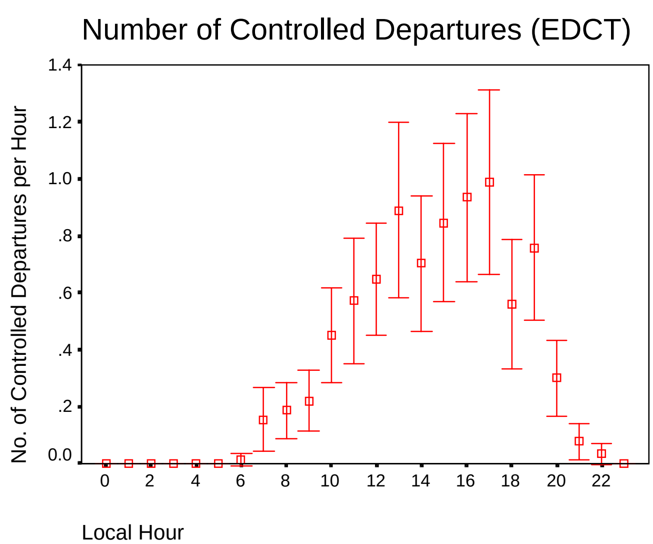


Observation: Top arrival demand occurred around 12 to 1 pm, and 7pm. Maximum arrival rate reached 103 flights per hour.

Number of Controlled Departures per Hour

A "controlled" flight is one that has received a controlled departure time (CDT) in order to guarantee the flight will arrive at an impacted air traffic controlled location at a specific time. For example, during bad weather condition at ORD, controlled departures were applicable at origin points for flights into ORD. During good weather at ORD, controlled departures could be imposed at ORD to control arrivals at a distant airport where weather was bad.

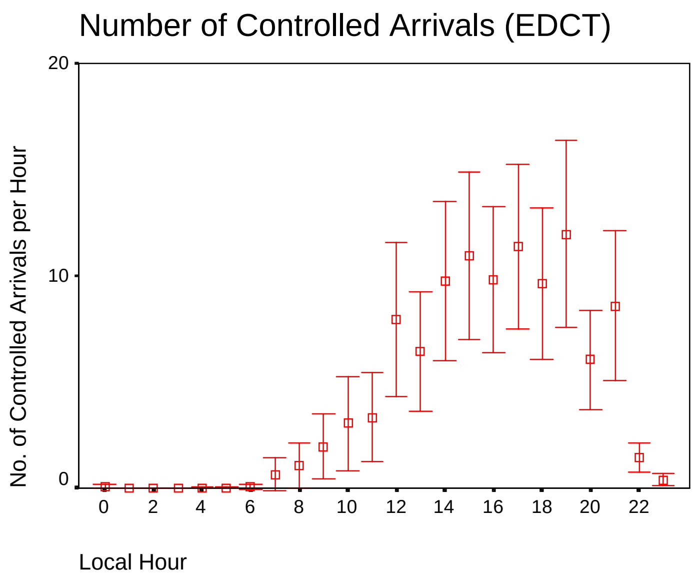
Due to adverse weather situation at destiny locations, ORD experienced EDCT controlled departures as follows.



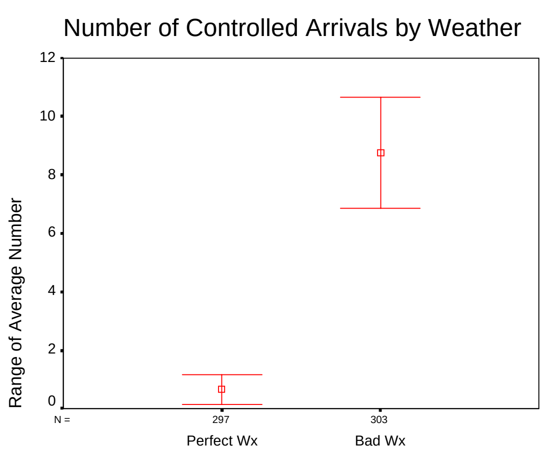
Observation: higher departure controls occurred from 3pm to 5pm, with an average of 1 controlled departure per hour during that period.

Number of Controlled Arrivals per Hour

Due to ORD local adverse weather situation, arrival capacity was controlled as follows:



Average number of Controlled Arrival by Weather Condition

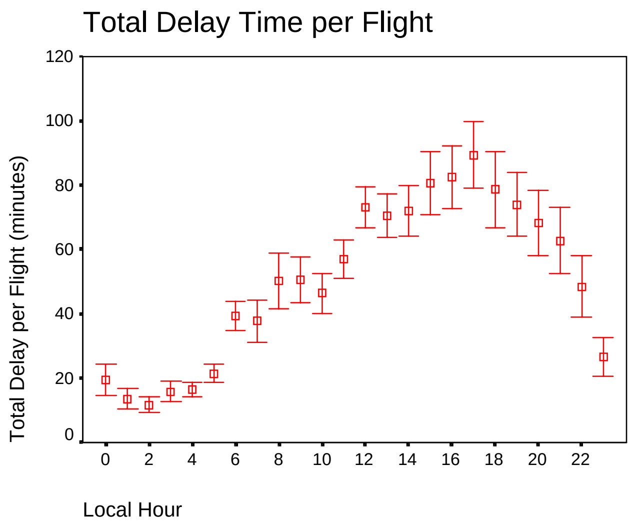


<u>Observation:</u> higher number of controlled arrivals also occurred between 3pm to 7pm, with an average of 10 controlled arrivals per hour during that period. When comparing controlled arrivals under perfect weather vs. bad weather days, their difference was very significant, approximately eight times bigger.

The process, caused by either local bad weather or the destiny bad weather, would tend to dilute the coupling between weather and controlled flights. This rippling effect should be further studied.

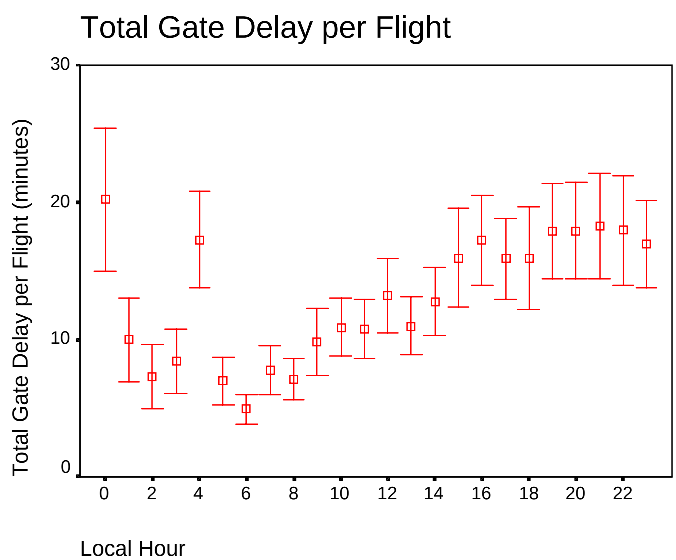
Delay Time per Flight

- **Total delay:** measures the sum of delays from adjusted gate delay, taxi-out, airborne, and taxi-in. This includes the ground delay occurred at ORD caused by arrival capacity limitation imposed at any other airports.



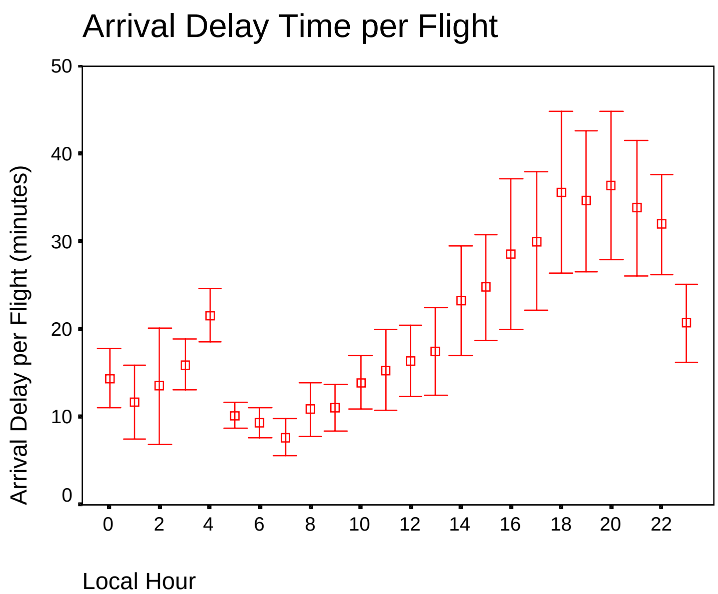
Observation: Higher total delay time per flight occurred around 5pm with an average of 90-minutes delay. Maximum total delay time experienced was 347 minutes.

- **Total gate delay per flight:** this measures the difference between actual gate departure time and the scheduled gate departure time regardless of the causes of delays.



Observation: Average gate delay time lasted between 10 to 20 minutes per flight, and early morning hours could occasionally experience outstanding gate delay too. Maximum gate delay experienced was 144 minutes.

- **Arrival delay per flight:** this measures the difference of actual arrival time from the scheduled arrival time**.**

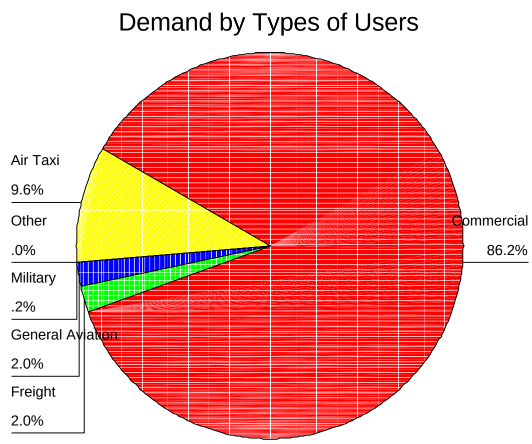


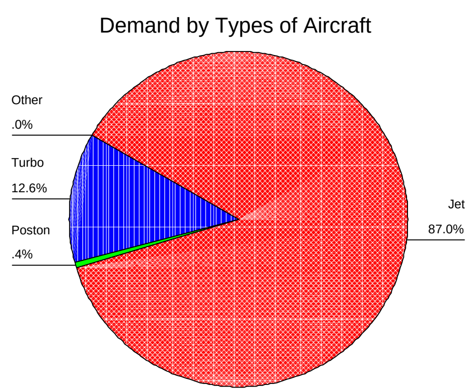
Observation: arrival delay topped between 6pm and 8pm, with an average of 35 minutes arrival delay during that period. Maximum arrival delay time experienced was 266 minutes.

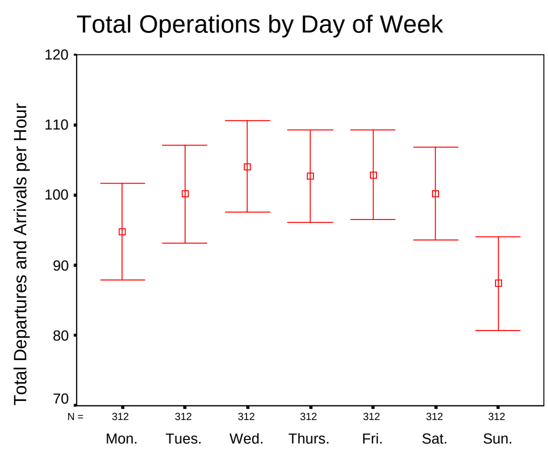
Summary of Performance Statistics on Service Level

	Maximum	Mean	Standard Deviation
No. of departures per hour	91	43.6	29.7
No. of arrivals per hour	103	43.6	28.2
Total delay per flight (minutes)	347.7	50.3	43.3
Total gate delay time per flight (minutes)	144.0	13.0	14.9
Arrival delay time per flight (minutes)	266.1	20.4	27.9
N (sample size)	2184	2184	2184

Demand by Types of Users, Aircraft and Day of Week

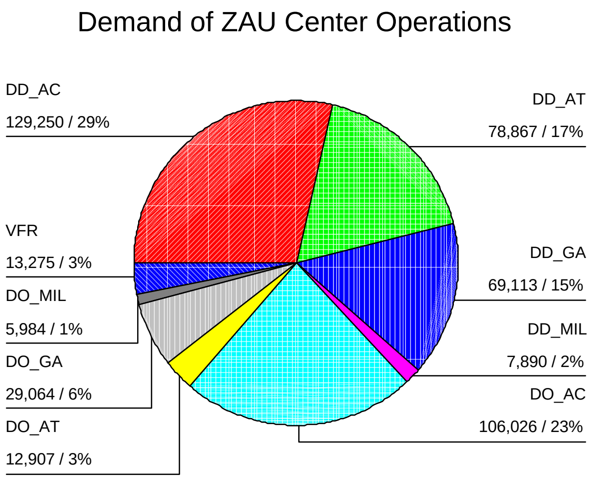






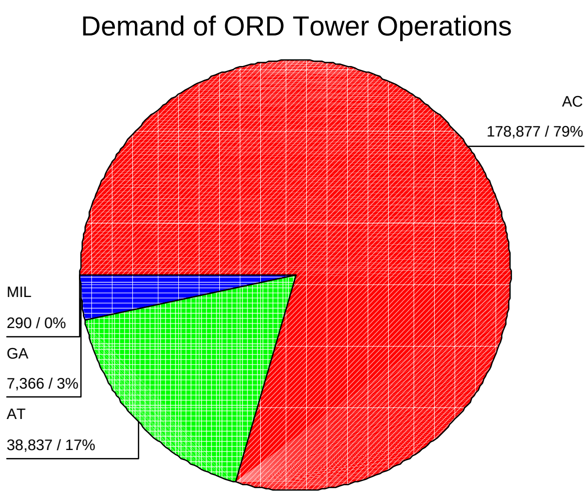
Observation: Demand by commercial carriers of jet aircraft occupied 87% of Chicago capacity, while the rest is used mostly by air taxi. Also, weekend demand is lower, while Mondays has the lowest traffic out of 5 weekdays.
Suggestion: A thorough study should look at all Chicago area airports together.

Demand of ZAU Center Operations - Number of operations and Percentage



Legend:
DD: domestic departures
DO: domestic overflight
OD: oceanic departures
OO: oceanic overflight
AC: air carrier
AT: air taxi
GA: general aviation
Mil: military

Demand of ORD Tower Operations



Observation: Among the operations handled at ZAU Center, 63% dealt with domestic departures, 33% with overflight, and 3% with VFR. Their average operations per month was 241,400 flights, with a maximum of 246,648 flights handled per month.

At ORD Tower, 79% of operations dealt with air carriers, and a 17% with air taxi. Average number of operations per month was with 75,120 flights, and a maximum number of flights handled were 76,318.

Capacity Constraints

To understand what factors that could limit the airport capacity, factors like weather or traffic volume, a stepwise regression model is used here. Stepwise regression model shows one highly correlated factor at a time, starting from the most correlated factor with delay. A probability of F-test value less than or equal to 0.05 is used to forwardly enter any qualified factors. Also, a probability of F-test value greater than or equal to 0.1 is used to backwardly eliminate any factors that no longer meet the F-test criterion at each successive step. As a result, an optimal set of factors was selected and could be considered as capacity constraints.

Here, the capacity constraints considered for weather and traffic volume include the following.

Weather related sub-factors used as independent variables in the regression model:

Cloud ceiling
Visibility range
Temperature
Wind speed
Wind angel
Gust speed if any

Traffic volume related sub-factors used as independent variables in the regression model:

No. of departures per hour
No. of arrivals per hour
Time of day
Day of week

To study the delay as a function of the above independent factors, the following dependent variables on delays are analyzed one at a time:

Average total delay time per flight
Average gate delay time per flight
Average arrival delay per flight

The following table delineates the degree of those factors that could influence delay time. The proportion of variation in the delay time explained by the set of independent factors entered is listed under the "R Square" column. The cumulative R Square value ranges between 0 and 1, which measures the degree of variation in the delay that could be explained by the independent factors entered.

For example, .153 (or 15.3%) of the delay is explained by time-of-day factor, and a total of .224 (or 22.4%) of variation is explained by both time-of-day and wind-speed factors. When all the independent factors that meet the F-test criteria exhausted, the remaining factors that didn't qualify or was a redundant factor are listed under "Remaining Factors" column after the last step.

a. Key factors influencing Total Delay time per flight

Key Factors	Cumulative R Square	Remaining Factors not qualified at the end
1. Time of day	.153	
2. Wind speed	.224	
3. Visibility	.275	
4. No. of arrivals per hour	.316	
5. Cloud ceiling	.323	
6. Wind Angle	.326	- No. of departure flights - Gust wind speed - Day of week

b. Key factors influencing Gate Delay time per flight

Key Factors	Cumulative R Square	Remaining factors not qualified at the end
1. Time of day	.056	
2. Visibility	.097	
3. No. of departures per hour	.129	
4. Wind speed	.162	
5. Gust speed	.165	- No. of arrivals per hour - Cloud ceiling - Wind angel - Day of week

c. Key factors influencing Arrival Delay time per flight

Key Factors	Cumulative R Square	Remaining factors not qualified at the end
1. Time of day	.097	
2. Cloud ceiling	.146	
3. No. of departure per hour	.170	
4. Wind speed	.193	
5. Visibility	.211	
6. No. of arrivals per hour	.214	
7. Wind Angel	.216	- Gust speed - Day of week

<u>Observation</u>:

- Delays occurred mainly during peak time, therefore, how to smooth out the flights during peak time or change the travel habit to eliminate peak time traveling is crucial.

- Visibility is a more important factor for departure delay than for arrival delay.
- Cloud ceiling is a more important factor for arrival delay than for departure delay.
- No. of departures per hour can affect arrival delay, but number of arrivals per hour doesn't affect gate delay.
- The above set of six independent factors can explain approximately one third of the variations in **total** delay time per flight. These selected set of weather and volume related factors could only explain approximately 17% of **gate** delay and 22% of **arrival** delay.
- The stepwise regression model technique, when informed by a well-considered hypothesis, is an efficient way to understand the sensitivity of delay to other factors such as equipment outage, runway usage, and airspace congestion. Further analysis could be carried out.

Impacts of Operational States on Delays

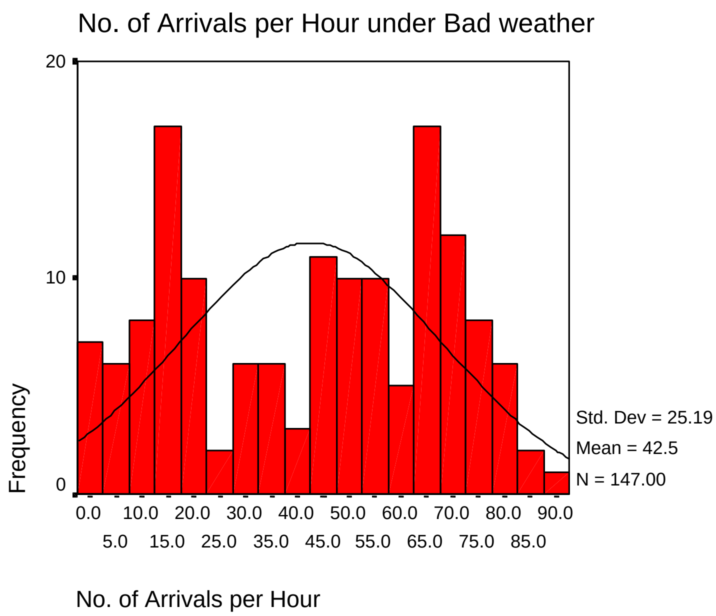
When assessing airport operational performance, one should also consider the operational state such as a perfect weather condition vs. bad weather, which is uncontrollable. Other than weather condition, there is traffic volume of high vs. low for example. The combination of these two factors creates four operational states. The delay situation is examined under these four operational states separately and their relationship with delay displayed. As a by-product, one can also understand when the capacity bottleneck occurred, i.e., when the delay time suddenly sharply increases under a particular operational state.

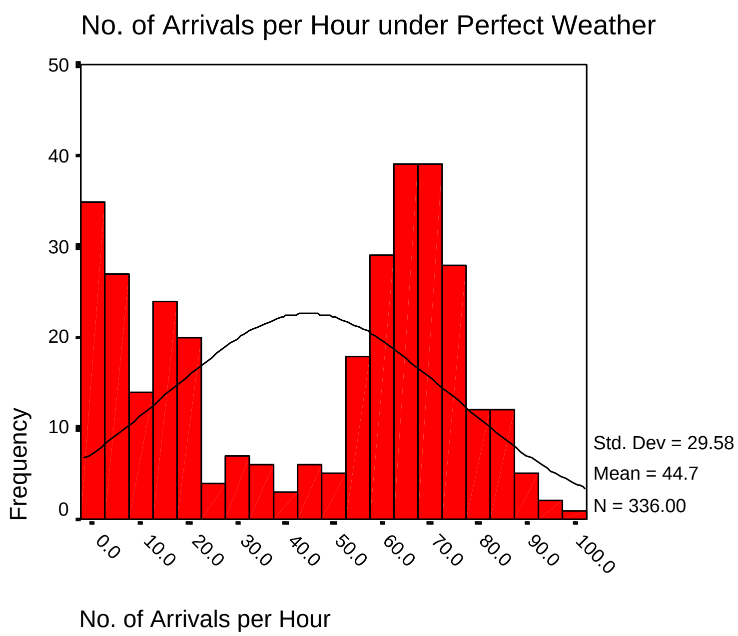
To define the operational state, one has to agree upon the criteria for a perfect day. Here, NOAA data was consulted in determining days and hours for a perfect day or a bad day. The criteria used:

Criterion	Perfect Day	Bad Day
Visibility (miles)	10	0.5 to 5
Sky Cover	Clear, SCT, FEW	Overcast, Rain, thunderstorm
Ceiling (100ft)	Not covered, 250	1 to 120
Wind (mph)	1.3 to 13.3	13 to 24
Humidity (%)	30 to 80	90 to 98
Days & hours of the day selected	April 7, 24, 29, 30 May 1, 2, 14, 19, 28, 29 June 7, 17, 20	April 8 (>18 hr), 15(>15 hr), 16 (3-15 hr), 22, 27 (>12 hr) May 6, 11, 21 (>15 hr) June 1 (>18 hr), 2 (3-9 hr), 11 (>15 hr), 13 (3-15 hr), 27
Selected sample size	336 cases	147 cases

The following charts examine traffic volume and delay time under bad weather vs. perfect weather in separate charts. .

Weather Impact on Traffic Volume - under perfect vs. bad weather

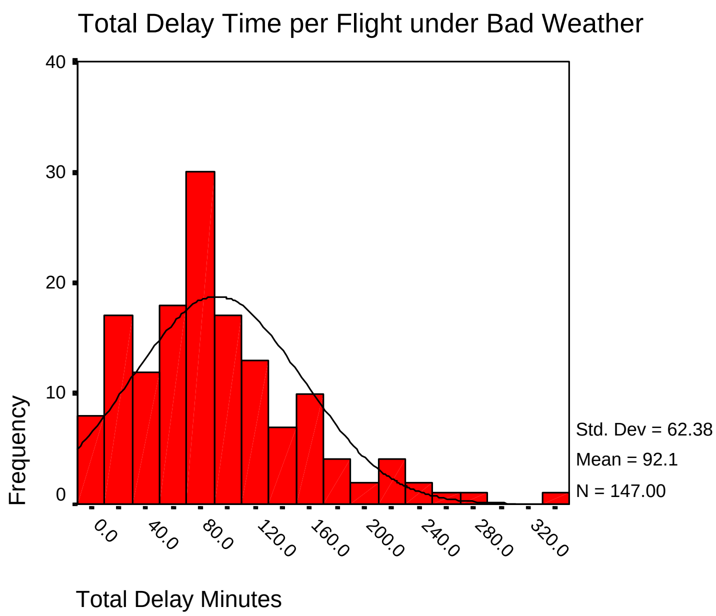


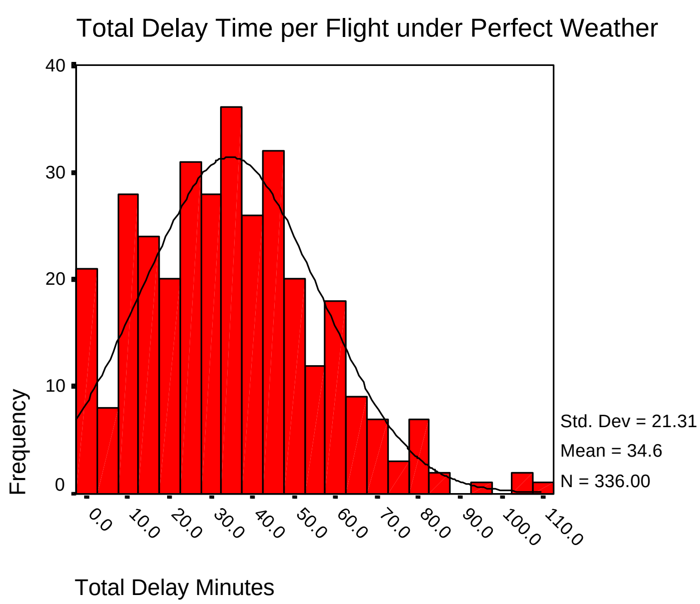


<u>Observation</u>: Under bad weather, arrival rate is slower -- spread between 40 and 80 flights per hour, while under perfect weather, arrival rate was more centered around 70 flights per hour.

Weather Impact on Delays

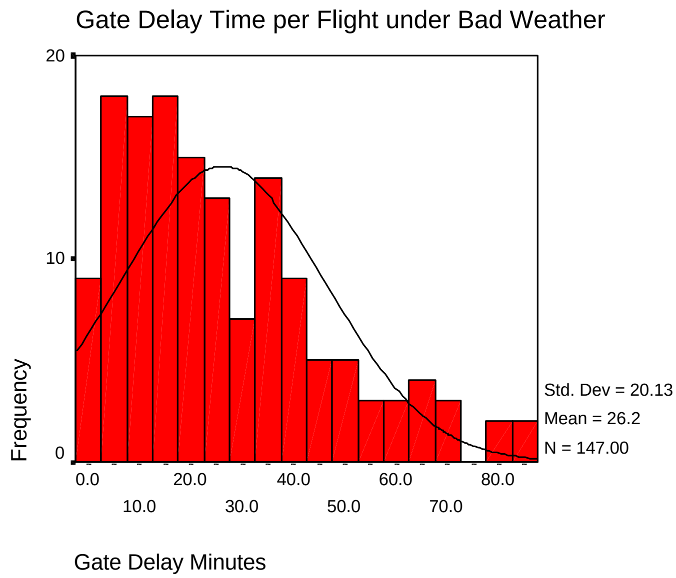
a) Weather Impact on Total Delay Time per flight

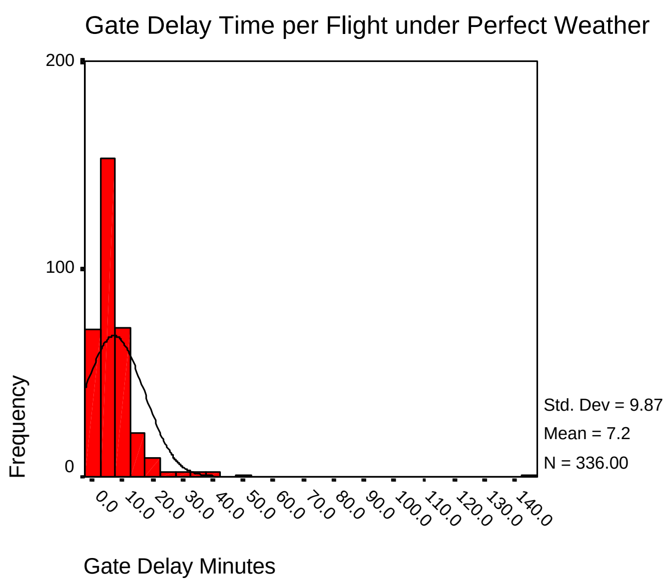




Observation: Total delay time under bad weather was spread between 20 to 160 minutes per flight with an average of 92 minutes delay. Under perfect weather, total delay time was about one third of the delay under bad weather.

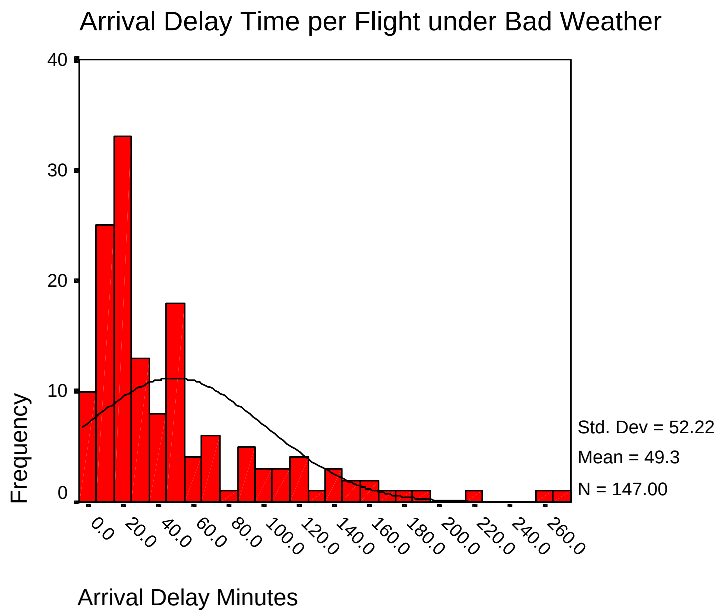
b) Weather Impact on Gate Delay Time per Flight

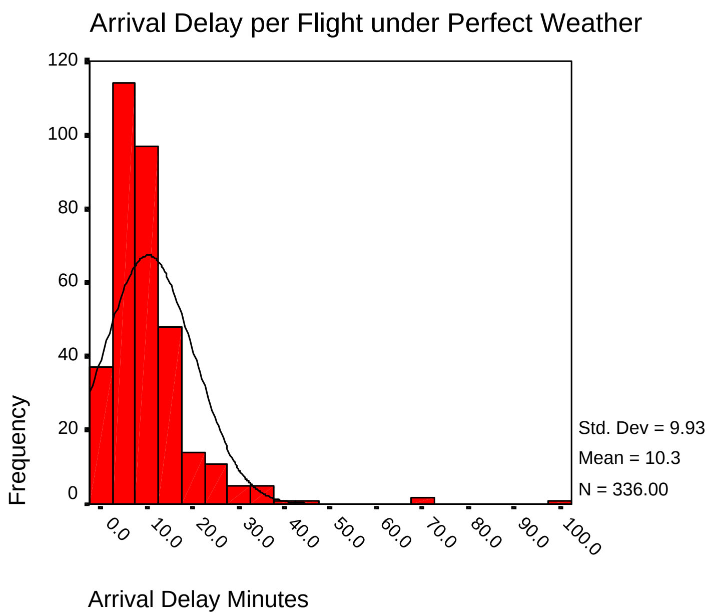




<u>Observation:</u> Bad weather caused gate delay time spreading between 5 to 50 minutes per flight with an average of 26 minutes delay. Under perfect weather, there was mainly 5 minutes of gate delay.

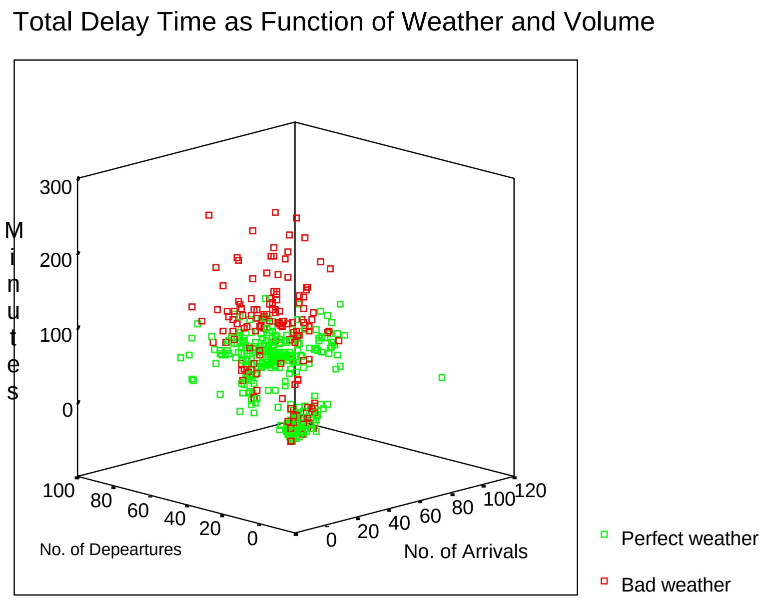
c**) Weather Impact on Arrival Delay Time**





<u>Observations</u>: Bad weather could cause approximately 5 times more arrival delay time than perfect weather.

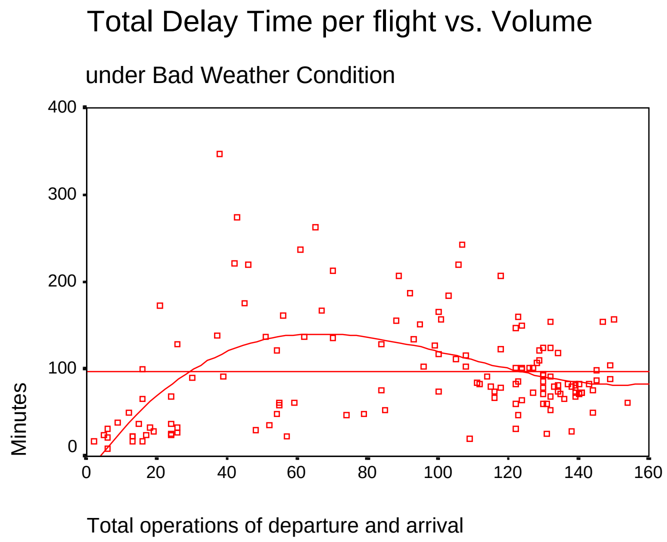
Total Delay Time as a Function of Weather and Traffic Volume

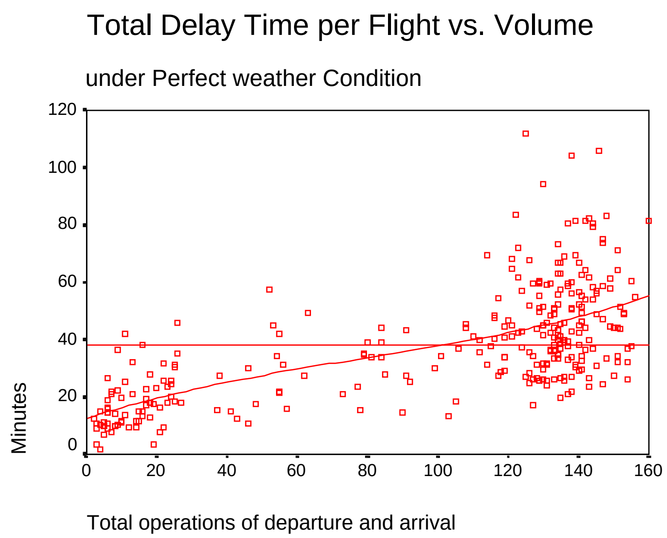


Observation: Total delay time per flight increases under bad weather (in red) especially when volume of departures and arrivals are high as shown above. There was a small amount of good cases at the bottom, where X, Y, and Z-axis met, -- where weather was bad and volume was high, but there was little delay time. These cases may deserve further investigation to understand how they become good performers under bad weather.

Relationship between Delay Time and Traffic Volume under Weather Conditions

A cubic regression fit was used below to show the relationship under different weather condition. The average delay time is indicated by a straight horizontal line below.



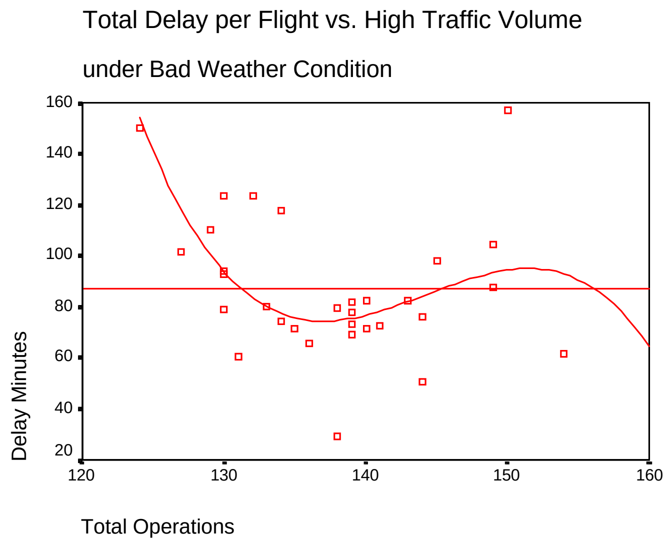


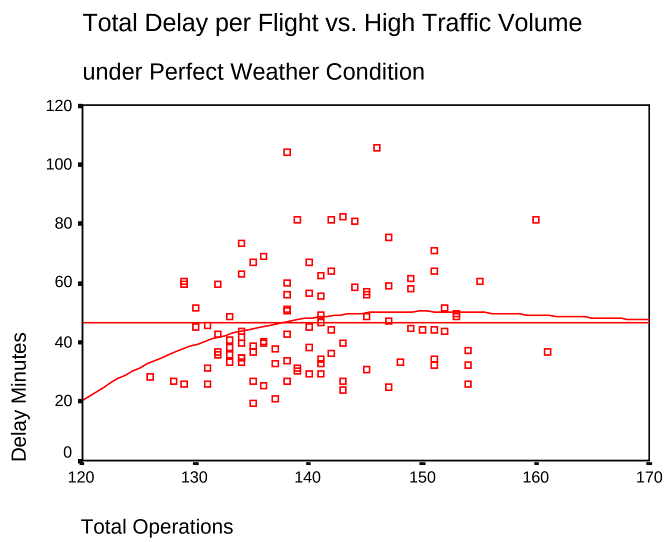
Observation: Under bad weather situation, delay increases with traffic volume until Chicago weather won't allow more traffic. The delay bottleneck occurred when total operations reached around 70 flights. Then, traffic controllers could be focusing on guiding the outstanding traffic into O'Hare, which made the delay time decreased slightly when total operations reached 100 to 140 operations. This phenomenon could warrant an extensive study to understand why delay time decreases when total operations were at high volume under bad weather.

Under perfect weather condition, delay time usually linearly increased with total operations, and the amount of delay time was much smaller than that under bad weather condition as indicated above (an average of 40 minutes delay vs. 100 minutes delay).

High Traffic Volume Situation and its Impact to Delay under Weather Conditions

To form high traffic volume situation, cases of departure count per hour greater than 60 and arrival rate also greater than 60 were selected, their delay time and weather condition were examined. This is another way of looking into operational state and its consequences.





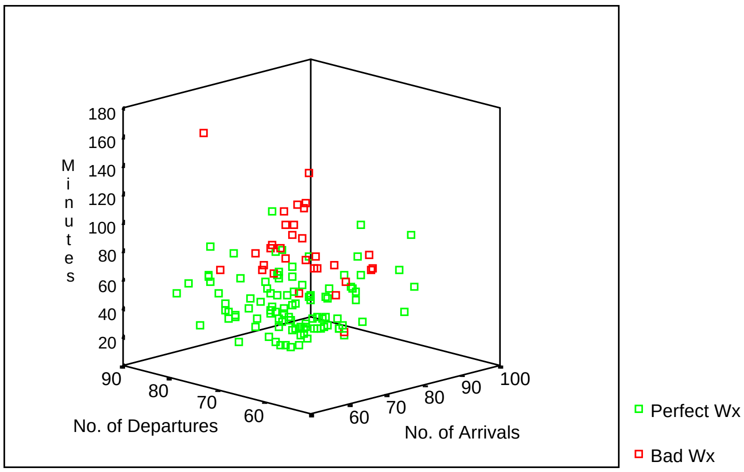
Observation: Under bad weather condition while dealing with high traffic volume, total delay time per flight was decreasing until it reached a threshold around140 flights, then delay time increased from there on. Exact cause of this phenomenon should be further studied. An average of 85 minutes delay experienced.

Under perfect weather condition and high traffic volume situation, the total delay time per flight mainly increased linearly and stabilized around 45 minutes of delay even with increasing traffic.

Weather Impact to Delay under High traffic Volume Situation

Weather Impact to Total Delay per Flight

for High Traffic Volume Situation



<u>**Observation:**</u> When examining only high volume traffic situation, weather still played a major role to delay time as shown above. The delay time is about doubled under bad weather compared to perfect weather.

Conclusion

This case study sets an example of using some basic techniques to establish performance baseline. Capacity demand by types of users, peak hour usage, and workload at Center and tower were examined. The relationship of delay performance under different operational states of weather and high volume constraints were analyzed. Portion of delay variation that could be explained by independent factors like weather and traffic volume was also demonstrated to indicate their influence.

In the follow-on performance baseline analysis, analyses will expand to include ripple effects from short-haul and long-haul flights, more data will be acquired, and different constraints will be identified. One of the major issues in analysis work is to obtain quality data with easy access, where ETMS and ATA-200 databases could be further enhanced.

I. Appendix I

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