

NASA/SP-2009-6115



# Metrics for the NASA Airspace Systems Program

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December 2009

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December 2009

Available from:

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# Abstract

This document defines an initial set of metrics for use by the NASA Airspace Systems Program (ASP).

ASP consists of the NextGen-Airspace Project and the NextGen-Airportal Project. The work in each project is organized along multiple, discipline-level Research Focus Areas (RFAs). Each RFA is developing future concept elements in support of the Next Generation Air Transportation System (NextGen), as defined by the Joint Planning and Development Office (JPDO). In addition, a single, system-level RFA is responsible for integrating concept elements across RFAs in both projects and for assessing system-wide benefits.

The primary purpose of this document is to define a common set of metrics for measuring National Airspace System (NAS) performance before and after the introduction of ASP-developed concepts for NextGen as the system handles increasing traffic. The metrics are directly traceable to NextGen goals and objectives as defined by the JPDO and hence will be used to measure the progress of ASP research toward reaching those goals.

The scope of this document is focused on defining a common set of metrics for measuring NAS capacity, efficiency, robustness, and safety at the system-level and at the RFA-level. Use of common metrics will focus ASP research toward achieving system-level performance goals and objectives and enable the discipline-level RFAs to evaluate the impact of their concepts at the system level.

## Acronyms

ACES	Airspace Concept Evaluation System
ADS-B	Automatic Dependent Surveillance-Broadcast
AMI	Airportal and Metroplex Integration
ASDO	Airspace Super Density Operations
ASP	NASA Airspace Systems Program
CADOM	Coordinated Arrival and Departure Operations Management
CADRS	Combined Arrival/ Departure Runway Scheduling
CD&R	Conflict Detection and Resolution
CDA	Continuous Descent Approach
DAC	Dynamic Airspace Configuration
FMS	Flight Management System
HITL	Human In The Loop
IFR	Instrument Flight Rules
JPDO	Joint Planning and Development Office
LoS	Loss of Separation
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
OPD	Optimal Profile Descent
RCM	Runway Configuration Management
RFA	Research Focus Areas
RNAV	Dynamic area navigation
RNP	Required Navigation Performance
SA	Separation Assurance
SESO	Safe and Efficient Operations
SLDAST	System-Level Design, Analysis, and Simulation Tools
SWG	JPDO Safety Working Group
TBSO	Trajectory Based Surface Operations
TCAS	Traffic Alert and Collision Avoidance System
TFM	Traffic Flow Management
VCSPRO	Very Closely Spaced Parallel Runway Operations
VFR	Visual Flight Rules

## Table of Contents

<b>1</b>	<b>INTRODUCTION.....</b>	<b>1</b>
1.1	PURPOSE OF THIS DOCUMENT.....	1
1.2	USERS OF THIS DOCUMENT.....	2
1.3	DOCUMENT SCOPE.....	2
1.4	DOCUMENT STRUCTURE AND CONTENT.....	2
<b>2</b>	<b>JPDO NEXTGEN GOALS, OBJECTIVES, AND METRICS .....</b>	<b>3</b>
<b>3</b>	<b>DEFINING CRITERIA FOR “GOOD” METRICS.....</b>	<b>6</b>
<b>4</b>	<b>DEVELOPING SYSTEM-LEVEL METRICS TO EVALUATE NASA ASP RESEARCH.....</b>	<b>7</b>
4.1	ACCEPTABLE NAS DELAY .....	7
4.2	ESTIMATING NAS PERFORMANCE .....	7
4.3	CALCULATING METRIC VALUES AND PERFORMING STATISTICAL ANALYSIS .....	8
4.4	ESTIMATING NAS CAPACITY .....	8
4.5	ESTIMATING NAS EFFICIENCY.....	9
4.6	ESTIMATING NAS ROBUSTNESS.....	11
4.7	ESTIMATING NAS SAFETY.....	13
4.7.1	<i>Justifying the Selection of System-Level Safety Metrics .....</i>	<i>14</i>
<b>5</b>	<b>EVALUATING SYSTEM-LEVEL METRICS.....</b>	<b>16</b>
5.1	DISCUSSION .....	19
<b>6</b>	<b>SYSTEM-LEVEL RFA METRICS.....</b>	<b>20</b>
6.1	SEPARATION ASSURANCE (SA).....	21
6.1.1	<i>Overview.....</i>	<i>21</i>
6.1.2	<i>Airborne SA .....</i>	<i>21</i>
6.1.3	<i>Ground-based SA.....</i>	<i>21</i>
6.1.4	<i>Key Functions, Features, Characteristics and Capabilities .....</i>	<i>22</i>
6.1.5	<i>Expected Performance Benefits.....</i>	<i>22</i>
6.1.6	<i>Flight Phase.....</i>	<i>22</i>
6.1.7	<i>Contribution to JPDO Top-Level Goals and Objectives .....</i>	<i>22</i>
6.1.8	<i>Impacts to ASP System-Level Metrics .....</i>	<i>22</i>
6.2	TRAFFIC FLOW MANAGEMENT (TFM) .....	24
6.2.1	<i>Overview.....</i>	<i>24</i>
6.2.2	<i>Key Functions, Features, Characteristics and Capabilities .....</i>	<i>24</i>
6.2.3	<i>Expected Performance Benefits.....</i>	<i>24</i>
6.2.4	<i>Flight Phase.....</i>	<i>24</i>
6.2.5	<i>Contribution to JPDO NextGen Top-Level Goals and Objectives .....</i>	<i>24</i>
6.2.6	<i>Impacts to ASP System-Level Metrics .....</i>	<i>25</i>
6.3	DYNAMIC AIRSPACE CONFIGURATION (DAC) .....	26
6.3.1	<i>Overview.....</i>	<i>26</i>
6.3.2	<i>Key Functions, Features, Characteristics and Capabilities .....</i>	<i>27</i>
6.3.3	<i>Expected Performance Benefits.....</i>	<i>27</i>
6.3.4	<i>Flight Phase.....</i>	<i>27</i>
6.3.5	<i>Contribution to JPDO Top-Level Goals and Objectives .....</i>	<i>27</i>
6.3.6	<i>Impacts to System-level Metrics .....</i>	<i>27</i>
6.4	AIRSPACE SUPER DENSITY OPERATIONS (ASDO) .....	28
6.4.1	<i>Overview.....</i>	<i>28</i>
6.4.2	<i>Key Functions, Features, Characteristics and Capabilities .....</i>	<i>29</i>
6.4.3	<i>Expected Performance Benefits.....</i>	<i>29</i>
6.4.4	<i>Flight Phase.....</i>	<i>29</i>
6.4.5	<i>Contribution to JPDO Top-Level Goals and Objectives .....</i>	<i>30</i>
6.4.6	<i>Impacts to ASP System-Level Metrics .....</i>	<i>30</i>

6.5	COORDINATED ARRIVAL AND DEPARTURE OPERATIONS MANAGEMENT (CADOM) .....	31
6.5.1	Overview.....	31
6.5.2	Key Functions, Features, Characteristics and Capabilities .....	32
6.5.3	Expected Performance Benefits.....	32
6.5.4	Flight Phase.....	32
6.5.5	Contribution to JPDO Top Level Goals and Objectives.....	32
6.5.6	Impacts to ASP System-Level Metrics .....	32
6.6	SAFE AND EFFICIENT SURFACE OPERATIONS (SESO).....	33
6.6.1	Overview.....	33
6.6.2	Key Functions, Features, Characteristics and Capabilities .....	34
6.6.3	Expected Performance Benefits.....	34
6.6.4	Flight Phase.....	34
6.6.5	Contribution to JPDO Top Level Goals and Objectives.....	34
6.6.6	Impacts to ASP System-Level Metrics .....	35
6.7	AIRPORTAL AND METROPLEX INTEGRATION (AMI) .....	37
6.7.1	Overview.....	37
6.7.2	Key Functions, Features, Characteristics and Capabilities .....	37
6.7.3	Expected Performance Benefits.....	37
6.7.4	Flight Phase.....	37
6.7.5	Contribution to JPDO Top Level Goals and Objectives.....	37
6.7.6	Impacts to ASP System-Level Metrics .....	38
<b>7</b>	<b>SUMMARY AND CONCLUSIONS .....</b>	<b>39</b>
	<b>ANNEX A: EXAMPLE VALUES FROM SIMULATION RESULTS .....</b>	<b>40</b>
	<b>REFERENCES .....</b>	<b>45</b>

### List of Tables

Table 1—JPDO NextGen goals and objectives within the scope of NASA ASP research	4
Table 2—JPDO NextGen top-level metrics relevant to NASA ASP research .....	5
Table 3—Criteria for defining metrics used to evaluate NASA ASP research .....	6
Table 4—System-level capacity metrics .....	9
Table 5—System-level efficiency metrics.....	10
Table 6—System-level robustness metrics.....	12
Table 7—System-level safety metrics .....	15
Table 8—Evaluation of NASA ASP system-level metrics versus criteria.....	17
Table 9—SA system-level metrics .....	23
Table 10—TFM system-level metrics .....	26
Table 11—DAC system-level metrics .....	28
Table 12—ASDO system-level metrics.....	31
Table 13—CADOM system-level metrics.....	33
Table 14—SESO system-level metrics.....	35
Table 15—AMI system-level metrics .....	38

### List of Figures

Figure 1—26th Sept. 2006 Baseline Delays for All Flights .....	42
Figure 2—26th Sept. 2006 Baseline Delays for Commercial Passenger Flights .....	42
Figure 3—2008 TSAM Scenario Delays for All Flights .....	43
Figure 4—2008 TSAM Scenario Delays for Commercial Passenger Flights .....	43
Figure 5—2008 TSAM Scenario 99th-percentile of Delay for Commercial Passenger Flights .....	44

# 1 Introduction

This document defines an initial set of metrics for common use by the NASA Airspace Systems Program (ASP).

ASP research is directly addressing the fundamental research needs of the Next Generation Air Transportation System (NextGen) in partnership with the member agencies of the Joint Planning and Development Office (JPDO).<sup>[1]</sup>

ASP supports this effort through the NextGen-Airspace Project and the NextGen-Airportal Project. The work in each project is organized along multiple, discipline-level Research Focus Areas (RFAs) and a single, system-level RFA. Each discipline-level RFA is responsible for developing future concept elements in support of NextGen, as defined by the JPDO. The system-level RFA (called System-Level Design, Analysis, and Simulation Tools, or SLDAST) is responsible for integrating concept elements across the NextGen-Airspace and NextGen-Airportal projects and for assessing system-wide benefits.

To support those system-wide assessments, SLDAST is defining scenarios, assumptions, and metrics for common use by the NextGen-Airportal and NextGen-Airspace projects. This document defines those metrics. A companion document defines the scenarios and assumptions<sup>[2]</sup>.

The set of metrics consists of system-level metrics and top-level metrics associated with discipline-level research in each RFA.

System-level metrics measure National Airspace System (NAS) performance as a whole. RFA top-level metrics are specific to individual RFAs but measure characteristics that clearly and directly relate to the system-level metrics. RFA top-level metrics can be the same as the system-level metrics if applicable to the concept element.

## 1.1 Purpose of This Document

The primary purpose of this document is to define a common set of metrics for measuring NAS performance before and after the introduction of ASP-developed concepts and technologies designed to enable NextGen as the air transportation system handles increasing traffic. The metrics are directly traceable to JPDO NextGen goals and objectives<sup>[3]</sup> and will be useful for measuring the progress of ASP research in enabling NextGen. Monitoring this progress can then ensure that ASP research is on track toward achieving its targeted goals.

Use of a common set of metrics across ASP will focus its research toward achieving system-level performance goals and objectives and enable the discipline-level RFAs to understand the impact of their concepts at the system level.

Direct traceability of system-level metrics and top-level RFA metrics to JPDO goals and objectives will facilitate effective and consistent performance assessments of new ASP concepts developed within the RFAs.

Traceability will also allow ASP to demonstrate how the detailed technical work in each RFA benefits system-wide performance.

## **1.2 Users of This Document**

The primary users of this document are:

- SLDAST RFA researchers and staff
- Other discipline-level RFA researchers and staff

SLDAST researchers and staff will use the system-level metrics to measure NAS performance in system-wide assessments and integration-design studies.

Other discipline-level RFA researchers and staff will use top-level RFA metrics to measure the contribution of specific concepts to broader, system-level measures of NAS performance. They can also use this document as a guide to define detailed, lower-level RFA metrics to support concept development.

## **1.3 Document Scope**

The scope of this document is limited to the definition of metrics for measuring NAS capacity, efficiency, robustness, and safety.

## **1.4 Document Structure and Content**

Section 1 introduces the purpose, users, scope and structure of this document.

Section 2 identifies JPDO NextGen goals and objectives that are within the scope of NASA ASP research. Section 2 also identifies top-level, JPDO NextGen metrics that are relevant to measuring NASA ASP research.

Note—Definition of JPDO NextGen metrics is ongoing; the set of JPDO NextGen metrics currently available is incomplete.

Section 3 presents a set of criteria for defining “good” metrics. The criteria derive from several sources, including a May 2008 presentation to the JPDO by the JPDO Metrics Team <sup>[4]</sup>.

Note—JPDO metrics are in development; hence, a published reference does not exist.

Section 4 presents system-level metrics, developed using the criteria specified in Section 3.

Section 5 presents an analysis of system-level metrics in Section 4. This analysis consists of evaluating the metrics against the criteria listed in Section 3, including justification for metrics that do not meet specific criteria.

Section 6 presents an initial set of top-level RFA metrics that are traceable to the system-level metrics presented in Section 4 and to JPDO NextGen goals and objectives within the scope of the NASA ASP presented in Section 2.

Section 7 presents a summary and conclusions.

Annex A presents example values for many of the system-level metrics calculated from Airspace Concept Evaluation System (ACES) simulation results <sup>[5]</sup>.

## **2 JPDO NextGen Goals, Objectives, and Metrics**

Table 1 lists the full set of six JPDO goals, together with the corresponding objectives from <sup>[3]</sup>.

Note—Not all JPDO goals and objectives fall within the scope of the NASA ASP. JPDO NextGen goals and objectives that are within the scope of ASP are shaded.

Table 2 lists only those JPDO objectives that are within the scope of the NASA ASP. Table 2 further examines NextGen system-level metrics obtained from <sup>[4]</sup> for relevance to ASP. ASP will not always adopt the same or entire metric as the JPDO and may revise for clarity. However, ASP will retain the essential content of the JPDO's NextGen system level metrics.

**Table 1—JPDO NextGen goals and objectives within the scope of NASA ASP research**

<b>JPDO NextGen Goal 1 Retain U.S. leadership in global aviation.</b>	<b>JPDO NextGen Goal 2 Expand capacity.</b>	<b>JPDO NextGen Goal 3 Ensure safety.</b>	<b>JPDO NextGen Goal 4 Protect the environment.</b>	<b>JPDO Goal 5 Ensure our national defense.</b>	<b>JPDO Goal 6 Secure the Nation.</b>
<p>Objective 1.1: Retain our role as the world leader in aviation.</p> <p>Objective 1.2: Reduce costs for air transportation.</p> <p>Objective 1.3: Enable services tailored to traveler and shipper needs.</p> <p>Objective 1.4: Encourage performance-based, harmonized global standards for U.S. products and services.</p>	<p>Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.</p> <p>Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).</p> <p>Objective 2.3: Minimize impact of weather and other disruptions.</p>	<p>Objective 3.1: Maintain aviation’s record as safest mode of transportation.</p> <p>Objective 3.2: Improve level of safety of U.S. air transportation system.</p> <p>Objective 3.3: Increase level of safety of worldwide air transportation system.</p>	<p>Objective 4.1: Reduce noise, emissions, and fuel consumption.</p> <p>Objective 4.2: Balance aviation’s environmental impacts with other societal objectives.</p>	<p>5.1: Provide for common defense while minimizing civilian constraints.</p> <p>5.2: Coordinate a national response to threats.</p> <p>5.3: Ensure global access to civilian airspace.</p>	<p>6.1: Mitigate new and varied threats.</p> <p>6.2: Ensure security efficiently serves demand.</p> <p>6.3: Tailor strategies to threats, balancing costs and privacy issues.</p> <p>6.4 Ensure traveler and shipper confidence in system security.</p>

NOTE 1—JPDO NextGen goals and objectives supported by the NASA Airspace Systems Program are SHADED.

**Table 2—JPDO NextGen top-level metrics relevant to NASA ASP research**

<p><b>JPDO NextGen Goal 1</b>  <b>Retain U.S. leadership in global aviation.</b></p>	<p><b>JPDO NextGen Goal 2</b>  <b>Expand capacity.</b></p>	<p><b>JPDO NextGen Goal 3</b>  <b>Ensure safety.</b></p>	<p><i><b>JPDO NextGen Goal 4</b></i>  <i><b>Protect the environment.</b></i></p>
<p>Objective 1.2: Reduce costs for air transportation.</p> <ul style="list-style-type: none"> <li>o Metric 1.2: Projected percent reduction in total air-transportation-system (ATS)-related costs per instrument-flight-rules (IFR)-flight where total ATS-related costs equals the sum of the following costs: ATS operations + equipage (annualized) + aircraft delay + Airport Improvement Program (AIP) + non-AIP airport capacity enhancements.</li> </ul>	<p>Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.</p> <ul style="list-style-type: none"> <li>o Metric 2.1.a: The number of flights that are projected to be operated on a good-weather day. Metric 2.1.b.: The average delay for that number of flights operated over the range of weather days expected during the course of a year.</li> </ul> <p>Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).</p> <ul style="list-style-type: none"> <li>o Metric 2.2: Projected percentage reduction of average curb-to-curb travel time as affected by ASP.</li> </ul> <p>Objective 2.3: Minimize impact of weather and other disruptions.</p> <ul style="list-style-type: none"> <li>o <i>Metric 2.3: The JPDO has not defined a metric for measuring Objective 2.3.</i></li> </ul>	<p>Objective 3.1: Maintain aviation’s record as safest mode of transportation.</p> <ul style="list-style-type: none"> <li>o Metric 3.1: The JPDO has not defined a metric for Objective 3.1. The JPDO Metrics Working Group is developing a safety risk metric that takes into account the severity and likelihood of occurrence of identified hazards. See “A proposal for the Integration Of Safety in NextGen Planning.” [11]</li> </ul> <p>Objective 3.2: Improve level of safety of U.S. air transportation system.</p> <ul style="list-style-type: none"> <li>o Metric 3.2: <i>The JPDO has not defined a metric for Objective 3.2. The JPDO Metrics Working Group is developing a safety risk metric that takes into account the severity and likelihood of occurrence of identified hazards. See “A Proposal for the Integration of Safety in NextGen Planning.” [11]</i></li> </ul>	<p><i>Objective 4.1: Reduce noise, emissions, and fuel consumption.</i></p> <ul style="list-style-type: none"> <li>o <i>Metric 4.1: Projected percent reduction in number of people exposed to &gt;65 decibel (dB) Day-Night Average Sound Level (DNL) at top 96 airports.</i></li> </ul> <p><i>Objective 4.2: Balance aviation’s environmental impacts with other societal objectives.</i></p> <ul style="list-style-type: none"> <li>o <i>Metric 4.2: Projected percent improvement in fuel “efficiency” of the aircraft fleet in terms of fuel consumed per aircraft-kilometer flown for all IFR operations.</i></li> </ul>
<p><i>NOTE 1—JPDO NextGen goals, objectives, and metrics supported by the NASA Airspace Systems Program are SHADED.</i></p>			

### 3 Defining Criteria for “Good” Metrics

This section defines the criteria for developing “good” metrics based on a survey of metrics-related literature. Most of the criteria were adapted from a May 2008 presentation to the JPDO <sup>[4]</sup>. This follows from the alignment of NASA ASP research with JPDO NextGen goals and objectives. Other sources include <sup>[5], [6], [7], [8], and [9]</sup>.

The criteria provide the basis for the selection of system-level metrics (presented in Section 4) and for the RFA metrics (presented in Section 6) that will be used to evaluate ASP research. Table 3 lists the criteria for defining the metrics.

**Table 3—Criteria for defining metrics used to evaluate NASA ASP research**

No.	Criteria Definition
1	The metric provides a direct indicator of progress toward one of more strategic goals and objectives cited in “Section 2: JPDO NextGen Goals, Objectives, and Metrics” of this document.
2	The metric is clear and unambiguous.
3	The description includes measurement assumptions and definitions.
4	The metric is sensitive to changes introduced by implementing NextGen.
5	The metric is easily measured in simulation with valid and consistent results.
6	The metric can be used to measure the performance of future concepts and compared with current performance.
7	The metric is robust, so it is applicable over a range of assumptions and different future scenarios.
8	The metric is convertible to dollars, so that related costs or benefits can be readily valued in monetary terms.
9	The metric must not drive the system toward optimizing something other than the relevant strategic goals.
10	The metric provides useful information for influencing NextGen concept development decisions at the system level.
11	The metric is consistent within the set of metrics; no metric shall conflict with any other metric. (Metrics that measures progress towards the same goal must indicate the same outcome.)

Because not all JPDO goals and objectives are within the scope of NASA’s ASP research agenda (as shown previously in Table 1), not all JPDO NextGen criteria are relevant to the selection of metrics that will used to evaluate NASA ASP research.

RFA metrics are traceable to the system-level metrics and meet the same criteria as the corresponding system-level metric. Not all metrics need to meet all criteria—e.g., not all metrics convert impacts to a dollar value. A discussion of exceptions is in Section 5.

## 4 Developing System-Level Metrics to Evaluate NASA ASP Research

This section discusses general principles for analyzing the value of metrics for evaluating NASA ASP research.

### 4.1 Acceptable NAS Delay

The JPDO Metrics Working Group introduced the idea of a “system operating point” for the NAS<sup>[4]</sup>, beyond which delays become unacceptable. Capacity, therefore, becomes a function of throughput and delay.

Determining how much delay is acceptable is a subjective process. One approach is to apply current practice. Today, the FAA defines a flight as late if it arrives more than 15 minutes after the scheduled arrival time<sup>[10]</sup>. However, the airlines’ practice of including extra time in their published schedules to accommodate anticipated delays is a complicating factor.

NASA’s Advanced Concepts Evaluation System (ACES)<sup>[5]</sup> determines delay by comparing a simulated NAS trajectory with an unimpeded ideal trajectory. Thus, using the 15-minute value for an ACES simulation is not strictly justified. However, it is necessary to define acceptable delay. Therefore, the NASA ASP uses the following definition:

- Mean delay must not exceed 15 minutes during any 1-hour period.
- The 95th-percentile of delay must not exceed 30 minutes during any 1-hour period.
- The 99th-percentile of delay must not exceed 60 minutes during any 1-hour period.

In addition, it is important to distinguish between *delay to commercial flights* and *delay to all flights*. Including non-commercial flights in the calculation of mean delay can be misleading, since many non-commercial flights use small, uncongested airports and will bias the delay results toward lower values. Therefore, it is necessary to calculate delay to all flights and to commercial passenger flights only; both must satisfy all conditions.

Accordingly, capacity metrics must be based on a common definition of acceptable delay that defines the system operating point. This will allow for consistent representation of future capacity impacts of new ASP concepts.

Simulation of any concept or synthesis of concepts using the ASP common scenarios<sup>[2]</sup> enables the system operating point to be determined. The common scenarios demand increments are 0.5X of the baseline demand; a curve fit between 0.5X increments should be sufficiently accurate to determine the operating point at which delay becomes unacceptable.

### 4.2 Estimating NAS Performance

ACES is the primary NAS-wide simulation used to estimate both current and future NAS performance. Currently, ACES simulates instrument flight rules (IFR) flights only, including general aviation flights that fly IFR.

Comparison of performance metrics with future concepts to a reference day’s performance representative of the current system without future concepts allows assessment of benefits. The

reference day is a good weather, high-volume day without any key system failures as defined in [2].

### **4.3 Calculating Metric Values and Performing Statistical Analysis**

Most non-commercial flights fly into small, uncongested airports and, thus, experience low-average delays. Commercial flights, on the other hand, can experience much higher average delays. Therefore, to avoid a biased result, it is necessary to calculate metric values for all flights separately from metric values for commercial passenger flights.

Calculation of the total, mean, 95th, and 99th-percentile values of metrics is required for metrics that have a distribution of values.

Reporting the corresponding values for metrics stated as a ratio or percentage is required for context. It is insufficient to report a factor or percentage improvement only, because this gives no indication of the significance of the improvement.

Metrics values will be calculated and annualized over the range of weather days (good to bad) and traffic volumes (low to high) expected during the course of a year as defined in [2].

### **4.4 Estimating NAS Capacity**

Throughput is defined as the number of flights or the number of passengers or tonnage of freight transported during the time of interest to the researchers—i.e., typically a year of NAS operations or day of simulated operations.

The scope of NASA ASP research is gate-to-gate. Therefore, NASA ASP research focuses on aircraft-related concepts. In contrast, the JPDO NextGen scope of research is curb-to-curb. Therefore, some JPDO metrics measure benefits related to airport-side improvements. One such metric is JPDO Metric 2.2: “Projected percent reduction of average curb-to-curb travel time.” This metric can include the value of improvements to security procedures for example that decrease passenger curb-to-gate times.

Even though NASA ASP research focuses on aircraft-related concepts, the NAS exists to transport passengers and cargo, not merely to move aircraft around, per se.

There are different viable scenarios that can transport the demand of passengers and cargo in the NAS. Alternate future scenarios can use different numbers and sizes of aircraft to transport the same future demand. Therefore, it is important to have capacity metrics that track passengers and cargo in addition to metrics for tracking aircraft. Scenarios that use larger aircraft and more routes that are direct may allow transport of more passengers from origin-to-destination for the same system operating point.

Table 4 lists system-level capacity metrics defined in terms of throughput within the acceptable delay limits specified in Section 4.1 “Acceptable NAS Delay.” The metrics relate directly to the following JPDO NextGen goal and objectives:

- Goal 2: Expand capacity.

- o Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.

**Table 4—System-level capacity metrics**

No.	NASA ASP	JPDO NextGen		Comment/how calculated
	Metric	Goal/objective	Metric	
<b>ASP-C1</b>	The number of flights that can be operated on a good-weather day within the delay limits specified in Section 4.1.	Goal 2: Expand capacity. Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.	Metric 2.1.a: The number of flights that are projected to be operated on a good-weather day.	Same metric as JPDO NextGen.  Obtained from ACES output, using common scenarios in 0.5X demand increments.
<b>ASP-C2</b>	The number of passenger origin-to-destination trips that can be operated on a good-weather day within the delay limits specified in Section 4.1.	Goal 2: Expand capacity. Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.	N/A	Metric ASP-C2 is not redundant to ASP-C1 since it depends on fleet mix and route structure.  Obtained from demand analysis.
<b>ASP-C3</b>	The freight tonnage that can be transported on a good-weather day within the delay limits specified in Section 4.1.	Goal 2: Expand capacity. Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.	N/A	Obtained from demand analysis.

## 4.5 Estimating NAS Efficiency

Table 5 defines system-level efficiency metrics in terms of reduction in trip times and fuel usage attributable to NextGen improvements. The efficiency metrics relate directly to the following JPDO NextGen goals and objectives:

- Goal 1: Retain U.S. leadership in global aviation.
  - o Objective 1.2 Reduce costs for air transportation.
- Goal 2: Expand capacity.
  - o Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).
- Goal 4: Protect the environment.
  - o Objective4.1: Reduce noise, emissions and fuel consumption.

**Table 5—System-level efficiency metrics**

NASA ASP		JPDO NextGen		Comment/how calculated
No.	Metric	Goal/objective	Metric	
<b>ASP-E1</b>	The reduction in gate-to-gate aircraft transit time.	<p>Goal 1: Retain U.S. leadership in global aviation.</p> <ul style="list-style-type: none"> <li>○ Objective 1.2 Reduce costs for air transportation.</li> </ul> <p>Goal 2: Expand capacity.</p> <ul style="list-style-type: none"> <li>○ Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%)</li> </ul>	Metric 2.2: Projected percent reduction of average curb-to-curb travel time as affected by NASA ASP.	<p>Concurrent with capacity increase.</p> <p>Obtained directly from ACES output.</p>
<b>ASP-E2</b>	The reduction in gate-to-gate passenger origin-to-destination trip time.	<p>Goal 1: Retain U.S. leadership in global aviation.</p> <ul style="list-style-type: none"> <li>○ Objective 1.2 Reduce costs for air transportation.</li> </ul> <p>Goal 2: Expand capacity.</p> <ul style="list-style-type: none"> <li>○ Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).</li> </ul>	Metric 2.2: Projected percent reduction of average curb-to-curb travel time as affected by NASA ASP.	<p>Measures the time saved by more direct routing.</p> <p>Obtained from ACES output combined with demand analysis.</p>
<b>ASP-E3</b>	The reduction in fuel usage of the aircraft fleet in terms of fuel consumed per aircraft nautical mile.	<p>Goal 1: Retain U.S. leadership in global aviation.</p> <ul style="list-style-type: none"> <li>○ Objective 1.2 Reduce costs for air transportation.</li> </ul> <p>Goal 4: Protect the environment.</p> <ul style="list-style-type: none"> <li>○ Objective 4.1: Reduce noise, emissions, and fuel consumption.</li> </ul>	Metric 4.1: Projected percent improvement in fuel efficiency of the aircraft fleet in terms of fuel consumed per aircraft-kilometer-flown for all IFR operations.	Obtained directly from ACES output.

NASA ASP		JPDO NextGen		Comment/how calculated
No.	Metric	Goal/objective	Metric	
ASP-E4	The reduction in fuel usage of the aircraft fleet in terms of fuel consumed per passenger nautical mile flown	Goal 1: Retain U.S. leadership in global aviation. <ul style="list-style-type: none"> <li>○ Objective 1.2 Reduce costs for air transportation.</li> </ul> Goal 4: Protect the environment. <ul style="list-style-type: none"> <li>○ Objective 4.1: Reduce noise, emissions, and fuel consumption.</li> </ul>	N/A	Measures the benefit of using larger aircraft that are generally more efficient per passenger mile. Obtained from ACES output combined with demand analysis.
ASP-E5	The reduction in fuel usage of the aircraft fleet in terms of fuel consumed per passenger origin-to-destination great-circle nautical miles.	Goal 1: Retain U.S. leadership in global aviation. <ul style="list-style-type: none"> <li>○ Objective 1.2 Reduce costs for air transportation.</li> </ul> Goal 4: Protect the environment. <ul style="list-style-type: none"> <li>○ Objective 4.1: Reduce noise, emissions, and fuel consumption.</li> </ul>	N/A	Measures the fuel savings of more direct routing, compared to using connections. Obtained from ACES output combined with demand analysis.
ASP-E6	The reduction in fuel usage of the aircraft fleet in terms of fuel consumed per freight ton nautical mile flown.	Goal 4: Protect the environment. <ul style="list-style-type: none"> <li>○ Objective 4.1: Reduce noise, emissions, and fuel consumption.</li> </ul>	N/A	Obtained from ACES output combined with demand analysis.

## 4.6 Estimating NAS Robustness

Table 6 presents system-level robustness metrics defined in terms that compare system performance under good weather and nominal operating conditions with system performance under less-than-nominal conditions. These conditions include extreme weather (e.g., hurricanes), system-level failures and emergencies, and a range of weather conditions routinely encountered throughout the year.

System robustness is not an explicit goal of the JPDO. However, the efficiency metrics defined here directly relate to the following JPDO NextGen goal and objectives:

- Goal 2: Expand capacity.
  - Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).
  - Objective 2.3: Minimize impact of weather and other operations.

Both objectives address robust system operation. Robustness is also a vital characteristic for achieving other JPDO NextGen goals:

- Goal 1: Retain U.S. leadership in global aviation.
- Goal 3: Ensure safety.
- Goal 4: Protect the environment.

Consequently, SLDAST will measure changes to certain robustness metrics between a baseline system state, and the projected future state employing new, ASP-developed concepts.

**Table 6—System-level robustness metrics**

No.	NASA ASP	JPDO NextGen		Comment/how calculated
	Metric	Goal/objective	Metric	
<b>ASP-R1</b>	The ratio of ASP capacity metrics for poor weather and/or system failure scenarios, within the delay limits specified in Section 4.1 compared with the good weather, nominal operating conditions scenario.	Goal 2: Expand capacity. <ul style="list-style-type: none"> <li>o Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).</li> <li>o Objective 2.3: Minimize impact of weather and other disruptions.</li> </ul>	N/A	Concepts that show less capacity reduction are more robust.  Obtained from ACES output, using common scenarios in 0.5X demand increments.
<b>ASP-R2</b>	The mean gate-to-gate delay for the good-weather number of flights, flown over the range of weather days expected in the course of a year.	Goal 2: Expand capacity. <ul style="list-style-type: none"> <li>o Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.</li> <li>o Objective 2.3: Minimize impact of weather and other disruptions.</li> </ul>	Metric 2.1.b: The average delay for that number of flights operated over the range of weather days expected during the course of a year.	Same metric as JPDO.  Obtained from ACES output using the five common weather day scenarios.

NASA ASP		JPDO NextGen		Comment/how calculated
No.	Metric	Goal/objective	Metric	
ASP-R3	The variance of gate-to-gate delay for the good-weather number of flights, for the poor weather and/or system failure scenarios, compared with the good weather, normal operating conditions scenario.	Goal 2: Expand capacity. <ul style="list-style-type: none"> <li>o Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).</li> </ul>	N/A	Measures predictability of travel times and how this degrades.  Obtained from ACES output.

## 4.7 Estimating NAS Safety

The JPDO Safety Working Group (SWG) has proposed an approach for integrating safety into NextGen planning. The approach is described in the document, *A Safety Working Group Proposal for the Integration of Safety in NextGen Planning* <sup>[11]</sup>. Key points include:

- Safety must be accounted for when estimating NextGen benefits.
- Two safety assessment tiers are proposed. They are:
  - o Focus on operational hazards by performing a concept hazard assessment for each proposed operational improvement.
  - o Perform a capability safety assessment that will focus integrating a set of operational improvements within a larger operational context.
- Data-driven, quantitative assessments will be made where possible. When this is not possible, qualitative assessments will be made based on subject matter expertise.

Risk analysis is a common technique for examining safety issues for airspace systems. Safety issues undergoing research in the NASA ASP relate to risks associated with aircraft collisions with other aircraft, birds, terrain, and static objects as well as to risks associated with aircraft encounters with severe weather and atmospheric/wake turbulence.

FAA Order 8040.4 defines a hazard as “a condition, event, or circumstance that could lead to or contribute to an unplanned or undesirable event.”

The notion of risk is a product of the likelihood of the event and the severity of the consequences. Combining the severity of consequence with the likelihood of occurrence in a matrix gives an assessment of risk. The FAA defines five categories of “consequence” as the following:

1. Catastrophic
2. Hazardous
3. Major
4. Minor
5. No safety effect

The FAA also defines four categories of “likelihood.” Each has an associated probability of occurrence per-operational-hour. The four categories of likelihood are the following:

1. Probable
2. Remote
3. Extremely remote
4. Extremely improbable

Although the assessment of consequence is subjective, the FAA gives clear guidelines. For example, the FAA defines “catastrophic” as “results in multiple fatalities and/or loss of the system.” The likelihood of a hazardous event for future concepts is usually difficult to quantify due to lack of data. However, it may be possible to estimate the probable range of the likelihood value based on simulation data that is validated using similar, current operational concept data. If such data are not available, a qualitative assessment based on subject matter expertise must be made. The JPDO SWG allows either, with an obvious preference for the data-driven approach.

Validation of simulation results is often problematic, and the use of subject matter opinion becomes unreliable when the future concept differs from current concepts. Therefore, it is important to use caution when estimating the likelihood of a hazardous event. Careful attention to the development process and use of advanced techniques (such as formal analysis) contribute to a safe design and should be used to the fullest extent possible. Thus, for these reasons, defining safety metrics that meet the criteria in Section 3 is not a straightforward process.

#### **4.7.1 Justifying the Selection of System-Level Safety Metrics**

This section presents a justification for the system-level safety metrics in Table 7.

The paradigm for addressing uncertainty related to collision risk is to utilize protection zones around aircraft and exclusion zones around weather, which are sized appropriately to allow for uncertainty. Intrusion into a zone constitutes a loss of separation (LoS).

Such LoS then, by definition, constitutes a safety incident without necessarily resulting in an actual collision. Therefore, LoS, by definition, serves as a surrogate for a safety metric, although it does not measure safety directly. The direct measure would be the number of collisions. However, it is not possible for ASP to measure collision metrics in simulation. Therefore, safety metrics S1–S3 in Table 7 are, by necessity, only precursors and represent necessary-but-insufficient criteria for an accident to occur.

The problem with defining safety metrics in this way is that there is no operational data available for future concepts. Therefore, it is not possible to correlate precursors to actual accidents. Furthermore, obtaining safety precursor data from simulation is difficult. System-level simulations, such as ACES, can collect these metrics. However, validation requires high fidelity simulation, which is likely to be computationally intensive, and because LoS are rare, require large amounts of simulation time to collect.

The metrics ASP-S4, “Consequence of hazardous event,” and ASP- S5, “Likelihood of hazardous event,” are included in accordance with the FAA and JPDO approach to risk analysis, although it may be difficult for the NASA ASP to obtain accurate estimates of likelihood.

**Table 7—System-level safety metrics**

NASA ASP		JPDO NextGen		Comment/how calculated
No.	Metric	Goal/objective	Metric	
<b>ASP-S1</b>	Number of losses of separation with traffic or weather.	Goal 3: Ensure safety. <ul style="list-style-type: none"> <li>o Objective 3.1: Maintain aviation’s record as safest mode of transportation.</li> <li>o Objective 3.2: Improve level of safety of U.S. air transportation system.</li> </ul>	N/A	This is a hazardous event.  Measure initially using ACES, then verify in high fidelity air-traffic operations laboratory.
<b>ASP-S2</b>	Time to predicted loss of separation from time of conflict detection.	Goal 3: Ensure safety. <ul style="list-style-type: none"> <li>o Objective 3.1: Maintain aviation’s record as safest mode of transportation.</li> <li>o Objective 3.2: Improve level of safety of U.S. air transportation system.</li> </ul>	N/A	This is an indicator of the probability of a missed detection.  Measure initially using ACES, then verify in high fidelity air-traffic operations laboratory.
<b>ASP-S3</b>	Variance of closest point of approach for resolved conflicts.	Goal 3: Ensure safety. <ul style="list-style-type: none"> <li>o Objective 3.1: Maintain aviation’s record as safest mode of transportation.</li> <li>o Objective 3.2: Improve level of safety of U.S. air transportation system.</li> </ul>	N/A	The closest point-of-approach is not a good indicator of safety, since an efficient system will minimize separations. Higher variance <b>may</b> indicate lower reliability of the conflict resolutions.  Measure initially using ACES, then verify in high fidelity air-traffic operations laboratory.

NASA ASP		JPDO NextGen		Comment/how calculated
No.	Metric	Goal/objective	Metric	
ASP-S4	Consequence of hazardous event.	Goal 3: Ensure safety. <ul style="list-style-type: none"> <li>o Objective 3.1: Maintain aviation’s record as safest mode of transportation.</li> <li>o Objective 3.2: Improve level of safety of U.S. air transportation system.</li> </ul>	This is consistent with JPDO approach <sup>[11]</sup> .	Based on FAA consequence categories.  Determine from safety analysis.
ASP-S5	Likelihood of hazardous event.	Goal 3: Ensure safety.  Objective 3.1: Maintain aviation’s record as safest mode of transportation.  Objective 3.2: Improve level of safety of U.S. air transportation system.	This is consistent with JPDO approach <sup>[11]</sup> .	Based on similar current operational concept data, simulation data or use subject matter expert opinion.  Determine from safety analysis.

## 5 Evaluating System-Level Metrics

This section evaluates system-level metrics for measuring capacity, efficiency, robustness, and safety (which were discussed in Section 4) using the criteria for “good” metrics (which were defined in Section 3). The evaluation is presented in Table 8 and in subsequent comments that reference the table. The system-level metrics need not meet all criteria to be useful. In addition, some criteria may not be relevant to a particular system-level metric. If a system-level metric does not meet the criteria for a good metric, an explanation is given.

**Table 8—Evaluation of NASA ASP system-level metrics versus criteria**

No.	ASP capacity, efficiency, robustness, and safety metrics																
	ASP-C1	ASP-C2	ASP-C3	ASP-E1	ASP-E2	ASP-E3	ASP-E4	ASP-E5	ASP-E6	ASP-R1	ASP-R2	ASP-R3	ASP-S1	ASP-S2	ASP-S3	ASP-S4	ASP-S5
1																	
2																	
3																	
4													G				Q
5													H	J	M		R
6														K	N		S
7													I				T
8	A	C	D							E		F					
9	B														O		
10														L	P		
11																	
<b>Fully Meets</b>				<b>Partly Meets</b>				<b>Does not meet</b>					<b>Not Relevant</b>				
<p>NOTE 1—The notations ASP-C1–ASP-S5 in the white row reference capacity, efficiency, robustness, and safety metrics defined in Section 4 and specifically in:</p> <ul style="list-style-type: none"> <li>○ Table 4—System-level capacity metrics (ASP-C1, ASP-C2, ASP-C3)</li> <li>○ Table 5—System-level efficiency metrics (ASP-E1, ASP-E2, ASP-E3, ASP-E4, ASP-E5, ASP-E6)</li> <li>○ Table 6—System-level robustness metrics (ASP-R1, ASP-R2, ASP-R3)</li> <li>○ Table 7—System-level safety metrics (ASP-S1, ASP-S2, ASP-S3, ASP-S4, ASP-S5)</li> </ul> <p><span style="color: red;">■</span> <span style="color: orange;">■</span> NOTE 2—The notations A-T in the gold and red cells reference comments in Section 5.1 (which follows).</p> <p><span style="background-color: #fce4ec;">■</span> NOTE 3—The notations 1-11 in the pink column reference criteria 1–11 (“No.”) described in Table 3: Criteria for Defining Metrics Used to Evaluate ASP Research.</p>																	

The following comments reference notations A–T in the yellow and red cells of Table 8.

- A. Capacity metric ASP-C1 does not fully meet Criteria No. 8 because it is not easy to obtain a monetary value for a flight. The increase in capacity expected to derive from NextGen in terms of number of additional flights accommodated is financially beneficial, but it would be difficult to quantify.
- B. Capacity metric ASP-C1 does not fully meet Criteria No. 9 because it measures capacity in units of the number of aircraft. This potentially drives the system toward maximizing the number of aircraft rather than maximizing the transport of the passengers and cargo.
- C. Capacity metric ASP-C2 does not fully meet Criteria No. 8 because it is not easy to obtain the average monetary value of a passenger trip.
- D. Capacity metric ASP-C2 does not fully meet Criteria No. 8 because it is not easy to obtain the average monetary value of a ton of freight.
- E. Robustness metric ASP-R1 does not fully meet Criteria No. 8. The same problems apply as for capacity metrics, with respect to the difficulty of obtaining a monetary value. See “A,” above.
- F. Robustness metric ASP-R3 does not meet Criteria No. 8. It is not possible to convert variance in gate-to-gate time to a monetary value.
- G. Safety metric ASP-S1 does not meet Criteria No. 4. Loss-of-separation occurs infrequently for any reasonable concept, so this metric is not very sensitive in that it will be difficult to obtain statistically meaningful results to compare concepts.
- H. Safety metric ASP-S1 does not meet Criteria No. 5. It requires high fidelity, computationally intensive simulation with numerous runs to provide valid and consistent results. It is therefore not easy to measure.
- I. Safety metric ASP-S1 does not fully meet Criteria No. 7. Losses-of-separation are likely to be sensitive to modeling assumptions. Lower fidelity simulation may lead to more (or possibly fewer) losses-of-separation than would be the case in high-fidelity simulation or in actual service.
- J. Safety metric ASP-S2 does not fully meet Criteria No. 5. Conflicts occur much more frequently than losses-of-separation, so this metric is easier to measure than S1. However, it still requires high-fidelity simulation to ensure validity.
- K. Safety metric ASP-S2 does not fully meet Criteria No. 6. It may not be possible to compare this metric with current system performance.
- L. Safety metric ASP-S2 does not fully meet Criteria No. 10. It may not be of interest at the system level.

- M. Safety metric ASP-S3 does not fully meet Criteria No. 5 because it requires high-fidelity simulation to ensure validity.
- N. Safety metric ASP-S2 does not fully meet Criteria No. 6. It may not be possible to compare this metric with current system performance.
- O. Safety metric ASP-S3 does not fully meet Criteria No. 9. This metric could induce a false goal, because reducing the variance of closest point-of-approach may not be an indicator of improved safety.
- P. Safety metric ASP-S3 does not fully meet Criteria No. 10. It may not be of interest at the system level.
- Q. Safety metric ASP-S5 does not fully meet Criteria No. 4. It may be difficult to measure likelihood, so may not be sensitive to changes to current system operations.
- R. Safety metric ASP-S5 does not fully meet Criteria No. 5. It may not be possible to use simulation to measure reliably the likelihood of a hazardous event associated with a future concept.
- S. Safety metric ASP-S5 does not fully meet Criteria No. 6. It may be difficult to measure likelihood, so it may not be possible to compare this metric with current system performance.
- T. Safety metric ASP-S5 does not meet Criteria No. 7. The estimate of likelihood could be very sensitive to assumptions.

## 5.1 Discussion

The capacity, efficiency, and robustness metrics meet the majority of the criteria defined in Section 3. However, capacity metrics are not easy to convert to a monetary value, although this may be of more importance to the JPDO than to the NASA ASP.

Capacity metric *ASP-C1*: *The number of flights that can be operated on a good weather day within the delay limits specified in Section 4.1* can drive the system toward a false goal if used unwisely. However, with sensible interpretation, it can be a useful metric. (A hypothetical example of using this metric unwisely might be to rate a concept highly because it made use of a large number of small aircraft to increase airport capacity. Small aircraft require less wake separation from other small aircraft, and thus they increase airport throughput in terms of operations. However, they are not likely to increase passenger throughput when compared to using a smaller number of larger aircraft.)

The safety metrics are more problematic; they fail several criteria. The best safety metric is *ASP-S1*: *Number of losses of separation with traffic or weather*. A concept that results

in a significant number of losses of separation is unsafe by definition, because safety concerns directly drive separation standards.

However, loss-of-separation must occur infrequently if the concept is useful, so it is difficult to measure with statistical significance. The validity of this metric is dependent on the availability of high-fidelity simulation.

Safety metric ASP-S2: Time to predicted loss of separation from time of conflict detection and safety metric ASP-S3: Variance of closest point of approach for resolved conflicts are easier to measure, because conflicts occur much more frequently than losses-of-separation. However, it is difficult to establish a direct link between these metrics and safety. Even so, these metrics may be the best that we can obtain from simulation and they relate to collisions in a logical and direct way.

Safety metric ASP-S4: *Consequence of hazardous event* is a useful metric to evaluate for any concept. The FAA consequence categories in Order 8040.4 include clear guidelines on how to categorize events. However, it may require extensive analysis to determine the set of possible hazardous events for a NextGen concept.

Safety metric ASP-S5: *Likelihood of a hazardous event* is the companion to ASP-S4: *Consequence of hazardous event* and is much more difficult to estimate. It may prove impossible for NASA ASP to evaluate this metric reliably for some or all of the NextGen concepts.

Even so, the metric ASP-S4: *Consequence of hazardous event* alone is a useful indicator. If a concept has potential for one or more hazardous events in the catastrophic category, this indicates that the concept requires scrutiny.

## 6 System-Level RFA Metrics

This section presents top-level RFA metrics for the NextGen-Airspace and NextGen-Airportal projects. Top-level RFA metrics shall be an indicator of system-level performance and shall address one or all of capacity, efficiency, robustness and safety. The RFAs likely need lower level concept-specific metrics to evaluate concept development but these are not the subject of this document.

NextGen-Airspace Project RFAs are the following:

- Dynamic Airspace Configuration (DAC)
- Traffic Flow Management (TFM)
- Separation Assurance (SA)
- Airspace Super Density Operations (ASDO)
- System-Level Design, Analysis, and Simulation Tools (SLDAST)

NextGen-Airportal Project RFAs are the following:

- Safe and Efficient Operations (SESO)
- Coordinated Arrival and Departure Operations Management (CADOM)

- Airportal and Metroplex Integration (AMI)

## **6.1 Separation Assurance (SA)**

### **6.1.1 Overview**

The SA RFA is addressing airspace capacity barriers arising from human workload issues related to responsibility for maintaining separation assurance by utilizing sequential processing of sequence and merging with separation for transition and cruise airspace. SA research consists of the following elements:

- A strategic conflict detection and resolution algorithm that uses aircraft intent information (planned trajectory) to detect and resolve conflicts predicted to occur up to about 30 minutes in the future.
- A tactical conflict detection and resolution algorithm that uses aircraft state information; may use limited intent information to detect and resolve conflicts predicted to occur up to about 5 minutes in the future.

The SA concept uses automation to detect conflicts and determine resolution maneuvers. There are two distinct concept variants; a centralized ground-based system and a distributed flight deck based system. On-going research will determine the allocation of SA functions between ground control and the aircraft.

Both concept variants rely on GPS for navigation and ADS-B to provide aircraft position and intent information. The Traffic Alert and Collision Avoidance System (TCAS) remains the system of last resort to prevent collisions.

### **6.1.2 Airborne SA**

The flight deck system has access to current-state and trajectory-intent data for aircraft within Automatic Dependent Surveillance-Broadcast (ADS-B) range (nominally 150 nm). ADS-B-equipped aircraft operate autonomously using automation to detect conflicts and calculate conflict-free resolution maneuvers. The flight crew selects from one or more resolutions for execution by the Flight Management System (FMS). The crew may request a different resolution or use tactical control to resolve the conflict, if necessary.

A description of the flight deck based concept is available in <sup>[12]</sup>.

### **6.1.3 Ground-based SA**

The ground-based system potentially has access to all of the NAS aircraft current state and trajectory intent data. ADS-B ground stations relay aircraft data to the centralized automation. The region of control of the automation could be center-wide or possibly the entire NAS. The automation system detects conflicts and then calculates a conflict-free resolution maneuver. This trajectory is uplinked to the aircraft for execution by the FMS after acceptance by the pilot. Controllers on the ground monitor the automation and may intervene, if necessary.

A description of the ground-based concept is available in <sup>[13]</sup>.

#### **6.1.4 Key Functions, Features, Characteristics and Capabilities**

Both ground-based and airborne concept variants rely on automation to detect conflicts and calculate resolutions using strategic and tactical algorithms. In normal operation, controllers do not resolve conflicts and do not need to give verbal directives to aircraft.

#### **6.1.5 Expected Performance Benefits**

The SA concept variants can increase airspace capacity by removing the human-workload limitations of the current controller-based system. This can potentially allow a larger number of aircraft to use regions of airspace, with less need for diversions. This can lead to reduced delays, shorter flight times, and less variability in gate-to-gate arrival times.

#### **6.1.6 Flight Phase**

The automated SA concept variants affect the en route phase of flight.

#### **6.1.7 Contribution to JPDO Top-Level Goals and Objectives**

The SA concept contributes to the following JPDO NextGen goals and objectives:

- Goal 1: Retain U.S. leadership in global aviation.
  - Objective 1.2: Reduce costs for air transportation.
- Goal 2: Expand capacity.
  - Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.
  - Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).
  - Objective 2.3: Minimize impact of weather and other disruptions
- Goal 3: Ensure safety.
  - Objective 3.2: Improve level of safety of U.S. air transportation system
- Goal 4: Protect the environment.
  - Objective 4.1: Reduce noise, emissions, and fuel consumption.

#### **6.1.8 Impacts to ASP System-Level Metrics**

ASP-C1: Automated SA increases en route airspace capacity by removing the en route sector workload constraint.

ASP-S1: Automated SA prevents losses of separation that may otherwise have occurred at traffic levels that exceed human workload constraints.

ASP-S2: Automated SA reduces the probability of a missed conflict detection that may otherwise have occurred at traffic levels that exceed human workload constraints.

ASP-S4: Automated SA has potential for hazardous events that are different from the current system - the consequences of these needs to be determined from a safety analysis.

ASP-S5: Automated SA has potential for hazardous events that are different from the current system - the likelihood of these needs to be determined from a safety analysis.

**Table 9—SA system-level metrics**

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>Capacity/ SA-C1</b>	Ratio of ASP-C1 with and without automated SA.	ASP-C1: The number of flights that can be operated on a good weather day within the delay limits specified in Section 4.1.	Airspace capacity will primarily be limited by delays due to resolution maneuvers. (An accurate determination of the number of LoS requires high-fidelity simulation.) Determined from ACES simulation.
<b>Capacity/ SA-C2</b>	Ratio of maximum traffic density with and without automated SA.	ASP-C1: The number of flights that can be operated on a good weather day within the delay limits specified in Section 4.1.	Either unacceptable numbers of resolutions (efficiency) or unacceptable likelihood of LoS (safety) will limit traffic density. Determined from high-fidelity simulation.
<b>Safety/ SA-S1</b>	Ratio of ASP-S1 with and without automated SA.	ASP-S1: Number of losses of separation with traffic or weather.	The safety of automated SA should be at least that of current SA, but should allow higher traffic densities. HITL <sup>1</sup> experiments may provide data for comparison with the current system.
<b>Safety/ SA-S2</b>	Ratio of ASP-S2 with and without automated SA.	ASP-S2: Time to predicted loss of separation from time of conflict detection.	The safety of automated SA should be at least that of current SA, but should allow higher traffic densities. HITL experiments may provide data for comparison with the current system.
<b>Safety/ SA-S3</b>	Consequence of hazardous event.	ASP-S4: Consequence of hazardous event.	Based on FAA Order 8040.4. Determined from safety analysis.
<b>Safety/ SA-S4</b>	Ratio of ASP-S5 with and without automated SA for hazardous events: - LoS	ASP-S5: Likelihood of hazardous event.	Automated SA should reduce the Likelihood of LoS at increased traffic levels compared to the current system. HITL experiments may provide data for comparison with the current system.

1. HITL - Human In The Loop

## **6.2 Traffic Flow Management (TFM)**

### **6.2.1 Overview**

The TFM concept uses a sequential optimization technique to manage air traffic flow under uncertainty in airspace capacity and demand.

A deterministic integer-programming model assigns delays to aircraft under en route capacity constraints. The model assigns only departure controls, and a tactical control loop consisting of a shortest-path routing algorithm and an airborne delay algorithm refines the strategic plan to keep flights from deviating into capacity-constrained airspace.

A description of the TFM concept is available in <sup>[14]</sup>.

### **6.2.2 Key Functions, Features, Characteristics and Capabilities**

TFM is focused on modifying airspace/airports capacity by using multiple optimization techniques to adjust demand through departure times, route modification, adaptive speed control, etc., in the presence of uncertainty. The TFM concept uses sequential traffic flow optimization to achieve optimal departure control assignment with an integer-programming model. Weather avoidance uses Dijkstra's algorithm with convective weather translation.

### **6.2.3 Expected Performance Benefits**

The TFM concept minimizes departure delays subject to weather-impacted airport and airspace capacity constraints. The concept enables better use of weather-impacted airspace through integrated ground and airborne flight controls and improves estimates of weather affected sector capacities. This allows more flights within acceptable delay limits and thus increases system capacity.

### **6.2.4 Flight Phase**

The TFM concept affects the pre-departure and en route phases of flight.

### **6.2.5 Contribution to JPDO NextGen Top-Level Goals and Objectives**

The TFM concept contributes to the following JPDO NextGen goals and objectives:

- Goal 1: Retain U.S. leadership in global aviation.
  - Objective 1.2: Reduce costs for air transportation.
- Goal 2: Expand capacity.
  - Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.
  - Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).
  - Objective 2.3: Minimize impact of weather and other disruptions
- Goal 3: Ensure safety.
  - Objective 3.2: Improve level of safety of U.S. air transportation system

- Goal 4: Protect the environment.
  - Objective 4.1: Reduce noise, emissions, and fuel consumption.

### **6.2.6 Impacts to ASP System-Level Metrics**

The TFM concept is a system-wide concept. Therefore, all TFM RFA top-level metrics correspond to ASP system-level metrics.

ASP-C1: Some delay will exist even on a good-weather day due to demand exceeding capacity at some airports or in airspace regions for some periods during the day. Therefore, TFM may provide some increase in capacity even under good-weather conditions.

ASP-E1: The TFM concept assigns optimal departure delays and shortest-path reroutes to flights subject to en route weather induced capacity constraints. As a result, the gate-to-gate aircraft transit times for such flights is reduced compared to current day operations, which relies on a collection of ground delay programs, airspace flow programs, and national-level reroutes that may not be optimal.

ASP-E3: The TFM concept uses a shortest-path rerouting algorithm for identifying flight paths that deviate around en route weather hazards. These routes result in reduced fuel usage of the aircraft fleet over current day operations.

ASP-R1: The TFM concept assigns optimal departure delays and shortest-path reroutes that improve schedule robustness by reducing delays due to weather and other disruptions compared to current day operations.

ASP-S1: The TFM concept may reduce the number of instances of demand exceeding airspace or airport capacity so may reduce the likelihood of LoS. This is only likely to be the case when weather or other disruption causes a large loss in capacity. Under these conditions, it is conceivable that without TFM action traffic density exceeds the capability of SA to maintain separation.

ASP-S2: As traffic-density increases, the number of conflicts increases and it is conceivable that the number of conflicts detected at short-notice due to unanticipated aircraft maneuvers also increases. The TFM will reduce the number of instances of demand exceeding capacity and hence may reduce the number of conflicts compared to not using TFM.

ASP-S4: Automated TFM has potential for hazardous events that are different from the current system - the consequences of these needs to be determined from a safety analysis.

ASP-S5: Given airport and airspace-capacity constraints, the TFM concept assigns optimal departure delays to prevent demand from significantly exceeding capacity. This may reduce the likelihood of hazardous events at increased traffic levels compared to the current system. Automated SA has potential for hazardous events that are different from the current system - the likelihood of these needs to be determined from a safety analysis.

**Table 10—TFM system-level metrics**

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>Capacity/ TFM-C1</b>	Ratio of ASP-C1 with and without automated TFM.	ASP-C1: Number of flights that can be operated on a good weather day within the delay limits specified in Section 4.1.	There may be a small benefit from TFM even on a good weather day with no disruptions. Determined from ACES simulation.
<b>Efficiency/ TFM-E1</b>	Ratio of ASP-E1 with and without TFM.	ASP-E1: Reduction in gate-to-gate aircraft transit time	Determined from ACES simulation.
<b>Efficiency/ TFM-E2</b>	Ratio of ASP-E3 with and without automated FM.	ASP-E3: Reduction in fuel usage of the aircraft fleet in terms of fuel consumed per aircraft nautical mile	Determined from ACES simulation.
<b>Robustness/ TFM-R1</b>	Ratio of ASP-R1 with and without automated TFM.	ASP-R1: Ratio of ASP system-level capacity metrics for poor weather and/or system failure scenarios, within the delay limits specified in Section 4.1 compared with the good weather, nominal operating conditions scenario.	Determined from ACES simulation.
<b>Safety/ TFM-S1</b>	Ratio of ASP-S1 with and without automated TFM.	ASP-S1: Number of losses of separation with traffic or weather.	Determined from ACES simulation. .
<b>Safety/ TFM-S2</b>	Ratio of ASP-S2 with and without automated TFM.	ASP-S2: Time to predicted loss of separation from time of conflict detection.	Determined from ACES simulation.
<b>Safety/ TFM-S3</b>	Consequence of hazardous event.	ASP-S4: Consequence of hazardous event.	Based on FAA Order 8040.4. Determined from safety analysis.
<b>Safety/ TFM-S4</b>	Ratio of ASP-S5 with and without automated TFM for hazardous events: <ul style="list-style-type: none"> <li>○ Intrusion into weather</li> <li>○ Significantly exceeding capacity</li> </ul>	ASP-S5: Likelihood of hazardous event.	Determined from high-fidelity simulation.

## **6.3 Dynamic Airspace Configuration (DAC)**

### **6.3.1 Overview**

DAC is focused on a new operational paradigm in ATM that seeks to modify static airspace resources (controllers/structure) by temporally increasing capacity based on the movement of resources. DAC research is focused on the following elements:

- Adapting airspace sector boundaries to balance controller workload as traffic demand fluctuates.
- Creating air corridors dedicated to major traffic flows so that traffic in these corridors does not cross sector boundaries. Traffic may potentially self-separate within these corridors.

Since the primary purpose of sectors is to partition traffic separation workload among controllers, DAC assumes a human controller workforce (as opposed to fully automated separation assurance), in at least some portions of the airspace. A description of the DAC concept elements is available in <sup>[15], [16], [17]</sup>.

### **6.3.2 Key Functions, Features, Characteristics and Capabilities**

The DAC concept uses dynamic airspace to even out controller workload. Air corridors reduce controller workload. Sector boundaries may be adapted and air corridors created or removed several times a day to meet traffic demand.

### **6.3.3 Expected Performance Benefits**

In the current system, sector boundaries are static and a dedicated team of controllers works each specific sector. Combination of these static sectors at times of low demand occurs today, but the DAC concept envisages a much more dynamic use of airspace. The main benefit is efficient use of resources, enabling accommodation of more traffic using the same number of controllers.

Use of air corridors does not require sector handoffs and promotes smoother, organized traffic flows. The separation assurance function is simpler within a corridor; delegation to the flight deck with reduced in-trail separations is a possibility. The main benefit is increased airspace capacity.

### **6.3.4 Flight Phase**

The DAC concept affects the en-route phase of flight.

### **6.3.5 Contribution to JPDO Top-Level Goals and Objectives**

The DAC concept contributes to the following JPDO NextGen goals and objectives:

- Goal 1: Retain U.S. leadership in global aviation.
  - Objective 1.2: Reduce costs for air transportation.
- Goal 2: Expand capacity.
  - Objective 2.1 Satisfy future growth in demand (up to 3 times current levels) and operational diversity.

### **6.3.6 Impacts to System-level Metrics**

ASP-C1: DAC can accommodate increased demand within acceptable delay limits, by dynamically adapting airspace boundaries to meet demand and by creating air corridors along high traffic routes.

ASP-S4: DAC has potential for hazardous events that are different from the current system - the consequences of these needs to be determined from a safety analysis.

ASP-S5: DAC has potential for hazardous events that are different from the current system - the likelihood of these needs to be determined from a safety analysis.

**Table 11—DAC system-level metrics**

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>Capacity/ DAC-C1</b>	Ratio of ASP-C1 with and without DAC concepts.	ASP-C1: Number of flights that can be operated on a good weather day within the limits specified in Section 4.1.	For a human-controller based system, a more optimal design of airspace structures may allow increased capacity. Determined from ACES simulation.
<b>Capacity/ DAC-C2</b>	Ratio of the number of airspace sectors (plus corridors if any) with and without DAC concepts.	ASP-C1: Number of flights that can be operated on a good weather day within the limits specified in Section 4.1.	For a human-controller based system, reducing the number of airspace structures may allow increased capacity. Determined from ACES simulation.
<b>Capacity/ DAC-C3</b>	Ratio of airspace complexity as defined in <sup>[17]</sup> with and without DAC concepts.	ASP-C1: Number of flights that can be operated on a good weather day within the limits specified in Section 4.1.	For a human-controller based system, reducing the airspace complexity may allow increased capacity. Determined from ACES simulation.
<b>Safety/ DAC-S3</b>	Consequence of hazardous event.	ASP-S4: Consequence of hazardous event.	Based on FAA Order 8040.4. Determined from safety analysis.
<b>Safety/ DAC-S4</b>	Ratio of ASP-S5 with and without DAC for hazardous events: <ul style="list-style-type: none"> <li>○ Loss of spatial awareness during sector reconfiguration</li> <li>○ Intrusion into airspace corridor by other traffic</li> </ul>	ASP-S5: Likelihood of hazardous event.	HITL experiments may provide data for comparison with the current system. Determined from high-fidelity simulation.

## 6.4 Airspace Super Density Operations (ASDO)

### 6.4.1 Overview

ASDO is addressing airspace capacity barriers due to human workload/responsibility for separation assurance by utilizing simultaneous sequencing, spacing, merging, and de-confliction for terminal airspace with nearby runway thresholds. ASDO research focuses on the following elements:

- Runway scheduler and router for very closely spaced parallel runway operations (VCSPRO)

- Dynamic area navigation (RNAV) and Required Navigation Performance (RNP) flexible routing
- Flight-deck-based merging and spacing for arrivals
- Continuous descent approach (CDA)/ optimal profile descent (OPD)

A description of the ASDO concept elements are available in <sup>[18], [19], [20]</sup>.

#### **6.4.2 Key Functions, Features, Characteristics and Capabilities**

Aircraft pairing and offset routing to VCSPR allows near-visual flight rules (VFR) capability under instrument flight rules (IFR).

GPS-based navigation and improved FMS allows aircraft to fly trajectories with less dispersion, which enables dynamic flexible routing.

ADS-B-based flight deck systems allow aircraft to accurately merge into an arrival stream and self-space from a lead aircraft. Combined merging and spacing with a CDA/ OPD allows aircraft to follow a more optimal descent.

#### **6.4.3 Expected Performance Benefits**

In the current system, the capacity of VCSPR is much less under IFR conditions because operational rules require the dependent runways operate as if they were a single runway. The runway scheduler will pair aircraft with wake characteristics that minimize the required spacing and compute the required time of arrival at the arrival fixes. This will improve runway throughput. Use of accurate, and possibly offset, routing will restore runway throughput to near-VFR values.

Dynamic, flexible routing with less trajectory dispersion allows more arrival and departure routes and allows routing more closely around weather and through smaller gaps in weather than is currently the case. The main benefits are improved throughput under all conditions and less degradation due to poor weather. Less reliance on fixed routes reduces the distance flown and hence reduces flight times during the arrival and departure phase.

Flight-deck-based merging and spacing allows arriving aircraft accurately meet a required-time-of-arrival at the runway threshold and reduces the spacing buffer between aircraft due to reduced uncertainty. The main benefit is improved runway throughput. A secondary benefit is reduced workload for the arrival controller, due to delegation of functions to the flight deck.

Use of a CDA/ OPD reduces fuel burn, emissions and noise but can have a negative impact on throughput. Combing a fuel-optimal descent with flight deck merging and spacing maintains throughput while allowing the aircraft to fly the desired OPD.

#### **6.4.4 Flight Phase**

The ASDO concept affects the arrival and departure phase of flight.

## 6.4.5 Contribution to JPDO Top-Level Goals and Objectives

The SA concept contributes to the following JPDO NextGen goals and objectives:

- Goal 1: Retain U.S. leadership in global aviation.
  - Objective 1.2: Reduce costs for air transportation.
- Goal 2: Expand capacity.
  - Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.
  - Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).
  - Objective 2.3: Minimize impact of weather and other disruptions.
- Goal 4: Protect the environment.
  - Objective 4.1: Reduce noise, emissions, and fuel consumption.

## 6.4.6 Impacts to ASP System-Level Metrics

ASP-C1: ASDO will provide increased throughput of VCSPR and allow increased traffic density in transition airspace and thus will increase system capacity.

ASP-E1: ASDO allows shorter arrival and departure paths with less additional distance required for weather rerouting. This contributes to reduced gate-to-gates times.

ASP-E3: The ASDO concept uses CDA/ OPD. This reduces fuel usage of the aircraft fleet compared to current day operations.

ASP-R1: The ASDO concept allows VCSPRO under IMC closer to the throughput of VMC conditions. Dynamic flexible routing with less trajectory dispersions allows shorter path rerouting due to weather. Both of these improve robustness by reducing the effect of weather on system capacity.

ASP-S1: The ASDO concept increases airspace capacity so may reduce the likelihood of LoS for increased traffic levels.

ASP-S4: The ASDO concept has potential for hazardous events that are different from the current system - the consequences of these needs to be determined from a safety analysis.

ASP-S5: The ASDO concept provides dynamic, flexible routing with less trajectory dispersion and precision merging and spacing that may reduce the likelihood of hazardous events by reducing uncertainty. The ASDO concept has potential for hazardous events that are different from the current system - the likelihood of these needs to be determined from a safety analysis.

**Table 12— ASDO system-level metrics**

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>Capacity/ ASDO-C1</b>	Ratio of ASP-C1 with and without ASDO.	ASP-C1: The number flights that can be operated on a good weather day within the delay limits specified in Section 4.1.	Determined from ACES simulation.
<b>Efficiency/ ASDO-E1</b>	Ratio of ASP-E1 with and without ASDO.	ASP-E1: The reduction in gate-to-gate aircraft transit time.	Determined from ACES simulation.
<b>Efficiency/ ASDO-E2</b>	Ratio of ASP-E3 with and without ASDO.	ASP-E3: The reduction in fuel usage of the aircraft fleet in terms of fuel consumed per aircraft nautical mile.	Determined from ACES simulation.
<b>Robustness/ ASDO-R1</b>	Ratio of ASP-R1 with and without ASDO.	ASP-R1: The ratio of ASP system-level capacity metrics for poor weather and/or system failure scenarios, within the delay limits specified in Section 4.1.	Determined form ACES simulation.
<b>Safety/ ASDO-S1</b>	Ratio of ASP-S1 with and without ASDO.	ASP-S1: The number of losses of separation with traffic or weather.	Determined from high-fidelity simulation.
<b>Safety/ ASDO -S2</b>	Consequence of hazardous event.	ASP-S4: Consequence of hazardous event.	Based on FAA Order 8040.4 Determined from safety analysis.
<b>Safety/ ASDO-S3</b>	Ratio of ASP-S5 with and without ASDO for hazardous events: - deviation from trajectory - loss of in-trail spacing	ASP-S5: Likelihood of hazardous event.	Determined from high-fidelity simulation.

## **6.5 Coordinated Arrival and Departure Operations Management (CADOM)**

### **6.5.1 Overview**

The CADOM RFA is exploring concepts and technologies focused on mitigating operational constraints to maximizing single-airport capacity and facilitating metroplex operations. CADOM research is focused on the following elements:

- Runway Configuration Management (RCM)

- Combined Arrival/ Departure Runway Scheduling (CADRS)
- Wake Vortex modeling and prediction

### **6.5.2 Key Functions, Features, Characteristics and Capabilities**

CADOM enables optimal runway configuration for weather conditions and allows use of the same runway for departures and arrivals with improved scheduling. Improved wake vortex position and intensity prediction given local weather conditions will enable reduced wake separations between aircraft.

### **6.5.3 Expected Performance Benefits**

Efficient use of runways, better co-ordination of runway configuration changes and reduced in-trail wake-spacing based on predicted weather conditions will contribute to increased runway throughput.

### **6.5.4 Flight Phase**

The CADOM concept affects the arrival and departure phase.

### **6.5.5 Contribution to JPDO Top Level Goals and Objectives**

The CADOM concept contributes to the following JPDO NextGen goals and objectives:

- Goal 2: Expand capacity.
  - Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.
  - Objective 2.3: Minimize impact of weather and other disruptions.

### **6.5.6 Impacts to ASP System-Level Metrics**

ASP-C1: CADOM increases runway throughput and hence improves system capacity.

ASP-R1: CADOM improves schedule robustness by reducing delays due to runway configuration changes due to weather and other disruptions compared to current day operations.

ASP-S4: CADOM has potential for hazardous events that are different from the current system - the consequences of these needs to be determined from a safety analysis.

ASP-S5: CADOM has potential for hazardous events that are different from the current system - the likelihood of these needs to be determined from a safety analysis.

**Table 13—CADOM system-level metrics**

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>Capacity/ CADOM-C1</b>	Ratio of ASP-C1 with and without CADOM.	ASP-C1: The number flights that can be operated on a good weather day within the delay limits specified in Section 4.1.	Determined form ACES simulation.
<b>Robustness/ CADOM-R1</b>	Ratio of ASP-R1 with and without CADOM.	ASP-R1: The ratio of ASP system-level capacity metrics for poor weather and/or system failure scenarios, within the delay limits specified in Section 4.1.	Determined form ACES simulation.
<b>Safety/ CADOM -S2</b>	Consequence of hazardous event.	ASP-S4: Consequence of hazardous event.	Based on FAA Order 8040.4  Determined from safety analysis.
<b>Safety/ CADOM-S3</b>	Ratio of ASP-S5 with and without CADOM for hazardous events: - simultaneous runway occupancy - loss of wake-separation	ASP-S5: Likelihood of hazardous event.	Determined from high-fidelity simulation.

## **6.6 Safe and Efficient Surface Operations (SESO)**

### **6.6.1 Overview**

The purpose of the SESO RFA is to manage traffic on the airport surface (gates, taxiways, and runways) safely and efficiently to enable maximum throughput and capacity in the airport environment. SESO research is focused on the following concept elements:

- Pushback scheduler
- Taxi planner
- Departure planner
- Environmental planner
- Conformance monitor
- Surface Conflict Detection and Resolution (CD&R)

SESO concept elements rely on Trajectory Based Surface Operations (TBSO) that allow the precise position of all surface vehicles to be monitored and predicted allowing for efficient planning of surface operations.

The result is a trajectory that enables an aircraft to leave the gate, taxi to the runway using the most efficient taxi route with minimal halts and smoothly take-off with minimal

holding at the runway threshold. Arriving aircraft similarly use TBSO, taking into account departing aircraft. An environmental planner assists with creating trajectories that minimize fuel burn and emissions.

A conformance monitor and automated surface CD&R assist the pilot and controllers with maintaining safe separation from other aircraft, ground vehicles and obstructions.

### **6.6.2 Key Functions, Features, Characteristics and Capabilities**

SESO uses a ground trajectory that includes the planned time at each waypoint for all aircraft and surface vehicles. Automation uses these trajectories to efficiently plan and schedule aircraft gate departures and taxi routes. Automated conformance monitoring and CD&R maintain separation.

### **6.6.3 Expected Performance Benefits**

At some major airports, taxi-operations today are quite inefficient where standard operating practice is to have aircraft leave the gate despite not having a clear path to the runway. Aircraft then queue up all along the taxi-routes with numerous stops and starts, often taking tens of minutes to reach the runway. Aircraft often hold for a few more minutes at the threshold before take-off. At busy times, this practice results in a large number of aircraft burning fuel, and creating emissions, making no-progress toward their destination. This is also a waste of pilot and passenger time and uses valuable aircraft operating hours resulting in increased maintenance costs.

There are good reasons for this inefficient practice; having a queue of waiting aircraft maximizes runway throughput in the presence of uncertainty and freeing up gates on time makes the gate available for arriving aircraft.

SESO concept elements enable a reduction in the uncertainty associated with surface operations reducing the need for queuing up of aircraft while maintaining runway throughput. Accurate departure planning allows the aircraft to depart from the gate at the scheduled time without obstruction along the taxiways or holding at the runway threshold. The benefits will be reduced taxi-times, reduced fuel burn and emissions, cost savings to the airlines and saving of passenger and crew time.

In addition, SESO may reduce the number of surface safety incidents by enabling more accurate and timely automated monitoring of conflicts between all surface traffic and obstructions.

### **6.6.4 Flight Phase**

The SESO concept affects the gate-to-runway threshold phase of flight.

### **6.6.5 Contribution to JPDO Top Level Goals and Objectives**

The SESO concept contributes to the following JPDO NextGen goals and objectives:

- Goal 1: Retain U.S. leadership in global aviation.

- Objective 1.2: Reduce costs for air transportation.
- Goal 2: Expand capacity.
  - Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).
- Goal 3: Ensure safety.
  - Objective 3.2: Improve level of safety of U.S. air transportation system
- Goal 4: Protect the environment.
  - Objective 4.1: Reduce noise, emissions, and fuel consumption.

### 6.6.6 Impacts to ASP System-Level Metrics

ASP-E1: The SESO concept reduces gate-to-runway transit time contributing to an overall reduction in gate-to-gate times.

ASP-E3: SESO reduces engine-idling times and the need to decelerate and accelerate the aircraft so reduces fuel consumption on the ground.

ASP-S1: SESO uses an automated system of surface CD&R with improved flight crew and controller situational awareness so may reduce the likelihood of LoS.

ASP-S4: SESO has potential for hazardous events that are different from the current system - the consequences of these needs to be determined from a safety analysis.

ASP-S5: SESO may reduce the likelihood of hazardous events by providing better situational awareness and using automation assisted CD&R on the ground. SESO has potential for hazardous events that are different from the current system - the likelihood of these needs to be determined from a safety analysis.

**Table 14—SESO system-level metrics**

RFA metric type/ no.	RFA metric	Related system-level metric	Comments/ how calculated
<b>Efficiency/ SESO-E1</b>	Ratio of ASP-E1 with and without SESO.	ASP-E1: The reduction in gate-to-gate aircraft transit time.	Determined form ACES simulation.
<b>Efficiency/ SESO-E2</b>	Ratio of ASP-E3 with and without SESO.	ASP-E3: The reduction in fuel usage of the aircraft fleet in terms of fuel consumed per aircraft nautical mile.	Determined form ACES simulation.
<b>Safety/ SESO-S1</b>	Ratio of ASP-S1 with and without SESO.	ASP-S1: The number of losses of separation with ground traffic.	Determined from high-fidelity simulation.

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>SESO-S2</b>	Consequence of hazardous event.	ASP-S4: Consequence of hazardous event.	Based on FAA Order 8040.4 Determined from safety analysis.
<b>Safety/ SESO-S3</b>	Ratio of ASP-S5 with and without SESO for hazardous events: ○ Collisions with aircraft and other vehicles on the ground. ○ Collisions with static objects.	ASP-S5: Likelihood of hazardous event.	Determined from high-fidelity simulation.

## **6.7 Airportal and Metroplex Integration (AMI)**

### **6.7.1 Overview**

The AMI RFA analyzes and integrates research across the NextGen-Airportal Project's technical areas, as well as performing crosscutting research (e.g., human/system and metroplex operational concepts development) and portfolio management. AMI research consists of three elements:

- Characterization of airspace interdependencies between airports within a metropolitan area, and methods for mitigating their effects
- Connectivity within a Metroplex area—i.e., how airports within a Metroplex area are connected (or not connected) and what type of connections are needed (including multi-modal transportation needs)
- Connectivity within the NAS—i.e., how Metroplex areas are connected with other airports or Metroplexes in the NAS and how to improve the quality of the connections and recover from lost connections (e.g., when an airport is shut down due to bad weather)

### **6.7.2 Key Functions, Features, Characteristics and Capabilities**

The AMI concept improves coordination of operations between different airports.

### **6.7.3 Expected Performance Benefits**

Increased capacity during times when airports' operations interact; increased capacity through greater use of secondary-level airports to offload excess demand from primary-level airports; delay reduction due to more efficient use of facilities.

### **6.7.4 Flight Phase**

The metroplex concept affects the departure/arrival phase.

### **6.7.5 Contribution to JPDO Top Level Goals and Objectives**

The Metroplex concept contributes to the following JPDO NextGen goals and objectives:

- Goal 1: Retain U.S. leadership in global aviation.
  - Objective 1.2: Reduce costs for air transportation.
- Goal 2: Expand capacity.
  - Objective 2.1: Satisfy future growth in demand (up to 3 times current levels) and operational diversity.
  - Objective 2.2: Reduce transit time and increase predictability (domestic curb-to-curb transit time cut by 30%).
  - Objective 2.3: Minimize impact of weather and other disruptions
- Goal 4: Protect the environment.
  - Objective 4.1: Reduce noise, emissions, and fuel consumption.

### 6.7.6 Impacts to ASP System-Level Metrics

ASP-C1: The metroplex concept can accommodate increased demand within acceptable delay limits, by better coordination of flights through airspace shared by multiple airports, through better scheduling of flights into congested areas, and through off-loading of flights from over-capacity airports.

ASP-E1, ASP-E3: The metroplex concept can reduce delays through better coordination and use of constrained resources; this can decrease flight times and reduce fuel usage.

ASP-R1: The metroplex concept can mitigate the loss in capacity that occurs due to poor weather and system disruptions by improving the connectivity of airports and speeding the recovery from lost connections.

ASP-R2: The metroplex concept can reduce delays due to poor weather by mitigating the effects of loss of airport capacity.

ASP-R3: The metroplex concept can improve gate-to-gate time predictability through improved coordination.

**Table 15--AMI system-level metrics**

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>Capacity/ AMI-C1</b>	Ratio of ASP-C1 with and without AMI concepts.	ASP-C1: The number of flights that can be operated on a good weather day within the delay limits specified in Section 4.1.	Determined form ACES simulation.
<b>Efficiency/ AMI-E1</b>	Ratio of ASP-E1 with and without AMI concepts.	ASP-E1: The reduction in gate-to-gate aircraft transit time	Determined form ACES simulation.
<b>Efficiency/ AMI-E2</b>	Ratio of ASP-E3 with and without AMI concepts.	ASP-E3: The reduction in fuel usage of the aircraft fleet in terms of fuel consumed per aircraft nautical mile.	Determined form ACES simulation.
<b>Robustness/ AMI-R1</b>	Ratio of ASP-R1 with and without AMI concepts.	The ratio of ASP capacity metrics for poor weather and/or system failure scenarios, within the delay limits specified in Section 4.1 compared with the good weather, nominal operating conditions scenario.	Determined form ACES simulation.

<b>RFA metric type/ no.</b>	<b>RFA metric</b>	<b>Related system-level metric</b>	<b>Comments/ how calculated</b>
<b>Robustness/ AMI-R2</b>	Ratio of ASP-R2 with and without AMI concepts.	The mean gate-to-gate delay for the good-weather number of flights, flown over the range of weather days expected in the course of a year.	Determined form ACES simulation.
<b>Robustness/ AMI-R3</b>	Ratio of ASP-R3 with and without AMI concepts.	The variance of gate-to-gate delay for the good-weather number of flights, for the poor weather and/or system failure scenarios, compared with the good weather, normal operating conditions scenario.	Determined form ACES simulation.

## 7 Summary and Conclusions

This document contains an initial set of metrics for measuring National Airspace System capacity, efficiency, robustness, and safety at the system-level and at the Research Focus Area (RFA) level. The paper shows that the top-level RFA metrics link directly to the system-level metrics and to NextGen goals and objectives, as defined by the Joint Program Development Office.

Planned updates to the document in 2011 and 2012 will complete the definition of RFA top-level metrics and will guide the work planned for integration design studies and system-level assessments.

## Annex A: Example Values from Simulation Results

This Annex presents example values for capacity metrics and shows how to calculate the metrics from TSAM data and ACES results.

### System-Level Capacity Metrics

#### ASP-C1

The number of flights that can be operated on a good-weather day within the delay limits specified in Section 4.1.

#### Method

1. Start with the baseline demand scenario (1X current traffic levels) and increase demand in e.g. 0.5X increments.
2. Run ACES to determine delays.
3. Plot the mean, 95th-percentile, 99th-percentile of system-wide delay at 1-hour increments, for commercial flights only and for all flights.
4. Determine the maximum demand, beyond which delay exceeds any of the specified limits (mean =15 minutes, 95th = 30 minutes, 99th = 60 minutes) for either commercial or all flights.
5. Graph the parameter (mean, 95th or 99th-percentile) that most exceeds the limit versus demand for the hour with maximum delay and interpolate to determine the system operating point.
6. Determine the corresponding number of flights.

#### Baseline NAS Capacity

For this example, delays are determined from ACES 6.0 simulation.

Scenarios are the 26 September 2006 baseline good weather high volume day scenario and future scenarios derived from this baseline with increased demand

The sector capacities are current day "CorrectedSectors\_2007-07-24" as supplied with ACES. The airport capacity file is "Top250AirportCapacity\_2004\_BASELINE" based on current day values in the FAA 2004 Airport Capacity Benchmark report.

Figure 1 depicts ACES delay results for all flights, i.e. commercial passenger, cargo and GA combined. For each hour of simulation, the mean delay is well below the specified limit. The overall mean value of delay is 111 seconds for all flights. The 99th and 95th-percentiles of delay are below the specified limits.

Figure 2 depicts ACES delay results for commercial passenger flights only. For each hour of simulation, the mean delay is well below the specified limit, with the 95th and 99th-percentiles are below the limits. The overall mean value of delay is 165 seconds for

commercial passenger flights. The mean delay for commercial passenger flights is longer than for all flights combined because the mean value for all flights includes the delays for many GA flights that fly into smaller less congested airports.

Figure 3 depicts ACES delay results for all flights using a scenario generated from TSAM demand projections, nominally for the year 2008. (Note baseline year scenario is 2006 for the ASP). This scenario includes some consolidation of passengers into larger aircraft as demand increases. The scenarios documentation<sup>[2]</sup> describes the method used to generate future scenarios.

For each hour of simulation, the mean delay is well below the specified limit. The overall mean value of delay is 165 seconds for all flights. The 95th-percentile of delay is also below the specified limits, but the 99th-percentile exceeds the 60-minute limit.

Figure 4 depicts ACES delay results for commercial passenger flights for the year 2008 scenario. For each hour of simulation, the mean delay is below the specified limit. The overall mean value of delay is 237 seconds for all flights. The 95th-percentile of delay is just above the 30-minute limit and the 99th-percentile significantly exceeds the 60-minute limit. The delays for commercial flights are longer than for all flights combined, as expected. The 99th-percentile exceeds the limit by the greatest margin, so this parameter, for commercial flights, is the one that determines the system operating point beyond which delays become unacceptable in this example case.

Figure 5 depicts the 99th-percentile of delay versus demand. The total number of flights in 24 hours for the 2006 scenario is 48,467 and for the 2008 scenario are 51,762 so the demand ratio is 1.07. Linear interpolation gives a demand ratio of 1.023 at the 60-minute delay limit. This corresponds to 49,581 flights.

The analysis shows that the capacity of the NAS for metric **ASP-C1**, using the sector and airport capacity assumptions documented above is approximately **49,500** flights per day before delays reach the limits specified in Section 4.1.

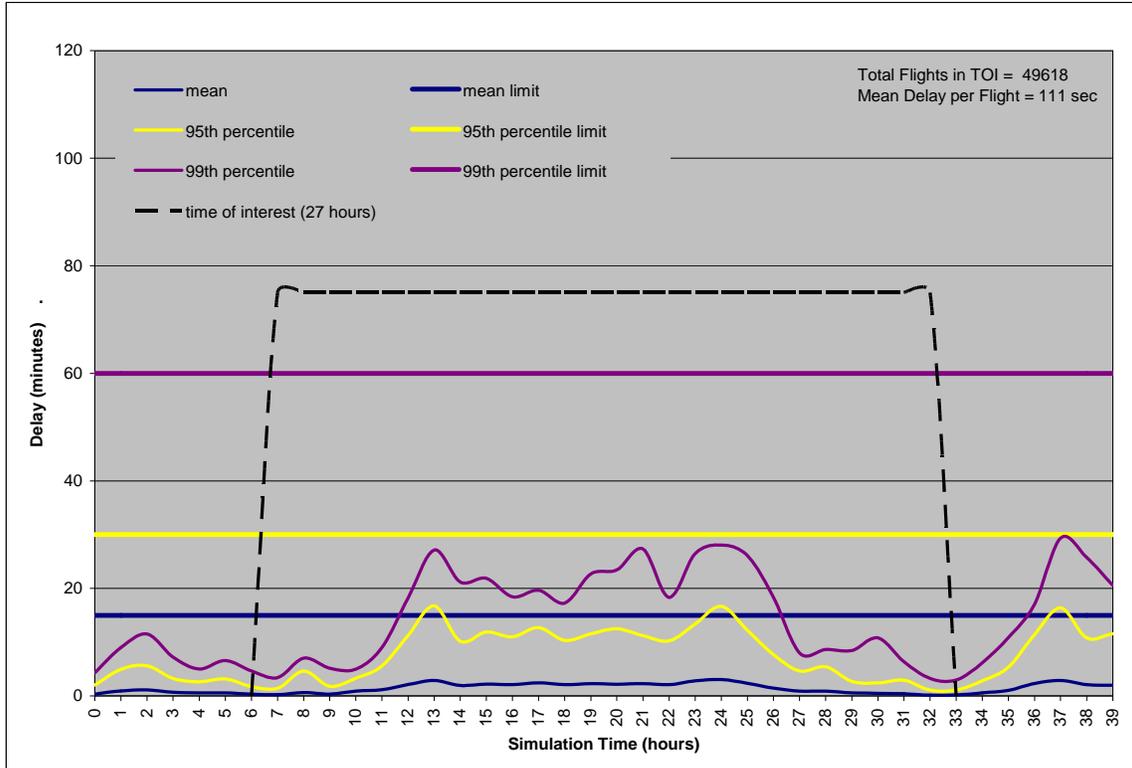


Figure 1—26th Sept. 2006 Baseline Delays for All Flights

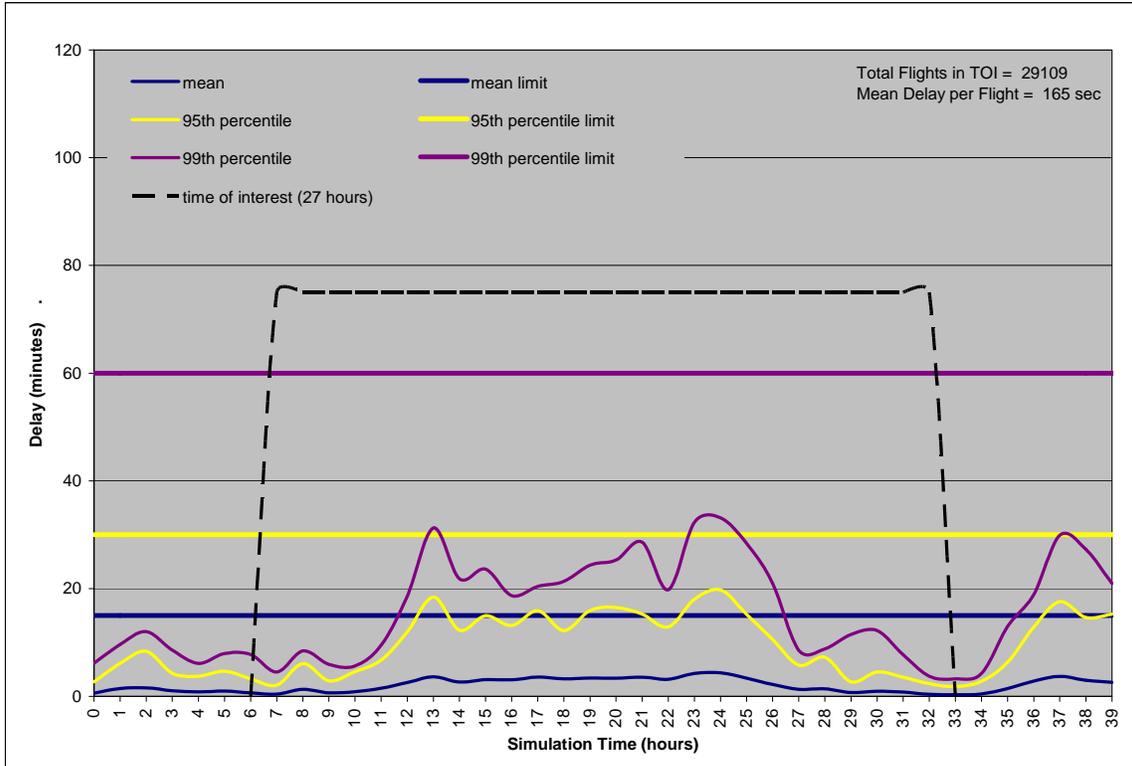


Figure 2—26th Sept. 2006 Baseline Delays for Commercial Passenger Flights

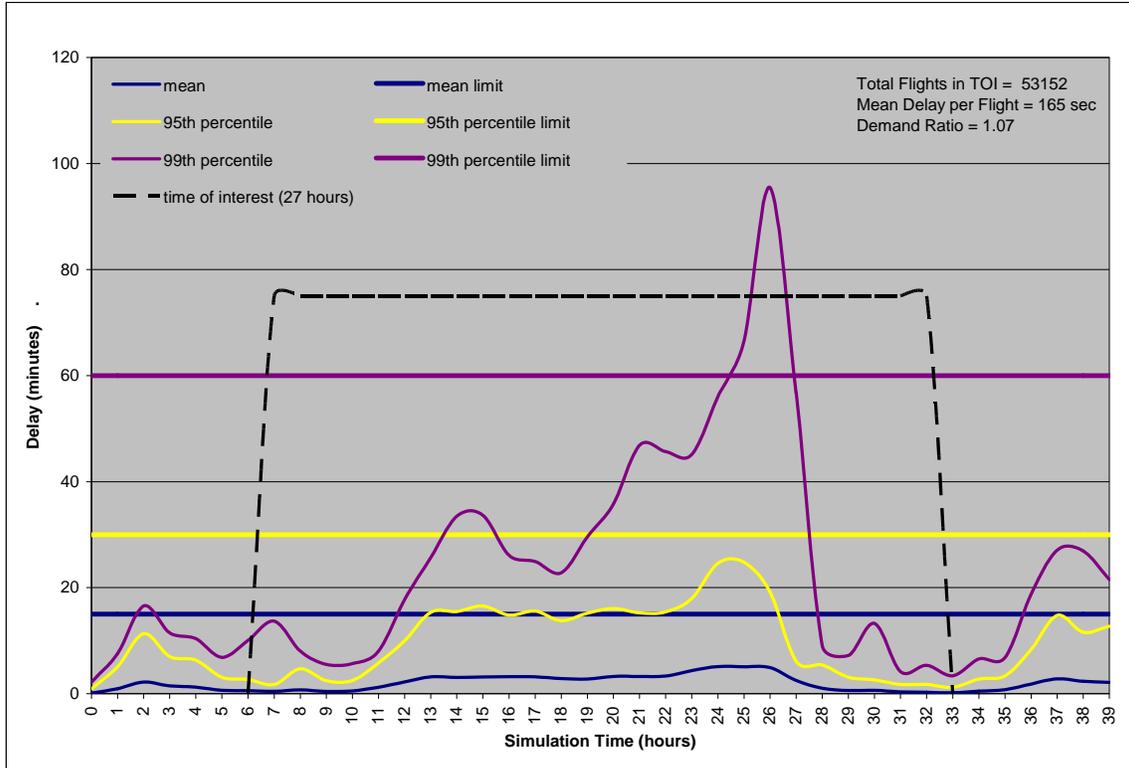


Figure 3—2008 TSAM Scenario Delays for All Flights

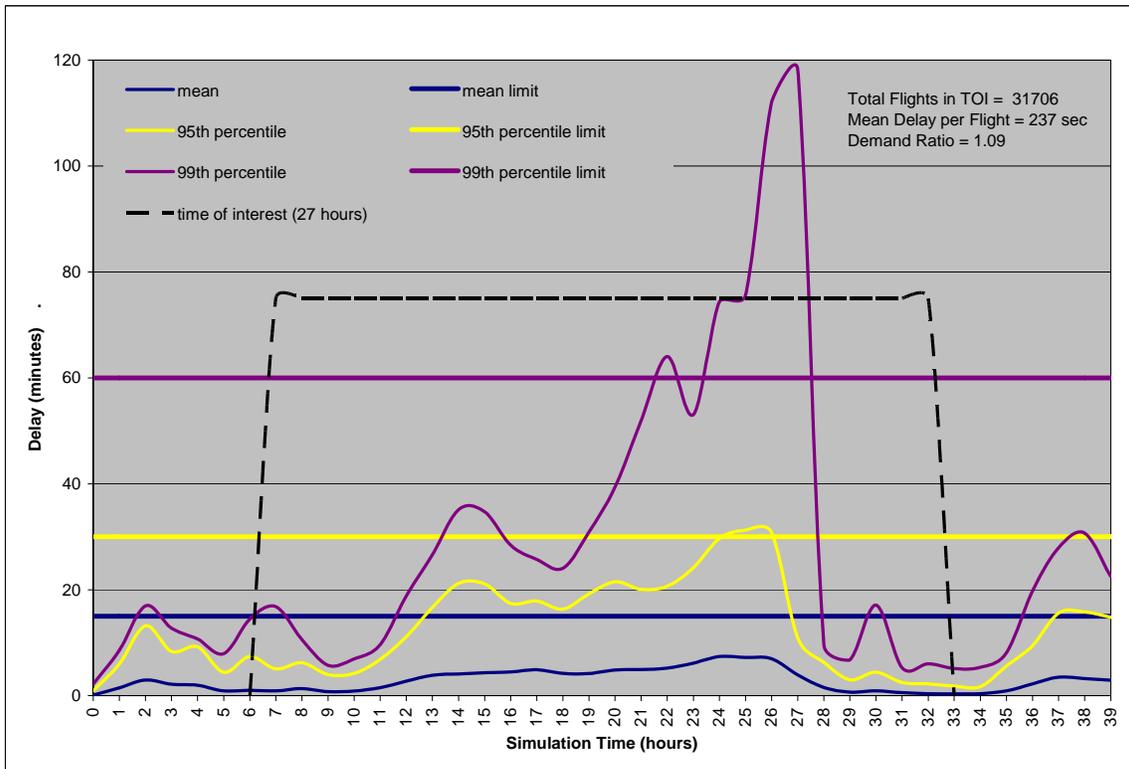


Figure 4—2008 TSAM Scenario Delays for Commercial Passenger Flights

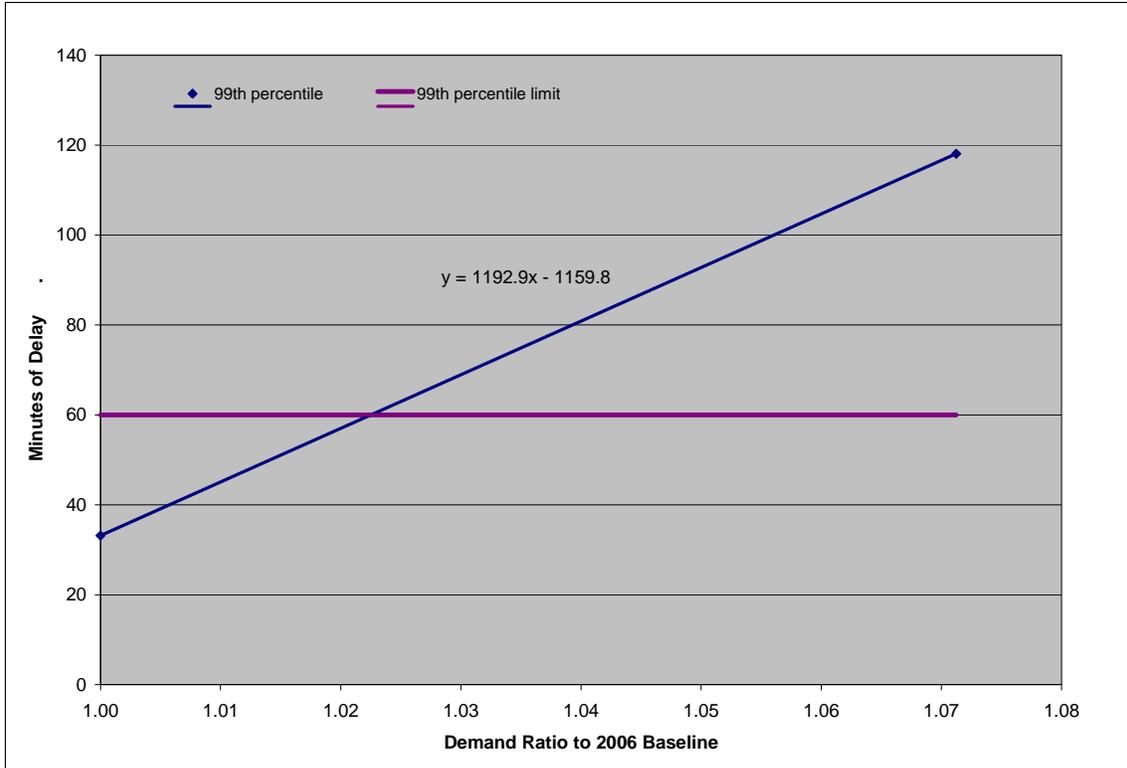


Figure 5—2008 TSAM Scenario 99th-percentile of Delay for Commercial Passenger Flights

## ASP-C2

The number of passenger origin-to-destination trips that can be operated on a good-weather day within the delay limits specified in Section 4.1.

### Method

1. Determine the number of flights that can be operated ASP-C1
2. Determine the corresponding number of passenger origin-to-destination trips from TSAM results.

The average number of origin-to-destination trips per day in 2006 is 1,317,094 and in 2008 is 1,743,163 according to TSAM analysis<sup>[2]</sup>. Linear interpolation to the system operating point gives a corresponding passenger origin-to-destination capacity of 1,457,270 trips.

The analysis shows that the capacity of the NAS for metric **ASP-C2**, using the sector and airport capacity assumptions documented above is **1,457,270** origin-to-destination trips per day before delays reach the limits specified in Section 4.1.

## References

- <sup>1</sup> NASA Airspace Systems Program, "FY2009 Project Plan", NextGen-Airspace Project, Dec. 2008, [http://www.aeronautics.nasa.gov/pdf/airspace\\_508.pdf](http://www.aeronautics.nasa.gov/pdf/airspace_508.pdf), Accessed Oct. 2, 2009.
- <sup>2</sup> Viken, J., "Scenarios and Assumptions for the NASA Airspace Systems Program", Version 1.0, September 2009.
- <sup>3</sup> JPDO, "Concept of Operations for the Next Generation Air Transportation System", Version 2.0, June 2007, [http://www.jpdo.gov/library/NextGen\\_v2.0.pdf](http://www.jpdo.gov/library/NextGen_v2.0.pdf), Accessed Oct. 2, 2009.
- <sup>4</sup> Creedon, J., Price, G., "NextGen System Level Metrics", Presentation to JPDO Metrics Team, May 2008, personal communication with Richard Barhydt NASA Airspace Project Scientist.
- <sup>5</sup> NASA contract number NNA05BE01C, Contract Data Requirements List 17.3, "Airspace Concept Evaluation System (ACES) Software User Manual", Jan. 2009.
- <sup>6</sup> Bradford, S., Breuning, T., and Liang, D., "Standardizing Performance Metrics", 5th USA /Europe Air Traffic Management R&D Seminar, Washington DC, June 2003.
- <sup>7</sup> Almes, G., Mathis, M., Mahdavi, M., Paxson, V., "Framework for IP Performance Metrics", Internet Engineering Task Force, Memo RFC 2330, May 1998.
- <sup>8</sup> Metron Aviation, JLP Performance Consulting and Virginia Tech, "Integrated Analysis of Airportal Capacity and Environmental Constraints", NS802T1, Version 1.
- <sup>9</sup> The MITRE Corporation, "Airspace Management Handbook", Version 2.2, Dec. 2005
- <sup>10</sup> FAA, "FY2009 Portfolio of Goals", HQ09753, 2009, [http://www.faa.gov/about/plans\\_reports/media/FY09\\_Portfolio\\_of\\_Goals.pdf](http://www.faa.gov/about/plans_reports/media/FY09_Portfolio_of_Goals.pdf), Accessed Oct 2, 2009.
- <sup>11</sup> JPDO, "A Safety Working Group Proposal for the Integration of Safety in NextGen Planning", May 2009, personal communication with Richard Barhydt NASA Airspace Project Scientist.
- <sup>12</sup> Vivona, R.A., Karr, D.A., and Roscoe, D.A., "Pattern-Based Genetic Algorithm for Airborne Conflict Resolution", AIAA paper 2006-6060, Keystone, Colorado, 2006.
- <sup>13</sup> Erzberger, H., "Transforming the NAS: The Next Generation Air Traffic Control System", *Proceedings of the International Congress of the Aeronautical Sciences (ICAS)*, Yokohama, Japan, Aug. 2004.

- <sup>14</sup> Grabbe, S., Sridhar, B., Mukherjee, A., "Sequential Traffic Flow Optimization with Tactical Flight Control Heuristics", *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 32, No. 3, May-June 2009.
- <sup>15</sup> Kopardekar, P., Bilimoria, K., and Sridhar, B., "Airspace Configuration Concepts for the Next Generation Air Transportation System", *Air Traffic Control Quarterly*, Vol. 16, No. 4, page 313-336, 2008.
- <sup>16</sup> Wing, D., Smith, J., and Ballin, M., "Analysis of a Dynamic Multi-Track Airway Concept for Air Traffic Management", NASA TP-2008-215323, Jul 2008.
- <sup>17</sup> Zelinski S., "A Comparison of Algorithm Generated Sectorizations", Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM June 2009), <http://www.aviationsystemsdivision.arc.nasa.gov/publications/2009/AF2009164.pdf>, Accessed Oct 2, 2009.
- <sup>18</sup> Krozel, J., Prete, J., Mitchell, J.S.B., Kim, J., and Zou, J., "Capacity Estimation for Super-Dense Operations", AIAA paper 2008-7226, Aug. 2008.
- <sup>19</sup> Prete J., Krozel, J., Mitchell, J.S.B., Kim, J., and Zou, J., "Flexible, Performance-Based Route Planning for Super-Dense Operations", AIAA paper 2008-6825, Aug. 2008.
- <sup>20</sup> Barmore, B., Abbott, T., Capron, W., Baxley, B., "Simulation Results for Airborne Precision Spacing Along Continuous Descent Arrivals", AIAA paper 2008-8931, Sept. 2008.