# Evaluating the Environmental Performance of the U.S. Next Generation Air Transportation System

## Quantitative Estimation of Noise, Air Quality, and Fuel-Efficiency Performance

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*Abstract*— The environmental impacts of several possible U.S. Next Generation Air Transportation scenarios have been quantitatively evaluated for noise, air-quality, fuel-efficiency, and $CO_2$ impacts. Three principal findings have emerged. (1) 2025 traffic levels about 30% higher than 2006 are obtained by increasing traffic according to FAA projections while also limiting traffic at each airport using reasonable ratios of demand to capacity. NextGen operational capabilities alone enable attainment of an additional 10-15% more flights beyond that 2025 baseline level with negligible additional noise, air-quality, and fuel-efficiency impacts. (2) The addition of advanced engine and airframe technologies provides substantial additional reductions in noise and air-quality impacts, and further improves fuel efficiency. 2025 environmental goals based on projected system-wide improvement rates of about 1% per year for noise and fuel-efficiency (an air-quality goal is not yet formulated) are achieved using this new vehicle technology. (3) Overall air-transport "product", as measured by total flown distance or total payload distance, increases by about 50% relative to 2006, but total fuel consumption and $CO_2$ production increase by only about 40% using NextGen operational capabilities. With the addition of advanced engine/airframe technologies, the increase in total fuel consumption and $CO_2$ production can be reduced to about 30%.

*Keywords – environmental sustainability, next-generation air transport, noise, air quality, fuel efficiency, $CO_2$ production*

## I. INTRODUCTION

The U.S. Next Generation Air Transportation System (NextGen) seeks to enable substantial traffic growth, while still attaining improved environmental performance and sustainability. The Joint Planning and Development Office (JPDO) was created to plan for transforming the U.S. National Airspace System (NAS) and to integrate the efforts of the Federal government and the aviation industry to achieve the desired results. The responsibilities of the JPDO's Interagency Portfolio and Systems Analysis (IPSA) Division include performing analysis of future operations to assess overall system performance in terms of a battery of different metrics.

IPSA supported the research reported upon here which quantitatively evaluates the noise, air quality, and fuel-efficiency impacts of NextGen under several different scenarios that embody moderate growth, both with and without NextGen capabilities. This is part of an on-going effort to consistently evaluate environmental performance of NextGen as envisioned operational and technological improvements evolve, and as different levels of feasible traffic growth are explored.

## II. OBJECTIVES

### A. Key Questions Addressed

We address the following questions from a quantitative perspective:

i. What are the impacts of NextGen with regard to fuel efficiency, local air quality, and noise?

ii. How do these impacts compare with likely goals for environmental sustainability?

iii. What is the relative contribution to NextGen environmental sustainability of engine/airframe technology improvements versus procedural and avionics improvements?

Answers to these questions depend upon detailed characteristics of NextGen future operational capabilities, future demand patterns, engine/airframe technology improvements, and environmental metrics and goals. We elaborate on these characteristics and our environmental analysis methods in the following section.

## III. METHODS

Our approach consists of five major steps: scenario development, modeling of noise, air-quality, and fuel-efficiency impacts, and comparison of impacts to environmental-sustainability goals.

*A. Scenario Development*

Key elements of future scenarios are the traffic demand, the capacity as influenced by operational capabilities of NextGen, the projected composition of the fleet, and projected technology improvements influencing environmental impacts. In addition, characteristics of terminal-area traffic behavior are addressed to reflect both traffic patterns and anticipated changes in certain operational capabilities.

1. Demand

Future demand is represented by detailed flight schedules developed by FAA/ATO-P based on traffic levels in the FAA Terminal Area Forecast [1] extrapolated to a future year, typically 2025. These "unconstrained" schedules are evaluated using LMINET [2] and trimmed to capacity-constrained levels considered to be feasible given envisioned NextGen operational capabilities. This trimming removes flights based which NAS resources they use and on assumptions concerning reasonable ratios of demand to capacity at these resources (on both quarter-hourly and hourly bases).

The feasible, trimmed schedules are then simulated in ACES, NASA's Airspace Concept Evaluation System [3,4,5], and the resulting outputs are used for environmental-impact modeling. As discussed below, the ACES outputs are augmented with environmentally important information on terminal-area trajectories and projected aircraft environmental performance.

2. Operational Capabilities

NextGen comprises a large number of envisioned operational improvements affecting airport and airspace capacities. In the scenarios analyzed here, the principal operational improvements included were as follows:

- *Airport capacity* increased by new runways at 10 major airports, independent parallel and/or converging approaches under IMC (Instrument Meteorological Conditions), by increased predictability at the outer marker, and by reduced wake-based longitudinal separation restrictions for both departures and arrivals. At 35 major airports, this resulted in estimated capacity improvements in 2025 of approximately 25% to 200% under IMC [6].

- *En route capacity* increased by improved collaborative pre-flight and in-flight rerouting, by trajectory-based management in the form of trajectory digital exchange, and by dynamic airspace re-configuration. This resulted in improvements of approximately 70% to 90% in sector capacities in 2025 [6].

In addition, two operational improvements, Continuous Descent Arrival (CDA) and Required Navigational Performance (RNP), were modeled as modifications to the terminal-area trajectories, and are discussed below.

3. Fleet Evolution

An evolving picture of fleet composition is termed *fleet evolution* to convey the fact that forecasts of the U.S. and global future fleet are influenced by a number of factors, many of which have a time-dependent component. Several aspects of NextGen concepts are significantly affected by fleet composition, including environmental impact. Environmental impact is particularly sensitive to aircraft type, size, and engine characteristics.

A 2007-2035 U.S. fleet forecast [7] was used as a basis for evolving the fleet in the modeled NextGen schedules. Flights by international carriers and GA operations were not evolved, and cargo and passenger flights were not evolved independently.

Each aircraft in the schedule and the fleet forecast was assigned an appropriate seat class and engine category. The engine categories were jet, turbo-prop and piston, and nine seat classes were used: <20, 20-49, 50-99, 100-150, 151-210, 211-300, 301-400, 401-500, and >501 seats.

For each aircraft within a seat class and engine category, the fleet forecast was used to define the proportion of that aircraft desired in the NextGen schedule. For example, if the fleet forecast showed 40% of the jets in the 151-210 seat class were B737-800s, then the distribution of aircraft in the NextGen schedule for that engine category and seat class would be 40% B737-800. Fleet evolution was performed on the unconstrained schedule.

4. Technology Improvements in Environmental Performance

We project technology-driven environmental performance beyond current levels in terms of fuel consumption, air-quality impacts, and noise. Each of these areas is improved to two different levels, termed N+1 and N+2, which refer to the goals of NASA's Subsonic Fixed Wing (SFW) Project [8], as shown in Figure 1. As noted in the figure, these technology targets are considered "corners" of an enlarged vehicle-design trade space, so the assumption that all three will be achieved completely and simultaneously is acknowledged as very optimistic.

| CORNERS OF THE TRADE SPACE | N+1 (2015 EIS) Generation Conventional Tube and Wing (relative to B737/CFM56) | N+2 (2020 IOC) Generation Unconventional Hybrid Wing Body (relative to B777/GE90) |
|---|---|---|
| Noise | - 32 dB (cum below Stage 4) | - 42 dB (cum below Stage 4) |
| LTO NOx Emissions (below CAEP 6) | -60% | -75% |
| Performance: Aircraft Fuel Burn | -33%** | -40%** |

Figure 1. Technology improvements for NASA's Subsonic Fixed Wing Program [8]

The FAA's Continuous Low Energy, Emissions, and Noise (CLEEN) [9] program goals match the SFW N+1 targets. Insertion rates for both N+1 and N+2 technology levels currently are assumed to begin in 2016 and continue to penetrate the fleet as new aircraft are purchased and older aircraft are retired and replaced, even though N+2 is not projected to be available before 2020. This was done to show

the relative impact of two different levels of technology enhancement within the same time period. The details of how these improvement levels are applied are given below.

(a) Fuel Consumption

For all flights in a future scenario designated as having the fuel improvement specified above, the fuel-flow rate, FF (kg/min), is modified as follows:

$$FF_{modified} = FF_{current} (1.0 - I_{fuel}) ,\qquad (1)$$

where $I_{fuel}$ is the fractional improvement over current levels. For scenarios corresponding to NASA N+1 goals, $I_{fuel}$ has been set to produce a reduction of 33% for 16,334 flights. For N+2 goals, $I_{fuel}$ has been set to produce a 40% reduction for the same flights. These modifications are applied to the International Civil Aviation Organization (ICAO)/ Emissions and Dispersion Modeling System (EDMS) and Eurocontrol Base of Aircraft Data (BADA) fuel-flow rates [10,11] used in modeling the fuel-efficiency impacts, as discussed below.

(b) Emissions

We apply a similar process to all flights in a future scenario designated as having the air-pollutant improvement specified above. We model these improvements in terms of production rates (kg/min), not in terms of emissions indices (kg pollutant per kg fuel). Since production rates are the product of fuel-flow rates and emissions indices, we adopt a conservative approach that modifies the emission index only if the projected production-rate improvement is greater than the projected fuel-flow-rate improvement. That is,

(i) If $I_{pollutant} > I_{fuel}$ , then $EI_{modified} = EI_{current} (1.0 - I_{pollutant})$ (2a)

(ii) Otherwise, $EI_{modified} = EI_{current}$ . (2b)

Then, for all flights in the future scenario designated as having this improvement, the pollutant production rate, PR (kg/min), is modified as follows:

$$PR_{modified} = FF_{modified} * EI_{modified} .\qquad (3)$$

Thus far, estimates for improvements have been made only for $NO_x$. For scenarios corresponding to NASA N+1 goals, the corresponding aircraft introduced to the fleet were modified to achieve a 60% reduction relative to the CAEP6 $NO_x$ standard for the engine associated with that aircraft. Likewise the aircraft introduced to the N+2 fleet were modified to achieve a 75% reduction to the CAEP6 $NO_x$ standard for the appropriate engine. These modifications are applied to the ICAO/EDMS and BADA fuel-flow rates used in modeling the fuel-efficiency impacts, as discussed below.

(c) Noise

We apply a similar process to all flights in a future scenario designated as having the noise improvement specified above. This improvement is given as a reduction in single-event noise levels, and we modify the noise-power-distance (NPD) curves by first determining how well the aircraft performs against the desired reduction, and then adjusting the arrival and departure curves appropriately. Based on discussions with the JPDO Environmental Working Group Technology Panel, we apply 70-80% of the appropriate noise improvement to the departure NPD curves, and 20-30% to the arrival curves, with narrow-body (single-aisle) aircraft using an 80/20 split and wide-body (dual-aisle) aircraft using a 70/30 split. The basic rationale is that projected noise improvements are anticipated to have more influence on departure noise since current technology has already attained arrival improvements.

For scenarios corresponding to NASA N+1 goals, $I_{noise}$ has been set to 32 dB below the Stage-4 cumulative thresholds and 42 dB below the Stage-4 cumulative thresholds for N+2. These modifications are utilized in the noise-impact modeling described below.

5. Terminal-area Trajectories, Including CDA and RNP

ACES simulations currently do not treat the terminal area in detail. However, environmental impacts are sensitive to terminal-area effects, so it is necessary to identify terminal-area traffic patterns for the airports included in the national analysis. We have developed two levels of terminal-area trajectory augmentation: high fidelity, data-driven augmentation at the 34 Continental United States Operational Evolution Partnership (CONUS OEP) airports, and lower-fidelity, algorithmic augmentation for other airports. In addition, we also modified terminal-area trajectories to reflect the use of CDA and RNP.

(a) High-fidelity Trajectory Development

For the terminal area, we develop a large number of flight-route data structures, referred to as "backbones", derived from radar-based data. The backbones capture information regarding operation (arrival or departure), location (fix, airport configuration and runway), and frequency of use (by time and aircraft category). In addition, each data structure contains information on the spatial dispersion of associated routes. These data were merged with ACES trajectories outside the terminal area to provide integrated inputs for the estimation of environmental impacts.

A 30-day radar-based traffic sample was used to generate the backbones for environmental modeling. Because the operational data modeled by ACES was characterized as a "good" weather day in the NAS, the radar data was sampled from a good-weather period. This is appropriate since there is some expectation that future NextGen capabilities will push the IMC capacity restrictions to VMC (Visual Meteorological Conditions) levels. Aviation System Performance Metrics (ASPM) and Ground Delay Program (GDP) data for the primary airports within the area were reviewed for September 2004 through September 2005, and April 2005 was selected as the good-weather period. Detailed terminal-area data for all modeled airports data for this 30-day period were then extracted from the FAA ATA-Lab Offload archive. From this data we derived time of day usage, fix loadings, runway use, and primary airport configurations.

Metron Aviation's ADT (Airspace Design Tool) was used to analyze the radar data for all modeled airports. The data

were separated first by airport, then by operation type (arrival, departure), and then further divided by runway used. Tracks were then grouped using characteristics such as departure headings, arrival intersections, and altitude. Key arrival and departure fixes were also used to identify unique traffic flows. Once the traffic flows were identified, a statistically-determined center track (or backbone) was calculated for each group based on track density within each flow. A set of sub-tracks associated with each center track were also defined to depict the observed lateral dispersion of operations within a flight corridor. The width and density of the flow determined the number of dispersed sub-tracks within a corridor, and the distribution of radar tracks within a corridor determined the percentage use or weighting of each sub-track. Additionally, each backbone's profile was reviewed to identify any deviations from a 3-degree angle of descent or an unrestricted climb. If sufficient deviations were identified, altitude controls recognized by the noise-model state generator were placed on the backbone in order to better emulate the performance and flight profiles. Finally, the operations from the ACES simulation were transferred to the resulting backbones and were used in the event-weighting process.

This process was applied at each of the 34 CONUS OEP airports. Figure 2 shows one example of how the underlying radar data (in black) is represented by backbones (in red) for a subset of arrivals into Chicago O'Hare International Airport. Spatial dispersion information associated with each backbone is not shown in this diagram, but is present in the data and utilized in the environmental modeling.
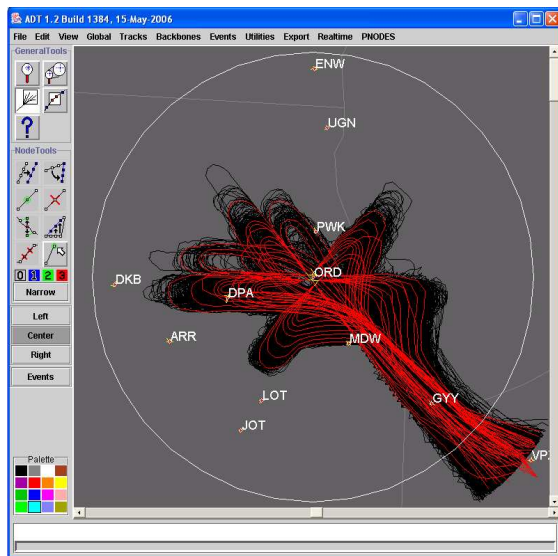


*Figure 2.* Example of terminal-area data augmentation prior to environmental modeling *(radar-based data in black; backbone representation in red; dispersion data not shown)*

(b)  Algorithmic Trajectory Development

The high-fidelity approach is time consuming, so an algorithmic approach is applied at the remaining domestic airports to generate reasonable extensions from/to the arrival/departure fixes. This algorithmic augmentation proceeds as follows:

1.  Since ACES places the metering fixes at 40 nautical miles from the airport, the ACES portion of the trajectory is truncated at 40 nmi from the airport.
2.  For each airport of interest, a default configuration consisting of one runway for arrivals and one runway for departures was specified and subsequently used during the construction of extensions at that airport.
3.  For an arrival, a reasonably realistic path is constructed from the last ACES-defined point (the truncation point) to the arrival runway. The path geometry assumes a standard arrival pattern (downwind, base, final) and features 3 degree/second turns. Additionally, the entry point into the arrival path is determined by the location of the ACES arrival fix.
4.  For a departure, a reasonably realistic path is constructed from the departure runway to the first ACES-defined point (the truncation point). The path geometry assumes an initial straight out path, then smooth (3 deg/sec) turns to connect to the ACES departure fix.

(c)  Modeling of CDA and RNP Capabilities

We model CDA and RNP procedures at the 34 CONUS OEP airports (all of which we have high-fidelity terminal-area trajectories), but not at the remaining secondary airports in the ACES simulation. We currently make three simplifying assumptions: (1) all aircraft originating or destined for these airports are appropriately configured with the proper aircraft navigational equipment; (2) both RNP and CDA procedures are overlays of current procedures represented in our terminal-area radar data (thus requiring no airspace modifications); and (3) procedures that may intersect due to the change in vertical profile caused by CDAs do not need to be resolved for current environmental-modeling purposes.

RNP levels currently modeled are 0.15 (nmi) for final approach and 0.5 (nmi) for the terminal area. We apply the RNP values to the existing traffic patterns in such a way that the modified traffic flows have the same centerline as current flows, but their lateral dispersion is reduced to the specified RNP values. We currently assume that RNP levels are achieved by 100% of the flights in the NextGen scenarios.

CDAs are currently modeled by extending procedure-step data in NIRS (Noise Integrated Routing System) [15] for arrivals to an altitude of 10,000 feet AFE (Above Field Elevation). Descent angles of 2.5 degrees (from 10,000 to 6,000 feet AFE) and 3.0 degrees (from 6000 feet AFE to the runway) are applied to all aircraft.

In the NextGen scenarios, we currently assume that 100% of the flights to and from the 34 CONUS OEP airports utilize

RNP and CDA. This is done to gauge the maximum benefit associated with inclusion of these capabilities. This assumption could be relaxed to reflect other utilization rates.

## B. Modeling of Noise Impacts

In order to address noise at a large number of airports, we utilize two approaches to noise impacts: a population-exposed approach is used at major airports (currently 34 CONUS OEP airports), and a contour-area approach is used at other airports (i.e., secondary airports).

### 1. Population Exposed (Major Airports)

Noise impacts are calculated using the Day Night Average Sound Level (DNL) metric and the FAA regional noise-impact model, NIRS.

First, the Sound Exposure Level (SEL) is determined for each population centroid for each segment of each trajectory modeled. Each appropriate SEL value is calculated from an FAA database of noise-power-distance curves specific to different aircraft/engine types. SEL is a time-integrated expression of sound energy in which each acoustic event is normalized to a duration of one second. Then DNL is calculated from SEL as follows:

$$D_{tot} \text{ (location j)} = 10 \log \{ (1/T) \sum_i (d_i + 10 n_i) \, 10^{(SELi)/10} \},$$
(4)

where the summation on $i$ is over each unique trajectory/equipment combination, and $D_{tot}$ is the total DNL at a given population location (j) due to all flights. In this equation, $d_i$ is the number of daytime events of a specific airframe/engine type on the same five-dimensional trajectory (x, y, z, speed, thrust), while $n_i$ is the number of night events. Night events are defined as being those occurring between 2200 to 0659 local time. Note that a night event has ten times the impact of a corresponding day event, and is equivalent to having an SEL value 10 dB higher. T is equal to the number of seconds in a day.

High-fidelity terminal-area trajectories (with operations assigned to them as simulated in ACES) are used in NIRS, which calculates thrust and speed along the trajectory, as well as the DNL metric for all population locations. For each airport analyzed, the total number of people affected at different levels of DNL (above 55 dB, above 65 dB) are tabulated from the location-specific DNL exposures produced by NIRS. Population locations and associated population counts were based on the 2000 U.S. Census, and were not projected to future years due to the large number of airports being analyzed.

### 2. Contour Area (Secondary Airports)

Since detailed terminal-area trajectories are not available for many of the secondary airports, we utilize an approximation technique known as the Area Equivalent Method [13] to estimate changes in noise-contour area at large numbers of secondary airports. For each aircraft and type of operation, NIRS is used to calculate contour area for eight different DNL levels, which is equivalent to eight different numbers of events at a fixed DNL level (e.g., 65 dB). A linear regression is performed on the logarithms of the area and the event number, yielding parameters a and b for each aircraft and each type of operation, such that the contour area can be calculated from:

$$A = aN^b,$$
(5)

where A is the contour area due to N events for this aircraft type. Using the subscript $i$ to refer to the $i^{th}$ aircraft type, the total contour area from multiple aircraft types is calculated using the following procedure:

$$A_{ref} = \max ( A_i )$$
(6)
$$E_{ref} = \sum_i [ (A_i / A_{ref})^{\wedge}(1/b_i) ]$$
(7)
$$W_{ref} = \sum_i [ (A_i / A_{ref})^{\wedge}(1/b_i) ] / b_i$$
(8)
$$b_{ref} = E_{ref} / W_{ref}$$
(9)
$$A_{total} = A_{ref} ( E_{ref}^{\wedge} b_{ref} ).$$
(10)

We apply this procedure to all flights at all U.S. secondary airports in each simulated scenario.

## C. Modeling of Air Quality Impacts

Emissions calculations utilize the value of fuel burned in each of several operational phases to estimate the mass of pollutants generated. For each of several pollutants (CO, HC, $NO_x$, and $SO_x$), the mass is given by:

$$M_{i,total} = \sum_m ( F_m * EI_{i,m} )$$
(11)

where $F_m$ is the fuel burned in mode $m$ (kg) and $EI_{i,m}$ is the emission index for pollutant $i$ in mode $m$ (g/kg fuel).

Taxi-in and taxi-out times are taken from the ACES out/off/on/in (OOOI) data. Engine-specific ICAO/EDMS taxi/idle fuel-flow values are used to derive the fuel burn during the taxi phase, and are combined with ICAO/EDMS taxi/idle emission factors to compute the pollutant totals emitted during surface movement. Note that since aircraft ground movement is not explicitly modeled in ACES (at present), zero distance is attributed to this phase of operation.

The airborne aircraft trajectory is broken into several phases. Below 3000 feet AGL, engine-specific ICAO/EDMS fuel-flow rates and emissions indices are applied, with takeoff values used from takeoff to 1000 feet AGL, climb values between 1000 and 3000 feet on departure, and approach values between 3000 feet and touchdown. The mapping from ACES

aircraft type to engine type is made based on a review of the domestic commercial fleet and default engine assignments specified in the FAA's Emission Dispersion Model (EDMS).

Above 3000 feet AGL, aircraft-specific BADA fuel-flow factors are used. Each distinct segment is classified as either a climb, cruise, or descent segment, and the mean altitude of the segment is used to determine the corresponding BADA fuel-flow rate for that segment type. Although we do not report emission inventories above 3000 feet AGL, we do calculate such emissions using ICAO/EDMS approach-mode emission indices as a temporary measure. This calculation will be replaced for future analyses with altitude-specific emission indices based on Boeing Method 2 [14,15] as implemented in elements of the FAA's Aviation Environmental Design Tool (AEDT) model.

The trajectory ground-track distance is computed from the beginning of takeoff roll to the end of touchdown on a segment-by-segment basis. This distance, as well as the great-circle distance between origin and destination airports is used in the fuel-efficiency metrics discussed below.

Most international flights in the ACES data (and possibly some others) do not contain both the departure and arrival portions of the trajectory. In these cases (approximately 5-10 percent of the flights), we base fuel and emissions calculations on the available portion of the trajectory. When OOOI data is available for a flight, taxi fuel and emissions are included.

As discussed above, terminal-area trajectories are developed from two sources. If the terminal area is for one of the 34 CONUS OEP airports, the higher-fidelity trajectories used for noise calculations are also used for fuel and emissions. For other airports algorithmic trajectories are used.

### D. Modeling of Fuel-efficiency Impacts

We currently calculate two metrics related to fuel efficiency: an aggregate fleet fuel-efficiency expressed as fuel/distance, and a payload-weighted fleet efficiency expressed as an energy intensity.

1. Fleet fuel efficiency

For a given scenario, this metric is given by the ratio of the total fuel used to the total distance flown:

$$FE_{fleet} = (\Sigma_i \text{fuel}_i) / (\Sigma_i FD_i), \qquad (12)$$

where FD is the flown distance and the summation is over all flights in the fleet. Both fuel and distance include all phases of flight, including taxi operations. For some flights, notably international, portions of the full flight are not modeled in ACES. In order to account for this and any other trajectory-modeling anomalies, we apply a filter to the fuel/distance data before calculating $FE_{fleet}$ that eliminates flights from the computation if their fuel/distance ratio does not fall within a reasonable range.

2. Payload-weighted fuel efficiency

For a given scenario, this metric is given by the ratio of the total energy of the fuel used to the total product of payload times great-circle distance between origin and destination:

$$PFE_{fleet} = (E_{fuel} \Sigma_i \text{fuel}_i) / (\Sigma_i \text{payload}_i * GCD_i), \qquad (13)$$

where GCD is the great-circle distance and the summation is over all flights in the fleet. This metric is similar to a metric discussed in [16], but uses the great-circle distance instead of the flown distance. $E_{fuel}$ is the mass energy density of jet fuel (42.98 MJ/kg), and is based on volumetric energy density of 34.6 MJ/liter and a fuel density of 0.805 kg/liter. Payload is calculated as the product of a nominal number of seats for each aircraft and a payload factor per seat that is currently set to 90.7 kg. For cargo flights, we utilize an appropriate number of seats to estimate the payload. The units of $PFE_{fleet}$ are thus MJ/(kg payload * km).

Fuel consumed includes all phases of flight, including taxi operations. For some flights, notably international, portions of the full flight are not modeled in ACES. In order to account for this and any other trajectory-modeling anomalies, we apply a filter to the data before calculating $PFE_{fleet}$ that eliminates flights from the computation if their (fuel energy)/(payload*distance) ratio does not fall within a reasonable range.

### E. Comparision of Impacts to Sustainability Goals

We compare the environmental impacts to sustainability goals that have emerged from discussion with various JPDO working groups. At present, interim candidate goals have been developed by the JPDO Environmental Working Group for noise and fuel efficiency:

- *Noise* – Reduce the number of persons exposed to 65 dB DNL by 4% per year (compounded) relative to a reference year. (Results below are also discussed relative to a goal of 1% per year.)
- *Fuel efficiency* – Improve the fleet fuel efficiency by 1% per year (compounded) relative to a reference year.

These targets originate from the FAA Flight Plan [17], but for purposes of our analyses are continued out to 2025. For each scenario, we compare the modeled estimate in a future year to the level that should be attained if the goals are to be met based on the improvement rate and the reference year. We apply the fleet fuel efficiency interim goal to payload fuel efficiency in the absence of a specific goal for this metric.

### IV. RESULTS

### A. Scenarios Evaluated

Most recently, we have applied the above methods to six scenarios:

I. *2006 Baseline* – A scenario based on actual traffic levels for 13 July 2006 and containing approximately 95,000 flights.

II. *2025 Without NextGen, Lower Feasible Demand* – A scenario with unconstrained demand projected to 2025 based on the FAA's Terminal Area Forecasts (approximately 150,000 flights) and trimmed to a feasible level based on demand/capacity limits of 1.2 quarter-hourly and 0.9 hourly. The resulting feasible demand is approximately 125,000 flights.

III. *2025 Without NextGen, Higher Feasible Demand* – The same as Scenario II, but trimmed to a feasible level based on increased airport capacity. The resulting feasible demand is approximately 135,000 flights.

IV. *2025 With NextGen, Higher Feasible Demand, No New Technology* – The same as Scenario III, but including NextGen operational improvements for airports, en route, and terminal (as discussed in the Methods section above).

V. *2025 With NextGen, Higher Feasible Demand, Significant New Technology* – The same as Scenario IV, but with the addition of new engine/airframe technology at the N+1 level (see description in Methods section above).

VI. *2025 With NextGen, Higher Feasible Demand, Very Significant New Technology* - The same as Scenario IV, but with the addition of new engine/airframe technology at the N+2 level (see description in Methods section above).

In each of these scenarios, the IFR and VFR flights were approximately equal.

*B. Noise Impacts*

For each of the above scenarios, we applied the population-exposed method to major airports and the contour-area method to secondary airports.

1. Population Exposed at Major Airports

IFR flights at the 34 major airports were analyzed for each scenario and the total number of people exposed at DNL levels of 65 dB or above was tabulated. These values are shown in Figure 3.

For this metric, we evaluated approximately 34,000 IFR flights in Scenario I, 42,000 in Scenario II, and 49,000 in Scenarios III-VI. The large increase in population exposed above 65 dB in Scenario III, relative to Scenario II, is explained by a substantial increase in the number of nighttime flights in Scenario III. This is due to increasing traffic without a complementary increase in capacity, which produces significant delays. This causes many more flights to slip into the nighttime, where they incur a 10dB penalty in the DNL calculation.
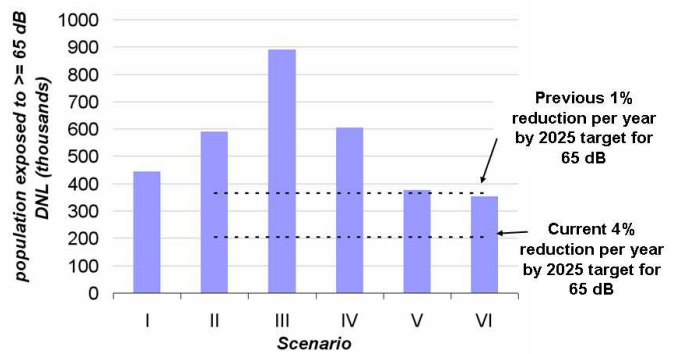


Figure 3. Estimated population exposed at 65 dB DNL or above at the top 34 U.S. Airports

Comparing the results for Scenarios III and IV, we see that the inclusion of NextGen operational capabilities provides a substantially smaller increase in total population above 65 dB at these airports, compared to the increase that would occur without NextGen. However, there is still a net increase compared to Scenario I, the 2006 Baseline.

Additionally, we see that the 2025 goal corresponding to an annual reduction rate of 1% is met by Scenario V due to the introduction of the N+1 technology improvements. The goal is somewhat surpassed by the introduction of N+2 technology improvements. However, the 2025 goal corresponding to a 4% annual reduction is not met in any of the scenarios.

Results for population exposed above 55 dB DNL were also calculated. For Scenarios I through VI, the approximate numbers of people exposed at this level were 5.7, 5.9, 9.3, 5.9, 4.2, and 4.0 million. These results show the same general trend as the above-65dB results, albeit at larger numbers of people exposed.

2. Contour Areas at Secondary Airports

IFR and VFR flights touching 1231 secondary domestic U.S. airports were analyzed for each scenario and the total area of the resulting 65 dB DNL contours was calculated. The change in total area relative to Scenario I is shown in Figure 4.

For this metric, we evaluated approximately 92,000 IFR and VFR flights in Scenario I, 122,000 in Scenario II, and 130,000 in Scenarios III-VI. The large increase in contour area in Scenario III, relative to Scenario II, is explained by a significant increase in the number of nighttime operations in Scenario III.

Results for total contour area at 55 dB DNL were also calculated. For Scenarios II through VI, the change in area relative to Scenario I was 15%, 40%, 17%, -6% and -13%. These results show the same general trend as the 65dB contour-area results.
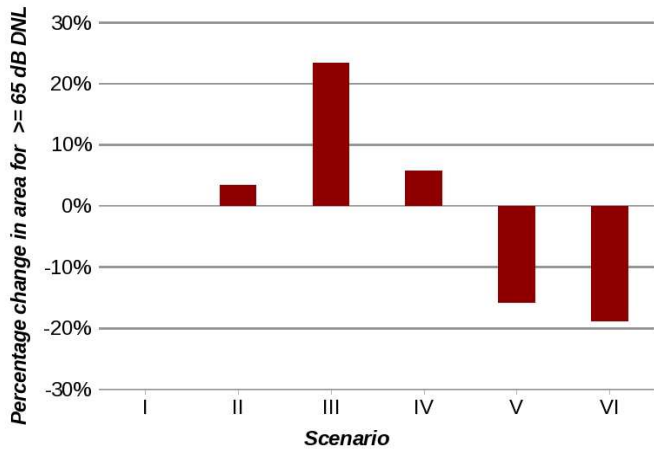
Figure 4. Relative change in the total 65-dB contour area at 1231 secondary airports

Overall, the contour-area results are similar to those for the population exposed to 65 dB or more at major airports. We see that NextGen operational capabilities provide a substantially smaller increase in total contour area, compared to the increase brought about by higher traffic levels (Scenario IV compared to III). We see absolute reductions in total contour area when new technologies are introduced (Scenarios V and VI).

## C. Air-quality Impacts

For each of the above scenarios, we applied the air-quality impact modeling methods discussed earlier to IFR traffic at 294 domestic U.S. airports. We tabulated the amounts of CO, HC, $NO_x$, and $SO_x$. The results are shown in Figure 5.
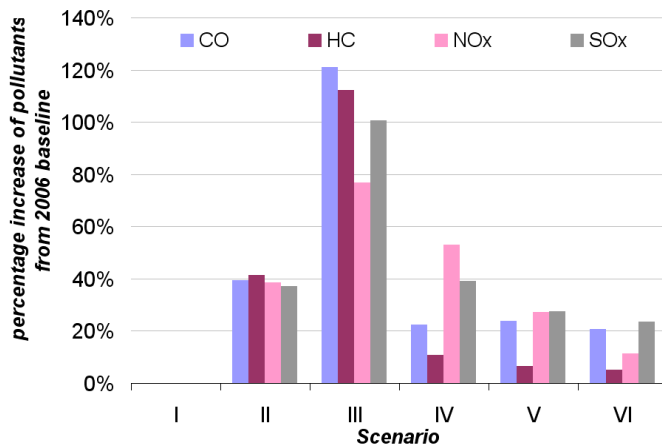


Figure 5. Relative change in pollutant inventories for emissions below 3000 feet AFE

For this metric, we evaluated approximately 44,000 IFR flights in Scenario I, 56,000 in Scenario II, and 63,000 in Scenarios III-VI. The large relative increases between Scenarios II and III are due to substantially longer taxi times in Scenario III. The average departure taxi time was 13.2 minutes in Scenario II and 17.4 minutes in Scenario III.

From these emissions inventories, we see that NextGen operational capabilities provide a substantially smaller increase in inventories, compared to the increase brought about by higher traffic levels (Scenario IV compared to III). We see relative increases substantially less than net traffic growth when new technologies are introduced (Scenarios V and VI compared with I or II).

Emissions inventories for 294 domestic U.S. airports were analyzed in regards to the maintenance and non-attainment designations for local air quality as defined by the Environmental Protection Agency. Currently, 113 of the 294 airports are located in counties that have either full or partial non-attainment status for at least one of the following pollutants, CO, $NO_2$, $SO_2$, or 8-Hour Ozone; while 51 of the 294 airports are located in counties designated as maintenance areas for one or more of these pollutants. In Scenarios II through VI, the percentage of these 164 airports with increases in all pollutants was 70%, 76%, 68%, 62%, and 54%.

## D. Fuel-efficiency Impacts

For each of the above scenarios, we applied the fuel-efficiency modeling methods discussed above to IFR flights using airports in the continental U.S. We calculated both the fuel/distance fleet efficiency and the payload efficiency. The results are shown in Figures 6 and 7.
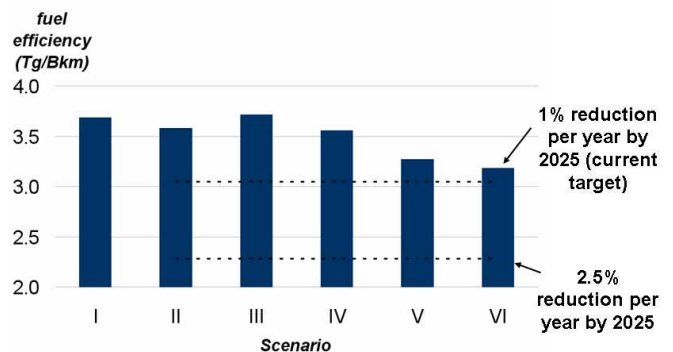


Figure 6. Fleet fuel efficiency in terms of the ratio of total fuel used to total flown distance.
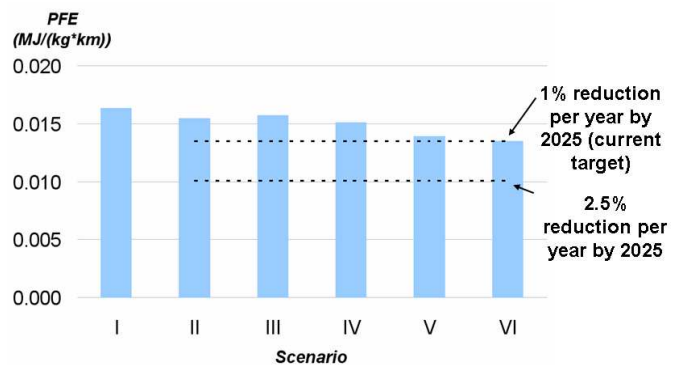


Figure 7. Payload fuel efficiency in terms of the ratio of total energy used to the product of the payload mass and the great-circle distance.

For these metrics, we evaluated approximately 43,000 IFR flights in Scenario I, 55,000 in Scenario II, and 62,000 in Scenarios III-VI. These numbers result from the application of a data-quality check that requires each flight to have an individual payload fuel-efficiency value between 0.002 and 0.1 MJ/kg_km. This range was based, in part, on independent data [16] and includes extensions at the low and high ends to accommodate reasonable variations.

For the fleet fuel-efficiency metric, we see that NextGen operational capabilities and projected evolution of the fleet (not including advanced technological improvements) enable about 13% more traffic at a fleet fuel-efficiency of about 3.7-3.8 Tg/Bkm (Scenario IV compared to II in Figure 6). Although the introduction of advanced technology further improves the fleet fuel efficiency to about 3.2-3.3 Tg/Bkm, neither level of technology attains the 2025 goal corresponding to an annual 1% improvement rate. An additional reference line is shown denoting a 2.5%/year annual improvement to show the impact of changing the fuel-efficiency target to a more stringent goal.

For the payload fuel-efficiency metric, we again see that NextGen operational capabilities and projected evolution of the fleet (not including advanced technological improvements) enable about 13% more traffic at a payload fuel-efficiency of about 0.015 MJ/kg_km (Scenario IV compared to II in Figure 7). The introduction of advanced technology further improves the fleet fuel efficiency to about 0.013-014 MJ/kg_km, with the N+2 level of technology attaining the 2025 goal corresponding to an annual 1% improvement rate, although we recognize that this is an extremely optimistic technology insertion schedule based on current R&D investment plans.

Relative to the 2006 baseline (Scenario I), total fuel and total flown distance, as well as total fuel energy and total payload distance, are shown in the figures below.
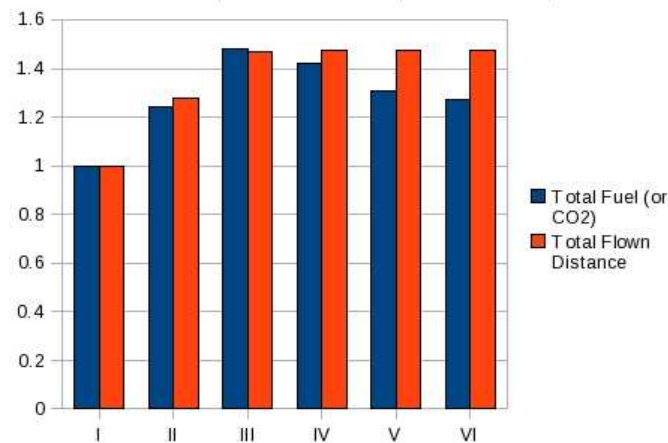


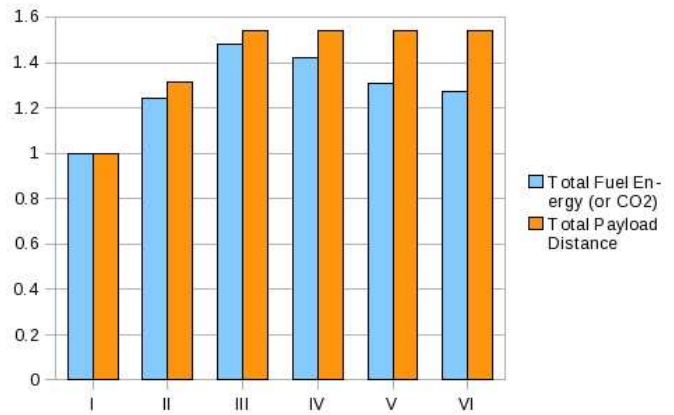Figure 8. Total fuel (or $CO_2$) and total flown distance relative to the 2006 baseline (Scenario I)



Figure 9. Total fuel energy (or $CO_2$) and total payload distance relative to the 2006 baseline (Scenario I)

Analysis of both of these figures indicate that NextGen operational capabilities and fleet evolution (not including advanced technological improvements) enable attainment of approximately 50% more air-transport "product" (flown distance or payload distance) with about 40% more expenditure of fuel (compare Scenario IV to I). However, with the addition of advanced technologies, this can be attained with only about 30% more expenditure of fuel (compare Scenarios V and VI to I).

## V. CONCLUSIONS AND NEXT STEPS

From this analysis of several NextGen scenarios, we draw the following key conclusions:

1. Baseline 2025 traffic levels are obtained by increasing traffic according to FAA projections and limiting the traffic at each airport based on assumptions concerning reasonable ratios of demand to capacity on both quarter-hourly and hourly bases. This results in baseline traffic levels about 30% higher than in 2006. NextGen operational capabilities alone enable attainment of an additional 10-15% more flights beyond that 2025 baseline with negligible additional noise, air-quality, and fuel-efficiency impacts.

2. The addition of advanced engine and airframe technologies provides substantial additional reductions in noise and air-quality impacts, and further improves fuel efficiency. 2025 environmental goals based on improvement rates of about 1% per year are met for noise and fuel-efficiency (an air-quality goal is not yet formulated).

3. Overall air-transport "product", as measured by total flown distance or total payload distance, increases by about 50%, but total fuel consumption and $CO_2$ production increase by only about 40% using NextGen operational capabilities. With the addition of advanced engine/airframe technologies, the increase in total fuel consumption and $CO_2$ production can be reduced to about 30%.

Major next steps in this research include the following:

- *Common metric for constraints due to system capacity and environmental sustainability* - We have also developed a technique that enables capacity limitations and environmental constraints to be quantitatively compared in the same units. This is done in terms of the number of flights that would need to be trimmed from the capacity-feasible demand to meet environmental constraints. Various approaches to trimming rules are being investigated.

- *Costs of environmental impacts* – We have begun collaboration with the FAA Aviation Portfolio Management Tool (APMT) team to link our environmental impacts to their model for the costs of these impacts.

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**Michael Graham -** Mr. Graham joined Metron Aviation in 2002 and has six years experience supporting research and development activities associated with the affects of aviation on the environment, airspace design, and traffic flow management. Mr. Graham has served as the project and technical lead for environmental analysis in support of the Interagency Portfolio and System Analysis Division (IPSA) of the JPDO. Mr. Graham holds a Bachelor of Science in Computer Science from Brigham Young University.

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