Air Traffic Flow Management under NextGen Mixed Equipage Conditions

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Unlike today's NAS, the NextGen airspace will consist of both ground-controlled and self-separated operations. Therefore, Traffic Flow Management (TFM) initiatives must distinguish between equipped and unequipped aircraft to maximize airspace regions that are viable for self-separation. Human factors studies indicate that mixed-equipage operations may be possible by maintaining an acceptable mixture of equipped and unequipped aircraft, overall complexity levels, and traffic density in each sector. We define a notion of a feasible region for self-separated airspace in 3D space of percent-equipped aircraft, traffic complexity, and aircraft count based on the human factors studies. We analyze futuristic traffic data to understand the relationship of these three parameters in each sector. Furthermore, we extend an existing TFM model to include requirements for mixed-equipage operations within the NextGen time frame. This model maximizes the number of sectors that are viable for self-separated operations under mixed-equipage conditions. We present the model formulation and results of an experimental scenario.

Nomenclature

$\alpha_{j,t}$	Maximum number of required aircraft in sector j to be considered SSA feasible at time period t
$\beta_{j,t}$	Minimum equipage level required in sector j to be considered SSA feasible at time period t
γ_j	Minimum number of time periods sector j should operate under SSA
$\mathcal{D}$	Maximum acceptable total delay
$\mathcal{F}$	Set of flights
$\mathcal{F}_e$	Set of equipped flights
$\mathcal{F}_u$	Set of unequipped flights
$\mathcal{L}_j^f$	Set of successor sectors for sector j in flight f
$\mathcal{P}_j^f$	Set of predecessor sectors for sector j in flight f
$\mathcal{S}$	Set of all sectors
$\overline{T}_j^f$	Latest time period flight f can get in sector j
ρ_1	Weight assigned to self-separated mode of operation
ρ_2	Weight assigned to ground-controlled mode of operation
MAP	Sector Monitor Alert Parameter
$\underline{T}_j^f$	Earliest time period flight f can get in sector j
a_f	Scheduled time of arrival
$A_k(t)$	Arrival capacity of airport k at time t
c_e	Cost coefficient for rerouting an equipped aircraft for a time unit from its user-preferred 4DT

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c_u	Cost coefficient for rerouting an unequipped aircraft for a time unit from its user-preferred 4DT
$D_k(t)$	Departure capacity of airport k at time t
$l_{f_{j'}}$	Transit time between sector j and j' for flight f
M_{can}	Flight cancelation cost
T	Set of time periods
4DT	4D trajectory
ANSP	Air Navigation Service Provider
BLO	Bertsimas, Lulli, Odoni
CNS	Communication Navigation and Surveillance
DD	Dynamic Density
FACET	Future Airspace Concept Evaluation Tool
HITL	Human-In-The-Loop
PBS	Performance Based Operations
SSA	self-separated airspace
TAF	Terminal Area Forecast
TFM	Traffic Flow Management

I. Mixed Equipage Operation

Automated separation assurance operations in the upper altitudes (high and super-high sectors) is a topic of ongoing research.[1] This operating environment may be enabled by employing ground-based or aircraft-based separation assurance methods. Operational requirements for automated separation conditions should be established as the system migrates to a more dynamic, heterogeneous airspace. One outstanding research question is whether the self-separated airspace (SSA) should be exclusionary or non-exclusionary.[1,2] Exclusionary (segregated) airspace allows access to only those aircraft that are equipped for either ground-based or aircraft-based separation assurance systems, whereas the non-exclusionary (integrated) airspace also allows access to unequipped aircraft under the control of human controllers. In this work, we mainly focused on developing a decision support algorithm for operations in a non-exclusionary airspace. In particular, an integer programming-based model is developed that efficiently utilizes TFM initiatives such as ground holding, airborne holding, and rerouting to maintain acceptable values for aircraft density, percentage of self-separated operations, and overall traffic complexity within sectors to enable mixed equipage operations. Such techniques can be used to organize airspace, and dynamically allocate SSA where and when the operational requirements are projected to be satisfied.

Given an unconstrained demand profile (including equipage data) and a set of high and super-high sectors, this optimization model would maximize the number of sectors that are viable for self-separation under mixed-equipage conditions. This is achieved while minimizing necessary deviation from the user-preferred trajectories. This model satisfies capacity limitations imposed by dynamic severe weather and traffic congestion thresholds, and maintains acceptable levels of mixed equipage.

A. Mixed Equipage Operation Within NextGen

NextGen envisions self-separated operations for high altitude airspace.[3] Aircraft in this class of airspace are responsible for self-separation, adherence to TFM initiatives, maintaining their 4D-trajectory (4DT) envelope, broadcasting position and intent to other aircraft, and avoiding weather-impacted areas. For self-separated aircraft, a ground-based Air Navigation Service Provider (ANSP) provides no service other than monitoring compliance with entry to and exit from this airspace. Access to SSA can be either exclusive to properly equipped aircraft or mixed. In lower altitude airspace, 4DT will be negotiated and unequipped aircraft will fly in positively controlled airspace.

B. Feasibility of Mixed Equipage Operation

Based on the analysis done by Kopardekar et al.,[1] mixed operation of self-separated and ground-controlled aircraft might be feasible if the number of controlled aircraft is held to a workable level. Results of this analysis indicate that the conflict detection and resolution automation, equipage level, and traffic density are important factors to be considered for airspace configuration. Therefore, acceptability of mixed operation closely depends on the level of traffic complexity, density, and equipage mix (i.e., equipped aircraft for self separation as a percentage of all aircraft) in the underlying airspace. The question regarding the acceptable mixture of these factors is a topic of ongoing research. However, one can assume that there exists a feasible region in three-dimensional space of traffic complexity, aircraft density, and percentage of equipped aircraft for self-separation in which the mixed equipage becomes feasible. The existing literature does not provide exact boundaries for such a feasible region, and further Human-In-The-Loop (HITL) studies are needed to establish both a definition and boundaries.[1,2,4–11]

C. Analysis of Futuristic Traffic

We analyze futuristic 2.0X traffic data to evaluate the operating conditions of future airspace in terms of three important factors for feasibility of mix-equipage operations. The first step is to generate a set of unconstrained, futuristic, and user-preferred trajectories, including equipage data. To generate traffic data that is not restricted by the inefficiencies and limited capacity of the existing system, trajectories should be based on user-preferred routes, including wind-optimal ones, and the cruising altitude should be based on what is most efficient for each flight and not based on historical operations. However, in generating futuristic data, researchers often use a schedule and fleet mix that is derived from historical data. We used schedule data that was derived from a baseline schedule of March 28, 2007 to 2.0X using FAA's 2007 Terminal Area Forecast (TAF) reports. This data was fed to NASA's Future Airspace Concept Evaluation Tool (FACET) to calculate wind-optimal trajectories. Finally, equipage data was fused to these trajectories, and this unconstrained data is used as input to our analysis. Details of this data preparation process can be found in Yousefi et al.[12]

We used this 2.0X unconstrained data to compute aircraft count, traffic complexity, and percentage of equipped aircraft for self-separation for each sector. To measure the traffic complexity we used Dynamic Density (DD) computed by FACET.[13] Fig. 1 shows these three parameters for sectors above FL240 for 15 minute intervals. It is apparent that some sectors will have as many as 150 aircraft during 15 minute intervals—that is much higher than current sector Monitor Alert Parameters (MAP) of about 20 aircraft. Additionally, due to the somewhat direct relationship between $\log_{10}$DD and aircraft count (see Fig. 2), congested sectors also exhibit high levels of traffic complexity. As shown in Fig. 3, the highly congested sectors are located along the New York-Chicago, Chicago-Atlanta, and Chicago-Southern California corridors. Moreover, much of the high altitude airspace is highly congested.

These observations indicate that to be able to handle NextGen traffic, either controllers should control many more aircraft or a portion of traffic should be self-separated—if no other new class of airspace (i.e., flow corridors) would be introduced.

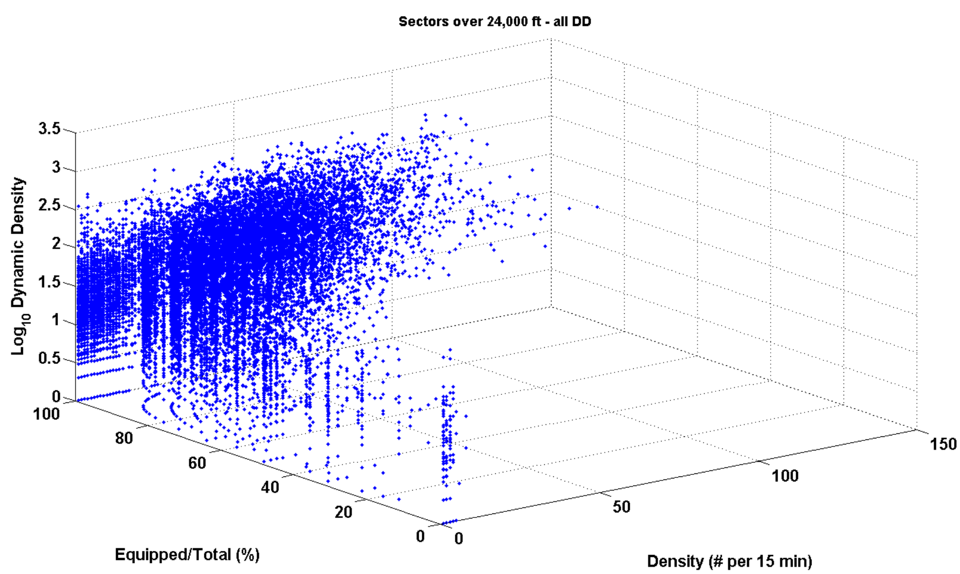


Figure 1. Dynamic density, aircraft count, and percentage of equipped aircraft for sectors above FL240 using 2X data.

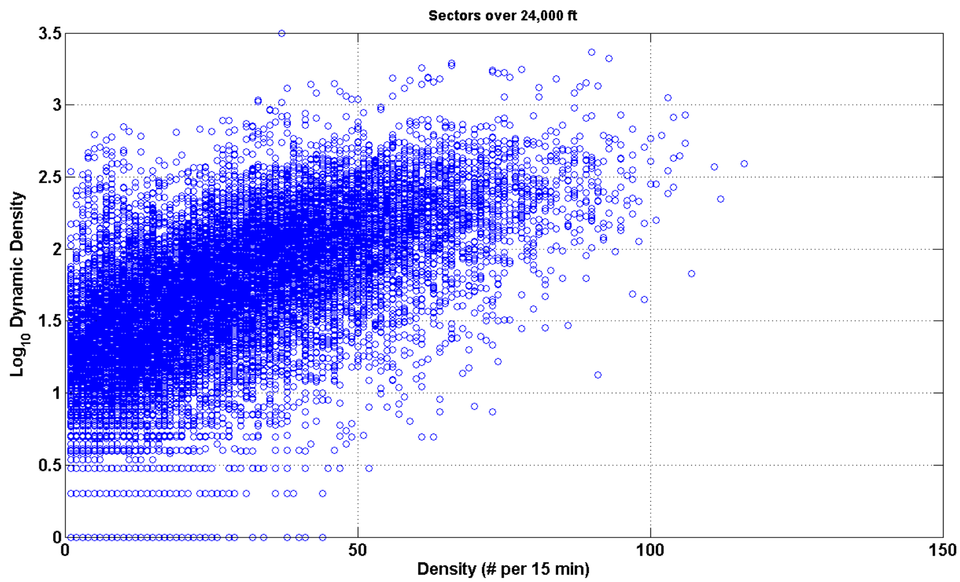


Figure 2. Log10 of dynamic density vs. aircraft count for sectors above FL240 for 15-minute intervals using 2X data

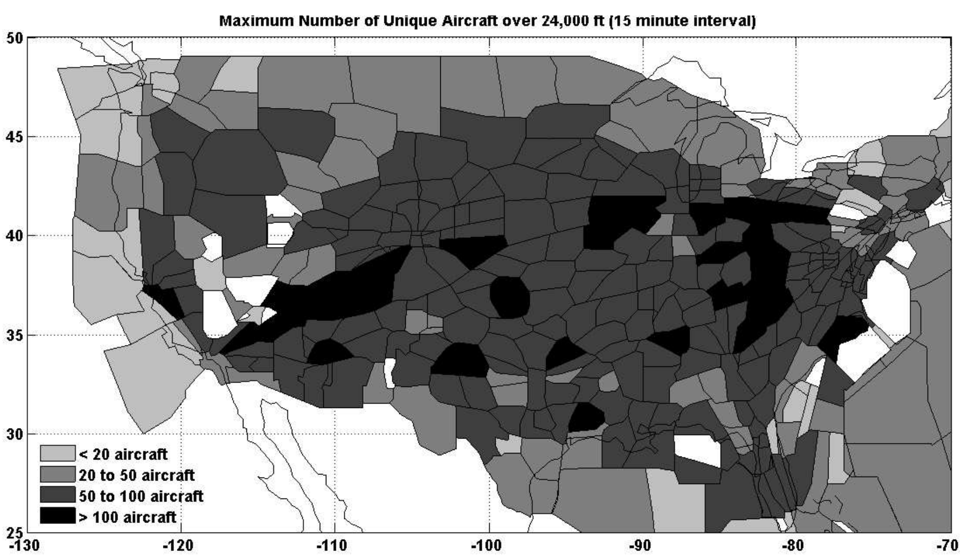


Figure 3. Maximum number of aircraft in 15-minute intervals for sectors above FL240 using 2X data.

Within the space defined in Fig. 1 one could hypothesis a three-dimensional shape inside which the mixed-equipage operation becomes feasible. Assuming feasible values in one dimension, the projection of this 3D feasible region to 2D planes produces feasible regions in two-dimensional space. For example, Fig. 4 indicates this projection into density-equipage plane. The solid black lines indicate boundaries of a hypothetical SSA feasible region. These feasible regions will be utilized in our TFM modeling methodology.

The percentile lines in Fig. 4 depict the distribution of data points along the x and y axes. It is apparent that the 50th percentile lines are located around 20 aircraft and 90% along the x and y axes, respectively. This indicates that for 2.0X traffic, 50% of sectors will have more than 20 aircraft during 15-minute intervals, while 90% of the traffic in 50% of sectors will have the equipage level required for self-separation. Again this indicates the possibility of deploying SSA in large areas of future, high-altitude airspace.

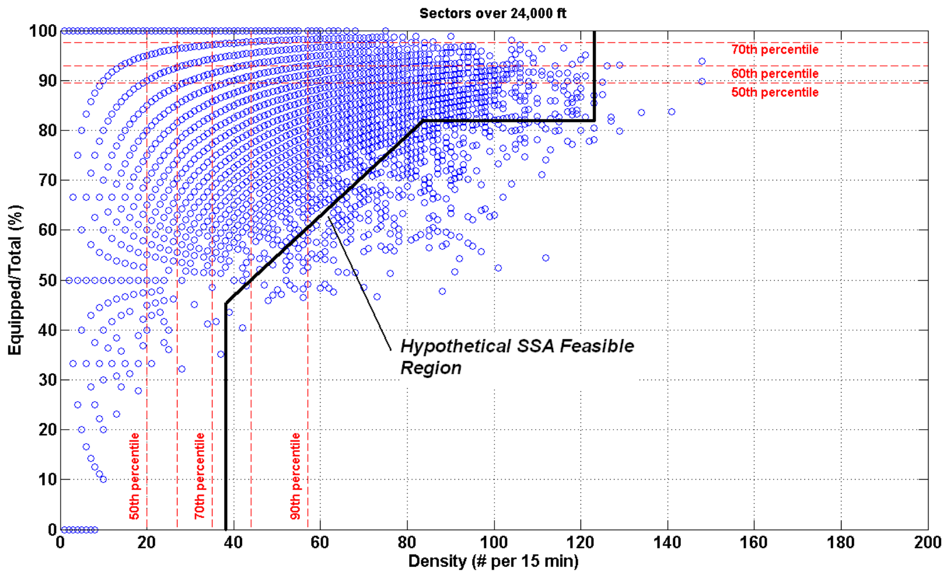


Figure 4. Aircraft count and percentage of equipped aircraft for sectors above FL240 for 15-minute intervals using 2.0X data. Dashed red lines indicate different percentiles along each axis. Solid lines indicate boundaries of a hypothetical SSA feasible region.

D. NextGen TFM Mechanism

Existing TFM models employ different modeling techniques to cap sectors' demand under stated capacity levels, the latter being expressed as maximum number of aircraft per time period (e.g., 15 minutes).[14–20] In these models, any NAS resource can be constrained in a similar fashion (e.g., limiting the airport arrival or departure flows to some stated capacity levels). However, within the NextGen mixed-equipage environment, one objective of TFM models could be to maximize the size of, or the number of aircraft within, the SSA-feasible regions, while minimizing the required deviation from user-preferred 4DTs. The TFM initiatives could include ground and airborne delays and reroutes. The notion of feasible region for SSA as defined in Figs. 1 and 4 provide a convenient way to include new objectives and constraints into TFM models. In other words, in Fig. 1, the TFM models should shift as many points as possible into a predefined SSA feasible region.

For simplicity, we develop models to operate in 2D space of density-equipage. After TFM initiatives are suggested by the model, we check for acceptable values of DD to ensure placement of sectors' operating conditions inside the 3D feasible region.

For a particular sector, if no TFM action can move the sector operating condition inside the SSA-feasible region (see Fig. 5-left), then the TFM model only ensures that sector demand remains below a pre-defined sector capacity (as measured by the sector's MAP value), so it can function under ground-controlled mode of operation. The feasible region in this case can be represented by a straight line (Fig. 5-right). A sector would be considered *nonoperational* if no TFM action can move its operating condition inside one of the feasible regions depicted in Fig. 5. This situation can happen when a sector's demand greatly exceeds its capacity during a time period.

As mentioned before, the exact definition of feasible regions requires further HITL studies. However, technically, any contiguous or non-contiguous 2D shape can be modeled as a collection of vertical, horizontal, and diagonal lines. Hence our model can be adapted to any shape that will be suggested by future studies.

The NextGen vision of implementing Performance Based Operations (PBS) indicates that priority should be given to appropriately equipped aircraft, thereby providing incentives for users to deploy advanced equipage.[3] Therefore, TFM actions should first be applied to those aircraft that are not equipped with advanced Communication Navigation and Surveillance (CNS) equipment.

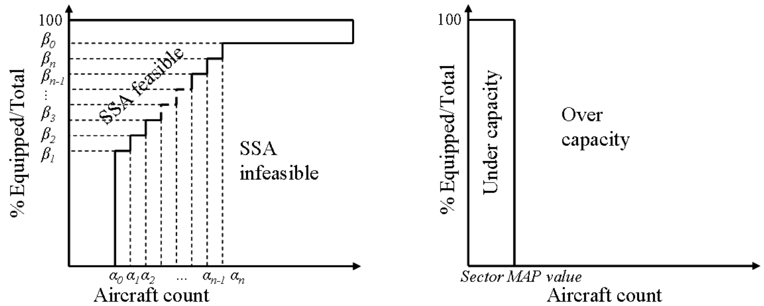


Figure 5. SSA feasible region

II. Modeling

In this section we describe our TFM modeling methodology: a binary integer program for dynamic configuration of SSA under mixed-equipage operations. In principle, any other TFM modeling framework, including heuristic methods, can be extended to include the feasible regions as defined in the previous section. In fact in heuristic models such as the one proposed in Kim et al.,[11] the airspace complexity can easily be included directly inside the model.

In this research we used as a starting point the latest model introduced by Bertsimas, Lulli and Odoni (BLO).[21] The BLO model essentially assigns ground and airborne holding and reroutes to each flight to maintain acceptable sector and airport demand levels. The distinguishing feature of the BLO model lies in the routing options it provides for each flight. Basically, a separate network is formed for each individual flight using a set of sectors it might traverse while flying the alternative routes. The many flight networks are linked by common capacity constraints provided for both sectors and airports.

In our new formulation, we significantly changed the BLO model. We replaced the minimization objective function in BLO with a maximization objective function, defined new variables, and introduced new sets of constraints for applying TFM under mixed equipage conditions. Given a set of high and super-high sectors, this new optimization model maximizes the total number of sectors that are viable for SSA operations while satisfying capacity constraints and the thresholds enforced by the defined SSA feasible region. In the following subsections, we introduce and expand on the various parts of this optimization model. Model notation is summarized in the nomenclature.

A. Decision Variables

Three sets of decision variables are used in this optimization model. To specify different stages of flight operations, the w class is used, and to identify the ground-controlled and self-separated operations, the v and u classes are used. The binary variable $w^f_{j,t}$ is defined as follows:

$$w^f_{j,t} = \begin{cases} 1, & \text{if flight } f \text{ arrives at sector } j \text{ by time } t, \\ 0, & \text{otherwise.} \end{cases}$$

These variables are defined only for the set of sectors an aircraft may fly through on its route to the destination airport. To efficiently control the number of variables defined in the model, $\{w^f_{j,t}\}$ are only defined for the set of feasible time periods $[\underline{T}^f_j, \overline{T}^f_j]$ during which flight f can possibly be present in sector j.

The other two sets of binary variables $v_{j,t}$ and $u_{j,t}$ represent the operating mode of each sector j (see Fig. 5) for all time periods t in the following format:

$$v_{j,t} = \begin{cases} 1, & \text{if sector } j \text{ is operating under self-separated mode at time period } t, \\ 0, & \text{otherwise.} \end{cases}$$

$$u_{j,t} = \begin{cases} 1, & \text{if sector } j \text{ is operating under ground-controlled mode at time period } t, \\ 0, & \text{otherwise.} \end{cases}$$

B. Objective Function

The goal of this optimization model is to maximize the total number of sectors operating in self-separated or ground-controlled modes during the optimization time horizon. The objective function of this model is defined as

$$\max \sum_{j\in\mathcal{S}}\sum_{t\in T}(\rho_1 v_{j,t} + \rho_2 u_{j,t}), \tag{1}$$

where ρ_1 and ρ_2 are respectively weights assigned to self-separated and ground-controlled modes of operation. We assign much higher values to ρ_1 than ρ_2 ($\rho_1 \gg \rho_2$) to force more sectors to operate under self-separated mode.

C. Constraints

We have five classes of constraints defined in this optimization model: capacity, delay, connectivity, mixed-equipage, and structural. The delay and the mixed-equipage constraint classes are introduced in this formulation for the purpose of seeking SSA feasible sectors. The other three classes are almost identical to those used in BLO, and are provided here for clarity.

1. *Capacity*

The following sets of constraints are respectively defined to enforce the airport departure and arrival capacity $(D_k(t), A_k(t))$ for each airport k at each given time period t:

$$\sum_{f\in\mathcal{F}:\mathrm{orig_f=k}} (w^f_{k,t} - w^f_{k,t-1}) \le D_k(t) \qquad \forall k\in\mathcal{K}, t\in\mathcal{T}, \tag{2}$$

$$\sum_{f\in\mathcal{F}:\mathrm{dest_f=k}} (w^f_{k,t} - w^f_{k,t-1}) \le A_k(t) \qquad \forall k\in\mathcal{K}, t\in\mathcal{T}. \tag{3}$$

The expression on the left-hand side of (2) will be equal to one only during the time period in which a flight actually arrives at an airport; similarly, the left-hand side of (3) will be equal to one only during the time period in which a flight actually departs from an airport. The left-hand side of both (2) and (3) are zero otherwise.

2. *Delay*

The delay constraint is defined as

$$c_e \cdot \sum_{f\in\mathcal{F}_e}\sum_{t\in T^f_{\mathrm{dest_f}}} (t-a_f)(w^f_{\mathrm{dest_f,t}} - w^f_{\mathrm{dest_f,t-1}}) \quad + \quad c_u \cdot \sum_{f\in\mathcal{F}_u}\sum_{t\in T^f_{\mathrm{dest_f}}} (t-a_f)(w^f_{\mathrm{dest_f,t}} - w^f_{\mathrm{dest_f,t-1}}) \\ + \quad M_{\mathrm{can}} \cdot (1 - w^f_{\mathrm{dest_f},\overline{\mathrm{T}}^{\mathrm{f}}_{\mathrm{dest_f}}}) \le \mathcal{D}. \tag{4}$$

This inequality sets a maximum acceptable total delay value $\mathcal{D}$ on a combination of the total delay for equipped (first term) and unequipped (second term) aircraft, and cancelation delay (third term). In inequality (4), a_f is the scheduled time of arrival, c_e is the cost coefficient for rerouting an equipped aircraft for a time unit from its user-preferred 4DT, c_u is the cost coefficient for rerouting an unequipped aircraft for a time unit from its user-preferred 4DT, and M_{can} is the flight cancelation cost. The value of c_e is set to be higher than c_u so that the unequipped aircraft are delayed with a lower cost compared to the equipped aircraft. This coefficient represents the cost users incur for being rerouted from their preferred flight plans, and therefore the incentive for them to equip their aircraft accordingly.

The right-hand side of the inequality (4) is a modified version of the objective function defined in BLO, which essentially seeks to minimize a function of the airborne delay and ground delay. In this model we do not distinguish between these two delays, and only aim to limit the sum of delay experienced by all the flights during the planning time horizon. Nevertheless, if necessary, these delays can be easily adapted into our formulation. BLO also does not account for flight cancelations in its formulation. In our formulation, the cancelation term is necessary to ensure a feasible solution when the maximum allowable delay for each flight is not large enough to let all flights reach their destination by the end of the planning horizon.

3. Connectivity

Constraints (5) and (6) represent the network connectivity between sectors. Constraint (5) ensures that flight f cannot arrive in sector j by time t if it has not arrived at one of its preceding sectors $\{j' \in \mathcal{P}_j^f\}$ by time $t - l_{f_{j'}}$, where $l_{f_{j'}}$ is the transit time between sector j and j' for flight f.

$$w_{j,t}^f \leq \sum_{j' \in \mathcal{P}_j^f} w_{j',t-l_{fj'}}^f \qquad \forall f \in \mathcal{F}, t \in T_j^f, j \in \mathcal{S}^f : j \neq \mathrm{orig_f}. \tag{5}$$

In addition, constraint (6) limits a flight f to visit only one of its successor elements,

$$\sum_{j' \in \mathcal{L}_j^f} w_{j',\bar{T}_{j'}^f}^f \leq 1 \qquad \forall f \in \mathcal{F}, j \in \mathcal{S}^f : j \neq \mathrm{dest_f}. \tag{6}$$

Constraint (7) ensures connectivity in time,

$$w_{j,t-1}^f - w_{j,t}^f \leq 0 \qquad \forall f \in \mathcal{F}, j \in \mathcal{S}^f, t \in T_j^f, \tag{7}$$

meaning that if flight f has reached element j by time $\bar{t}$, then the value of $w_{j,t}^f$ must be 1 for all future time periods $t \geq \bar{t}$.

4. Mixed-Equipage

The mixed-equipage set of constraints are introduced to define the feasible regions for the two modes of operation depicted in Fig. 5. Constraint (8) ensures that each sector has a specific mode of operation: self-separated, ground-controlled, or nonoperational.

$$v_{j,t} + u_{j,t} \leq 1 \qquad \forall j \in \mathcal{S}, t \in T. \tag{8}$$

Constraint (9) ensures that if a sector is in ground-based mode of operation during a given time period, the total number of flights in that sector does not exceed the sector's MAP value for that time period.

$$\sum_{f \in \mathcal{F}: j \in \mathcal{S}_f} (w_{j,t}^f - \sum_{j' \in \mathcal{L}_j^f} w_{j',t}^f) \leq \mathrm{MAP}_j(t) + (1 - u_{j,t}) \cdot M \qquad \forall j \in \mathcal{S}, t \in T. \tag{9}$$

The left-hand expression in constraint (9) becomes one for flights that have arrived in sector j but have not yet departed from sector j to its successor sectors $\{j' \in \mathcal{L}_j^f\}$ by time t. M is consistently used as a large positive number in the mixed-equipage constraint class.

Constraints (10–13) are inequalities added to the formulation to define the SSA's feasible region. As indicated in Fig. 5-left, to formulate the diagonal lines in this figure, we approximate them with step functions.

$$\sum_{f \in \mathcal{F}: j \in \mathcal{S}_f} (w_{j,t}^f - \sum_{j' \in \mathcal{L}_j^f} w_{j',t}^f) \leq \alpha_0 + (2 - v_{j,t} - r_{j,t}^0) \cdot M \qquad \forall j \in \mathcal{S}, t \in T_j^f. \tag{10}$$

$$\beta_0 \cdot \sum_{f \in \mathcal{F}: j \in \mathcal{S}_f} (w_{j,t}^f - \sum_{j' \in \mathcal{L}_j^f} w_{j',t}^f) - \sum_{f \in \mathcal{F}_e: j \in \mathcal{S}_f} (w_{j,t}^f - \sum_{j' \in \mathcal{L}_j^f} w_{j',t}^f) \leq (2 - v_{j,t} - r_{j,t}^1) \cdot M \qquad \forall j \in \mathcal{S}, t \in T_j^f. \tag{11}$$

$$\sum_{f \in \mathcal{F}: j \in \mathcal{S}_f} (w_{j,t}^f - \sum_{j' \in \mathcal{L}_j^f} w_{j',t}^f) \leq \alpha_n + (2 - v_{j,t} - r_{j,t}^n) \cdot M \qquad \forall j \in \mathcal{S}, t \in T_j^f, n \in \mathcal{N}. \tag{12}$$

$$\beta_n \cdot \sum_{f \in \mathcal{F}: j \in \mathcal{S}_f} (w_{j,t}^f - \sum_{j' \in \mathcal{L}_j^f} w_{j',t}^f) - \sum_{f \in \mathcal{F}_e: j \in \mathcal{S}_f} (w_{j,t}^f - \sum_{j' \in \mathcal{L}_j^f} w_{j',t}^f) \leq (2 - v_{j,t} - r_{j,t}^n) \cdot M \qquad \forall j \in \mathcal{S}, t \in T_j^f, n \in \mathcal{N}. \tag{13}$$

Constraints (10) and (11) respectively assure that a sector is qualified to become SSA at time period t if the total number of aircraft in that sector is less than or equal to α_0, or if the percent of equipped aircraft

$\{f \in \mathcal{F}_e\}$ for self-separation is greater than or equal to β_0. Moreover, constraints (12) and (13) together define the corners of the SSA feasible region in Fig. 5-left for each pair of α_n and β_n where $\{n = 1, \ldots, |\mathcal{N}|\}$ and $\mathcal{N}$ is the set of corner points in the feasible region. To properly define the SSA feasible region, a set of auxiliary binary variables ($r^0_{j,t}$, $r^1_{j,t}$, and $\{r^n_{j,t}\}$) are added to the mixed-equipage inequalities.

Constraint (14) ensures that for sector j to become SSA feasible at time period t, it should at least fall into one of the feasible regions defined by constraints (10) and (11), or into the regions defined by constraint pairs (12) and (13).

$$r^0_{j,t} + r^1_{j,t} + \sum_{n \in \mathcal{N}} r^n_{j,t} \geq 1 \qquad \forall j \in \mathcal{S}, t \in T^f_j. \tag{14}$$

Constraint (15) can be added to the set of constraints to ensure that when sector j becomes SSA feasible, it stays SSA feasible for at least γ_j consecutive time periods.

$$\sum_{i=1}^{\gamma_j} v_{j,t+i} + M \cdot v_{j,t-1} \geq \gamma_j \cdot v_{j,t} \qquad \forall j \in \mathcal{S}, t \in T^f_j. \tag{15}$$

5. Structural

The $\{w^f_{j,t}\}$, $\{v_{j,t}\}$, and $\{u_{j,t}\}$ decision variables and the auxiliary variables ($r^0_{j,t}$, $r^1_{j,t}$, and $\{r^n_{j,t}\}$) must be binary, as follows:

$$w^f_{j,t} \in \{0,1\} \qquad \forall f \in \mathcal{F}, j \in \mathcal{S}^f, t \in T^f_j, \tag{16}$$

$$v_{j,t} \in \{0,1\} \qquad \forall j \in \mathcal{S}, t \in T^f_j, \tag{17}$$

$$u_{j,t} \in \{0,1\} \qquad \forall j \in \mathcal{S}, t \in T^f_j, \tag{18}$$

$$r^0_{j,t}, r^1_{j,t}, r^n_{j,t} \in \{0,1\} \qquad \forall j \in \mathcal{S}, t \in T^f_j, n \in \mathcal{N}. \tag{19}$$

D. Model Run Time

As discussed in Bertsimas et al.,[21] the computational complexity of large-scale TFM models can be reduced by decomposing the problem in time or space, by reducing the number of underlying flights, or by reducing the number of capacitated elements. The number of variables in the BLO model has in particular a significant effect on the model run time and can grow quite fast as the problem size becomes bigger.

In this model, to reduce the run time when dealing with NAS-wide problems, the size of the model can be controlled by lowering the problem time resolution. The planning horizon and the maximum allowable lateness for each flight into each of its sectors are other parameters that contribute to the complexity of this model, and can be adjusted to control the size of the problem.

III. Experiments and Results

In this section, we present a sample scenario to study the performance of the optimization model discussed in the previous section. ILOG Java Concert Technology and ILOG CPLEX Interactive Optimizer version 12.1 were used to develop and solve this integer-programming model. More details about the experimental scenario and its results are given in the following subsections.

A. Experimental Scenario Description

We selected a high-volume region of the NAS, the Indianapolis Center (ZID), and extracted the flight plans for a four-hour time period (12:00z to 15:59z) from the 2.0X data described in Section IC. This resulted in 3,490 flights where 86% of them were equipped for self-separated operations. Next, the optimization model was used to maximize the total number of high and super-high sectors in ZID, which can be operated under self-separated mode during the planning time horizon. In this scenario, we did not generate any reroutes for the listed flights, and therefore the optimization model could only delay the flights to maximize the number of sectors that were viable for self-separation.

Fig. 6 shows the density-equipage distribution of the sectors in ZID for five-minute intervals before running the optimization model. The feasible regions for self-separated and ground-based operations are respectively indicated by solid and dashed lines on this figure. The set of nonoperational, SSA feasible, and ground-controlled feasible sectors are also distinguished by different colors on Fig. 6. The optimization model shifts as many red points as possible in Fig. 6 into the defined feasible regions by delaying or canceling flights while it maintains the total delay below some acceptable level.

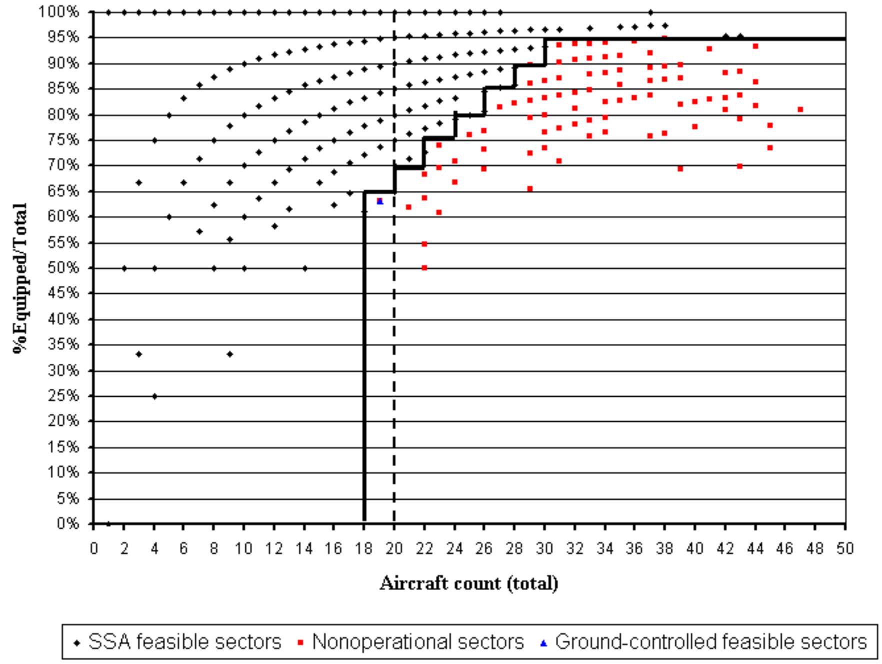


Figure 6. Density-equipage distribution of the ZID scenario before applying the optimization model.

The schedule data for these flights were processed into five minute intervals. Flight cancelations were permitted in the model at a cost equivalent to 240 minutes of delay. The maximum allowable delay for each flight was 10 minutes, and the optimality gap for MIP was set at 5%. Airport capacities were not taken into consideration in this analysis.

B. Results

Tables 1 and 2 summarize the results for the scenario outlined in the previous subsection. For the base case run, we set the acceptable delay to zero and ran the model to study the modes of operations for different sectors during various time periods when no TFM initiatives is in effect. For the next 3 runs, we gradually increased the value of total acceptable delay, and reported the optimization results on the total number of sectors in each mode of operation, the total number of delayed flights (equipped and unequipped), the total number of canceled flights, and the total minutes of delay experienced by all flights.

Run Name	Total Acceptable Delay	# Sectors in Each Mode of Operation		
		Self-Separated	Ground-Controlled	Nonoperational
Base Case	0	937	3	138
1	1,000	1,028	0	50
2	15,000	1,047	0	31
3	40,000	1,069	0	9

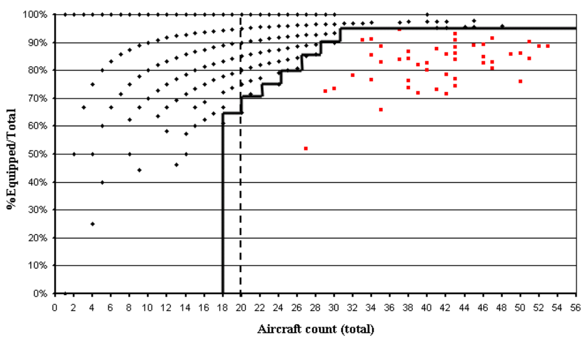
Table 1. Number of sectors in each mode of operation for the base case and 3 runs of the optimization model for various total acceptable delay values.

It is clear from the results in Tables 1 and 2 and from the density-equipage curves in Fig. 7 that as the value of total acceptable delay increased, more sectors became viable for self-separated operation and the number of nonoperational sectors reduced. The three curves in Fig. 7 illustrate how the nonoperational

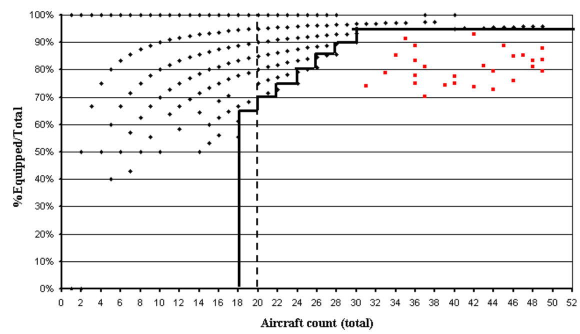
Run Name	Total Acceptable Delay	# Delayed Flights		# Canceled	Total Delay
		Equipped	Nonequipped	Flights	(mins)
Base Case	0	-	-	-	-
1	1,000	31%	30%	15	5445
2	15,000	35%	38%	23	8105
3	40,000	84%	69%	58	21980

Table 2. Flight cancelation and delays experienced by equipped and unequipped flights for the base case and 3 runs of the optimization model for various total acceptable delay values.

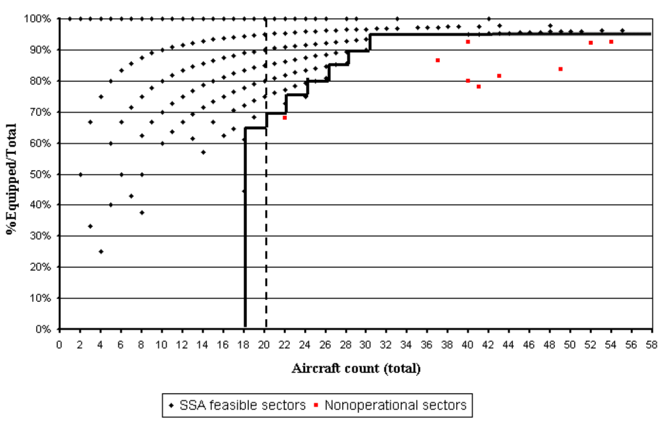
sectors (red points) moved to the SSA-feasible region (black points) by optimally applying TFM initiatives such as delays and cancelations.



(a) Run 1.



(b) Run 2.



(c) Run 3.

Figure 7. Sectors mode of operation for different levels of acceptable delay

IV. Conclusions and Future Work

We generated a set of unconstrained and user-preferred trajectories of 2.0X traffic, and showed that some of the high-altitude sectors will experience significant over-capacity situations. Regardless, a significant portion of the excessive traffic was shown to be adequately equipped for self-separation.

Introduction of new classes of airspace with different operating conditions and dynamic allocation of airspace resources within NextGen will introduce new requirements for TFM modeling. In particular, mixed operation of controlled and self-separated aircraft in high-altitude airspace requires TFM models to include factors such as traffic complexity and equipage levels in addition to traditional sector capacity defined as number of aircraft in each sector during a given time interval. In this paper, we attempted to develop a modeling framework to include these new factors. We established the notion of SSA-feasible region in three-dimensional space of traffic complexity, aircraft density, and equipage level, and utilized this definition in our modeling. Although we used binary integer programming techniques, other formal or heuristic TFM modeling techniques can also be extended to include the new requirements.

An experimental scenario was developed to test the model and study its performance in maximizing the total number of self-separated sectors by applying TFM initiatives. Our analysis showed that as the value of the total acceptable delay increased, more sectors became viable for self-separated operation and the number of nonoperational sectors reduced.

There are several areas to which this research can be extended. The most important effort may be further human factors and HITL studies to better define the boundaries of SSA feasible regions. Exact definition of these boundaries may not be possible due to variations of operating conditions in different areas of the NAS and variation of human controllers' mental capacity and training. A more practical approach could be to define different safety margins for sub-regions of a feasible region, and assign priority orders to each sub-region based on their perceived safety level. The TFM models should then attempt to maintain high levels of safety in addition to other required objectives and constraints. Additionally, it may be more reasonable to define the SSA feasible regions for individual facilities or groups of sectors based on the similarity of traffic within each group of sectors.

The interaction of SSA with other futuristic classes of airspace, such as flow corridors, should also be explored. The introduction of flow corridors in the NAS will provide a means to off-load properly equipped traffic from controlled sectors by assigning them to flow corridors. Within the TFM models, flow corridors can be modeled as airspace resources separate from regular sectors.

In this research we tested our model using an experimental scenario for only one center, and did not include reroute as a TFM action. Future research should include a NAS-wide scenario with possibility of reroutes. However, due to inherent nature of mixed integer programming, the run time of BLO model may be unreasonably long. In such cases, other TFM models, including heuristics, can be extended to include the new requirements.

Finally, this research could be applied for NextGen investment and policy analysis. Technically, instead of applying TFM actions to maintain sectors' operating conditions within feasible regions, one could extend the feasible region. For example, the feasible region can be extended along the equipage axis by investment in CNS systems to enable more aircraft for self-separation. Similarly, to extend the feasible region along the aircraft density axis, automated tools (such as datalink, conflict prob, or automated hand-in/off technology) must be provided to human controllers to enable them to handle higher levels of congestion. The same analogy can be applied to the traffic complexity axis. In the future we intend to perform sensitivity analysis along each axis to understand which technology could deliver the most benefit in terms of enabling more self-separated aircraft or larger SAA regions.

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