Establishing an Upper-Bound for the Benefits of NextGen Trajectory-Based Operations

Guillermo Calderón-Meza (Ph.D. Candidate)
Research Assistant
Center for Air Transportation Systems Research
George Mason University
Fairfax, Virginia, 22030, USA
Email: gcaldero@gmu.edu

Lance Sherry (Ph.D)
Director
Center for Air Transportation Systems Research
George Mason University
Fairfax, Virginia, 22030, USA
Email: lsherry@gmu.edu

***Abstract*—NextGen enabling technologies and operational initiatives seek to increase the effective-capacity of the National Airspace System. Concepts-of-operations, such as Trajectory-Based Operations, will allow flights increased flexibility in their 4-D trajectories as they traverse Center airspace. Shifting trajectories in this way can minimize the airlines operating costs (i.e., distance flown), shift the geography of Air Traffic Control (ATC) workload (i.e., sectors used), shift the time-intensity of ATC workload (i.e., flights counts per sector).**

This paper describes the results of an analysis of one day of operations in the NAS using traditional navigation aid-based airway routes compared to direct, i.e., Great Circle Distance, routes. The results yield: (i) a total of 599 thousand nm (average 30 nm per flight) savings generated by flying direct routes, (ii) a redistribution of flights across sectors resulting in a reduction of 3% in the total time the flights in a sector are in excess of the Monitor Alert Parameters for that sector, (iii) a reduction in ATC workload reflected by a 47% drop in the number of flights requiring conflict resolution. These results indicate upper bound of benefit opportunities for both ATC and the airlines based on the introduction of flexible routing structures in NextGen.

***Index Terms*—NextGen, evaluation, conflicts, FACET, distance flown, delays.**

I. Introduction

NextGen [1] enabling technologies and operational initiatives seek to increase the effective-capacity of the *National Airspace System* (NAS) by opening up unused airspace, increasing the availability of airspace in all weather conditions, and increasing the utilization of existing airspace by reducing spacing between flights on the same routes.

Concepts of operations, such as *Trajectory-based Operations* (TBO), will allow flights increased flexibility in their 4-D trajectories as they traverse center airspace. Whereas the airlines may benefit from reduced distance flown, the adjustment of the 4-D trajectories will shift the geographic distribution of flights across *Air Traffic Control* (ATC) sectors, as well as the distribution of instantaneous flight counts in individual sectors. Several related concepts are identified as Trajectory-Based Operations [1], [2]: 1) *Continuous Decent Arrivals* (CDA)) that smooth the transition from top-of-decent to near idle speed. These include *Tailored Arrivals* that use technology (automation tools and data communications) to provide a preferred trajectory path and transfer it to the flight management system on the aircraft. 2) *3D Path Arrival Management* that designs fuel-efficient routes to decrease controller and pilot workloads. 3) *4D Trajectory-Based Management* that defines 3-dimensional flight paths based on points in time (the 4-D) from gate-to-gate. 4) *Required Navigation Performance* in which navigation performance requirements for operation within an airspace define the trajectories. In this paper, only the third definition is considered.

This paper analyzes the potential upper bound of impact of the shifting trajectories to minimize the airlines operating costs (i.e., distance flown), the geographic workload (i.e., sectors used), and the time workload (i.e., flights counts per sector) for Air Traffic Control (ATC). Similar studies have been carried out to evaluate the impact of this change and other changes proposed by NextGen. Barnett [3] evaluates the impact in safety caused by using direct routes instead of airways. The study concludes that using direct routes diminishes the risk of en-route collision. These results are valid only if certain rules for TFM remain in effect after the change. A caveat of the study is that the results will depend on the capacity of the technology and humans to match the current performance of the ATC. Agogino and Tumer [4] evaluate policies intended to optimize performance of the TFM. The metrics used are congestion and delays. The study evaluates several ATC algorithms as well as the use of multi-agent technology. The algorithms achieve significant improvements in performance compared to previous algorithms and the current practices. Magill [5] also analyzes the change from airway routes to direct routes. The study uses the number of conflicts (called interactions in this case) as an approximate metric of the ATC workload. The study modifies the separation rules as well as the type of routes. The paper concludes that the reduction of traffic density due to the use of direct routes is the most significant factor in the reduction of workload for the ATC.

The Future ATM Concept Evaluation Tool (FACET[1]) [6] was used for this experiment that included 19,900 domestic flights between 287 airports (4,170 O/D pairs). The experiment

[1] See www.aviationsystemsdivision.arc.nasa.gov/research/modeling/facet.shtml

consisted of two scenarios: (i) flights followed *Great Circle Distance* (GCD) routes from TRACON to TRACON, and (ii) flights followed traditional navigation aid-based airway routes. The flights in each scenario used the same cruise flight levels and cruise speeds. The results are summarized below:

(i) Great Circle Distance routes generated a total of 598,724.8 nm (average 30.1 nm per flight) savings in reduced distance flown.

(ii) Great Circle Distance routes resulted in a redistribution of ATC workload reducing the time sectors were above their *Monitor Alert Threshold* (MAP) from 32% to 21%.

(iii) Great Circle Distance routes resulted in reduced ATC workload reducing the number of flights with conflicting trajectories by 47%.

These results establish an upper bound on the benefits to be derived by Trajectory-based Operations. The result is a win-win scenario for both the airlines and air traffic control. The use of Great Circle Distance routes geographically redistributed the flights reducing workload in the most congested sectors and well as significantly reducing conflicts in flight trajectories. It should also be noted that the use of Great Circle Distance routes did not alleviate the flight delays resulting from over-scheduled departure and arrivals.

This paper is organized as follows: Section 2 describes the design of the experiment, the simulation used for the experiment, and the configuration and parameters used in the experiment, Section 3 describes the results of the experiment, and Section 4 provides conclusions, implications of these results, and future work.

II. Method and Design of the Experiment

The experiment was conducted using the Future ATM Concept Evaluation Tool (FACET) [6]. The tool has been used in previous studies [4], [7], [8] to evaluate new *Traffic Flow Management* (TFM) concepts in the NAS. FACET offers many options like the possibility connecting to real-time data sources for weather and traffic, real-time conflict detection and resolution, batch processing of input data (as an option to real-time streams), and a Java API[2]. In the absences of random inputs (like weather phenomena) the simulation is deterministic. The results will be the same regardless of the number of executions.

Other metrics of the system, like number of sectors or centers flown, distance flown, and number of conflicts, can be obtained from the API or from the GUI[3].

A. The input files for FACET

The main input to FACET is the flight schedule, flight tracks and cruise flight-levels. FACET accepts several formats for these input files known as ASDI, TRX. To achieve the goals of this experiment, a TRX input file was generated based on actual historical data from the *Airline On Time Performance Data* data provided by *Bureau of Transportation Statistics* (BTS). The procedure for generating the TRX file is described bellow.

First, the sample TRX files that come with FACET were parsed and the O/D pairs and corresponding flight plans were extracted and exported to a database.

Second, the BTS Airline On-Time Performance (AOTP) data was queried to obtain a single day of domestic operations. The query extracted the O/D pair, the coordinates for the airports (taken from a proprietary table), the scheduled departure and arrival times, the flight and tail numbers, and the aircraft type (taken from a proprietary table related to On Time by tail number). The results of this query are sorted, ascending, by scheduled departure time.

For each record returned by the query the great circle distance of the O/D pair, the expected flight time (that is the difference of the scheduled departure and arrival times both converted to GMT), the required ground speed (and integer number of knots), the heading (an integer number computed from the coordinates of the airports assuming 0 degrees for North heading, and 90 degrees for West heading), and the flight level (a uniformly distributed random integer number from 200 to 450), and the flight plan (taken randomly from available plans for the O/D pair). The coordinates of the airports are converted into integer numbers with the format [+|-]DMS where D stands for degrees (two or three digits), M stands for minutes (two digits), and S stands for seconds (two digits). FACET requires western longitudes to be negative.

Third, for each group of records with the same GMT scheduled departure time one "TRACKTIME" record is written to a text file. The value of the TRACKTIME record is the GMT scheduled departure date/time converted into the number of seconds from January 1, 1970 GMT. After this TRACKTIME record, the individual "TRACK" records for the flights are written using the data computed in the second step. The process repeats until there are no more records from the query. An input file generated this way does not track the flights through the National Airspace System. It only describes every flight with a single record. So this file can be used for simulation purposes only, not for playback in FACET.

The file used in this experiment contains 19,900 domestic (USA) flights scheduled to departure from Friday July 27 2007 at 05:30:00 GMT to Saturday July 28 2007 at 09:20:00 GMT. The actual landing date/time of the last flight differs between scenarios because flights could be delayed or they could fly different distances.

B. Design of Experiment

The goal of this experiment is to evaluate the effect of changing from the current airway routes, i.e., flight plans, to Great Circle Distance routes, i.e., direct routes, as it is proposed by NextGen.

This paper presents and compares the results of one experiment divided into two scenarios (see Table IV). The first scenario simulates one day of NAS operations in which all the flights use airway routes, i.e., flight plans, as it is done today in the NAS. The second scenario simulates the same day of

[2]API: Application Program Interface.

[3]GUI: Graphical User Interface.

operations, but flights follow Great Circle Distances routes, i.e., direct routes, between the origin and the destination.

The outcomes of interest for each scenario are the total number of *centers* and *sectors*, and the *distance* flown by the flights, the total number of *conflicts* detected, and the *flight delays* generated in the OEP-35[4] airports. The benefits and costs for the airlines, controllers, and the environment can be computed using these outcomes.

The distances flown are compared using a paired two-tail t-test. The paired t-test applies since the simulator (FACET) uses the same input file in both scenarios, so each flight in one scenario can be compared to its similar in the other scenario. However, it was observed that some flights do not appear in both scenarios, even if the input file is the same. The reasons for this fact are still not completely understood. But, only flights that appear in both scenarios are used in the t-test.

The comparison of the total number of conflicts is only done for a single pair of numbers, so no statistical test is applied in this case.

The distribution of the sectors load is multi-dimensional. There is spatial distribution and temporal distribution. In this paper mainly the temporal distribution will be analyzed, leaving the spatial distribution for future work. The two scenarios are compared using the percentage of time in which at least one sector contains a number of flights that is on or over the sectors Monitor Alert Parameter (MAP) value, i.e., it is overloaded. To get an idea of the distribution, also the percentage of time in which at least one sector is at or over 80% of its MAP is compared between scenarios.

No external disturbances are included during the simulations, i.e., there are no restrictions due to weather, congestion, push-back delays, or other stochastic events. So, the simulations are deterministic. The only limitation that is imposed in the arrival capacity of the EOP-35 airports, which is set to the VFR departure and arrival rates for the whole day (see Table I). Even with VFR rates, this limitation generates ground delays via *Ground Delay Programs* (GDP), but their effect is not strong because the airports are not significantly over-scheduled in the scenario input file used for the experiment. However, the ground delays are compared using the total minutes of delays and the average minutes in the OEP-35 airports which are the only ones restricted using GDPs.

C. FACET settings used in experiment

In this experiment, FACET takes its input from batch files, and the outputs are taken from the simulation via the API. The input file was loaded using the *loadDirectRouteSimAsynch* and the *loadFlightPlanSimAsynch* functions of the API. With the first function, FACET sets itself to use Great Circle Distance routes, i.e., direct routes. With the second function, FACET uses the airways routes, i.e., flight plans, provided in the input file. Both functions accept the same number and types of arguments. The *trajectory update interval* is set to 60. The *integration time step* is set to 60.0. And the *additional update delay* is set to 0.2.

[4]OEP: Operational Evolution Partnership Plan.

TABLE I
DEFAULT VFR AIRPORT ARRIVAL RATES (AAR) FOR THE OEP-35 AIRPORTS USED IN THE SIMULATION

Airport name (ICAO)	Airport Arrival Rate (Moves per hour)	Airport name (ICAO)	Airport Arrival Rate (Moves per hour)
KATL	80	KLGA	40
KBOS	60	KMCO	52
KBWI	40	KMDW	32
KCLE	40	KMEM	80
KCLT	60	KMIA	68
KCVG	72	KMSP	52
KDCA	44	KORD	80
KDEN	120	KPDX	36
KDFW	120	KPHL	52
KDTW	60	KPHX	72
KEWR	40	KPIT	80
KFLL	44	KSAN	28
KHNL	40	KSEA	36
KAID	64	KIAH	72
KSFO	60	KJFK	44
KSLC	44	KLAS	52
KSTL	52	KLAX	84
KTPA	28		

The API provides an interface (ConflictInterface) with functions to enable (setEnabled) and configure (setConflict-DetectionParameters) the conflict detection functionality. The parameters are as follows. The center index is set to -1, i.e., all the centers. The *surveillance zone* is 120 nm. The lookahead time is 0. The *horizontal separation* is 6 nm. The *vertical separation* below f1290 is 1000 ft. The *vertical separation* above f1290 is 1000 ft. Also, the detected conflicts are displayed during the simulation.

The arrival rates (AAR) of the airports are infinite by default in FACET. For this experiment, the capacities are limited using FACET's GDP functionality. The OEP-35 airports are assigned a maximum capacity in the form of an *arrival delay GDP* from the 0:00 to 24:00 (see Table I). With these limits in the capacity of the airports, FACET starts recording delay statistics during the simulations.

A total of 35 hours and 55 minutes (2,155 minutes) of operations are simulated. All other parameters of FACET are left to their default values.

An external Java program, using the FACET API, measures the distance traveled as follows. At each simulation time step (one minute) the distance flown by each flight is updated based on the previous and current coordinates. The computation of distance is done with the *utils.getGCDistanceNM* function of FACETs API. The external program also records the total number of flights in each sector, including all the sector levels, i.e., low, high, and super. Distances and sector loads are written into text files for further analyses.

III. RESULTS

A. Distances flown

Figure 1 compares the histogram of the distance flown when using airways to the histogram of the distance flown when using direct routes. The figure also includes the descriptive statistics for the scenarios. When using airways, most of

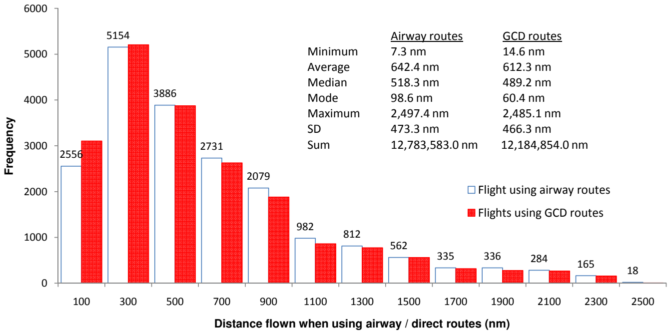

Fig. 1. Comparison of histograms of the distances flown using airways and direct routes

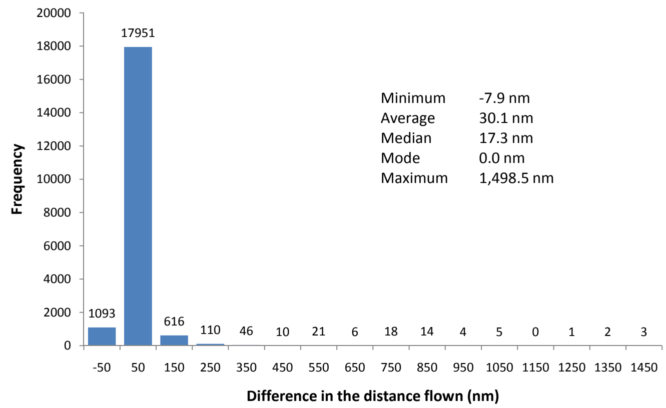

Fig. 2. Histogram of the flight-by-flight difference in the distance flown

the flights travel less than 1,000 nm, with a peak of flights between 200 and 400 nm. Short flights, i.e., less than 200 nm are frequent, but not a majority in this input file. There is a long tail in the distribution, but the actual number of flights is low compared to the other distances. The flights with longer distances correspond to flights from Alaska or other US territories not directly in the continent.

When using direct routes, most of the flights travel less than 1,000 nm, with a peak of flights between 200 and 400 nm. Short flights, i.e., less than 200 nm are more frequent than when using airways. This is an immediate benefit of using direct routes: shorter flown distances. The comparison of the tails shows that their frequencies are similar.

The distribution for the scenario of the direct routes is shifted toward the shorter distances. This is evident in that the average, median, and mode are smaller in this scenario than they are in the airways scenario. The standard deviation is also smaller indicating that the distribution is less disperse in this scenario.

The figure shows that the input file used in this experiments is dominated by short to mid distance distance flights. This reflects that the input file comes from a database that contains only data for actual domestic flights in the US. The greater changes in the frequencies are observed in the flights from 0 to 200 nm, and from 800 to 1,000 nm. This suggests that the benefits of using direct routes are clearer in short flights or in trans-continental flights.

Figure 2 shows the distribution of the differences of distance flown by corresponding flights in both scenarios, i.e., it is a paired comparison of distances. The figure also includes the descriptive statistics for the distribution. The 1,093 (5.5%) of the differences in the distance flown are negative indicating that the direct routes are longer than the airway routes. This is mathematically incorrect. This is due to errors in the measurement of the distance during the simulation. Notice that the minimum difference is -7.9 nm, and the bin of the histogram goes from -100 to 0 nm, so the negative differences are in this 7.9 nm range. The peak of the histogram occurs when the difference is between 0 and 100 nm, 90% of the differences are in this range.

A paired two-tail t-test shows that the mean of the difference between the distances flown by corresponding flights in the two scenarios is significantly different than zero (M=30.1, SD = 60.7, N = 19,900), t = 69.9647 and the two-tail p = 0.000. A 95% confidence interval about the mean is (29.2, 30.9). This average reduction in the distance flown adds to 598,724.8 nm saved when using direct routes instead of airways. The reduction in distance flown benefits the airlines and the environment, through a reduction in fuel burned, i.e., less pollution and lower costs.

TABLE II
NUMBER OF MINUTES WITH AT LEAST ONE SECTOR SATURATED OR ON THE VERGE OF SATURATION

Scenario	Number of minutes with at least one sector on or above (% of the total 2,114 minutes)	
	MAP	80% of MAP
Flights using airway routes	689 (32%)	944 (44%)
Flights using direct routes	456 (21%)	917 (43%)

B. Sectors over MAP

A metric for the load of sectors is a function of time, space, the number of flights, and routes of the flights. The number of flights did not change between scenarios in this experiment. The routes are expected to change significantly when going from flight plans to direct routes. With this change in the type of route the distribution of sector load through time and space is also expected to change.

The time distribution of the sector load is analyzed in this experiment. TABLE II shows that controllers spend 32% of their time managing congested sectors, i.e., at or above the sector's MAP, when the flights use airway routes. But controllers spend 21% of their time managing congested sectors when the flights use direct routes. The values for 80% of MAP give an idea of the distribution of sector load in the two scenarios. The percentage of time controllers spend managing sectors with 80% or more of their MAPs is similar in both scenarios with a small reduction for the case of direct routes. This similarity indicates that using direct routes mostly reduces the frequency of overloaded sectors, but does not change the total time controllers spend managing "almost saturated" sectors.

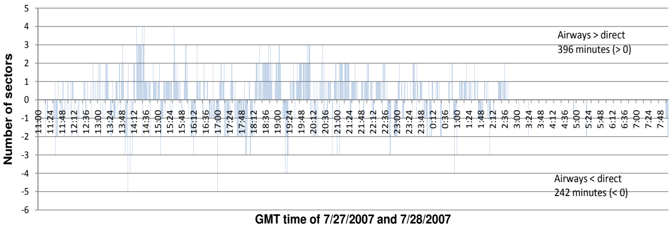

Fig. 3. Minute by minute difference in the number of sectors on or above MAP

Comparing the sector loads minute by minute provides more insight of effect of using direct routes in the NAS. Figure 3 shows that using airways produces load peaks (396 minutes, positive side of the vertical axis) that are often higher in value and closer in time than when using direct routes. Using direct routes produce few intense peaks (value -4 and -5), but the peaks (242 minutes) are more scattered in time. So controllers will have more time to "rest" between peaks of saturation when flights use direct routes and the saturation will be, in average smaller than when using airways.

C. *Conflicts*

The total number of conflicts detected reduced from 23,071 when using flight plans to 12,308 when using direct routes. This is an improvement in safety, i.e., lower probability of accident, and a further reduction in the workload of the controllers, i.e., they have to resolve 46.7% less conflicts. Magill [5] found that, for similar separation rules, the reduction was about 35%.

D. *Delays*

The flight ground delays generated by the GDPs defined for the OEP-35 airports are summarized in Table III. The arrival capacities of the OEP-35 airports were set to VFR rates for the whole day. Ground Delay Programs were activated at all the OEP-35 airports.

The total ground delay generated for the OEP-35 airports reduces from 14,076.4 minutes when using airway routes to 13,444.0 minutes when using direct routes. The average delay for all the OEP-35 airports remains similar between scenarios: the reduction is in the order of few seconds.

The mean flight delay differs from airport to airport ranging from 7.5 min to 0.3 min in the case of the airway routes, but from 6.8 min to 0.3 min in the case of direct routes. These numbers are low with respect to the observations of the actual airports due to (i) absence of international flights, (ii) the scenarios resulted in the same degree of over-scheduling of departures and arrivals. The effect of the direct routing would be equally likely to over-schedule arrivals as it would be to reduce simultaneous arrivals.

TABLE IV summarizes the results of the two scenarios and the previous tables and charts.

IV. Conclusions

This experiment consisted of two scenarios with the same set of 19,900 domestic flights in the NAS. The scenarios were executed using FACET. In one scenario flights used airways the same way they currently do in the NAS. In the second scenario flights used direct routes. The arrival rate of the OEP-35 airports was set to the VFR rates using the GDP functionality provided by FACET.

TABLE III
Flight delays on the OEP-35 airports obtained by limiting arrival capacity

	Flight plan			Direct route		
Airport code (ICAO)	**Number of flights**	**Total delay (min)**	**Avg delay (min)**	**Number of flights**	**Total delay (min)**	**Avg delay (min)**
KATL	941	7,066.9	7.5	960	6,550.3	6.8
KBOS	167	90.0	0.5	169	85.0	0.5
KBWI	147	120.8	0.8	148	143.5	1.0
KCLE	130	188.8	1.4	132	206.2	1.6
KCLT	262	275.7	1.0	265	265.7	1.0
KCVG	244	246.5	1.0	247	234.8	1.0
KDCA	161	145.0	0.9	163	156.1	1.0
KDEN	413	128.2	0.3	416	131.2	0.3
KDFW	562	178.3	0.3	569	188.7	0.3
KDTW	203	163.2	0.8	206	167.0	0.8
KEWR	212	278.7	1.3	213	246.5	1.2
KFLL	103	84.4	0.8	105	90.0	0.8
KHNL	81	85.0	1.0	88	54.8	0.6
KIAD	117	74.9	0.6	117	114.6	1.0
KIAH	363	278.8	0.8	364	252.5	0.7
KJFK	156	168.6	1.1	157	178.4	1.1
KLAS	216	207.0	1.0	222	249.3	1.1
KLAX	328	173.4	0.5	333	167.6	0.5
KLGA	187	207.0	1.1	191	221.8	1.2
KMCO	219	191.6	0.9	222	179.2	0.8
KMDW	163	315.5	1.9	164	241.6	1.5
KMEM	93	35.7	0.4	95	43.7	0.4
KMIA	111	55.4	0.5	113	53.5	0.5
KMSP	247	330.3	1.3	249	277.4	1.1
KORD	695	885.2	1.3	706	921.8	1.3
KPDX	83	84.3	1.0	84	81.3	1.0
KPHL	183	161.2	0.9	186	166.0	0.9
KPHX	76	30.3	0.4	76	28.2	0.4
KPIT	66	23.2	0.4	66	20.2	0.3
KSAN	128	244.0	1.9	130	248.2	1.9
KSEA	139	206.3	1.5	142	170.2	1.2
KSFO	179	98.0	0.5	184	91.8	0.5
KSLC	267	903.7	3.4	268	894.8	3.3
KSTL	119	93.1	0.8	121	89.0	0.7
KTPA	136	257.5	1.9	137	233.0	1.7
Totals	7,897	14,076.4	1.8	8,008	13,444.0	1.7

TABLE IV
Experimental design and experimental results

	Scenario	
	Great Circle Distance routes	**Airway routes**
Total distance flown (Average distance per flight)	12,184,854.0nm (612.3nm)	12,783,583.0nm (642.4nm)
Percentage of time with sectors above MAP threshold (% of time with sectors 80% or more of MAP)	21% (43%)	32% (44%)
Number of airborne conflicts detected by ATC	12,308	23,071
Total flight delays (Average delays)	13,444.0min (1.7min)	14,076.4min (1.8min)

The goal of the experiment was to evaluate the effect of introducing direct routes for domestic flights.

The distance flown is smaller, in average 30.1 nm, when flights use direct routes. And the difference is statistically significant. There are more flights with routes of less than 200 nm when flight use direct routes that when they use airway routes. But all the other route distances are less frequent in the case of direct routes than in the case of airways. This reduction in the distance flown results in savings of fuel and time. Airlines and the environment benefit from such a reduction.

Sector congestion is also reduced by using direct routes instead of airway routes. Controllers spend 21% of their time managing overloaded sectors when the flights use direct routes, but they spend 32% when flights use airways.

Peaks of sector congestion are also more separated in time. This reduction might result in safety benefits.

The total number of conflicts detected is reduced about 46.7% (from 23,071 to 12,308) when using direct routes. This results in safety benefits by a reduction of the workload of the controllers.

Ground delays (at the origin airports) reduced when using direct routes, but the reduction is not significant. There was a limitation in the way FACET uses to assign delays that did not allow, in this experiment, to measure the airborne or arrival delays. The delays recorded are only due to the GDPs. And the GDPs are using maximum arrival rates for the OEP airports. This does not impose enough restrictions and generates small delays.

Implications of results

These results establish an upper bound on the benefits to be derived by Trajectory-based Operations. The result is a win-win scenario for both the airlines and air traffic control. The use of Great Circle Distance routes geographically redistributed the flights reducing workload in the most congested sectors and well as significantly reducing conflicts in flight trajectories. It should also be noted that the use of Great Circle Distance routes did not alleviate the flight delays resulting from over-scheduled departure and arrivals.

Future work

Further work is required to monetize the benefits. For example, how does the reduction in conflicts compares to the reduction in distance in terms of costs? What will be the effect of the distance reduction at the destination airports, e.g. will it produce more congestion?. Also studies with more realistic input files, i.e., including all domestic and international flights, are required to observe congestion and reflect the actual effect of the change. Future work also includes resolution of several anomalies in the results including: (i) great circle distance routes in excess of the associated flight plan routes, (ii) excessive route distance, (iii) missing flights. Detailed statistical data are needed for the delays, e.g., standard deviations, modes, medians, and ranges. More studies in which the conditions of the airports are set to IFR instead of VFR will bring more insight of the problem. The environmental effects of the reduction in distance must also be studied by using more specific tools.

Acknowledgment

The authors would like to acknowledge the contributions and help from the following persons and institutions.

The research this study is part of is funded by NASA (NRA NNA07CN32A). Furthermore, Natalia Alexandrov, Kapil Sheth, María Consiglio, Brian Baxley, Kurt Neitzke, and Shon Grabbe, all NASA employees, have provided suggestions and comments throughout the whole research process.

From Sensis Corporation, George Hunter and Huina Gao. From George Mason University, Dr. Thomas Speller Jr., Dr. Kenneth De Jong, Dr. Robert Axtell, Dr. George Donohue, Dr. John Shortle, Dr. Rajesh Ganesan, John Ferguson, and Keith Sullivan. From Metron Aviation, Jason Burke, Dr. Terry Thompson, and Norm Fujisaki. From FAA, Joe Post and Tony Diana. They have contributed to the improvement of the research.

Finally, thanks to the Ministerio de Ciencia y Tecnología (Minister of Science and Technology) of Costa Rica.

References

[1] JPDO, *Concept of Operations for the Next Generation Air Transportation System, Version 2.0*. Washington DC, USA: Joint Planning and Development Office, June 2007.

[2] G. Hayman. (2009, June) Trajectory based operations. [Online]. Available: http://www.afceaboston.com/documents/events/cnsatm2009/Briefings/Tuesday%20Briefs/Tuesday%20Afternoon/Track%202/2%20TBO%20PresentationGeneHayman:pdf

[3] A. Barnett, "Free-flight and en route air safety: A first-order analysis," in *Operations Research*. INFORMS, Nov-Dec 2000, vol. 48, no. 6, pp. 833–845. [Online]. Available: http://www.jstor.org/stable/222992

[4] A. Agogino and K. Tumer, "Regulating air traffic flow with coupled agents," in *Proceedings of 7th Int. Conf. on Autonomous Agents and Multiagent Systems (AAMAS 2008)*, M. Padgham, Parkes and Parsons, Eds., Estoril, Portugal, May 2008, pp. 535–542.

[5] S. Magill, "Effect of direct routing on air traffic control capacity," in *Air Transportation Systems Engineering*, G. L. Donohue and A. G. Zellweger, Eds., vol. 193. USA: American Institute of Aeronautics ans Astronautics, 2001, pp. 385–396, iSBN 1-56347-474-3.

[6] K. Bilimoria, B. Sridhar, G. B. Chatterji, K. Sheth, and S. Grabbe, "Facet: Future atm concepts evaluation tool," *Air Traffic Control Quarterly*, vol. 9, no. 1, pp. 1–20, 2001.

[7] B. Sridhar, G. B. Chatterji, S. Grabbe, and K. Sheth, "Integration of traffic flow management decisions," *American Institute of Aeronautics and Astronautics*, 2002.

[8] R. Jakobovits, P. Kopardekar, J. Burke, and R. Hoffman, "Algorithms for managing sector congestion using the airspace restriction planner," ATM. ATM, 2007.