

Economic and Safety Impacts of Flight Routing in the National Airspace System

Kee Palopo* and Robert Windhorst†
NASA Ames Research Center, Moffett Field, CA, 94035-1000

Bassam Musaffar‡ and Mohamad Refai§
University of California Santa Cruz, Moffett Field, CA, 94035-1000

A study analyzing the economic and safety impacts of different flight routing methods in the National Airspace System is presented. It compares filed flight routes, wind-optimal routes, and great-circle routes. Routing differences are measured by flight time, fuel burn, sector count, and number of conflicts. Wind-optimal routes exhibit on average approximately one percent less flight time and fuel burn than filed flight routes. In addition, they produce an average of 13 less conflicts in Class A airspace (18,000 feet and above). All three routing methods are qualitatively equivalent in terms of sector count distribution. These results agree with earlier studies, which investigated some combinations of these types of routes and metrics. The contribution of this paper is that it consistently compares the three routing methods across the United States using the four metrics.

I. Introduction

Airborne delays cost as much as several hundred dollars a minute.^{1,2} In 2006, fuel cost \$38.5 billion.³ Airlines can save cost by flying wind-optimal routes that minimize flight time or fuel burn. However, the current airspace system requires flight plans to be defined in terms of predetermined routes (e.g., jet routes) and nav aids.⁴ This constrains route optimization. The advent of onboard precision navigation systems⁵ allows aircraft to fly routes that are not constrained by the existing route structure. The economic and safety impacts of wide scale adoption of wind optimal routes are of great interest.

Earlier studies examined the benefits and costs of flight routings similar to those presented in this paper.⁶⁻¹³ In Ref. 7, it was shown that significant cost savings could be achieved without adversely impacting the traffic management functions. In Ref. 8, fuel savings in Free Flight due to airspace modernization were estimated by simulation models and extrapolations to the future. The modernization involves Federal Aviation Administration's investment in Communication, Surveillance, and Navigation technologies. In Ref. 9, it was asserted that Free Flight would save billions of dollars annually in flight times and fuel burn. In Ref. 10 the benefits of wind-optimal routing in the Central East Pacific region were evaluated. The study found an average time and distance savings of 4.8 minutes and 4.0 nmi per flight, respectively. In Ref. 11, the conflict counts produced by great-circle routes (GCR) and those used today were calculated. GCR had significantly fewer conflicts (46% less). In Ref. 12, a computationally efficient, wind optimal routing algorithm using neighboring optimal control technique was described. In Ref. 13 a relationship of air traffic density and conflicts in terms of wind-optimal routing was described.

This study compares user-filed, great circle, and wind optimal flight routes to determine their economic and safety benefits in the National Airspace System (NAS). In addition, it provides wind-optimal routing with fuel burn model data. The metrics considered are flight time, fuel burn, sector count, and number of conflicts. These are calculated for all routes flown in the NAS during 8 March 2007. The study used the Advanced Concepts Evaluation System (ACES)¹⁴ simulation tool and wind-optimal routes were created using the algorithm presented in Ref. 12.

* Aerospace Engineer, Aerospace Operations Modeling Branch, MS 210-8.

† Chief, Aerospace Operations Modeling Branch, MS 210-10, and AIAA Senior Member

‡ Technical Area Manager, Aerospace Systems, U.C. Santa Cruz, MS 210-8

§ Senior Programmer/Analyst, Aerospace Systems, U.C. Santa Cruz, MS 210-8

The rest of this paper is organized as follows. Section II describes the three types of routes used in this study. Section III describes the experiment design, consisting of the approach and metrics of the study. The results are discussed in Section IV, followed by the conclusions in Section V.

II. Types of Routes

Figure 1 depicts filed flight routes, GCR, and wind-optimal routes between Los Angeles International Airport (KLAX) and John F. Kennedy International Airport (KJFK); it serves to demonstrate their structural differences. Filed Flight Routes (FFR) are shown in blue, GCR is shown in green, and Neighboring-Optimal Wind Routes (NOWR) are shown in red. The figure shows multiple NOWR routes, which reflect wind fields at different departure times. There are also multiple FFR. These routes exhibit variations due to other factors such as Special Use Airspace (SUA) and jet route structure. Wind optimal routes and GCR do not avoid SUAs.

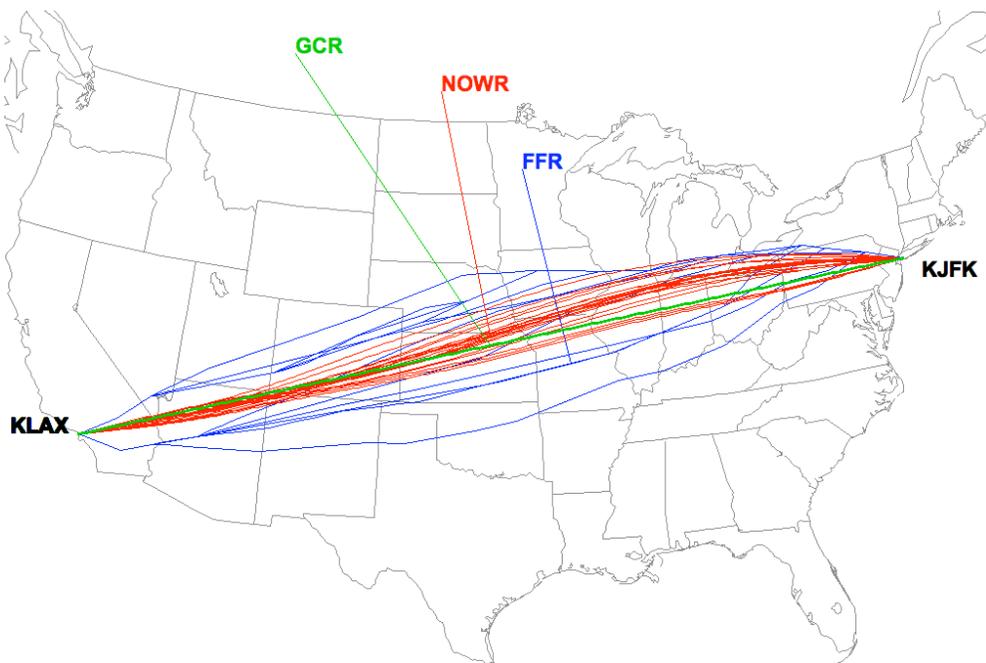


Figure 1. KLAX to KJFK

A. Filed Flight Routes

FFRs in this study come from the Enhanced Traffic Management System. A scheduled flight plan associated with an FFR contains the flight's scheduled departure time, origin and destination airports, aircraft type, proposed cruise airspeed and altitude, and a series of waypoints. The waypoints must be located at the intersections of current jet routes, Standard Instrument Departure Routes (SIDS) and Standard Terminal Arrival Routes (STARs), or at navaids. Note that a user may file multiple flight plan updates for each flight prior to departure time. For this study, only the most recent flight plan prior to departure is used. Similarly, flight plan amendments in flight are not considered in this study.

B. Neighboring Optimal Wind Routes

Wind-optimal routes are generated for an airport pair using the algorithm in Ref. 12. It assumes that flights travel with constant altitude and airspeed. These assumptions are suitable for a long-haul flight. The inputs to the algorithm are the user-filed flight plan described above and a wind field. While FFR are optimized on a number of criteria including winds,¹⁵ NOWR are optimized on winds exclusively.

The performance of NOWR varies under different wind-fields. NOWR could be updated in flight to account for wind field prediction updates generated on the ground or in-flight. Finally, the performance of NOWR is expected to reflect seasonal wind patterns. These daily and yearly wind changes are not explored in this paper.

C. Great Circle Routes

The GCR waypoints are aligned along a great circle path connecting origin and destination airports. Great circles are geodesics (i.e., paths of shortest distance) between two points on a sphere (in this study the earth is modeled as a sphere). These routes are an attractive baseline for comparison with other types of routes because they are shortest paths. They have been used in Refs. 6 and 11 for this purpose. Although GCR are geodesic, they are not minimum time when winds are introduced.

III. Experiment Design

This section describes the simulation approach and the metrics of the study. The traffic on 8 March 2007 was used in this study to represent a reasonable daily traffic in the NAS of around 50,000 flights.¹⁶ This day represents a recent “low weather” day, as measured by average delay due to weather, reported by the Federal Aviation Administration’s Operations Network data. The daily average delay in minutes in March 2007 ranged from 30.32 to 62.76 with an average of 43.74. On 8 March 2007 the average delay was 34.18 minutes. Although the delay on this date is relatively low, it is not due to low traffic demand, which would lead to an unreasonable reference day.¹⁷ The Rapid Update Cycle wind “analysis” data¹⁸ were used. These data are based on a 40 km grid with 37 pressure altitude levels ranging from 1000 to 100 mb.

Prior to using the traffic data in simulation, data pruning was necessary. A total of 2,023 of 54,531 FFR do not contain origin or destination airports, cruise airspeeds, or cruise altitudes. These were filtered out. For ACES purposes, the remaining flight plans (52,508 flights) are stored in text files called the flight data set. A total of six simulations were run. Each of the first three simulations uses 52,508 flights. Each of the last three simulations uses a single flight. A more detailed description of flight data set file format and its source is given in Refs. 19 and 20.

In this study, both ACES Air Traffic Control and Traffic Flow Management functionalities are disabled. These controls are disabled so the open-loop response (i.e., sector loading and conflict counts) to changes in route structure can be studied. Furthermore, the study considered only one day in the NAS. More variation of traffic scenarios based on combinations of low-to-high traffic volume and low-to-high weather days is necessary and planned for future studies. As such, the results in this study should be interpreted as preliminary.

A. Simulation Approach

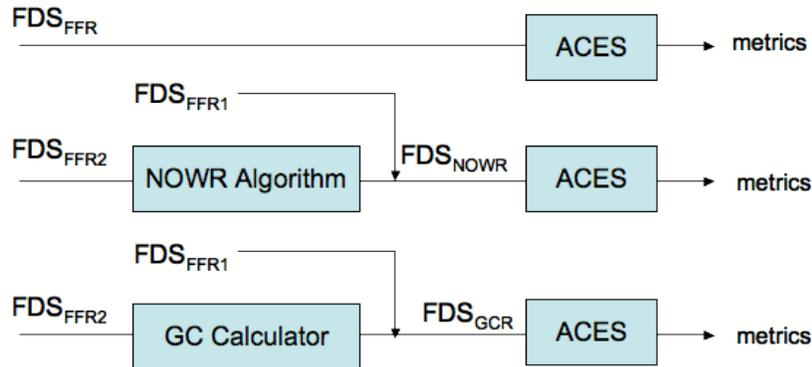


Figure 2. Experiment Setup

Figure 2 shows the steps used for the first three simulations. For FFR, the input is FDS_{FFR} , and it is fed directly into the ACES simulation. For NOWR, which are better suited for long-haul flights, FDS_{FFR} is split into two parts: one part that has flight plans for airport-to-airport distances of 500 nm or more for optimum cruise energy range²¹ and for cruise altitudes of 18,000 feet** or more, and another part that has the remaining flight plans. The former – consisting of 19,340 flights – is fed into the NOWR. The output of this algorithm is combined with the aforementioned remainder to become the FDS_{NOWR} , which is fed into ACES. For GCR routing, the FDS_{FFR} is split as before. The output is similarly combined with the remainder to become FDS_{GCR} , which is fed into ACES. By

** An altitude of 18,000 feet was chosen to match that studied in Ref. 11 to compare conflict properties.

splitting the data this way, only the common 19,340 flights are effectively compared, while still maintaining a full day of overall traffic.

The NOWR algorithm is applied to the above 19,340 flights from airport of origin to destination airport. The algorithm, which assumes constant airspeed and constant altitude, thus leads to some error in flight time estimates. The altitudes in this case are the cruise altitudes. The two sources of error are the climb and descent segments—which are flown at different calibrated airspeed and to a different wind field than that at cruise altitude—and more importantly the addition of SIDS and STARS to the NOWR flight plan in ACES. To help assess the impact this optimization method has on the overall performance, a single flight—from San Francisco International Airport (KSFO) and Washington Dulles International Airport (KIAD)—was optimized from top of climb to top of descent with FFR climb and descent segments maintained. This single flight was used in the aforementioned last three simulations: FFR, GCR, and NOWR. Results are presented in section IV.

B. Metrics

Four metrics were selected for comparison. The first two metrics, flight time and fuel burn, measure economic impacts and the last two metrics, sector count and conflicts, measure safety impacts of changing the route structures. Both sector count and conflict count are instantaneous metrics. More sophisticated ways of characterizing sector loading and conflict are discussed in Refs. 22 and 11, respectively. This study uses the instantaneous sector count and conflict count metrics as high-level indicators of safety impacts.

1. Flight Time

A flight time can be divided into surface time and airtime. The air time consists of the time from take off to a departure fix, en route time, and the time from an arrival fix to touch down. Furthermore, the en route time consists of the flight time from a departure fix to the top of climb, the cruise time, and the time from top of descent to an (initial) arrival fix. For simplicity, this paper compares the en route flight times for the 52,508 flights.

2. Fuel Burn

The fuel burn metric is the total fuel burn in pounds. This metric is obviously correlated with the time metric. In ACES, fuel calculations for each flight are determined near the terminal areas and for its en route segment. Around terminals, fuel burn is derived using lookup tables, which contain fuel burn rate based on aircraft type. The fuel burn is proportional to the actual time spent in the terminal area. In the en route segment, fuel burn is modeled as a function of thrust, true airspeed, and altitude using the Base Aircraft Data. The mathematical relationship is detailed in Ref. 23. Unlike the aggregate fuel burn model in Ref. 6, the model in ACES is for each flight. Although the results presented in this paper are also aggregate, a drill-down look at an individual aircraft's fuel burn can be performed.

3. Sector Count

The sector count metric addresses congestion in service provider airspaces. The sector count affects manageability of the airspace, human workload, and safety. The instantaneous maximum flights count during the 24-hour period on 8 March 2007 for each sector is compared to its Monitor Alert Parameter (MAP) value, which specifies the capacity or the maximum number of flights an air traffic controller can safely handle based on average time aircraft spend in the sector. In Ref. 22, it is shown that MAP values today do not reflect a realistic relationship between sector design capacity and sector volume and geometry. Metrics based on more realistic sector capacities and effects of route structure changes on workload and complexity are topics for future studies.

4. Conflicts

The conflicts metric is the number of conflict pairs (i.e., one flight in conflict with another at any instant of time counts as one conflict pair) in each type of routing. A conflict is defined by a loss of separation, which occurs when aircraft are within five nautical miles laterally or 1000 feet vertically from each other. The vertical separation is based on the Reduced Vertical Separation Minimum (RVSM) introduced in January 2005 for the Continental United States, for FL290 to FL410. In this study, conflicts are checked every 10-seconds for flights at FL180 or above. Similar to sector count, the number of conflicts in a sector impacts the manageability of the airspace, human workload, as well as safety. Conflict resolution was disabled.

IV. Results

This section compares the three routing approaches in flight time, fuel burn, sector count, and conflicts. The results reflect expected trends but should not be interpreted in absolute terms. These results can be validated as more data become available and as user preferred routes become more widespread.

A. Flight Time

NOWR optimization results in 1.3% reduction in en route flight time compared to FFR. The average per flight is 1.2 minutes. In Ref. 10, the average per flight was 4.8 minutes for central pacific routes. There are two explanations for this apparent discrepancy. First, this study optimizes routes that are 500 nmi or longer. On the other hand, the typical route length in Ref. 10 is 2000 nmi. Second, the per-flight savings of 1.2 minutes is averaged over all the flights, of which only 19,340 was optimized.

The improvement over GCR is 0.3%. The total amount of time saved (over 50,000 minutes) could translate into significant economic impact to the airlines. Airlines can use the time saving as headroom for re-scheduling around delays. If this time can be applied to reducing delay, which according to the Air Transport Association of America, Inc. (ATA) statistics are on average \$37.49^{††} per minute for direct-operating cost (excluding fuel) and \$30.48 per hour for a passenger's time, the potential impact is over 4.3 million dollars^{‡‡} that day.

As mentioned previously, wind optimization was performed from origin to destination at cruise altitude for simplicity. The trajectories flown will therefore differ from the optimal flight plans because of standard departure and arrival routes and because of the wind field altitude variations. To understand the impact these factors have on the overall flight time, a single flight plan was optimized over the cruise portion with FFR climb and descent segments maintained (i.e., only the segments from the top of climb to top of descent are wind optimal). For this single flight the cruise time improvement is around 0.4% (one minute) over that optimized from origin to destination. The majority of this time difference is attributed to the course correction resulting from the addition of departure and arrival routes to the wind optimal flight plan. Should this prove to be representative of all flights then the flight time benefit over the NAS would be closer to 1.7% as compared to FFR.

C. Fuel Burn

NOWR routing results in a 1.4% improvement over FFR routing and around 0.3% over the GCR routing. This is consistent with the results in Ref. 6 wherein GCR consumed 2.6% less fuel than air-traffic-control preferred routes (equivalent to FFR). In this study, the percentage saved is based on the total fuel consumption, including the non-optimized, short-haul routes. This fact could account for the difference between this study and that of Ref. 6. For the single flight optimized over the cruise segment—discussed in the previous paragraph—fuel burn is improved by around 0.4% over the flight optimized from origin to destination. Again this could mean that fuel savings are closer to 1.7% for the NAS. As a rough idea of the potential annual savings, the 1.4% reduction in fuel consumption amounts to over 1.6 million dollars that day.^{§§}

D. Sector Count

Overall, sector count comparison does not indicate that any method is preferable to the others. This is consistent with the results in Ref. 10. The following paragraphs describe the sector count comparison in detail.

For the purposes of the description in this section, recall that flights are flown unconstrained; i.e., ATC and TFM are disabled in the ACES simulation. For this reason we shall avoid the use of 'overload' and 'demand' terms. Instead we use $\text{Count}_{\text{MAP}}$ to refer to the amount by which the maximum count exceeds the Monitor Alert Parameter (i.e. $\text{Count} - \text{MAP}$) for a specified sector (note that Count is a sector's maximum count over the scenario's duration). We distinguish between three cases when comparing the counts (or equivalently $\text{Count}_{\text{MAP}}$) for any two-route structures. The first of these is the case where a sector count remains below its MAP value for both route structures; e.g., $\text{Count}_{\text{MAP}}(\text{NOWR}) < 0$ and $\text{Count}_{\text{MAP}}(\text{FFR}) < 0$. The second is the case where the sector count is below its MAP for one route type but exceeds it for the other type of route; e.g., $\text{Count}(\text{NOWR}) < \text{MAP} < \text{Count}(\text{FFR})$. The last case is where the sector count exceeds its MAP for both route structures; e.g., $\text{Count}_{\text{MAP}}(\text{NOWR}) > 0$ and $\text{Count}_{\text{MAP}}(\text{FFR}) > 0$.

It is expected that the cost and safety impacts of each of these cases—which henceforth are referred to as cases I, II, and III—are different. Case I represents a manageable impact on airspace operations. Cases II and III on the other hand represent a likelihood of increased delays and increased complexity in airspace operations to effectively manage the added load on impacted sectors. Note that the MAP values are only valid for current NAS operations

^{††} Source: Air Transport Association. In 2006, total direct-operating cost was \$65.80 per block minute and fuel cost was \$28.31 per block minute. 50,000 minutes * 37.49 amounts to about 1.8 million dollars.

^{‡‡} Assume 100 passengers per flight for 19,340 flights. (50,000 / 19,340) minutes per flight * 19,340 flights * 100 passengers per flight * (\$30.48 per hour / 60 minutes per hour) amounts to about 2.5 million dollars.

^{§§} Assuming \$2.17 per gallons of jet fuel spot price (Source: US Energy Information Administration). Simulation of FFR case resulted in about 368 million lbs of fuel consumed that day. 1.4% * 368M lbs/6.7lbs-per-gallon * \$2.17 amounts to about 1.6 million dollars.

and that a change in route structure may well obviate their validity. Nevertheless they are used to provide a common basis for comparison.

The results shown in Figure 3 and Figure 4 compare the high sector counts for the various route types for case II sectors; sectors are color coded in green if $Count_{MAP}(NOWR) < 0$ and in orange if $Count_{MAP}(NOWR) > 0$. Figure 3, for example, shows case II sectors for NOWR vs. FFR, where green indicates that NOWR routing has decreased the sectors' maximum count to below MAP (when it was higher than MAP for FFR) while orange indicates that NOWR has increased it to above MAP (when it was lower than MAP for FFR).

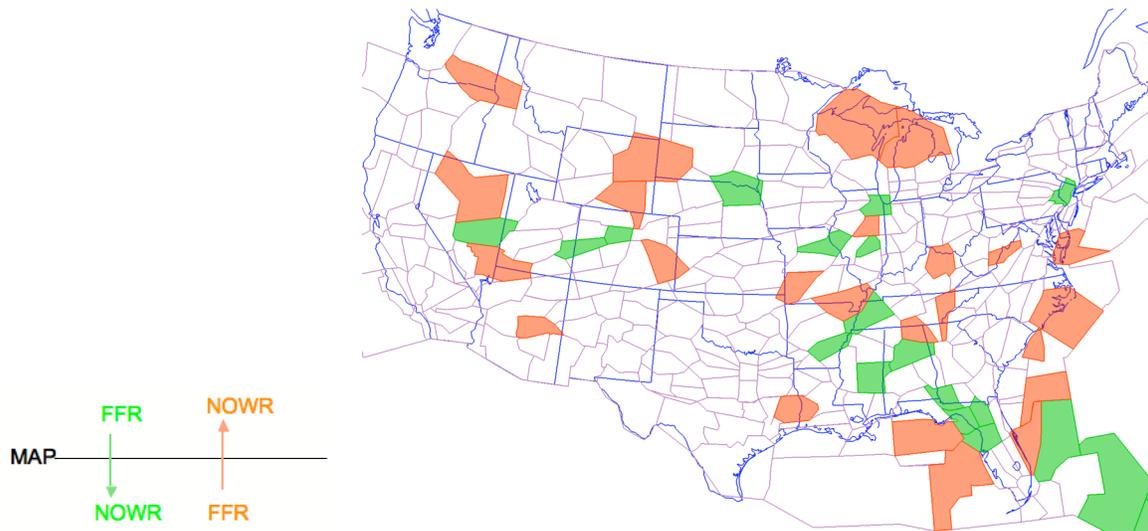


Figure 3. High Sector Counts—Green if $NOWR < MAP < FFR$; Orange if $NOWR > MAP > FFR$

Figure 4 similarly shows case II sectors for NOWR vs. GCR; the important point to note (see discussion below) is that very few sectors exhibit a change in count from below to above MAP or vice versa. Overall the transition from GCR to NOWR does not lead to significant changes in $Count_{MAP}$ patterns (compared to NOWR vs. FFR case).

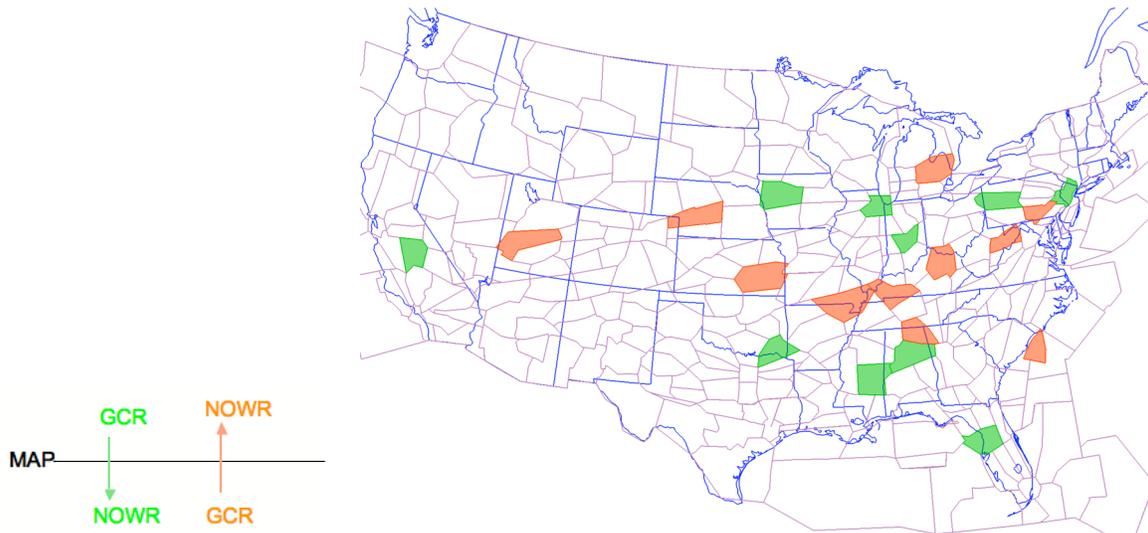


Figure 4. High Sector Counts—Green if $NOWR < MAP < GCR$; Orange if $NOWR > MAP > GCR$

Figure 5 and Figure 6 depict the high sector counts with respect to Case III. Here blue is used to identify sectors whose count is reduced and red is used to identify sectors whose count is increased ($Count_{MAP} > 0$ for both route types). Figure 5 compares NOWR to FFR while Figure 6 compares NOWR to GCR.

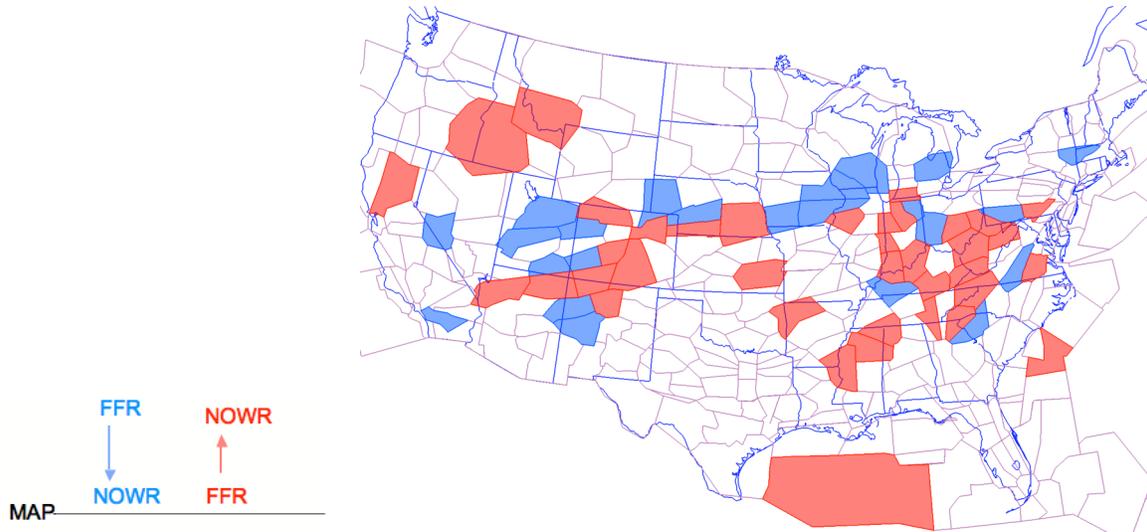


Figure 5. High Sector Counts—Blue if $FFR \geq NOWR > MAP$; Red if $NOWR > FFR > MAP$

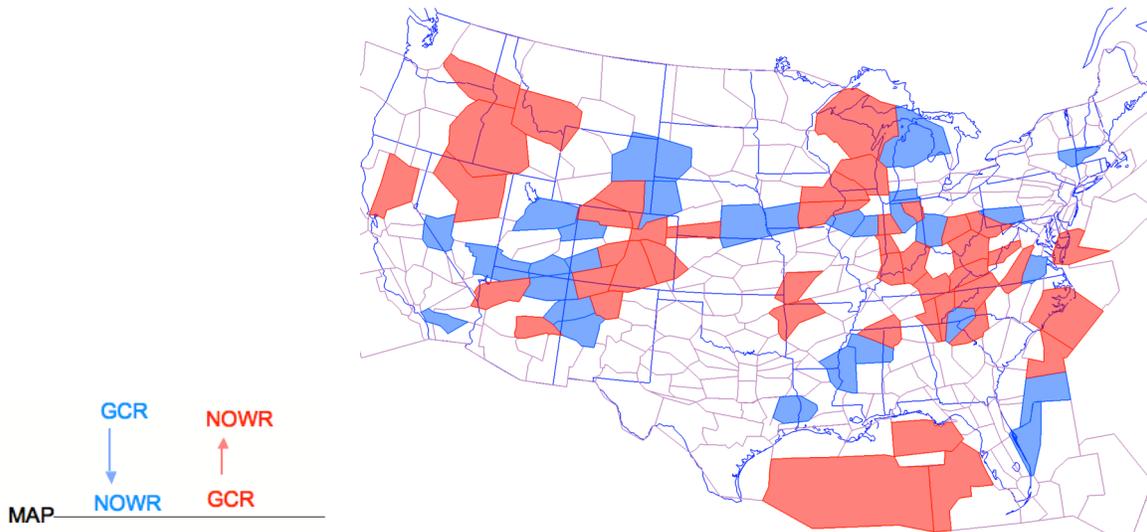


Figure 6. High Sector Counts—Blue if $GCR \geq NOWR > MAP$; Red if $NOWR > GCR > MAP$

Tables 1 and 2 summarize the results shown in Figure 3–Figure 6. Table 1 shows that the number of impacted sectors is essentially unchanged for the three route types. The total count in excess of MAP in these sectors is however different, with NOWR faring the worst. On the other hand in terms of the maximal counts NOWR fares the best (the maximal counts occur in Chicago sector ZAU76, for FFR and NOWR, and Miami sector ZMA02, for GCR). Table 2 summarizes the number of sectors whose $Count_{MAP}$ changes with route type. Overall NOWR and GCR behave similarly in terms of sector $Count_{MAP}$ (sectors with the same $Count_{MAP}$ account for a quarter of the totals) because the routes—given the day’s wind patterns—are similar for NOWR and GCR (see for example the sample routes depicted in Figure 1).

	FFR	GCR	NOWR
Number of Sectors ($Count > MAP$)	81	84	85
Total ($Count > MAP$)	315	354	361
Average ($Count > MAP$)	3.89	4.21	4.25
Max $Count_{MAP}$ (Sector)	22 (ZAU76)	18 (ZMA02)	17 (ZAU76)

Table 1. High Sector Non-Negative $Count_{MAP}$ properties for FFR, GCR, and NOWR

NUMBER OF SECTORS	NOWR VS. FFR		NOWR VS. GCR	
	NOWR > FFR	NOWR < (=) FFR	NOWR > GCR	NOWR < (=) GCR
Count A < MAP < Count B (see Figure 3 and Figure 4)	24	20	11	10
Both Counts > MAP (see Figure 5 and Figure 6)	26	23 (12)	24	29 (21)
Total	50	55	35	60

Table 2. Number of High Sectors Exhibiting Change in Count_{MAP}

Figure 7 shows a histogram of the number of sectors at each Count_{MAP} for high sectors. Blue, yellow, and magenta are used to depict FFR, GCR, and NOWR respectively. The bell shape favors Count_{MAP} < 0—indicating an overall similarity in behavior—across all three types. Figure 7 also shows that NOWR re-distribute traffic from some sectors to other sectors. The GCR is found to be similar in its behavior.

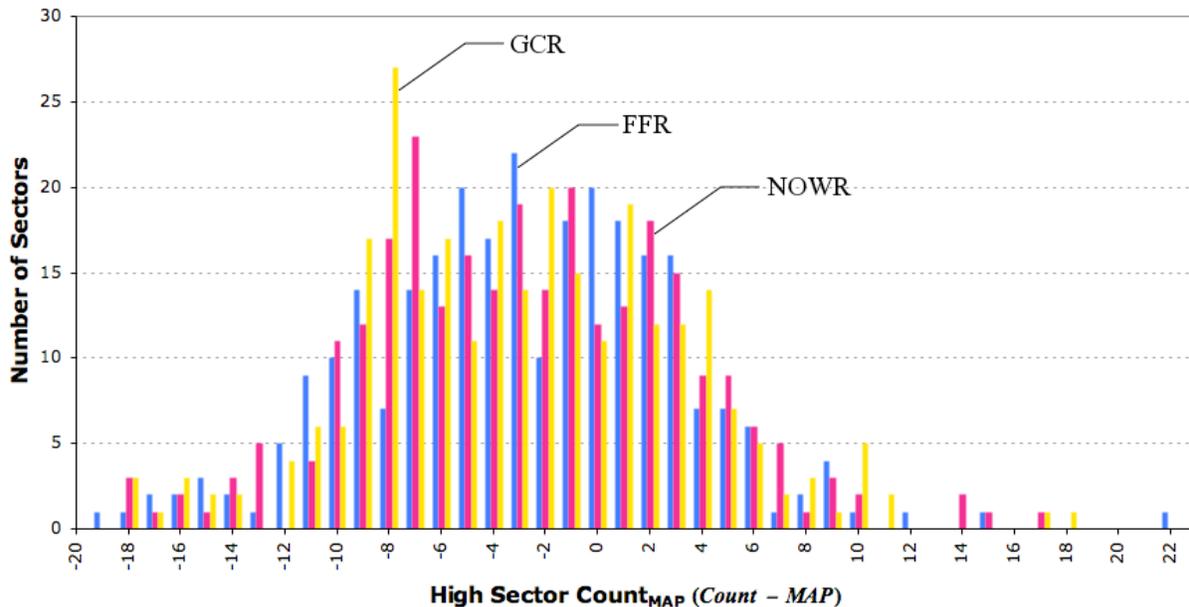


Figure 7. High-Sector Count Histogram, 8 March 2007 (Magenta=NOWR, Blue=FFR, Yellow=GCR)

E. Conflict

Conflicts have a severity associated with them such as those described in Ref. 11 and are not investigated in this study. Furthermore, conflict geometry has a bearing on the degree of difficulty in resolving them; e.g. a low angle of incidence conflict is more sensitive to uncertainty and speed variations than a perpendicular incidence conflict. It is therefore also necessary to take conflict geometry into account in performance comparisons on such a metric. The metric used in this study provides only a high-level analysis of safety impact. The simulations were run without air traffic control actions, separation assurance, and without automated conflict resolution.

Figure 8 shows the relative sizes of the FFR number of conflicts to the number of flights at FL180 or above. At the peak of traffic (2527 flights), the number of conflict pairs (73) is less than 3%. On the other hand, at the peak of conflict, the number of conflict pairs (101) is about 5% of the number of flights (1871). Neither case shows a significant number of conflicts with respect to the traffic at FL180 or above. As a comparison, Ref. 13 found that only about 2% of the aircraft (out of 3000 aircraft in Class A airspace in the continental United States) would be expected to be in conflict alert at any instant in time without any air traffic control actions. The binomial model for conflict count presented in Ref. 13 predicts 72 conflicts for FFR and 56 conflicts for GCR. The conflict counts in

this study, while different, are within the error margins reported therein. Figure 9 shows the number of conflicts in FFR routing and in NOWR routing.

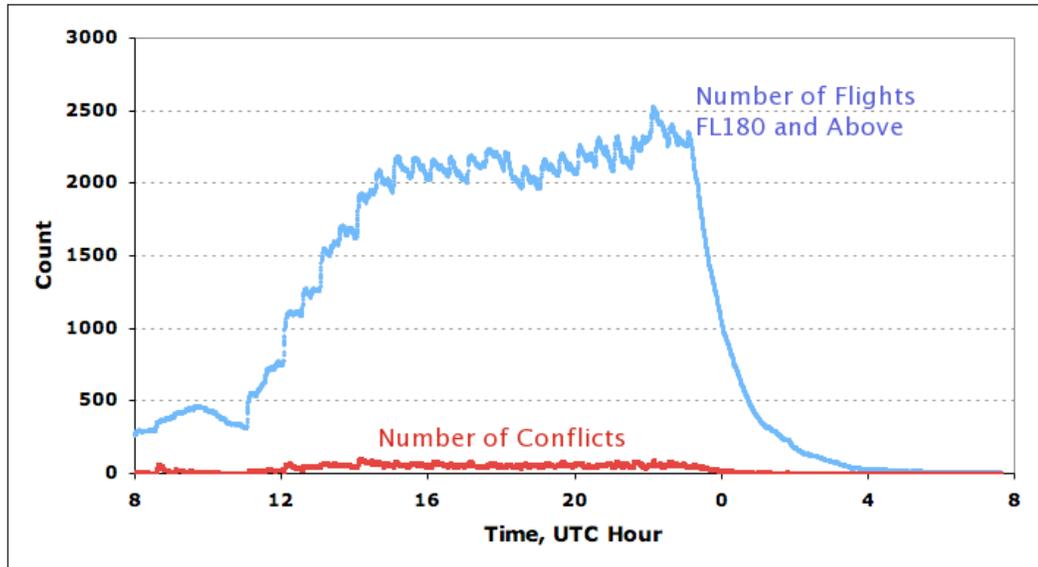


Figure 8. Number of Conflicts and Number of Flights, FFR

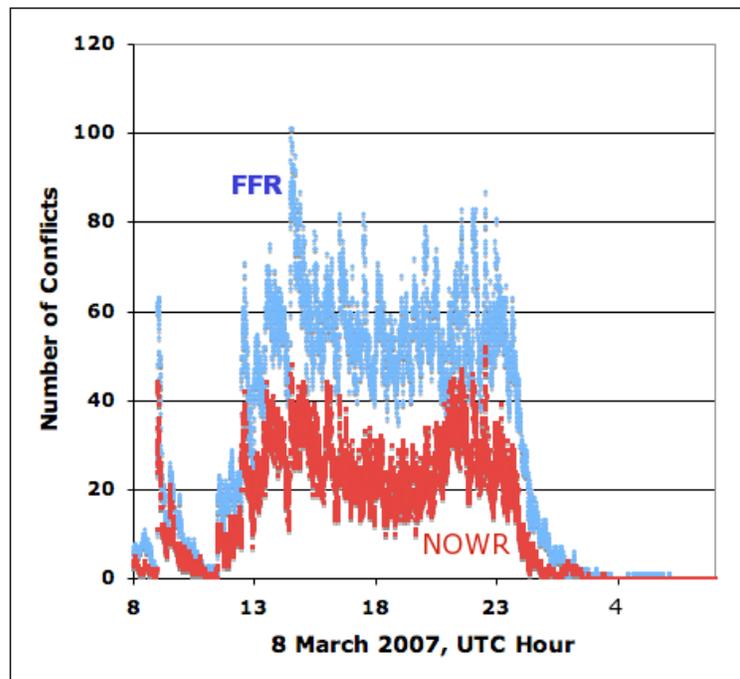


Figure 9. FFR vs. NOWR, Number of Conflicts

As another view of conflict count reduction, Table 3 lists the maximum, average, and total of the conflict counts of the three route types. NOWR’s maximum number of conflicts is 52, roughly half of FFR’s. Similarly, its average number of conflicts is 14, less than half of FFR’s.

	MAX	AVERAGE	TOTAL COUNT
FFR	101	30	257,039
NOWR	52	14	119,105
GCR	49	13	115,647

Table 3. Conflict Count for 24-hour period, 8 March 2007, 8 UTC to 9 March 2007, 8 UTC

Figure 10 shows a decreasing trend in the number of conflicts going from FFR to NOWR. Similarly, Figure 11 shows a no particular trend in the number of conflicts between NOWR and GCR. In the NOWR case, as varying wind fields are expected to produce different results in NOWR, more studies are required to draw a more conclusive answer. It is surmised that the decreasing trend in number of conflicts moving away from structured routing in FFR to NOWR or to GCR is due to presumably more available airspace¹³ and the removal of merge points along structured routes, resulting in less number of conflicts. As pointed out in Ref. 11, in actual terminal airspace operations below FL180, aircraft trajectories can be significantly different from those at FL180 and above, due to air traffic control actions for separation assurance. In Ref. 7 the conflict count was shown to be relatively unchanged for direct-to routes as compared to structured routes. It is surmised that the difference results from the way direct-to routes are synthesized; namely the direct-to terminates at a flight plan fix (when using the Future ATM Concepts Evaluation Tool). This means that some of the original route structure is maintained particularly the merge points and intersections.

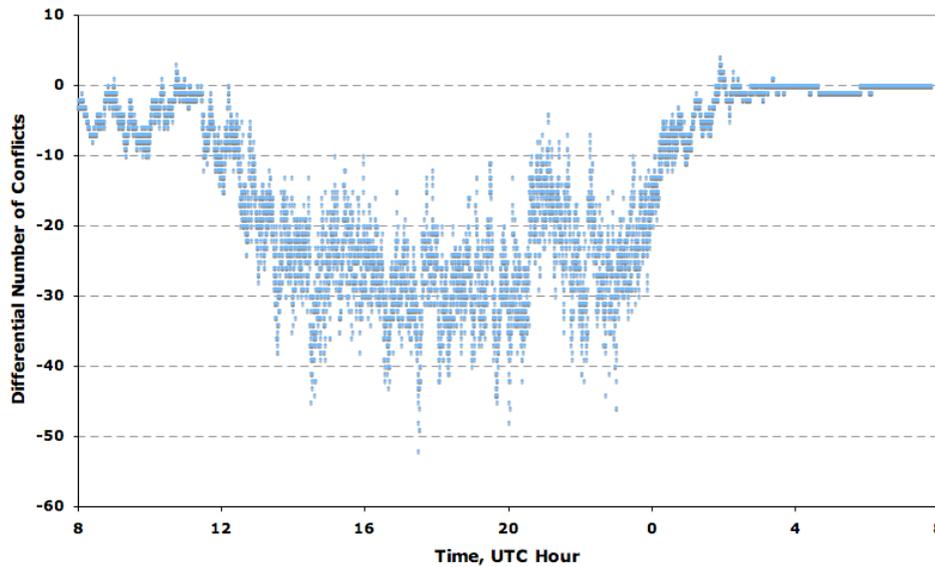


Figure 10. Difference in Number of Conflicts between NOWR and FFR

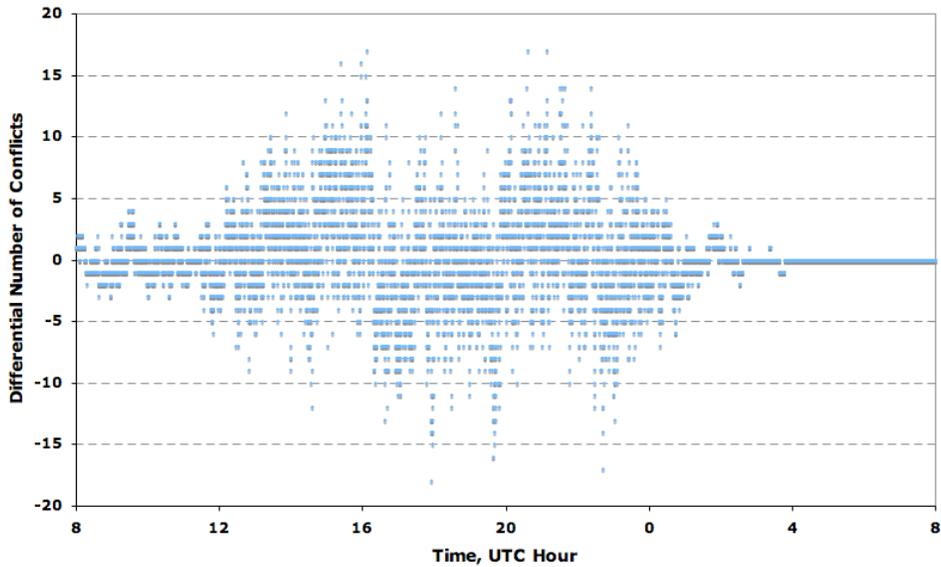


Figure 11. Difference in Number of Conflicts between NOWR and GCR

V. Conclusions

Six simulation runs were performed during this study to evaluate the economic and safety impacts of the different routing methods used in the NAS. Three different routing methods, FFR, GCR, and NOWR were compared. The study shows both NOWR and GCR have preferable flight times and fuel burns than FFR without detrimental costs in sector loading and conflict counts. These results agree with earlier studies. NOWR are most time- and fuel-efficient. All three routing methods are qualitatively equivalent in terms of sector count. However, traffic may be concentrated in different sectors by different methods.

In terms of safety, this study shows that the decreasing trend of the number of conflicts in NOWR and GCR is promising in reducing controller workload. As varying wind fields are expected to produce different results in NOWR and this study is limited to only one day in the NAS, more studies are required to draw a more conclusive answer.

A future study can examine scenarios of using different traffic loads and different wind fields. One scenario would be to perform simulation using several traffic loads (high, medium, light) and several wind fields (severe, moderate, good). A more extensive study would be to perform a Monte-Carlo simulation with many more variation of traffic loads and wind fields, including using forecast data at various look-ahead times. In addition to the three NAS flight routings, comparison with Coded Departure Route routing and Playbook Route routing can be added as well.

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