

Wind-Optimal Routing in the National Airspace System

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A study analyzing the economic benefits and safety impacts of different flight routing methods in the National Airspace System is presented. It compares wind-optimal routes and filed-flight routes for 365 days of traffic, from 2005 to 2007, in Class A airspace. Routing differences are measured by flight time, fuel burn, sector loading, conflict counts, and airport arrival rates. From the results, wind-optimal routes exhibit an average/per-flight time saving of 2.7 minutes and an average fuel saving of 210 lbs, compared to filed-flight routes. In addition, the airport arrival rates at the top 73 United States domestic airports do not show notable differences between wind-optimal routing and filed-flight routing. The study shows an average of 29 percent less conflicts. Finally, wind-optimal routes have at most one high-altitude sector with increased sector workload than filed-flight routes at any time instance.

I. Introduction

TODAY, most flight segments still must use the air traffic controller specified routes such as jet routes, airways, and VHF Omni-directional Radio Range waypoints, instead of flying user-preferred, optimal routes, which airlines have been capable of flying for decades. This is done for safety. Therefore, from an air traffic controller perspective, flying optimal routes in the continental United States airspace could only be allowed if these routes do not increase air traffic controller workload. This is unlike flights in the Pacific where near-wind optimal routes are flown.

Numerous earlier studies looked at the benefits and costs of flight routings similar to those presented in this paper.^{1,2,3,4,5,6,8,9} In Ref. 1, a cost and benefit study on proposed Free Flight, represented and approximated by great-circle flight plan routing, was performed. The study found reduced number of conflicts in en route flight segments and found potential aggregate fuel savings. In Ref. 2, it was shown that significant cost savings can be achieved without adversely impacting the traffic management functions. In Ref. 3, fuel saving due to National Airspace System modernization was estimated by simulation models and extrapolation to the future. In Ref. 4, it was asserted that “free flight” would save flight times and fuel consumption, and save billions of dollars annually. In Ref. 5 the benefits of wind-optimal routing in the Central East Pacific region were evaluated. The study found an average time and distance savings of 9.9 minutes and 36 nmi per flight, respectively. In Ref. 6, the conflict rates produced by great-circle routes (GCR) and those used today were calculated. GCR had significantly fewer conflicts. In Ref. 7, a wind optimal routing algorithm using neighboring optimal control technique was described. In Ref. 8, a relationship of air traffic density and conflicts in terms of wind-optimal routing was described. In Ref. 9, an economic and safety benefits comparison study was performed on user filed, great circle, and wind-optimal flight routes, using a one-day traffic demand set of 8 March 2007. The time and fuel savings that day amounted to 1.3% and 1.4%, respectively. The sector loading was qualitatively determined to be equivalent and the first-loss-of-separation conflict pair count was around 50% lower for the wind-optimal routing. The study found that wind-optimal routing has potential positive economic benefits without sacrificing safety, albeit based on a single day of data. Ref 9 and other previous studies’ results were limited to a small number of days.

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The follow-on study presented in this paper also compares the economic and safety impacts of flying wind-optimal routes and flying user-filed routes, but with 365 days in the National Airspace System. The associated traffic demand and wind data are from 2005 through 2007. This large, annual data set is expected to provide representative distributions of flights in the National Airspace System and statistically significant results. As a main contribution, this extended data set allows an insight into the variability of economic and safety benefits of flight routings in terms of their upper bound, an insight into some flights not flying more optimal routes, and an insight into portions of airspace with high complexity in the National Airspace System. In addition to flight time, fuel burn, sector loading, and number of conflicts metrics, this study also examines airport arrival rates as an additional safety factor. The study uses the same NASA Ames Research Center's Airspace Concept Evaluation System simulation tool described in Ref. 10.

The rest of the paper presents wind-optimal routes and user-filed routes in section II and the metrics in section III. Section IV describes the study approach, and the simulation results are presented in section V. Section VI concludes the paper with implications of using such routes based on metrics such as flight time, fuel burn, sector loading, conflicts, and airport arrival rates.

II. Routes

This section describes the two types of routes used in the study. A corresponding traffic demand set for each day is used for each type in the simulation.

A. Filed Flight Route (FFR)

The flight plans associated with the user FFRs for 365 days come from the FAA's Enhanced Traffic Management System data, which contains user-filed flight plans that include route waypoints. As a user normally files and updates a flight plan for each flight, there are multiple entries per flight up to flight departure. Only the most recent flight plan prior to departure of each flight is used in this study. This flight plan is used in Airspace Concept Evaluation System (ACES) simulation and its resulting route serves as a baseline route for the comparison.

B. Near-Optimal Wind Route (NOWR)

The flight plan associated with NOWR contains a wind-optimized version of the FFR route with respect to flight time. Wind-optimal routes are generated off-line for an airport pair using the algorithm described in Ref. 7 for the same 365 days. The algorithm assumes flights travel at constant altitude and airspeed. In this study, NOWRs are generated for flights that are flying between airports at least 500 nmi apart and are flying at a cruise altitude of Flight Level 180 or 18,000 feet (FL180) or higher. The former is to ensure each flight has non-negligible cruise segment with constant altitude and speed. The latter is to have a comparable class of airspace with previous studies. The inputs to the algorithm are the user-filed flight plan described above and a wind field. While FFRs are optimized and constrained on a number of criteria including winds, crew costs, and fuel amount (See Ref. 11), NOWRs are optimized on winds exclusively with no other constraints. The performance of NOWRs varies under different wind-fields and is expected to reflect seasonal wind patterns. These daily wind changes are explored in this study.

For simplicity, the NOWR algorithm is applied to flights from airport of origin to destination airport at cruise altitude, as described in Ref. 7. The algorithm assumes constant airspeed and constant altitude (equal to cruise altitude), thus leading to some error in flight time estimates. This error accrues in the climb and descent segments, which are flown at different calibrated airspeeds and in a different wind field than the cruise altitude. The error is relatively small as already discussed in Ref. 9. Additionally, the algorithm is only neighboring optimal, causing a relatively small number of NOWR cases to produce negative savings compared to their FFR counterparts as discussed later.

III. Metrics

Five metrics are used in the study. The first two metrics (Flight Time and Fuel Burn) allow researchers to look at economic impacts, the last three metrics (Sector Loading, Conflicts, and Airport Arrival Rates) help provide insight into safety impacts. The aim is to show benefits without incurring costs or at least no significant change.

A. Flight Time

A flight time can be divided into surface time and airtime. The airtime 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 daily demand of flights. Within en-route time portion, time saving is broken down into two components: that due to distance saving and that due to wind saving as described in detail in the Appendix. Flight time from flights below FL180 or flights shorter than 500 nmi is excluded from time saving calculations.

B. Fuel Burn

The fuel burn metric is the total fuel burn in pounds. This metric is 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 described in Ref. 12. The mathematical relationship is detailed in Ref. 13. Although a drill-down look at an individual aircraft's fuel burn can be performed, the results presented in this paper are aggregate. Fuel burn from flights below FL180 or flights shorter than 500 nmi are excluded from fuel saving calculations.

C. Sector Loading

The sector loading metric addresses congestion in various flight service provider areas. As with the next two metrics, sector loading affects manageability of the airspace, human workload, and safety. It is measured in this study by looking at the 15-minute peak count of flights in each sector for all 265 high-altitude sectors at FL180 and above. These peak counts are used to generate histograms of daily average number of sectors against peak counts and against sector Monitor Alert Parameter (MAP) value as described in the Results section. Sector loading in the presence of weather is beyond the scope of this study.

D. Conflicts

The conflicts metric is the number of conflict pairs. One flight in conflict with another at any instant of time counts as one conflict pair. A conflict is defined by a loss of separation, which occurs when aircraft are within five nautical miles laterally and 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 all flights at FL180 or above with the same vertical separation in RVSM. Similar to sector loading, the number of conflicts in a sector impacts the manageability of the airspace, human workload, as well as safety.

E. Airport Arrival Rate (AAR)

The airport arrival rate metric measures the hourly flight arrivals at an airport. In this study, the nation's top airports as defined by the Federal Aviation Administration Aviation System Performance Metrics (ASPM) are examined. There are currently 77 ASPM airports, but the four ASPM airports outside the continental United States are excluded from the analysis. This metric is used to gain insight into whether wind-optimal routing will increase the arrival loading, at least at these major airports.

IV. Approach

This approach taken in this study consists of flight plan preparation, running simulations, output data post-processing, and analysis. The approach begins with data preparation including selecting flight plans and Rapid Update Cycle (RUC) nowcast wind data for a desired simulation date.

Figure 1 illustrates the overall simulation approach and is described below. As shown in Figure 1, an ACES simulation is performed for each type of routing. The corresponding flight plan for each route type

is fed into ACES for simulation. Simulation results that include the previously described metrics will be analyzed and presented.

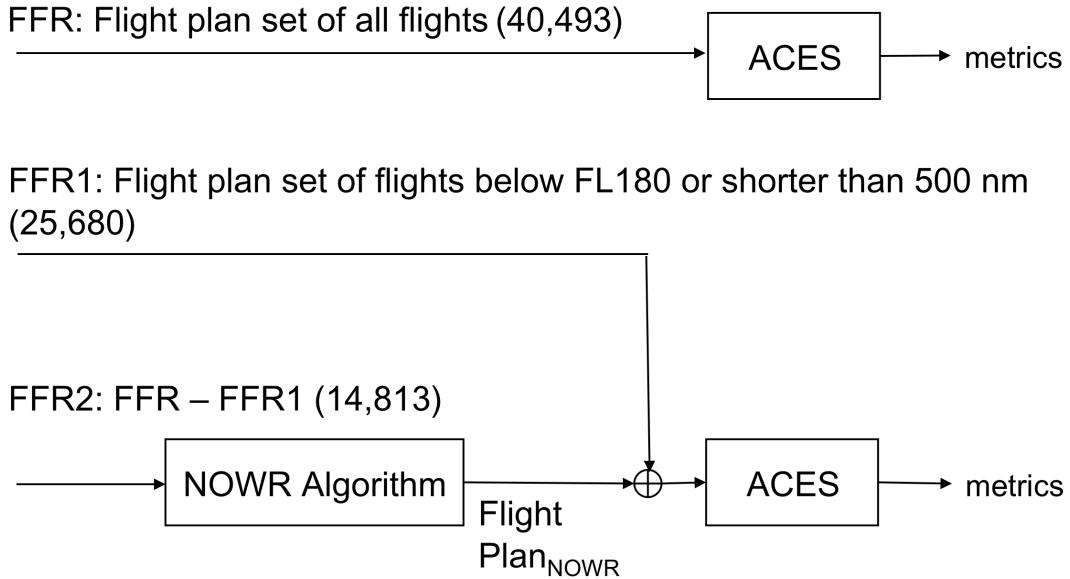


Figure 1: Simulation Approach

The following description details how each flight plan for each day and each route type is prepared. For FFR, described in the Routes section, the corresponding input to ACES is FFR flight plan, and it is fed directly into ACES simulation. For NOWR, the same input flight plan is first split into two parts. One part is FFR2 and it has flight plans for airport-to-airport distances of 500 nmi or more and for cruise altitudes of 18,000 feet or more. Another part is FFR1 and it has the remaining flight plans. The former consists of 14,813 NOWR flights on average or around 37 percent of average total of 40,493 flights. This part is fed into the NOWR algorithm to generate a wind-optimal version of the flight plans. The output of this algorithm is combined with FFR1 to become the flight plan for NOWR, which is then fed into the ACES simulation. Although metrics are computed for all 40,493 flights, by splitting the data this way, only the common 14,813 flights are effectively compared while still maintaining a full day effect of overall traffic. This is due to the same results for the non-optimized flights for both FFR and NOWR and therefore falls out of the comparison calculations.

Figure 2 shows the overall three-year wind variation, which includes the one-year-period data of interest. It shows the maximum wind speed for around 92% of three years from 2005 through 2007. The remaining 8% of wind data is not available, and therefore its corresponding dates are not simulated. Of the available data, the average maximum wind speed is 151 knots, while the maximum wind speed ranges from 95 knots on 6/15/2005 to 215 knots on 1/15/2005 and 11/13/2006. Stronger maximum wind speeds are in the winter periods while weaker maximum wind speeds are in the summer periods. As a result, the benefits of wind-optimal routing are hypothesized to be larger in the winter months.

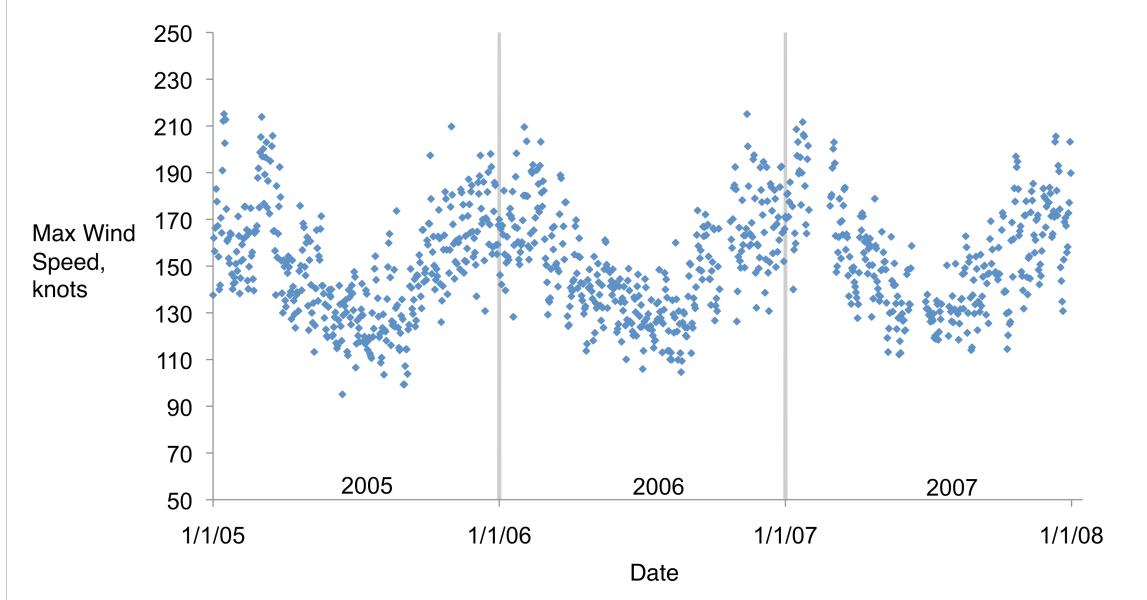


Figure 2: Max Wind Speed, 2005-2007, in knots

Finally, ACES' conflict resolution, Air Traffic Control (ATC), and Traffic Flow Management (TFM) functionalities are disabled. These controls are disabled so the open-loop system response to changes in route structure can be studied under the unsafe/upper-bound conditions.

V. Results

Results based on 365 days are presented below. The days are intended to span the calendar year 2007. However, some days from 2007 could not be simulated due to missing wind or flight-plan data, and days from 2006 and 2005 for which data was available were substituted. The substitutions were made on a day of the week basis, rather than by calendar date. For example, Tuesday, May 16th 2006 was substituted for Tuesday, May 15th, 2007. This substitution method was selected to better preserve weekly traffic periodicity, as demonstrated later in this section. Among 365 days, 165 days are directly from 2007, 139 days are from 2006, and 61 days are from 2005. The results show the range of time savings, fuel savings, sector loading, conflict counts, and airport arrival rates throughout the simulated year.

A. Time and Fuel Savings

An average of 40,493 flights were simulated per day. Roughly 63 percent of flights, being shorter than 500 nmi or cruising at less than 18,000 ft, are not wind-optimized, and are excluded from time and fuel saving calculations. Traffic counts throughout the simulated year were fairly steady, with a slight decrease in traffic during the winter months, as shown in Figure 3.

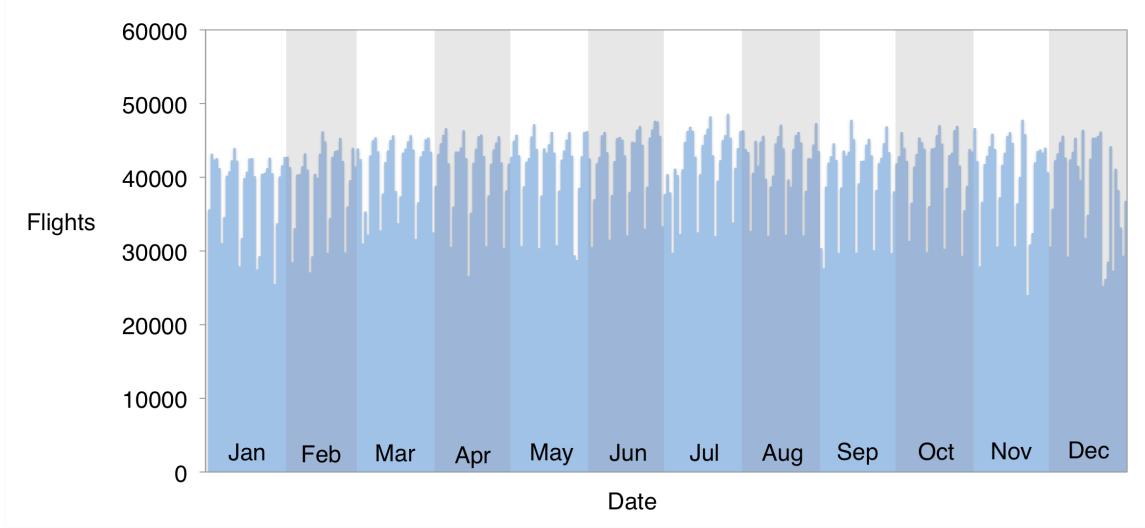


Figure 3: Daily Traffic Count Variations of 365 Days in 2005-2007

In total, 14,780,004 flights were simulated, including 5,406,777 flights on wind-optimal routes. Out of these optimized flights, 4,097,457 had time and fuel savings. On average, 14,813 flights were optimized per day, and 11,226 or around 76% realized time and fuel savings. These values are depicted in Figure 4 (a).

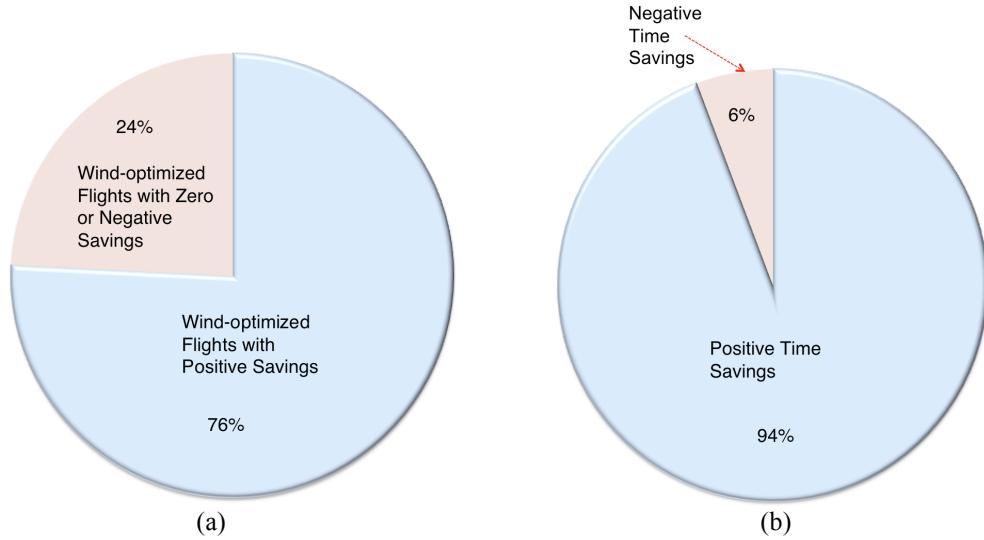


Figure 4: Daily Breakdown by Flights and Minutes

Negative savings result from the NOWR algorithm generating wind-optimal routes by examining the wind gradient solely along the great circle route. Since the assumptions underlying the NOWR algorithm are only valid for small perturbations from a locally optimum solution as described in Ref. 14, flights can be routed into unfavorable wind fields if the route significantly deviates from the great circle.

In the worst case, time saving from both distance and wind is negative for NOWR. Although 24 percent may seem high in terms of the number of flights shown in Figure 4 (a), the negative total time saving is relatively low at 6 percent as shown in Figure 4 (b). On average, positive saving is 3.8 minutes per flight and negative saving is 0.7 minutes per flight.

Among flights that were optimized, average time and fuel savings realized were 2.7 minutes and 210 lbs per flight, respectively, per flight. Daily average time and fuel savings per flight are shown in Figure 5

and Figure 6, respectively. These plots do not show a significant seasonal trend, but do demonstrate that wind-optimized routes realize consistent time and fuel benefits throughout the year. However, wind-optimal routes used in this experiment are, on average, 13.5 nmi shorter than their filed flight route (FFR) counterparts. Time savings due solely to wind are separated from time savings due solely to distance by the method detailed in the Appendix. Examining only the wind time savings, flights realize an average time savings of 0.76 minutes, per flight. Daily average wind time savings per flight are plotted in Figure 7. A significant seasonal trend can be seen in this figure, with much smaller benefits occurring in the summer. This is consistent with the behavior of the jet stream, which is less pronounced in the National Airspace System (NAS) during the summer months and is consistent with that shown in Figure 2 where stronger wind occurs in the winter period.

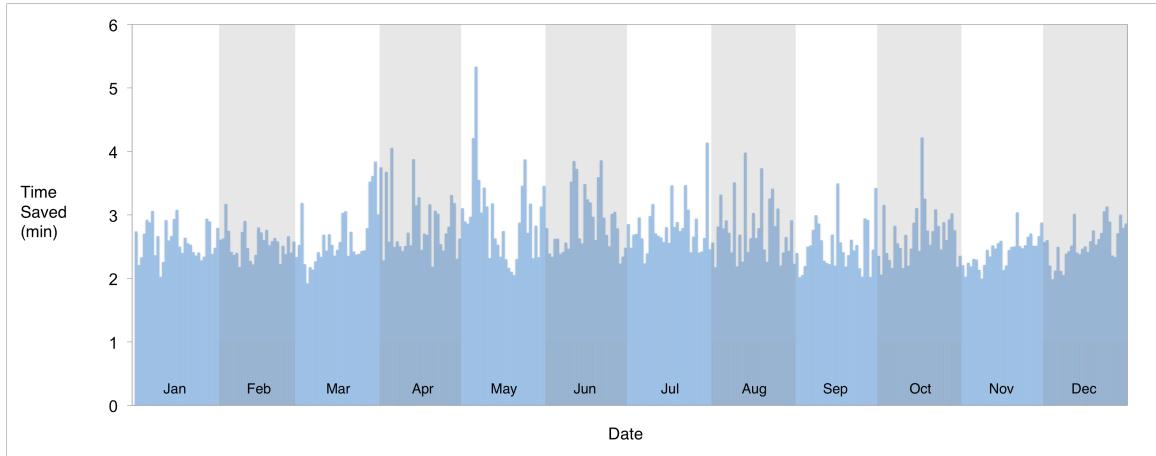


Figure 5: Daily Average En Route Time Savings, Per Flight (mins)

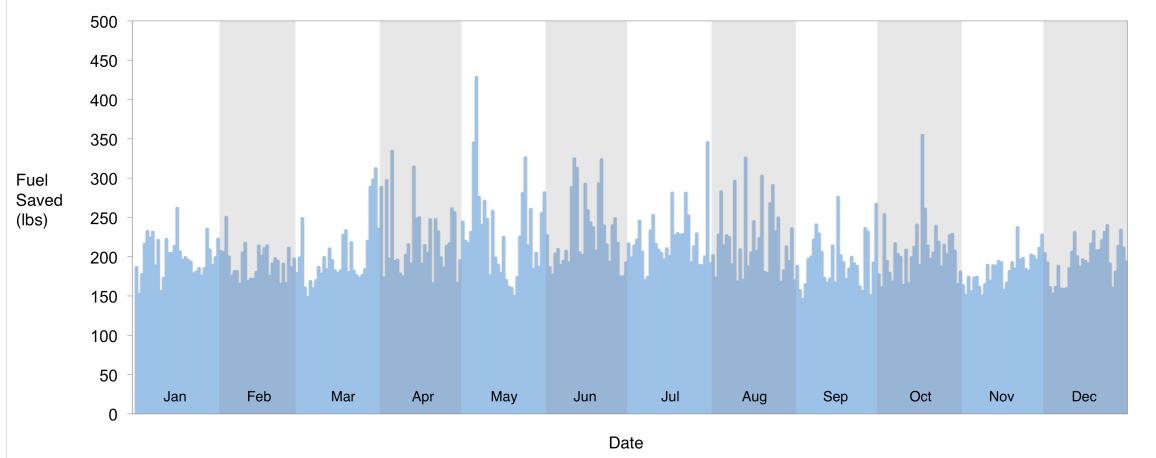


Figure 6: Daily Average Fuel Savings Per Flight (lbs)

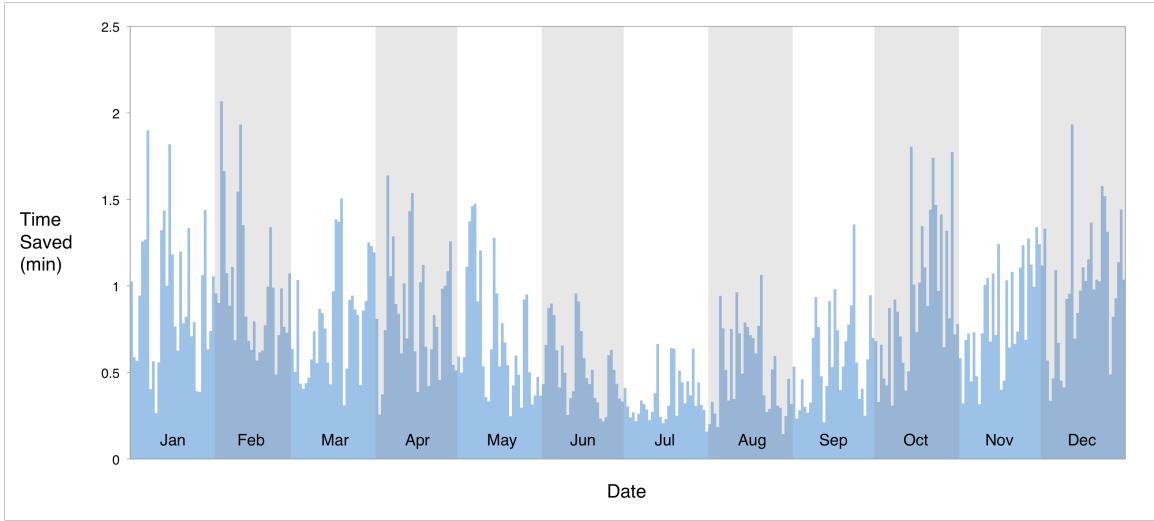


Figure 7: Daily Average Time Savings Due to Wind-Optimization, Per Flight (mins)

Savings numbers that do not distinguish wind time savings from time savings due to distance do not account for certain real-world conditions. Some flights incur time and fuel savings that are unrealistically large, due to significant deviations in the FFR, usually around convective weather or Special Use Airspace. Wind-optimized routes do not include these deviations, so some NOWR flights fly much shorter distances, and correspondingly report very large savings, compared to FFR. As an example, SkyWest flight SKW3874, departing General Mitchell International Airport in Milwaukee, WI on April 3rd, 2007, maneuvered widely around convective weather activity on its way to Hartsfield-Jackson Atlanta International Airport. The flight's NOWR counterpart, ignorant of weather conditions, took a much more direct route. This resulted in presumptive time and fuel savings of almost 40%. The two flight routes are presented in Figure 8, and a map of the convective weather activity on April 3rd, 2007 is presented in Figure 9. In Figure 8, the track on the left corresponds to the FFR route and the track to the right corresponds to the NOWR route.

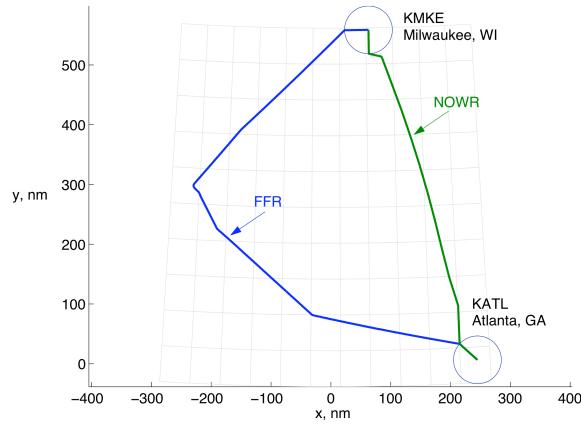


Figure 8: Flight SKW3874 from KMKE to KATL: FFR in blue on the left, NOWR green on the right.

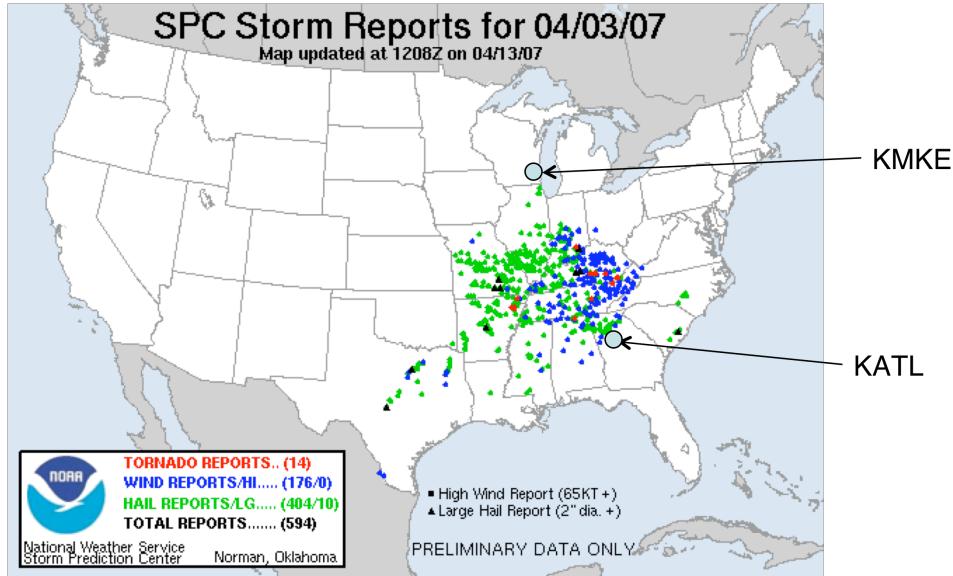


Figure 9: Convective Weather Activities on April 3rd, 2007

B. Sector Loading

Sector loading is studied by examining the time duration when the aircraft count is over the MAP value. Average time durations are calculated for each sector by adding the time duration that the sector's aircraft count is over the MAP value for each day and dividing the sum by 365. Table 1 lists the top ten sectors in terms of the highest difference of these time durations between FFR and NOWR. The top sector ZTL50 spent only 2.3 hours per day above MAP in the FFR case, but 7.5 hours in the NOWR case, a difference of 5.2 hours per day.

Table 1: Top Ten Sectors Where NOWR's Overloaded Durations Compared to FFRs Overloaded Duration is the Highest

Sector	MAP Value	Additional Overloaded Duration of NOWR	
		Hours / Day	Percent
ZTL50	13	5.2	22%
ZNY75	15	3.8	16%
ZFW93	18	2.9	12%
ZMP12	18	2.9	12%
ZDC37	12	2.8	12%
ZLA37	15	2.6	11%
ZHU26	14	2.3	10%
ZMA02	20	1.7	7%
ZAU45	13	1.4	6%
ZNY73	14	1.3	5%

Figure 10 shows average-day histograms of high-altitude sectors against sector loading with respect to their respective MAP values, NOWR in red and FFR in blue. The vertical axis shows the number of high-altitude sectors and the horizontal axis shows the percent capacity bins with respect to MAP values. When

NOWR loading is at 100 percent and above, the average number of over-capacity sectors in any 15-minute period is less than four. This small difference is shown in the zoomed-in portion to the right, by adding the counts of the two red bars. The difference in sector loading between NOWR and FFR is even smaller. It is less than one sector at any 15-minute period at a time.

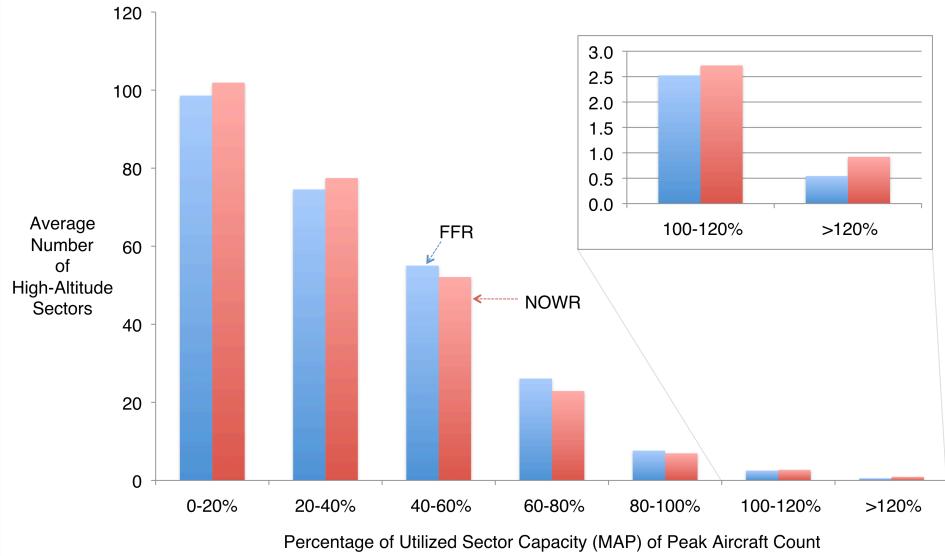


Figure 10: Average Number of High-Altitude Sectors Broken Down by the Percentage of Utilized Sector Capacity

Finally, Figure 11 shows the sector loading differences between NOWR and FFR for the worst performing sector ZTL50 as listed in Table 1 before. This sector has the highest overload above the MAP values. This figure shows the maximum and average curves corresponding to an average-day peak count on the vertical axis and 96 15-minute bins a day on the horizontal axis. The minimum curves are not shown to reduce clutter, but both curves lie below the MAP value.

The curves in this figure are generated as follows. For the maximums, in each 15-minute period of a day, its peak count is compared to all other peak counts of the same period from the rest of the 365 days. The highest count corresponds to a point for the period on the maximum curve. The peak counts from all 96 bins form a maximum load curve for the sector. The same procedure is used to generate the minimum peak count curves and average peak count curves.

This figure shows the worst-case sector load variation of flying wind optimal routes. At the largest difference between the maximum curves, NOWR has 12 flights more than FFR. On average NOWR is worse than FFR by 3.5 flights. Issues such as this would need to be addressed in other studies such as those done in the dynamic sectorization area before wind-optimal routes would be allowed. NASA has ongoing programs studying dynamic airspace configuration based on congestion and flow patterns.

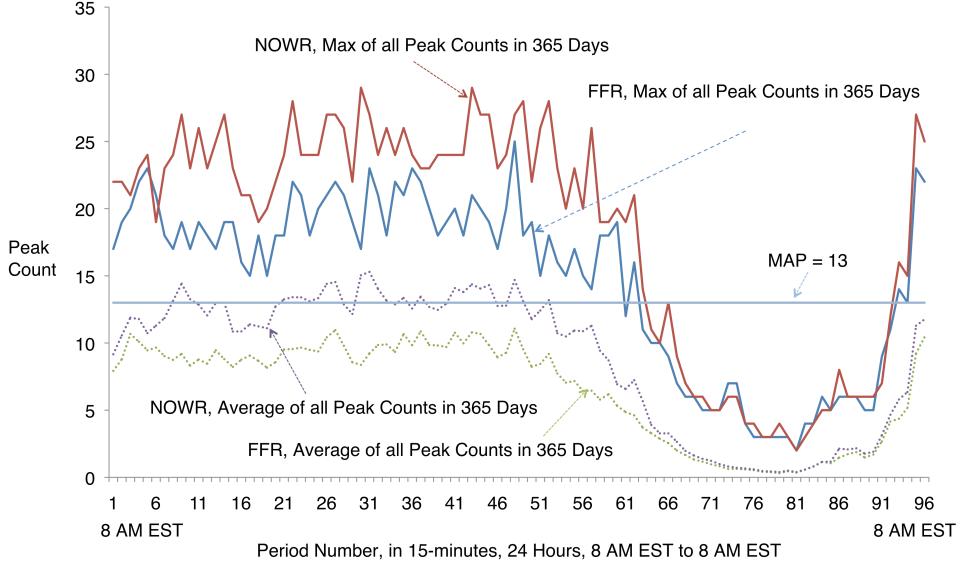


Figure 11: Year Max and Year Average Peak Counts in ZTL50, in One Average Day (96 15-Minute Bins)

C. Conflicts

Peak and average values of instantaneous conflict counts were used to gain insight of the system safety. Lower number of conflicts was observed in the NOWR cases, as expected from their more distributed routes away from fixed routes such as jetways. Daily peak conflict counts decreased on average by about 29%. Figure 12 shows the percent reduction of the peak conflict count of NOWR compared to

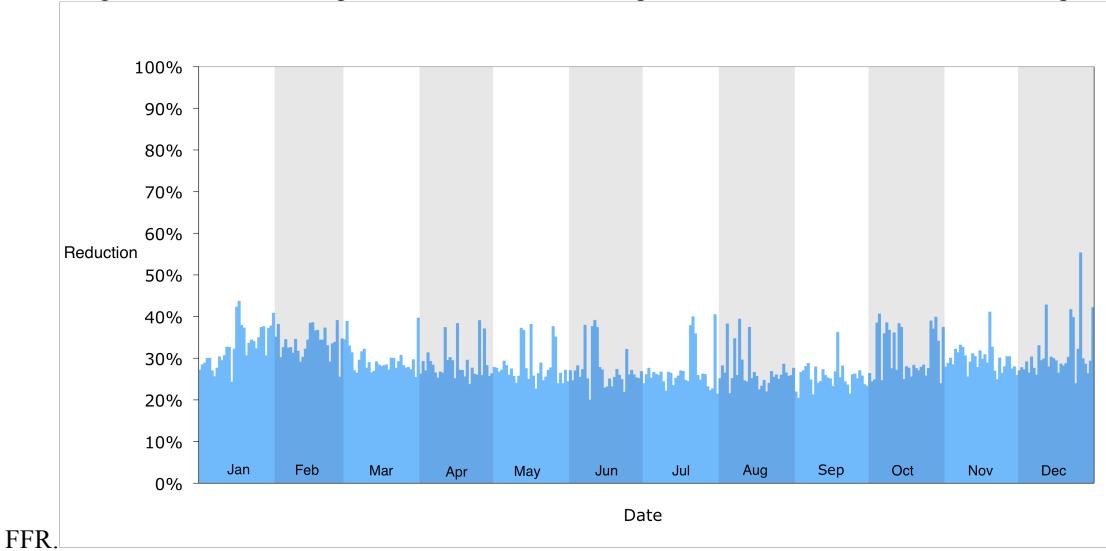


Figure 12: Reduction in Average Conflict Counts

D. Arrival Rates

Airport arrival rates (AAR's) remain approximately unchanged from FFR to NOWR operations. For each of the 365 simulated days, the peak hourly arrival rate was calculated for both the FFR and NOWR cases at each of the 73 Aviation System Performance Metrics (ASPM) airports in the continental United States. A histogram of these peak counts was created, and then normalized by dividing by 365, so that,

similar to the presentation of sector loading, the histogram can be regarded as the distribution of ASPM airports on an average day. No significant differences were observed between FFR and NOWR cases.

Airport arrivals as a percentage of published arrival capacities are also considered. The arrival capacities used in this paper are reported in Ref. 15. For all 365 days, at the 73 ASPM airports, the hourly arrival rate is divided by the airport's arrival capacity at every hour; so 24 values are calculated per day for each airport. These values are averaged by number of days and hours to show the distribution of ASPM airports at any given hour. This histogram is displayed in Figure 13, with blue columns representing the FFR case, and red columns the NOWR case. Difference between the two cases is very small.

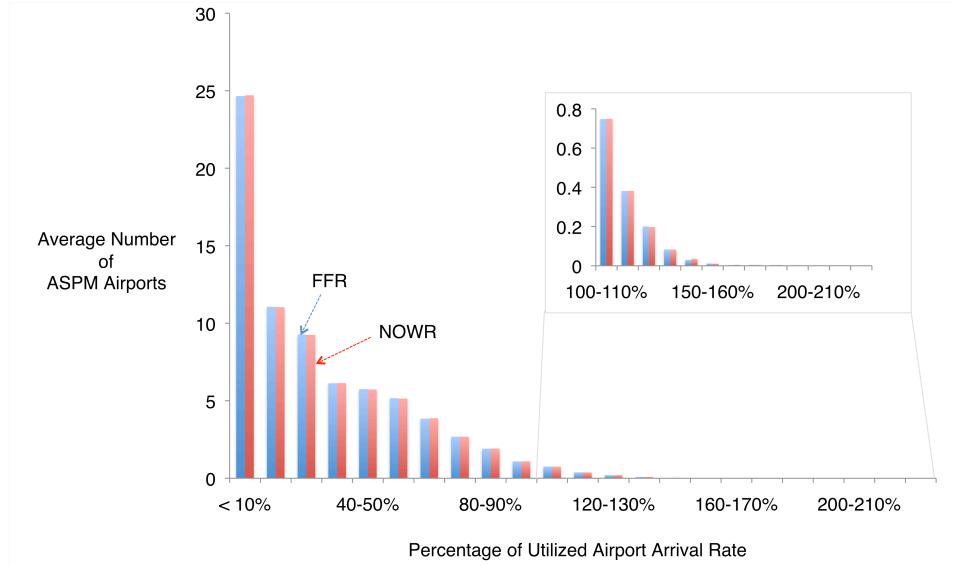


Figure 13: Average Number of ASPM Airports vs. Utilized Airport Arrival Rates

The airports where NOWR operation increased arrival loading are shown in Table 2. Atlanta is the most affected airport, and there are, on average, 6 minutes per day when arrival loading increased for the NOWR case. This is not considered to be a significant detriment to operations. Figure 14 demonstrates the average and max arrival rates for each hour of the day, and it is clear that arrivals do not change significantly under NOWR operation.

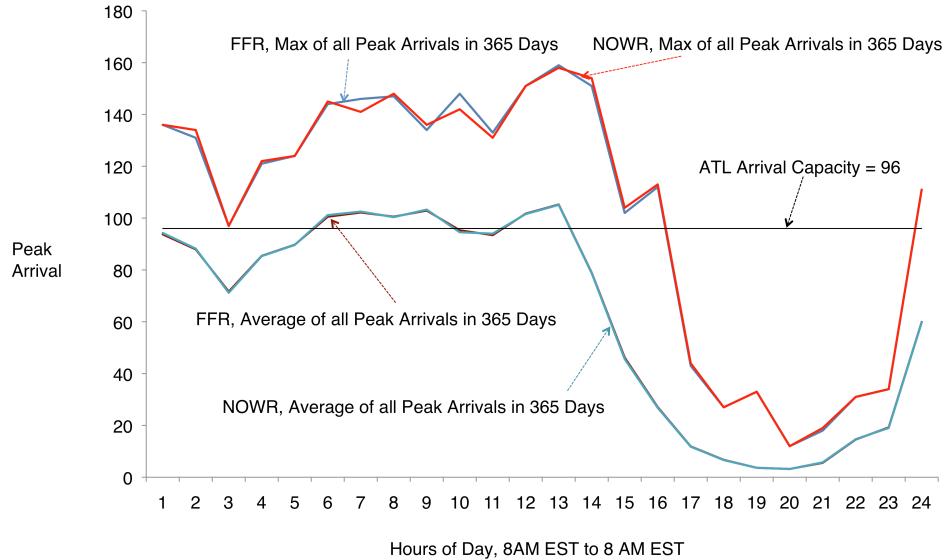


Figure 14: Maximum and Average of Peak Arrival Rates in ATL for an Average Day

Table 2: Top 8 ASPM Airports where Overloaded Time Duration of NOWR is Longer than FFR

Airport	Arrival Capacity	Additional	Overloaded
		Duration of NOWR Minutes / Day	Percent
KATL	96	6	0.4%
KORD	100	5	0.3%
KEWR	48	3	0.2%
KSFO	32	2	0.1%
KHOU	28	2	0.1%
KDTW	72	1	0.1%
KRSW	18	1	0.1%
KTPA	35	1	0.1%

VI. Conclusion

An insight into benefits and cost variability is presented in support of flying wind-optimal routes. The time and fuel savings realizable through wind-optimization have been well known, documented, and practiced for decades. This paper reinforces previous findings of savings with an extensive data set, and finds no significant cost variation. Conflicts in Class A airspace are significantly reduced by the dispersion of flights from prescribed, structured routes. Airport arrival rates remain almost identical. On average, wind-optimization leads to at most one additional high altitude sector to be overloaded. These results are summarized in Table 3 below.

Table 3: Cost and Benefit Summary

Metric	Cost and Benefit
Flight Time	On average, NOWR saves 2.7 minutes per optimized flight per day
Fuel	On average, NOWR saves 210 lbs per optimized flight per day compared to FFR
Sector Loading in High-Altitude Sectors	No significant variation.
Conflicts in Class A airspace	NOWR has an average of 29 percent less conflict than FFR
Arrival Rate	No significant variation.

VII. Acknowledgements

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VIII. Appendix

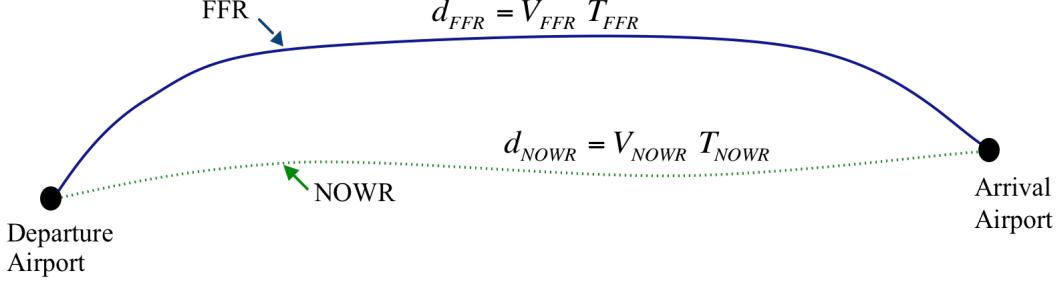


Figure 15: FFR vs. NOWR

FFR and NOWR differ in many ways. Since the FFRs have to take into account many factors such as jet route structures, navaids, weather, or SUAs, FFRs tend to be indirect. NOWR is also indirect in order to take maximum advantage of the wind. Since the two routes generally have different distances, it is difficult to directly compare the flight times. To mitigate the effect of distance variation, a speed-distance metric is devised.

If constant speeds are assumed, the relations between the speed, time, distance for FFR and NOWR are shown in Fig. 23 and Eqs. 1 and 2.

$$T_{FFR} = \frac{d_{FFR}}{V_{FFR}} \quad (1)$$

$$T_{NOWR} = \frac{d_{NOWR}}{V_{NOWR}} \quad (2)$$

Total time saving is the difference between the FFR flight time and NOWR flight time as shown in Figure 16 and Eq. 3.

$$\Delta T = T_{FFR} - T_{NOWR} \quad (3)$$

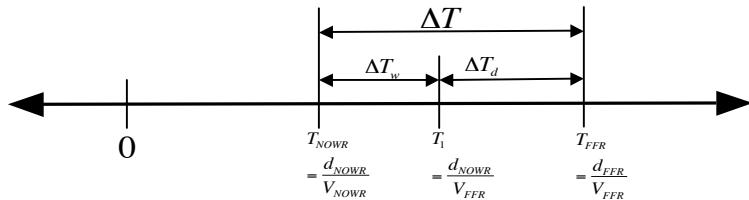


Figure 16: Time Saving Portions from Wind vs. from Distance

Let T_i be the time that takes an aircraft to fly the NOWR route with FFR speed.

$$T_i = \frac{d_{NOWR}}{V_{FFR}} \quad (4)$$

The time difference between the T_{FFR} and T_i represents the time difference due to the distance difference.

$$\Delta T_d = T_{FFR} - T_1 = T_{FFR} - \frac{d_{NOWR}}{V_{FFR}} = T_{FFR} \left(1 - \frac{d_{NOWR}}{d_{FFR}} \right) \quad (5)$$

So, the time saving due to optimally utilizing wind can be computed by subtracting the distance influence from the total time saving.

$$\Delta T_w = \Delta T - \Delta T_d = T_{FFR} \frac{d_{NOWR}}{d_{FFR}} - T_{NOWR} \quad (6)$$

Since these metrics assume constant speed, they will not provide the exact break down between savings due to distance and savings due to wind. However for relatively long haul flights that have larger cruise portions, the constant speed assumption holds reasonably well. These metrics will provide general idea of net time savings due optimally utilizing wind.

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