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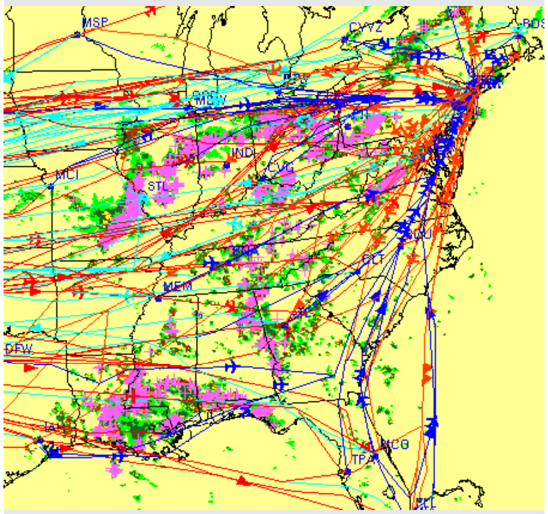

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prepared by
Andrew Malwitz, Timothy Yoder, Sathya Balasubramanian, Gregg Fleming, Ian Waitz

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1. Introduction

Commercial aircraft are responsible for approximately 13 percent of transportation-related fossil fuel consumption, and approximately 2 percent of all anthropogenic carbon dioxide emissions.[1] Additionally, most projections estimate that air travel will grow by 2 percent to 5 percent per year for the next 10 to 20 years.[1] Therefore, there is concern that the environmental impact of aviation, including the production of carbon dioxide and other greenhouse gases, will increase in the coming years. In addition, as air travel grows, the air transportation system is expected to become increasingly capacity-constrained at some airports and flight corridors. The Reduced Vertical Separation Minimum (RVSM) standard was introduced to address these two areas of concern: airborne capacity, and fuel consumption and its related emissions.

Beginning over the North Atlantic in March of 1997, and recently over the domestic US in January of 2005, worldwide aviation regulatory bodies enacted the RVSM standard[2] as shown in Figure 1. The RVSM standard stipulates that the minimum separation between cruise altitudes is 1000 feet. Prior to the new standard, the minimum separation altitude was 2,000 feet. This new standard of separation created six new cruising altitudes between 29,000 and 41,000 feet. With more available cruise altitudes, airspace capacity is increased. Additionally, each aircraft may be flown at more efficient cruising altitudes and flight profiles.

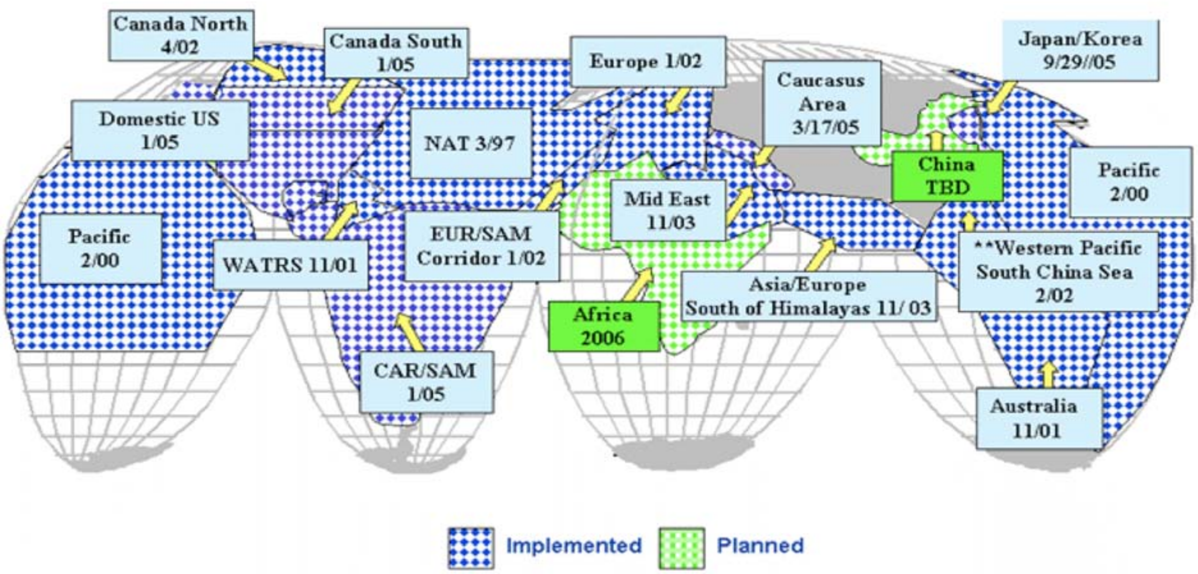


Figure 1: Dates of RVSM Implementation Worldwide[2]

Two previous studies estimated the fuel burn and emissions benefits of RVSM. The first study, conducted by EUROCONTROL in 2002,[3] analyzed the impact of RVSM implementation in European airspace in January of 2002. The EUROCONTROL study found a benefit of 1.6 to 2.3 percent reduction in fuel burn, and 0.7 to 1.0 percent reduction in emissions of nitrogen oxides (NO_x) as a result of implementing RVSM. The second study, conducted by the Federal Aviation Administration (FAA),[4] analyzed the impact of RVSM implementation in US airspace in January 2005 for 12 origin-destination pairs. The FAA study found that each flight in RVSM airspace saved approximately three pounds (1.36

kg) of fuel per minute at cruise altitude, which is equivalent to an approximately 2.5 percent reduction in fuel burn and CO_2.

The study reported here investigated the impact of RVSM when it was enacted over the domestic US in 2005 for a larger segment of data than previously assessed, and used more advanced modeling methods in an effort to more accurately assess the benefits. The study was conducted jointly by the US Department of Transportation Volpe Center (Volpe) and the Massachusetts Institute of Technology (MIT), under the Partnership for Air Transportation Noise and Emission Reduction (PARTNER), for the FAA's Office of Environment and Energy (FAA/AEE).

2. Study Methodology

Our assessment of the impact of the domestic US implementation of RVSM on fuel burn and emissions required a source of schedule and flight trajectory data for a timeframe that included both pre-RVSM and post-RVSM conditions, and an aircraft performance model capable of estimating small changes in performance with flight conditions and routing. For schedule and flight trajectory data, we used the Enhanced Traffic Modeling System (ETMS).[5] ETMS is a management tool utilized by the FAA for air traffic planning purposes. It contains both reported flight-plan data and position data obtained directly from radar sources. Thus, if a flight provides flight plan information, and/or enters radar-controlled airspace, ETMS will have information on the flight schedule (such as departure/arrival time and airport), as well as position data (how the flight is flown in three-dimensional space). ETMS encompasses the North American airspace, as well as portions of Western Europe.

The pre-RVSM period of study included domestic US flights during four weeks before the implementation of RVSM, and the post-RVSM period included domestic US flights after the January 2005 implementation of RVSM. The weeks chosen for analysis were the same weeks as used in the 2005 FAA-ATO study,[4] and are summarized in Table 1 (the weeks were chosen to purposefully avoid irregular holiday traffic in an effort to provide a more consistent comparison). In addition, we limited the study to flights that were represented in both scenarios. Thus, the pre- and post-RVSM scenarios had the same number of flights for distinct origin-destination pairs. We also limited the study to matched aircraft types so that there were no differences in the fleet between the pre- and post-RVSM analysis cases.

Table 1. pre-RVSM and post-RVSM Dates

	Dates	Days
pre-RVSM	11/14/2004-11/20/2004	7
	12/05/2004-12/18/2004	14
	1/9/2005-1/15/2005	7
	pre-RVSM Total	**28**
post-RVSM	2/13/2005-3/12/2005	28
	post-RVSM Total	**28**
	Grand Total	**56**

We used EUROCONTROL's Base of Aircraft Data Revision 3.6 (BADA)[6] to model en-route aircraft performance. BADA was also used in the two prior studies[3,4] that estimated the impact of RVSM. EUROCONTROL developed BADA to provide trajectory simulation and prediction algorithms for Air Traffic Management (ATM) purposes. It has been shown that, on a fleet-wide level, BADA can estimate fuel burn within 5% of airline-reported fuel burn values.[7] However, for specific flight conditions, BADA methods may produce fuel burn estimates with more than 20% error relative to reported values.[7] Since the previous studies indicate that the impact of RVSM can be less than the uncertainties of the BADA method, we sought to address some of the uncertainties in the BADA method for this study.

A previous study conducted by the FAA quantitatively ranked the largest errors in BADA fuel burn estimates (when using no wind data and standard atmospheric conditions) as uncertainties in: aircraft drag coefficients, engine performance coefficients, winds aloft, takeoff weight, and temperature at cruise altitudes.[7] Our study addressed three of these concerns: winds aloft, temperature at cruise, and engine performance coefficients. Winds aloft and temperature at cruise were addressed by including detailed meteorological data. Issues regarding engine performance coefficients were addressed by developing an alternative fuel burn computation, using a statistical analysis of Computer Flight Data Recorder (CFDR) information as a basis.

3. Inclusion of Meteorological Data

BADA and many aircraft performance models compute fuel burn as a function of aircraft thrust. For steady, level, cruise flight conditions (undergoing no climb or descent, and no acceleration), thrust equals drag. For flight conditions where this is not the case, such as takeoff and arrival procedures or acceleration and climb operations during cruise, kinetic or potential energy of the vehicle change as a function of time. Thus, a power balance is used to compute thrust as a function of drag, velocity, and changes in aircraft kinetic and potential energy. For all drag approximations BADA uses the following equation for drag:

$$D = (C_D \rho \, V_{TAS}^2 S) / 2$$

Where D is the total drag, S is the wing reference area, V_{TAS} is the true air speed, C_D is the coefficient of drag, and ρ is the air density. The drag coefficient, C_D, is then determined using aircraft type-specific BADA coefficients C_{d0} and C_{d2} along with a non-BADA correction for transonic drag rise, ΔC_{dC} described by Yoder.[8]

$$C_D = C_{d0} + C_{d2}(C_L)^2 + \Delta C_{dC}\text{, where } C_L \text{ is the lift coefficient, } C_L = \frac{2mg}{\rho V^2 S}$$

True air speed is defined as the speed in which an aircraft moves through its local air medium. Since we use radar data for flight trajectories, we have a direct measure of ground speed. If wind data are not present, ground speed is typically approximated as equal to true air speed. Thus, if a flight experiences a head wind, the drag, thrust and fuel burn are underestimated; conversely, if a flight experiences a tail wind, drag, thrust, and fuel burn are overestimated. If wind data are used, true air speed can be better approximated.

Air density is related to the air pressure and temperature (e.g., by the ideal gas law). Typically, in flight trajectory computations for aircraft flight levels below 11,000 meters (about 36,000 feet), temperature is assumed to be 288.15 Kelvin at sea level, lapsing at a rate of 0.0065 K for every meter of elevation; pressure is assumed to be 101325 Pascals at sea level, lapsing as a ratio of sea level to ambient temperature. Above 11,000 meters (the region of the atmosphere known as the tropopause), temperature is held constant and a separate equation is used to compute pressure. If more accurate estimates of temperature and pressure are used, the drag estimate can be further improved.

The meteorological information we used was from the Goddard Earth Observing System (GEOS). GEOS is a division of the Goddard Earth Sciences Data and Information Services Center. The meteorological information has a spatial resolution of 1.25 degree by 1 degree, is updated every 6 hours, and includes wind speed and direction, temperature, and pressure, for a wide range of altitudes.[9]

4. CFDR-Derived Fuel Burn Computation

BADA uses the following equation to calculate fuel burn during cruise:

$$f = S * SFC_{\mathrm{BADA}} * T$$

where f is the fuel burn during some portion of the flight, S is the elapsed time (in seconds), T is the thrust, and SFC is the specific fuel consumption, a measure of the rate at which an engine consumes fuel (typically presented in terms of kilograms of fuel per minute per kiloNewton of thrust). The standard equation for SFC in BADA is:

$$SFC_{BADA} = \frac{C_{f1}}{60000}\left(1 + \frac{1.9438V}{C_{f2}}\right)C_{fcr}$$

where V is the true air speed, and C_{f1}, C_{f2}, and C_{fcr} are unique constants for each aircraft. This equation, and all of the unique aircraft constants (C_{f1}, C_{f2}, and C_{fcr}), are the same for all level cruise conditions. Therefore, any variation of atmospheric conditions or throttle setting related to changes in cruise altitude (e.g. from RVSM) will not be reflected in the SFC estimate. That is not to say variations in altitude will not result in changes in the total fuel burn estimate, because changes in density are reflected in changes in the drag and thrust estimates. However, the rate at which an engine consumes fuel for a given thrust will remain constant, and this is not an accurate representation of the behavior of gas turbine engines.[10]

Therefore, we derived a new equation for SFC that takes into account the variability of engine performance with meteorological conditions and throttle setting, and can also be used with the standard BADA method. To develop this new SFC equation, we acquired computer flight data recorder (CFDR) information for over 2,800 flights, representing 12 different aircraft/engine combinations, and about 7% of the global fleet, or 5% of the US fleet. A list of the aircraft/engine combinations and the number of flights of CFDR data for each is provided in Table 2.

Table 2. Available CFDR Data

Aircraft Type	Engine Type	Number of flights
A319	CFM56-5B5-2	191
A320-214	CFM56-5B4-2	240
A321	CFM56-5B1-2	176
A330-202	PW4168	224
A330-243	RR Trent 700	238
A330-223	PW4168A	264
A340-300	CFM56-5C4/P	188
A340-500	RR Trent 500	262
B757-200	RB211-535C	178
B767-300	CF6-80C2	222
B777-300ER	GE90-115B1	365
AR85	LF 507-1F	266

We assumed that the most relevant variables for calculating SFC were: ambient temperature and pressure, Mach number, and net thrust. Ambient temperature and pressure, as well as Mach number, are directly measured during a flight and are available in the CFDR data set. Net thrust, is not directly measured, so the BADA-estimated thrust was used. Using non-dimensional parameters, (see for example the textbook *Mechanics and Thermodynamics of Propulsion*[10]) we represented SFC as a function of Mach number, pressure, and net thrust. The function is provided below:

$$\frac{SFC}{\sqrt{\theta}} = \alpha + \beta_1 M + \beta_2 e^{-\beta_3 \left(\frac{\tau}{\delta^{0.9}} \right)^{0.3}}$$

where θ, δ, and τ are the ratio of at-altitude temperature, pressure and thrust to sea level temperature, pressure, and thrust, respectively; *M* is the Mach Number; and α, β_1, , β_2, *and* , β_3 are constants derived through a regression analysis of the CFDR data. We found the following values for these four constants for each aircraft present in the CFDR data:

Table 3. Derived Aircraft-Specific SFC Coefficients

Aircraft Type	α	β_1	β_2	β_3
A319	1.25E-05	5.03E-06	1.64E-04	6.40E+00
A320-214	1.13E-05	7.84E-06	1.46E-04	5.70E+00
A321	1.26E-05	5.47E-06	1.63E-04	6.50E+00
A330-202	1.11E-05	7.46E-06	6.79E-05	5.00E+00
A330-243	1.05E-05	8.61E-06	2.18E-04	8.00E+00
A330-223	1.05E-05	8.38E-06	1.47E-04	7.50E+00
A340-300	1.26E-05	4.69E-06	3.19E-05	3.30E+00
A340-500	9.52E-06	8.38E-06	1.95E-04	6.60E+00
B757-200	1.04E-05	9.51E-06	8.84E-05	4.60E+00
B767-300	1.45E-05	2.87E-06	1.38E-04	8.90E+00
B777-300ER	1.24E-05	5.99E-06	3.10E-04	1.00E+01
ARJ85	6.84E-06	2.16E-05	3.64E-04	5.80E+00

These fitted coefficients provide an improvement in fuel burn modeling capability when compared with the original BADA methods for the specific aircraft types we analyzed. Figures 2 through 5 provide a comparison of the results using the aircraft-specific SFC models derived here, with results obtained using the original BADA SFC model, and also with the estimates derived using the reported CFDR fuel flow data. Figures 2 and 3 show thrust and SFC, respectively, for one example flight of a B757-200; Figures 4 and 5 show thrust and SFC for one example flight of an ARJ85. While the estimate of the fuel burn value is dominated by the amount of thrust required as shown in Figures 2 and 4, the ability to capture the effects of ambient conditions and operational factors is of significant value in improving the fidelity of SFC estimate as shown in Figures 3 and 5. In particular, as we show in Section 6, it is important to accurately capture the sensitivity of SFC to these factors in order to assess the effects of small operational changes such as those related to implementation of RVSM.

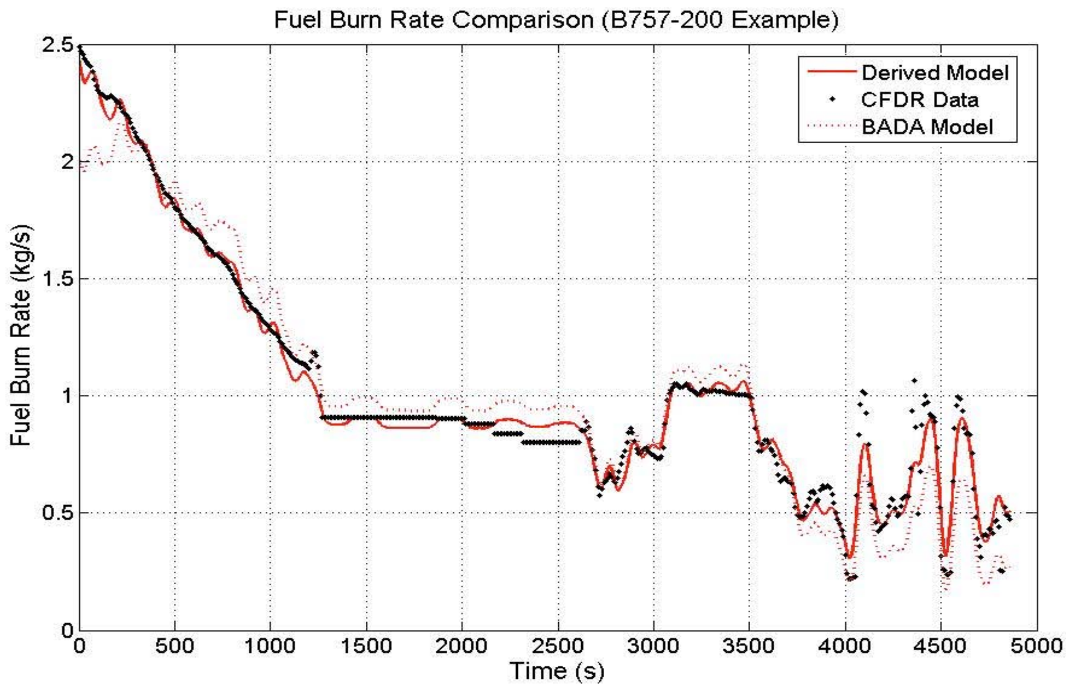


Figure 2 – Example Comparison of Fuel Burn Rate (B757-200)

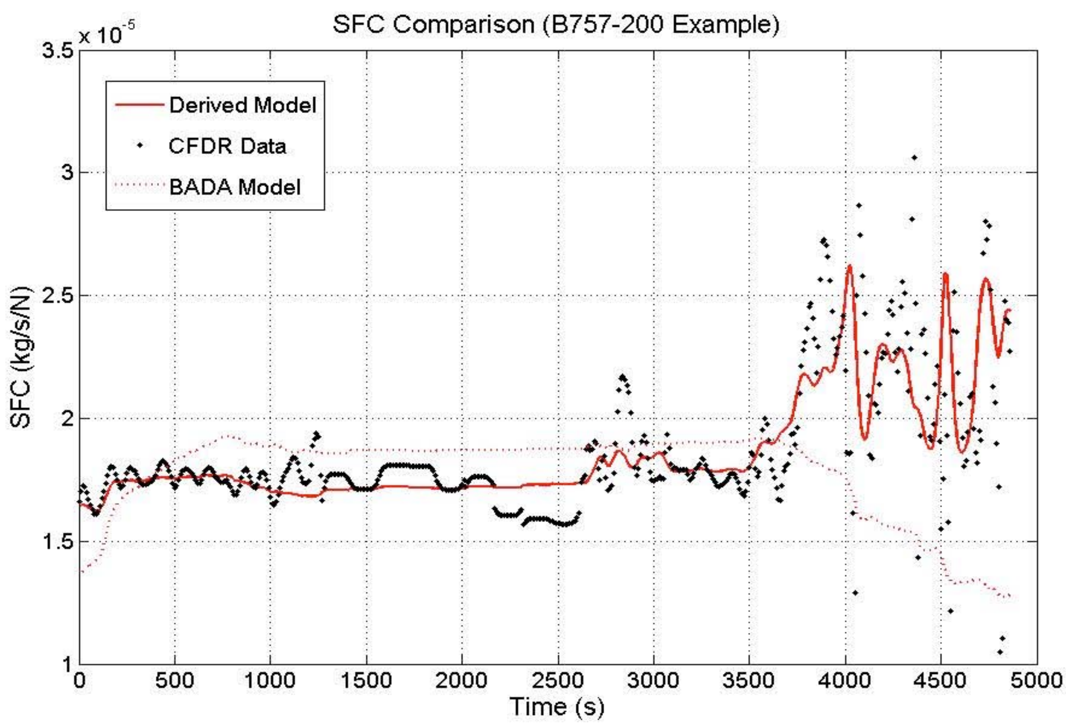


Figure 3 – Example Comparison of SFC Models (B757-200)

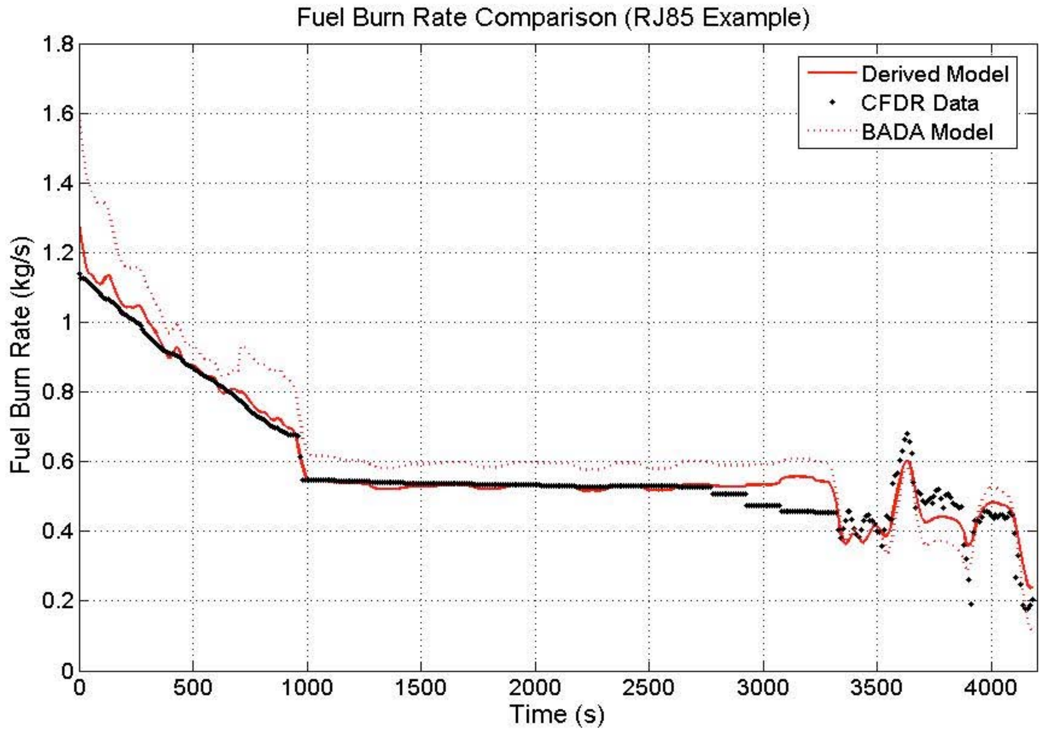


Figure 4 – Example Comparison of Fuel Burn Rate (RJ85)

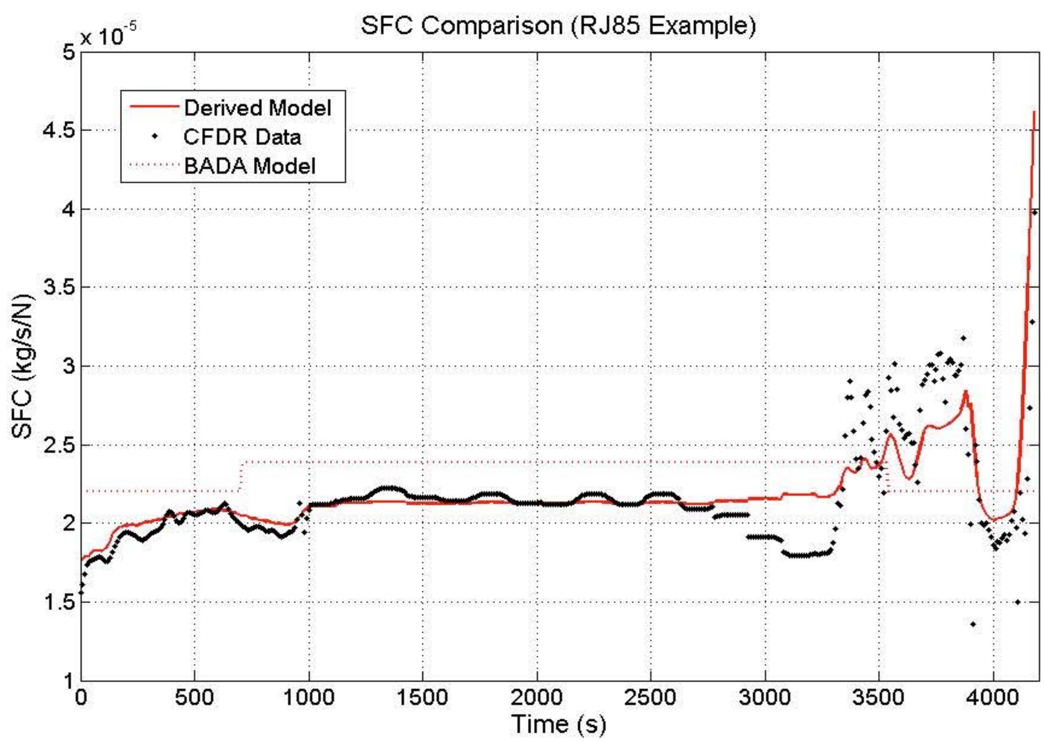


Figure 5 – Example Comparison of SFC Models (RJ85)

Figure 6 shows a comparison of the fuel burn error (CFDR-reported fuel burn vs. computed fuel burn) for each aircraft in the CFDR data set using the two modeling techniques: traditional BADA equations, and BADA with the SFC equation derived above.

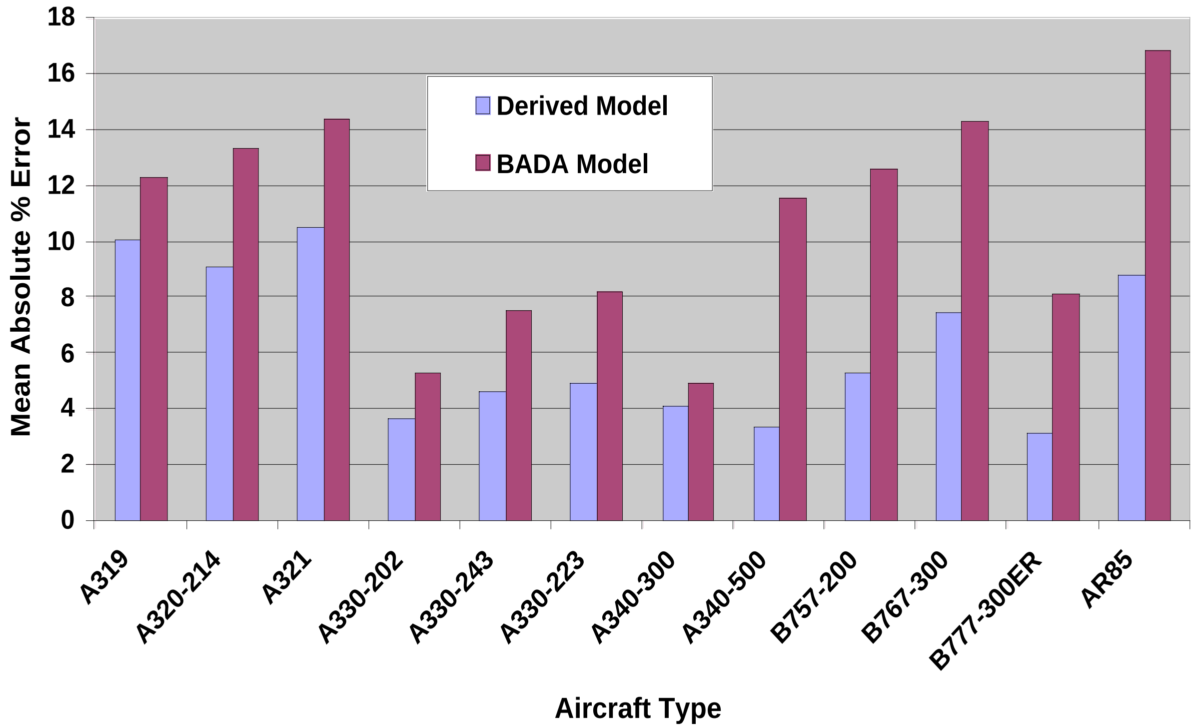


Figure 6 – SFC Model Error Comparison

For each aircraft type the error is reduced when the CFDR-derived SFC model is implemented. The CFDR-derived SFC model led to a 41% average reduction in mean absolute error across all 12 aircraft types. The comparison was made using the trajectory, weight and meteorological information available from the CFDR data. Therefore, remaining errors in the fuel burn estimates are very likely due to inaccuracies in the aircraft-specific drag coefficients in the BADA model. However, the functional dependence of the BADA drag model on atmospheric and flight conditions is appropriate, so it is expected that *changes* in drag due to RVSM may be accurately captured. The focus on improving the SFC model was motivated by the lack of functional dependence of the BADA SFC equation on meteorological conditions and engine throttle setting.

The 12 aircraft-engine combinations in the CFDR data set are only a subset of the aircraft in the fleet. Therefore, a more general modeling technique was developed for application to other jet aircraft represented in BADA. (Note: BADA does include a model for non-jet aircraft, e.g., piston engine and turboprop powered aircraft. However, since the total fuel burn from aircraft other than jet aircraft in the US fleet is less than 5% of the overall US commercial aviation fuel burn, and since RVSM does not generally affect these aircraft, we only derived a general SFC equation for jet-powered aircraft.) We found that α (one of the constants derived above) and the BADA constants C_{f1}, C_{f2}, and C_{fcr} may be approximately related using the following formula:

$$\alpha = \frac{C_{f1}}{60000}\left(1 + \frac{1.9438(240)}{C_{f2}}\right)C_{fcr} - 5.3(10)^{-6}$$

Thus, BADA-derived coefficients may be used within our SFC equation to provide a general SFC approximation. For the β_1, , β_2, and β_3 terms, the average values from the CFDR-derived aircraft constants were used:

$$\beta_1 = 7.70(10)^{-6}$$

$$\beta_2 = 1.86(10)^{-4}$$

$$\beta_3 = 6.75$$

Figures 7 through 9 provide a comparison of three SFC computations to the SFC values estimated from CFDR data (using the BADA drag model as described earlier). The three different methods for computing SFC shown are: 1) the aircraft-specific, CFDR-derived SFC; 2) the generalized CFDR-derived SFC model that can be used with all BADA aircraft; and 3) the original BADA SFC method.

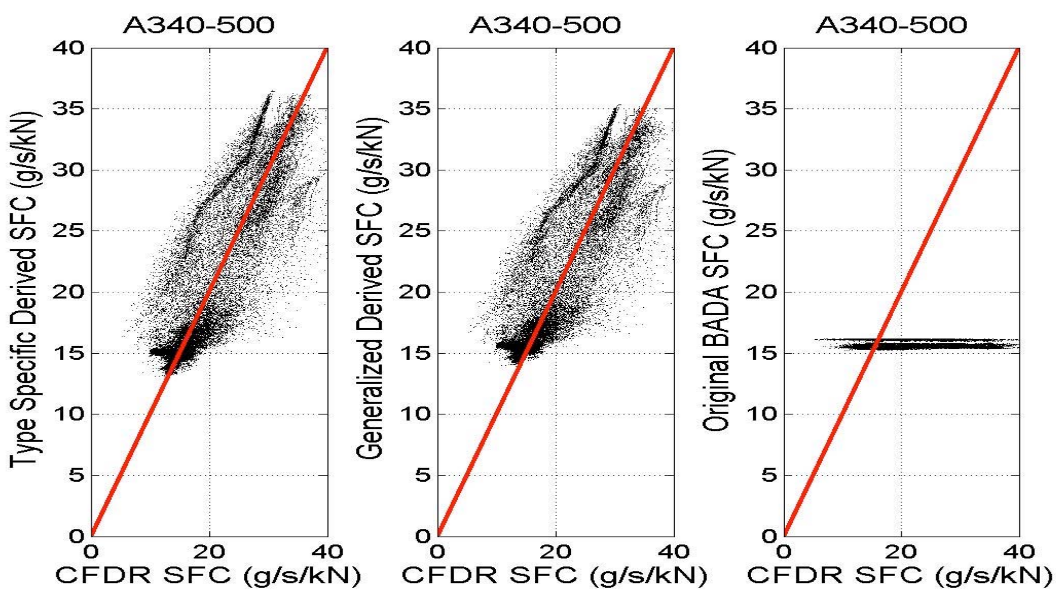


Figure 7. SFC Model Comparison (A340-500)

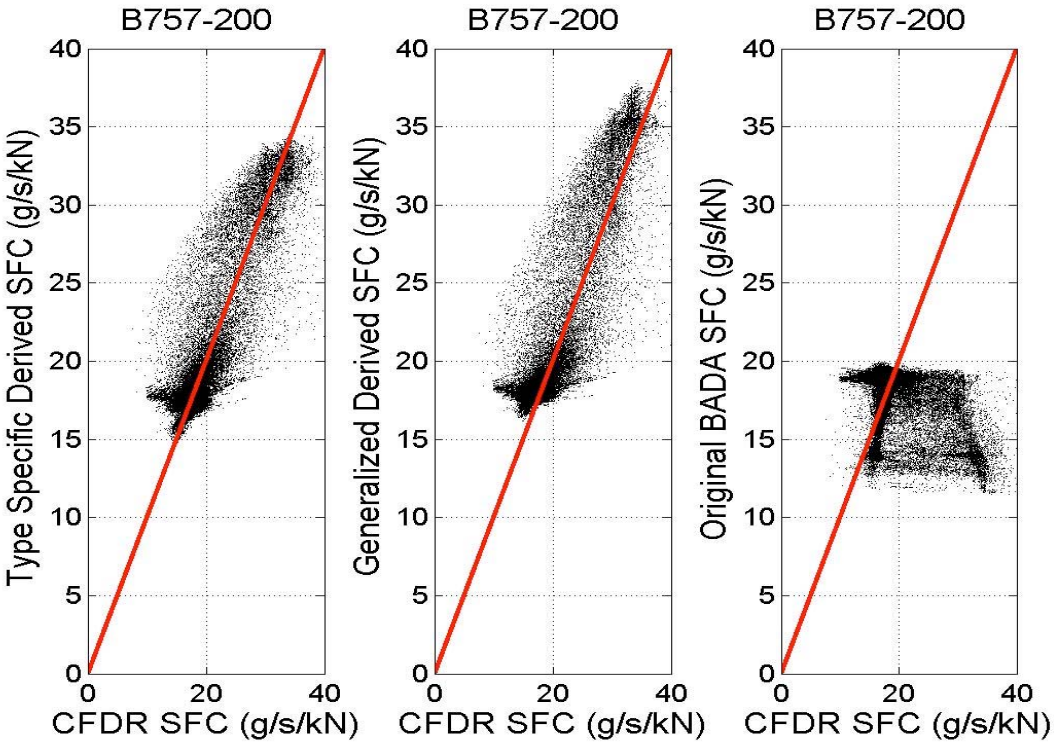


Figure 8. SFC Model Comparison (B757-200)

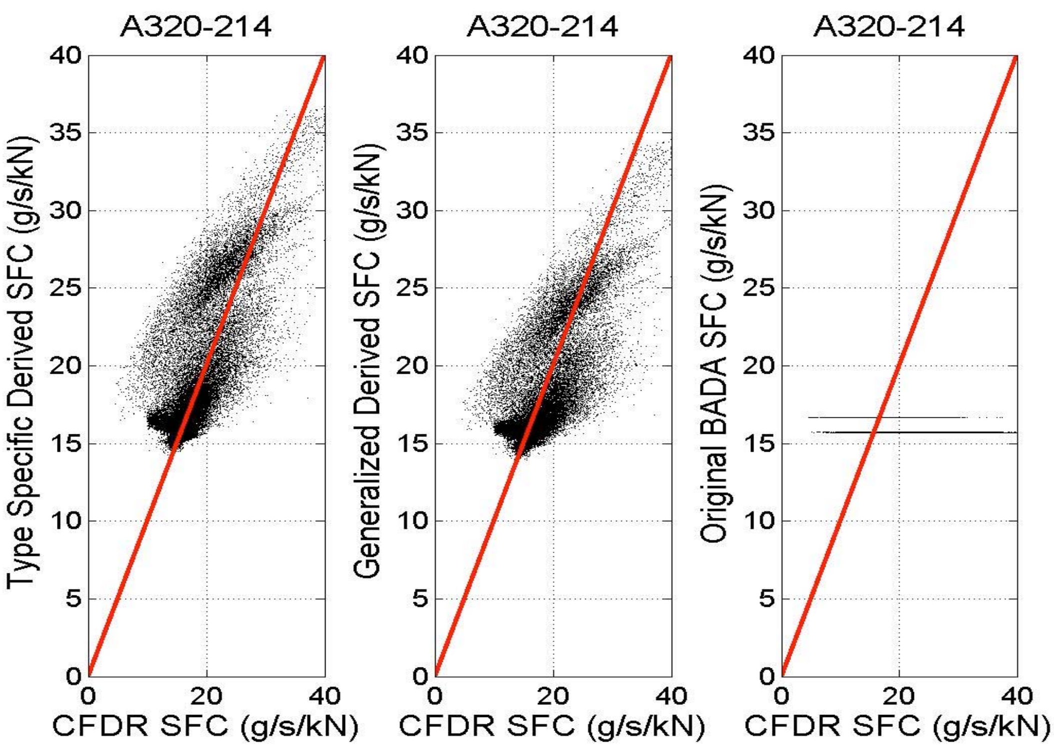


Figure 9. SFC Model Comparison (A321-214)

As can be seen in these figures, the type-specific, CFDR-derived SFC method, and generalized CFDR-derived SFC method provide comparable results, and improve significantly upon the SFC approximation from the original BADA methods. The process of generalizing diminishes the accuracy somewhat as compared with the aircraft-specific model; however, the mean absolute error is still reduced by an average of 21% compared to the original BADA method. Of particular importance, the functional dependencies of important variables (such as throttle setting and meteorological conditions) are largely preserved in the generalized CFDR-derived SFC method; retaining the model's enhanced utility in evaluating operational alternatives.

5. RVSM Analysis

The general metric we used to assess fuel efficiency changes due to RVSM is fuel burn per distance traveled. We considered two distances: the distance a flight traveled in relation to the ground (ground distance); and the distance a flight traveled in relation to local air space (air distance). The latter accounts for differences in routing due to winds and is more relevant for comparing pre-RVSM and post-RVSM aircraft performance since meteorological conditions were different between the two periods. To test the effect of our derived SFC equation and inclusion of meteorological conditions, we calculated fuel burn and emissions estimates for the pre- and post-RVSM periods using four techniques shown in Table 4:

Table 4. Analysis Technique Assumptions

Method	Fuel Burn Model	Weather	Distance Efficiency Metric
1	BADA	Standard Atmosphere	Ground
2	BADA	GEOS weather data	Ground
3	BADA drag, w/ derived SFC	GEOS weather data	Ground
4	BADA drag, w/ derived SFC	GEOS weather data	Air

Method 1 can be considered the typical implementation of BADA: standard BADA equations using the Standard Atmosphere assumption. Methods 2, 3, and 4 make use of the GEOS weather data. Methods 3 and 4 make use of the BADA drag prediction, but use the SFC equation derived from CFDR data. Method 4 has the added improvement of measuring efficiency based on air distance traveled to better account for differences in winds aloft between the pre- and post-RVSM periods.

We used the change in efficiency, $\Delta\eta$ as a measure of the benefit associated with RVSM. The change in efficiency was calculated as:

$$\Delta\eta = \frac{\eta_{pre} - \eta_{post}}{\eta_{pre}}$$

Thus, a positive $\Delta\eta$ indicates an increase or improvement in efficiency.

We also estimated the variability of the results associated with the choice of time periods. Both of the original 28-day study periods were divided into two 14-day periods. The first two week period of the pre-RVSM scenario (11/14/2004-11/20/2004 and 12/05/2004-12/11/2004) was compared to the first two week period of the post-RVSM scenario (12/13/2005-2/26/2005); the second two week period of the pre-RVSM scenario (12/12/2004-12/18/2004 and 1/9/2005-1/15/2005) was compared to the second two week period of the post-RVSM scenario (2/27/2005-12/13/2005). The results of these two sub-analyses differed somewhat from the aggregate results and were taken as an estimate of the potential variability due to the small (one month long) sample of flights considered. This variability was the basis for the estimated uncertainty in the aggregate results shown in Section 5. We note, however, that other sources of uncertainty exist and may be significant including lack of knowledge of aircraft weight (discussed in Section 7) and uncertainties in the BADA aircraft drag computation (discussed previously in Section 4).

Finally, in an effort to substantiate the accuracy of the US domestic comparison, we performed an additional comparison using ETMS data for flights in North Atlantic and European Union (EU) airspace. RVSM was implemented over the North Atlantic in 1997; therefore, the pre- and post-RVSM conditions in our study should have no discernable change in efficiency in this airspace. This was considered a control test of our methods.

6. Results

The results of the US domestic analysis are presented numerically in Table 5 and graphically in Figure 10 for each of the four analysis methods. The total fuel burn, NO_x, and flight distance for all flights in the data analysis period, and a system wide efficiency were calculated.

Table 5. US Domestic RVSM Analysis Results

Analysis Method	Method 1 Standard BADA, efficiency based on ground distance		Method 2 Standard BADA with GEOS weather, efficiency based on ground distance		Method 3 BADA drag with GEOS weather and derived SFC, efficiency based on ground distance		Method 4 BADA drag with GEOS weather and derived sfc, efficiency based on air distance flown	
Period	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Number of Flights	218335							
Total Distance (nm)	123734247	123841509	123540856	123551562	123540921	123551560	124027835	124283913
Total Fuel Burn (kt)	873.7	873.3	878.5	867.2	843	829.8	843	829.8
Total NOx (kt)	11.43	11.37	11.61	11.34	10.82	10.51	10.82	10.51
Δη Fuel Burn per distance (%)	0.14		1.31		1.61		1.81	
Δη NOx per distance (%)	0.59		2.35		2.94		3.14	

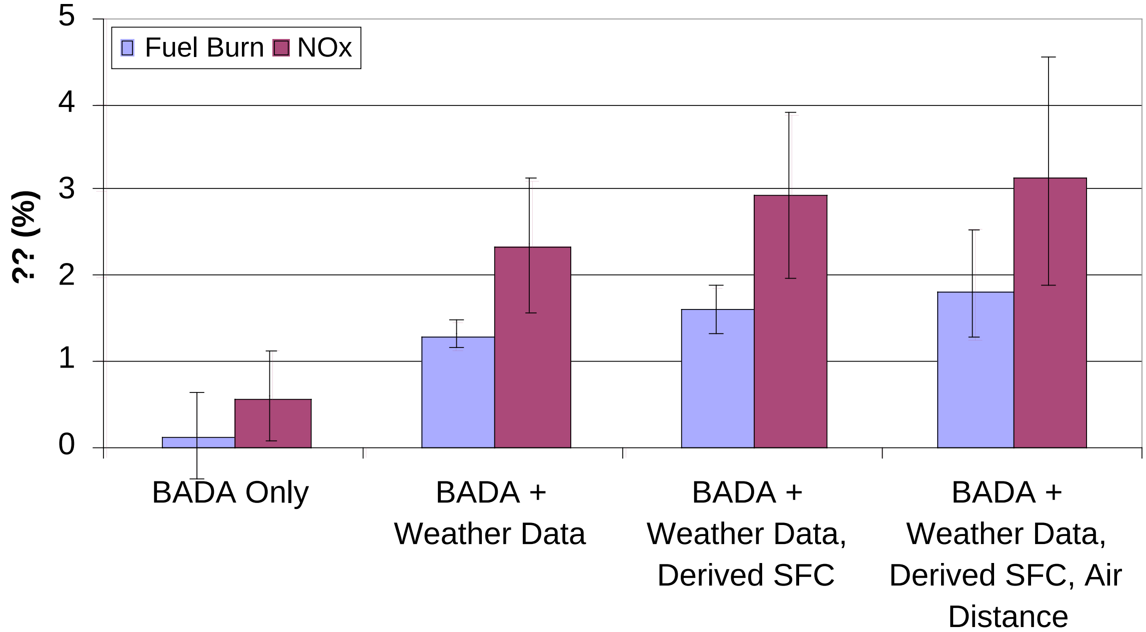


Figure 10. US Domestic RVSM Analysis Results. Shown is the percent change in the quantity per distance

The use of weather data accounts for the largest change in estimated efficiency improvement; fuel burn and NOx efficiencies increase by 1.17% and 1.76%, respectively, from analysis method 1 to 2. The derived SFC model further increases the estimated efficiencies, albeit by a smaller amount (0.30% increase in fuel burn efficiency, and 0.59% for NOx) comparing analysis method 2 to 3. Finally, when considering efficiency as measured by air distance flown (the pair of bars on the right side of Figure 10), the fuel burn and NOx efficiencies increase by 0.2% compared to the third analysis method. 70% of the difference in estimated efficiency benefit (both fuel and NOx) relative to the original BADA method can be attributed to including meteorological data, 18% to including a new SFC calculation, and 12% to measuring efficiency based on a metric of air-distance-traveled.

The control comparison of the North Atlantic and EU region consisted only of a fuel burn comparison and resulted in a nearly zero efficiency change when GEOS weather data, the derived SFC method, and the efficiency based on air distance are used as indicated in the pair of bars on the right side of Figure 11. As can be seen from Figure 12, wind patterns differed greatly over the North Atlantic between the pre- and post-RVSM scenarios. Thus, the difference in wind velocity between the two study periods appears as a substantial negative change in efficiency if the ground distance is used as shown by the bars on the left side of Figure 12. Using the air distance efficiency resulted in an estimated efficiency change (pre- to post-RVSM) of only 0.012%, providing support for the validity of the methods used in this study.

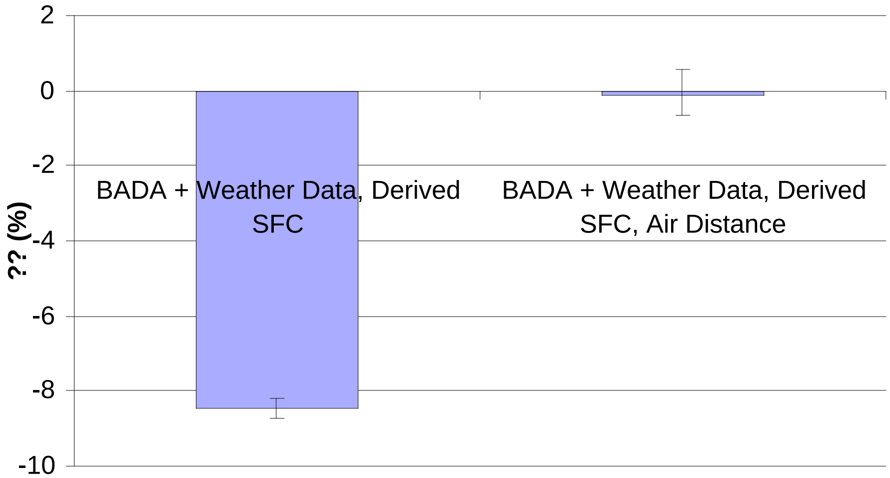
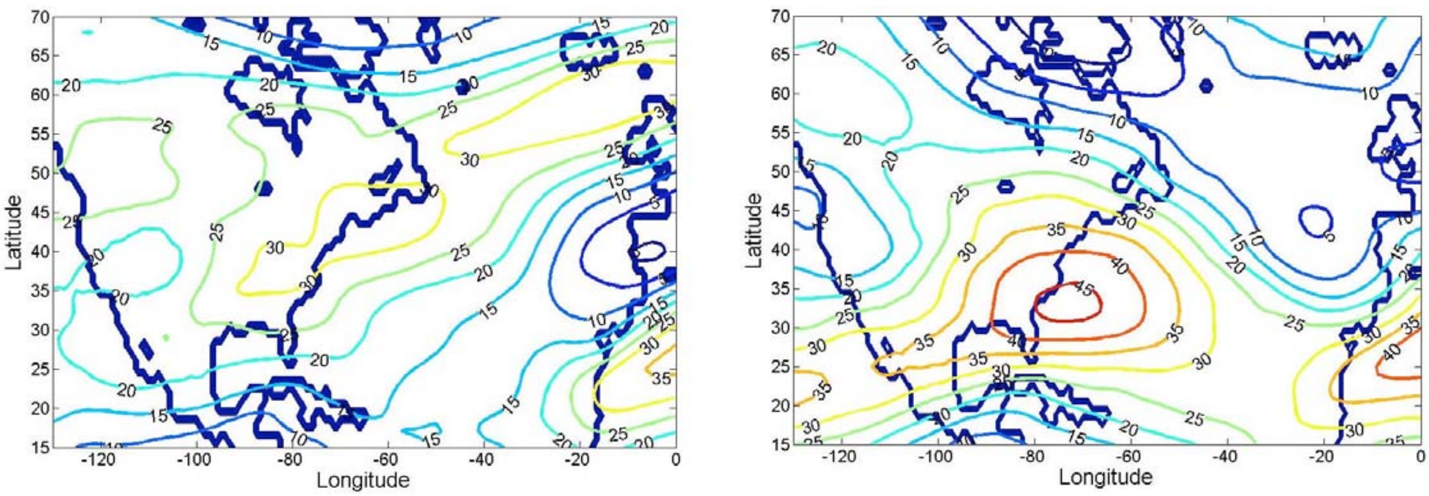


Figure 11. North Atlantic and E.U. (control) RVSM Analysis Results. Change in fuel burn per distance between the pre- and post-RVSM periods.



Pre-RVSM **Post-RVSM**

Figure 12. Comparison of Average Cruise Altitude (8000m-12000m) Winds as Derived from GEOS Data Set

7. Effect of Aircraft Weight Estimates

As previously mentioned, one of the largest uncontrolled areas of uncertainty in this study is the use of standardized aircraft weight estimates that are a function of stage length, but that do not reflect potential differences in aircraft loading between the pre- and post-RVSM periods. If detailed information on aircraft weight or load factor were available, a more appropriate basis for comparison would be an efficiency metric based on the amount of fuel required to move a given payload mass a certain distance. This new efficiency metric would be calculated as follows:

$$\eta = \frac{\sum (m_p \Delta X)}{\sum m_f}$$

Where m_p is the mass of the payload, m_f is the mass of the fuel, and ΔX is the distance traveled. Unfortunately, system wide information on payload is not available at the level of resolution necessary to evaluate this metric. Aggregated load factors could be used as a possible surrogate for flight-by-flight payload estimates. The FAA reports aggregated monthly load factor data provided by carriers. The load factors for the timeframe we analyzed are provided in Table 6.

Table 6. US Domestic Monthly Load Factors

	Nov-04	Dec-04	Jan-05	Feb-05	Mar-05
ton-km avail	30800000000	32900000000	30600000000	29000000000	33200000000
ton-km Used	16600000000	18500000000	16600000000	16100000000	20100000000
load factor	0.538	0.562	0.543	0.556	0.605

We did not analyze entire months, but rather selected weeks within each month, and we did not have the information required to disaggregate these monthly load factors into individual weeks. Additionally, we purposely excluded weeks that would be greatly affected by holiday travel, and these weeks will influence the monthly average load factor estimates. Therefore, we were unable to determine the influence of variation in load factor in our results.

8. Conclusions

The overall benefit in fuel efficiency due to RVSM we estimated is comparable to the benefit estimated in the 2002 EUROCONTROL and 2005 FAA-ATO studies. We estimate that RVSM led to an improvement of fuel burn of 1.8% ± 0.5%. This estimate was made using a longer period of time (one month prior and one month after) than used in previous studies. We also used improved modeling methods that took account of meteorological conditions and variations in engine performance with flight conditions and throttle setting. Notably, if we were to have used the standard BADA methods as used in the prior studies, we would have estimated no improvement in fuel efficiency between the pre- and post-RVSM periods we analyzed.

BADA methods were designed to provide fleet-level performance estimates. We developed methods that can be used to improve upon these methods when estimating small changes in operating conditions (such as those due to RVSM). Both the aircraft-specific, CFDR-derived SFC model, and the model that is generalized for application to all jet-powered aircraft may be valuable to other researchers. However, the most significant factor influencing our estimates relative to prior methods was the inclusion of meteorological information. 70% of the difference in estimated efficiency benefit (both fuel and NOx) relative to the original BADA method can be attributed to including meteorological data, 18% to including a new SFC calculation, and 12% to measuring efficiency based on a metric of air-distance-traveled.

9. References

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