CHALLENGES
IN EUROPEAN
AEROSPACE
5TH CEAS AIR & SPACE CONFERENCE

CEAS

Understanding Fleet Impacts of Formation Flight

Bryan Boling, Ph.D.
RAND Corporation
Associate Engineer
1776 Main St., Santa Monica, CA, 90291, USA
bboling@rand.org

Yaolong Liu, Institute of Aerospace Systems (ILR), RWTH Aachen University, Germany

Prof. Eike Stumpf, Director of Institute of Aerospace Systems (ILR), RWTH Aachen University, Germany

ABSTRACT

Formation flight is a novel operational concept being explored within commercial aviation for its potential to reduce fuel burn. While the aerodynamics of reducing induced drag through the utilization of a lead aircraft's upwash is well understood, the aggregation of this effect in real air carrier fleets is an active area of study. The following research will introduce work towards this endeavor. A series of response surface models are introduced quantifying the individual impact of reduced drag at the vehicle level, based solely on easily measurable aircraft parameters. Further, a method for the determination of route pairing and selection is presented in relation to real air carrier operations, and is ultimately integrated into an established cost-effectiveness model of the global air transportation system. This work is used to study the potential impacts of including formation flight for a real air carrier, such as Lufthansa. The results from this work show that fuel burn reductions on the order of 3-4% may be likely.

NOMENCLATURE

AC	Aircraft
AR	Aspect ratio
ATS	Air transportation system
b	Wing span
BF	Block fuel
CAEP FESG	Committee on Aviation Environmental Protection Forecasting and Economics Support Group
DoE	Design of Experiments
FF	Formation flight
GATS	Global Air Transportation System Model
kg	Kilograms
km	Kilometres
LTA	Large twin aisle
LQ	Large quad aisle
m	Meters
MICADO	Multidisciplinary Integrated Conceptual Aircraft Design Optimization
MTOW	Maximum takeoff weight
RPK	Revenue passenger kilometre
RSE	Response surface equation
RSM	Response surface model

SA	Single aisle
STA	Small twin aisle
SoS	System-of-systems
W/S	Wing loading

1 INTRODUCTION

One operational efficiency concept which is not yet common but could provide significant fuel burn and economic benefits to the air transportation system is formation flight. Formation flight is the practice of flying two or more aircraft in a specific pattern such that the induced drag of aircraft behind the lead aircraft can be reduced. This concept appears throughout nature, and has shown aerodynamic benefits [1]. Previous work in this area has been accomplished by a number of researchers. Some of this work has been focused on understanding the flight conditions on widely utilized aircraft, such as the Boeing 777, Boeing 757, Airbus A320, and Airbus A300, necessary to maximize the benefits of formation flight. An extension of this work that is explored here regards generalizing the induced drag and fuel burn reductions achieved during formation flight based on basic geometric and aerodynamic parameters of the aircraft. The ultimate goal is to produce estimates that can be used in fleet level analysis for any combination of aircraft occurring in real world operations.

Including these estimates in fleet level analysis provides a starting point for the determination of realized benefits with a specific use case. In order to accomplish this, cost and performance models have been developed, as well as algorithms to determine the optimal meeting and split up points of routes [2-6]. While the results generated from many initial studies of formation flight have been limited in scope to either just vehicle level results or generic fleets, this study will expand upon this body of work to include real air carriers in the global air transportation system. However, based on the results from previous studies, it seems likely that fuel burn benefits in the 4-6% range for air carriers could potentially be accomplished if formation flight is implemented, which serves as a benchmark for this study. Additionally, the likelihood of incorporating formation flight into air carrier operations based on the logistical and regulatory obstacles will also be discussed qualitatively. The hope is that this work will serve as a valid first order approximation of the benefits that can be achieved through novel operational efficiency measures, and will highlight the regulatory and logistical challenges that must be overcome to realize these benefits.

2 VEHICLE LEVEL BENEFITS OF FORMATION FLIGHT

In order to determine the fuel burn reductions for an air carrier, the benefits at the vehicle level must first be understood. One of the key challenges of this endeavor in the context of the global air transportation system is the large number of unique vehicles operating throughout the world. To fully understand the benefits for each specific vehicle necessitates knowledge of every combination of formation flight configuration. For example, the benefits for a Boeing 737 will differ based on the aircraft that is serving as the lead. Due to the combinatorial nature of such a problem, studying all combinations is prohibitive, and future vehicles that may enter the fleet cannot be included. To circumvent this obstacle, surrogate representations of the fuel burn benefit are created based on geometric and aerodymic parameters of the aircraft, such that basic knowledge of all vehicles can be more rapidly explored.

The following section elaborates on the approach for estimating formation flight (FF) fuel burn benefit for different aircraft combinations, and presents the determinied surrogate equations. In order to build up the surrogates aforementioned, the FF benefit dependent aircraft parameters have to be determined. Therefore, this section begins with the identification of representative aircraft parameters, followed by the determination of appropriate combinations of these parameters according to expected formation flight configurations, and finally the method of calculating each configurations fuel burn is presented. The final surrogates for chosen aircraft groups are presented at the end of this section.

2.1 Determination of Relevant Aircraft Parameters

The induced drag is reduced as a result of the upwash impact from the leading aircraft during formation flight. Therefore, relavent aircraft parameters for this study should capture the main impact of upwash and the characteristics of induced drag, as well as the overall aircraft performance changes. Previous studies on formation flight have given insight into identifying aircraft parameters that have dominant influence on formation flight aerodynamics and performance. Using an analytic approach, [7] determined that power reduction of bird formations are a function of wing span, wing aspect ratio, wing loading, and the relative configuration spacing in formation. Further, the research of [8] on heterogeneous aircraft formation showed that the relative values of wing span, geometric mean chord, wing area, aspect ratio, taper ratio, sweep angle, and dihedral between formation lead and trail aircraft had significant impact on the induced drag savings. More recently, [9] achieved an approximation of the magnitude of the induced upwash velocity, showing it is a function of weight and wing span of the leading aircraft. Previous research by the authors [10] also showed a similar trend. As a result of this previous work, wing span, wing area, and take-off weight have been chosen as representative parameters to group aircraft, and in order to fit the fuel burn benefit surrogates descriptive combinations of these parameters are explored.

Through investigation of flight operations data, and the assumptions of potential formation flight candidate vehicles, aircraft in the Single Aisle (SA), Small Twin Aisle (STA), Large Twin Aisle (LTA), and Large Quad Aisle (LQ) classes are explored. The detailed formation flight performance, measured through mission fuel burn, is based on an in-house preliminary aircraft design and optimization platform, (MICADO), which requires gross weight at each mission segment, detailed aerodynamic polars as functions of Mach number, altitude, and full thermodynamic engine models. Due to a lack of data availablity of the the STA and LQ aircraft classes in MICADO, they have been neglected in this study. As such, the following work will focus on the SA and LTA classes.

First, the boundary conditions of the aircraft class to be investigated is established, and the formation flight configurations are divided into four cases. Case 1: both lead and trailing aircraft are of the same type and belong to aircraft class SA; Case 2: lead and trailing aircraft are of different types and belong to aircraft class SA; Case 3: both lead and trailing aircraft are of the same type and belong to aircraft class LTA; Case 4: the lead and trailing aircraft are of different types and belong to aircraft class LTA. Due to the decrease of formation flight benefit and possible safety issues with significantly different size aircraft in formation [11], heterogeneous formation flight only occurs within a single aircraft class in this study.

2.2 Formation Flight Calculation Environment

To capture the impact of formation flight at the aircraft design level, a flexible aircraft design and assessment platform is needed. The present work uses the existing preliminary aircraft design software environment developed in recent years at the Institute of Aerospace Systems (ILR) of RWTH Aachen University [12]. The multidisciplinary integrated conceptual aircraft design optimization (MICADO) platform has been extended by the authors for formation flight calculations. The detailed descriptions of formation flight estimation can be found in another publication from the authors [10]. In this section the approach will be briefly explained.

Figure 1 provides an overview of the formation flight simulation platform developed at ILR. The main steps are:

1. Creation of a convergent aircraft through MICADO loops, with all aircraft data being saved as an aircraft exchange file in MICADO.
2. Search of formation flight configuration sweet spot, and the creation of formation induced drag polar after taking the geometry data from the aircraft exchange file in MICADO as input.
3. Determination of fuel burn of each aircraft in formation flight by employing the formation flight polars as function of Mach number and altitude. The detailed mission analysis requires inputs such as aircraft gross weight at each mission increment and the full thermodynamic engine model in the MICADO mission tool.
4. Finally, further economic and ecological assessment of formation flight is also provided.

In order to build up the final surrogates for FF benefit, each individual run derived from a selected design of experiemnts (DoE) is carried out within the assessment framework aforementioned.

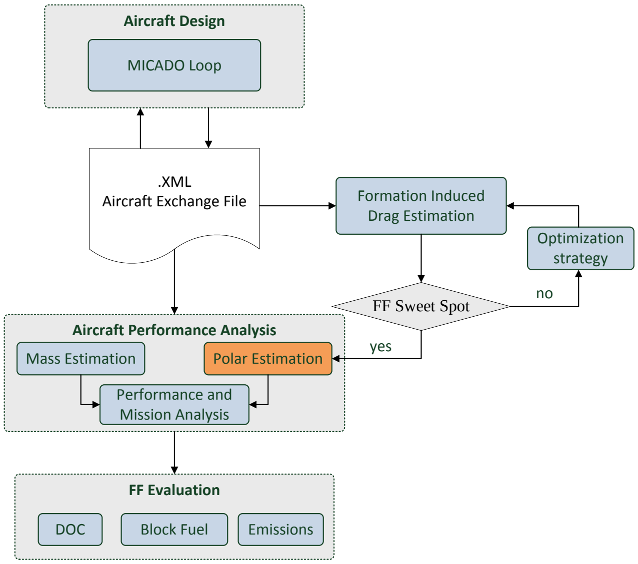

Figure 1: Overview of formation assessment approach.

2.3 Design of Experiments and Response Surface Model

To achieve the needed level of information at a minimal computational expense for the creation of the formation flight fuel burn reduction surrogates, a design of experiments is employed. For this study the Latin Hypercube design is chosen in order to fully populate the potential aircraft parameter space explored here. It is be noted that wing span and area can be directly given as input, while the maximum take-off weight (MTOW) is a design output. Hence, an input payload is used here as a representative weight element. Upon completion of these experments, the wing span, area, and the resulting MTOW can be used in the construction of the formation flight fuel burn benefit surrogates. The class specific aircraft parameters used to define the parameter ranges for the DoE implemented in this study are provided in Table 1 and 2.

Table 1: Selected AC Parameters of AC Class SA

AC Type	B (m)	AR	W/S (kg/m^2)
Airbus A320	34.1	9.5	605.86
Boeing 727	35.225	6.95	526.54
Boeing 737-200	28.4	8.9	606.48
Boeing 737-300	28.9	7.9	568.07
Boeing 737-400	28.9	7.9	621.44
Boeing 737-500	28.9	7.9	535.58
Boeing 737-600	34.3	9.4	477.36
Boeing 737-700	35.05	9.45	518.98
Boeing 737-800	35.05	9.45	616.73
DC-9	22.97	6.375	480.06
MD 81-88	32.8	9.6	620.40

Table 2: Selected AC Parameters of AC Class LTA

AC Type	B (m)	AR	W/S (kg/m^2)
Airbus A330	60.3	10.1	640.21
Airbus A340	61.9	9.65	806.33
Boeing 777	62.85	9.15	711.97
DC-10	50.4	7.5	754.43
MD 11	55.9	8.55	712.13

2.4 Resulting Formation Flight Vehicle Fuel Burn Surrogates

While it has not been explicitly mentioned yet, the surrogate representatios of fuel burn benefit for formation flight have fit using response surface equations (RSE). Before presenting the final surrogate results, it is necessary to take a look at the response surface model (RSM) utilized for the analysis.

For constructing the response surface equations for the block fuel reduction, the regression model described in Equation 1 is employed, which is a second order multivariate RSE. In this study the variables are confined to three parameters, wing span, wing area, and MTOW of both leading and trailing aircraft. In particular, the four cases mentioned in subsection 2.1 are divided into groups. Group one represents homogeneous formation flight, where the lead and trailing aircraft are of the same aircraft type, while group two represents heterogeneous FF, where the lead and trailing belong to the same aircraft class but are different aircraft types. For the homogeneous group, the wing span, aspect ratio and wing loading of the trailing (which are also the same for the lead) are input to calculated the fuel burn benefit as in Equation 2. Heterogeneous formation flight is much more complex. Here the wing span of the trailing aircraft, and the aspect ratio and wing loading values of the lead aircraft divided by the trailing aircrafts are combined as seen in Equation 3.

The final formation flight fuel burn benefit surrogates are regressed for the four cases aforementioned. Table 3 provides the resulting coefficients for the equations detailed below, and Table 4 provides the resulting coefficients of determination which represent the goodness of fit. Additionally, the goodness of fit is illustrated by plotting the actual model response over the predicted response, which depicts the residuals more clearly. As an example, Figure 2 shows the deviations from the actual data for the SA-SA aircraft class homogeneous regressions, which serves to demonstrate that the derived surrogates have good predictive capabilities.

Ultimately, these surrogates are employed in the fleet level analysis tool for investigation of potential benefits for real air carriers.

$$R = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

R : response
k : number of variables
x_i : main effects
x_i^2 : quadratic effects
$x_i x_j$: second order interaction terms
β_0 : intercept term
β_i : regression coefficients for first degree terms
β_{ii} : regression coefficients for quadratic terms
β_{ij} : regression coefficients for interaction terms
ε : error term

$$\begin{aligned} \Delta BF &= \beta_0 + \beta_1 \cdot b + \beta_2 \cdot AR + \beta_3 \cdot \left(\frac{W}{S}\right) + \beta_{12} \cdot b \cdot AR + \beta_{13} \cdot b \cdot \left(\frac{W}{S}\right) \\ &\quad + \beta_{23} \cdot AR \cdot \left(\frac{W}{S}\right) + \beta_{11} \cdot b^2 + \beta_{22} \cdot AR^2 + \beta_{33} \cdot (W/S)^2 \end{aligned} \qquad (2)$$

$$\begin{aligned} \Delta BF &= \beta_0 + \beta_1 \cdot b_T + \beta_2 \cdot (AR_L/AR_T) + \beta_3 \cdot \left[\left(\frac{W}{S}\right)_L / \left(\frac{W}{S}\right)_T)\right] \\ &\quad + \beta_{11} \cdot {b_T}^2 + \beta_{22} \cdot (AR_L/AR_T)^2 + \beta_{33} \cdot \left[\left(\frac{W}{S}\right)_L / \left(\frac{W}{S}\right)_T)\right]^2 \\ &\quad + \beta_{12} \cdot b_T \cdot (AR_L/AR_T) + \beta_{13} \cdot b_T \cdot \left[\left(\frac{W}{S}\right)_L / \left(\frac{W}{S}\right)_T)\right] \\ &\quad + \beta_{23} \cdot (AR_L/AR_T) \cdot [(W/S)_L/(W/S)_T)] \end{aligned} \qquad (3)$$

Table 3: Coefficients of FF Benefit Surrogates

Coefficient	Case 1	Case 2	Case 3	Case 4
βo	9.15471	-105.19866	974.73309	-30.72412
β1	-11.46878	5.10591	11.72599	2.29971
β2	38.40165	71.12871	-202.03435	53.48640
β3	0.01516	-6.34124	-1.05992	-106.48225
β12	-0.78374	-1.02788	1.62497	-0.94165
β13	0.02174	-0.00880	-0.00661	-0.36123
β23	-0.07202	3.61310	0.12167	34.06218
β11	0.09103	-0.06613	-0.17853	-0.00891
β22	1.69666	-11.57407	0.99600	-1.17544
β33	-0.00005	-1.38863	0.00020	42.56253

Table 4: Coefficients of Determination for FF Benefit Surrogates

	R2
Case 1	0.912
Case 2	0.910
Case 3	0.992
Case 4	0.989

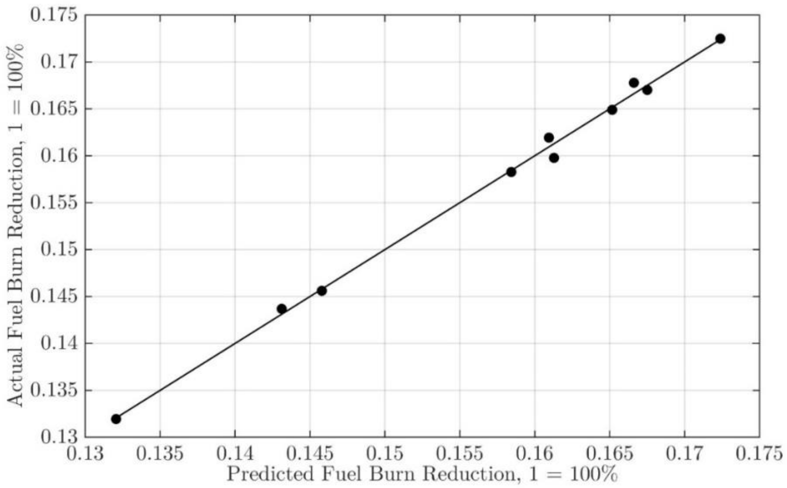

Figure 2. Actual vs. predicted fuel burn reduction for two SA class AC combination

3 FLEET LEVEL FORMATION FLIGHT BENEFIT

Providing the realized benefit of formation flight for specific air carriers necessitates the determination of optimal meeting and split up points for routes, as well as the determination of optimal route pairings. These topics are addressed in the following analysis. It should be noted that even the improvements on previous efforts considered here come with a large number of assumptions. First, it should be understood that only two aircraft flying in formation are considered. Further, it is assumed that only a single meeting and split point will exist, and only two routes can be paired together. Once a route is paired with another, it cannot be paired with other routes. Future iterations of the formation flight calculation can be updated to loosen the restrictions imposed by these assumptions with continued development efforts.

3.1 Optimal Meet and Split Point Determination

In order to determine whether any two routes can provide potential benefit through formation flight, the first determination is the optimal meeting and split points. This problem can generally be stated as an unconstrained optimization problem, where fuel burn is minimized while changing two mid points along two different routes where flight paths might converge. In order to orient the reader to this concept Figure 3 is provided. Here, two routes meet at a rendezvous point and eventually depart to their corresponding destinations.

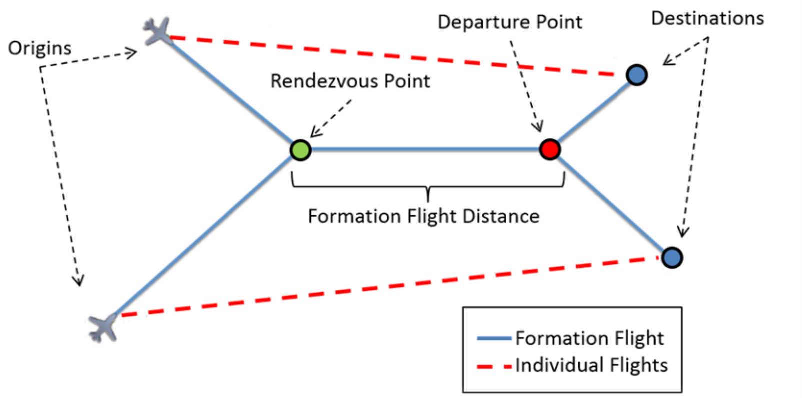

Figure 3: Example Re-Routing for Formation Flight

In the current implementation of the formation flight model, a coordinate pattern search algorithm is employed for the determination of the meeting and split points for combinations of flights [13]. The initial guess of the rendezvous point is chosen as longitude of the innermost origin and the average latitude of both of the origins considered. A similar approach is employed on the destination airports for the determination of the initial departure point.

Once the meet and split points are initialized the potential fuel burn savings are assessed using the great circle distances of all portions of each route. Further, the fuel burn reduction surrogates aforementioned are input to determine potential fuel burn savings. It should be noted here that the fuel burn reduction may be different depending on which aircraft is the leader, thus both scenarios are tested and the formation with the greatest benefit is pursued.

Given determination of the fuel burn at the initial guess points, coordinate points around this initial guess, with a spacing of 1 degree of latitude and longitude are tested. The point with the lowest total fuel burn is selected and the process continues until no further reductions are possible. At this point, the step size is halved and the process proceeds again. Currently this halving is continued for five iterations, resulting in the determination of the optimum point to within 1/16th a degree in latitude and longitude. Further, it should be noted that this process proceeds first on the meeting point with the departure point held constant, and then on the departure point. Upon initial testing of this method it has been determined to provide good estimates of rendezvous and departure points, as well as estimates of the fuel burn reductions possible using formation flight on scheduled routes from real airline data. It should be noted, that in subsequent determination of applicable route pairings the fuel burn at the optimal meet/split combination is compared to the original flight fuel burn to assess whether benefits are possible, and only route pairings resulting in fuel burn reduction are stored for future consideration.

Ultimately, the reason for implementing this optimization scheme is to minimize the number of function evaluations for formation flight, as this is just one piece of the overall algorithm determining route pairings. In testing of this algorithm it has been shown to find the optimum for most inputs within 20 to 60 steps. As an example of the functionality of this meeting and split point optimization consider the example displayed below in Figure 4. Here, two routes are tested for a potential benefit from formation flight. These include a flight from JFK to LHR and one from ATL to TFN, both of which are assumed to be accomplished using an A320 type aircraft.

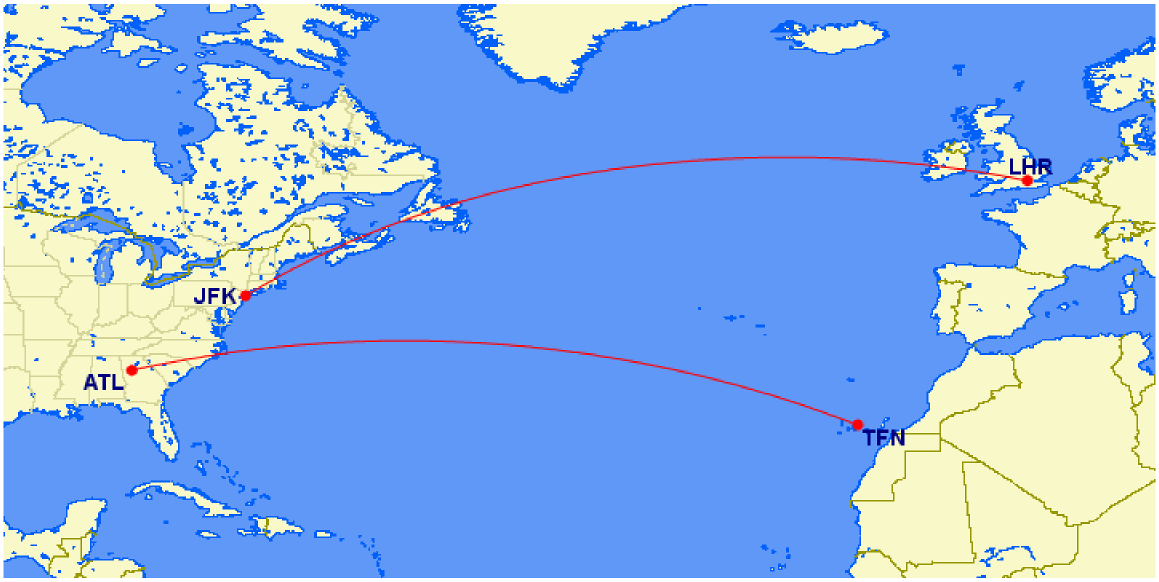

Figure 4: Formation Flight Test Routes

While the routes are quite divergent, the optimization scheme still finds the optimal meeting and split points for formation flight within 54 steps. Further, it is determined that under these assumptions, formation flight could potentially save 861 kg of fuel per flight. The re-routing occurring as a result of the method described here is shown in Figure 5.

Figure 5: Formation Flight Test Re-Routing

3.2 Route Pairing Selection

The main purpose of evaluating formation flight capabilities is to select optimal route pairings to provide the greatest fuel burn benefit. Currently, inputs to this problem include the minimum frequency of flights occurring on a route, the similarity of the initial heading, the minimum distance of the routes, and which carrier operations should be considered. Additionally, there is also an input for the percentage of formation flight use, which simply controls the frequency at which possible formation flights would be attempted given knowledge that benefits can be achieved. In a sense this last parameter is meant to act as a measure of logistical complexity of scheduling formation flight on these route pairs for real air carriers. While further analysis would be needed to comment with any certainty on the problem of scheduling formation flights, any future scenario will likely take advantage of just a fraction of all possible flights due to this scheduling problem.

The route pairing selection algorithm begins with the given assumptions for the aforementioned inputs and a real air carrier’s operations. The applicable routes are first filtered by the input flight frequency and minimum distance, such that any routes not flown at or above the frequency or minimum input are removed from consideration. Next, the initial headings of all remaining route combinations are compared, and the potential combinations are again filtered based on the heading similarity input.

With a final determination of all possible route pairings, each combination is evaluated using the optimal meeting and split point determination and total fuel burn reduction potential. Any route pairings that do not provide a benefit in terms of fuel burn are automatically discarded from the selection set as aforementioned. Finally, the total fuel burn benefit of each combination that is left is determined using the number of possible formation flights (which would be the minimum number of flights for any pair of routes) and the input use percent.

Given the known potential fuel burn benefits of all applicable route combinations, the selection strategy to determine the final route pairings can begin. This is accomplished by selecting the route pair that provides the greatest overall benefit, storing a route pair identifier and the applicable meeting and split points in the operations dataset. The other route combinations containing these routes are then removed from the selection process since they are already paired, and the selection process continues onto the next maximum potential benefit. This process proceeds until all possible routes have been paired or removed from selection. Ultimately, the air carrier operations dataset is then replaced in the fleet level model with route pairing identifiers, latitude and longitude points for the intermediate points in the routes, and the potential benefit of using formation flight on the routes.

3.3 Fuel Burn Reductions in the Fleet

Once the route pairings and associated fuel burn benefits have been determined for the airline, future projections of benefits are based on the output fuel burn benefit of the route pairs. Since only the trailing aircraft receives the benefit, this is the only value used in future projections, along with the assumed growth in demand. While a more complete analysis would consider the use of alternative vehicles in future years for formation flight, the computational expense required to iterate on the formation flight route selection strategy would be prohibitive. As it is currently implemented, the selection of applicable routes for reasonable inputs can result in hundreds of thousands of possible combinations to evaluate and select from, which may take anywhere from minutes to many hours depending on the data set. If future updates of this selection process or optimal rerouting are updated, these assumptions can also be updated.

3.4 Integrating Formation Flight Considerations In An Air Transportation Model

In order to determine the potential benefit of formation flight to real air carriers throughout the world, the aforementioned considerations must be integrated into an air transportation system model capable of evaluating individual airlines. Such a model has been developed for the study of environmental policy and market based measures within the air transportation system, known as the Global Air Transportation System (GATS) model. This model serves as a good first order estimate of the effects of aviation, and includes consideration of real operations of air carriers and their associated inventories.

This initial release of the GATS Model is preloaded with the top 15 air carriers, as measured by revenue passenger kilometers (RPK), and includes surrogate representations of 52 of the most commonly utilized aircraft. In order to forecast operations and inventory into the future, estimates for traffic growth and retirements have been included from the CAEP\8 FESG Traffic and Fleet Forecast for each route group [14].

The structure of this model is based on the system-of-systems (SoS) structure of the ATS and its associated measures, which is depicted here in Figure 6.

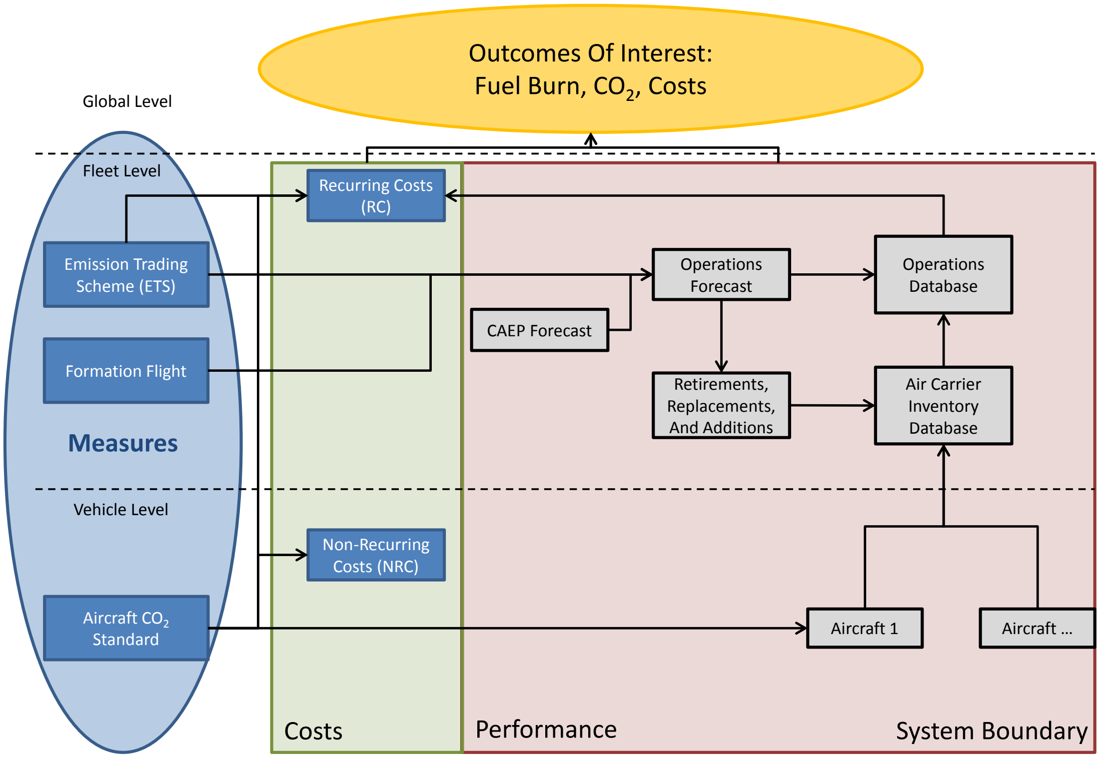

Figure 6: GATS Model Structure

4 AIRLINE CASE STUDY

Given the integration of the formation flight fuel burn reduction surrogates, route pairing and selection algorithm, and the global air transportation system model, the impacts of formation flight on real air carrier operations can be assessed. This section will present the results generated from the GATS model by considering the potential implications of Lufthansa incorporating formation flight on its routes at least 25% of the time. In order to assess the beneifts to a carrier like Lufthansa, the formation flight results are compared against a baseline scenario in which formation flight is not pursued, and the reduction in fuel burn from that case is presented.

For this particular study, the resulting fuel burn benefit for a number of minimum flight distance have been tested in order to understand the tradeoff in greater fuel burn reductions and additional scheduling concerns. It is expected that having a smaller minimum flight distance for consideration of formation flights will lead to greater fuel burn reductions since a larger number of flights will be paired to give a greater benefit. However, this greater benefit neglects the fact that shorter flights are often much more schedule constrained than long haul hub to hub flights. As such, considering these presents an obstacle in scheduling complexity that cannot be solved in the current models implemented here. Thus, only substantial reductions in fuel burn by incorporating these fligths would warrant further consideration of their implementation for real air carriers.

To test this hypothesis, a sweep in the minimum flight distance (from 500km to 3,000km) has been completed for Lufthansa, and the resulting fuel burn reductions are illustrated in Figure 7 below. As can be seen, there is less added benefit for the smaller minimum flight distances (500 to 1,000km) than for more long haul flights, such as those in the 1,000 to 2,000km range. Additionally, the total fuel burn reduction remains in the 3.1% to 3.2% range for all flight distances tested, which indicates that the qualitatively identified complexity of adding shorter routes into formation flight considerations would likely be inadaquate to justify the added benefits. This result is significant in identifying the types of flights that should likely be considered for other air carriers as well.

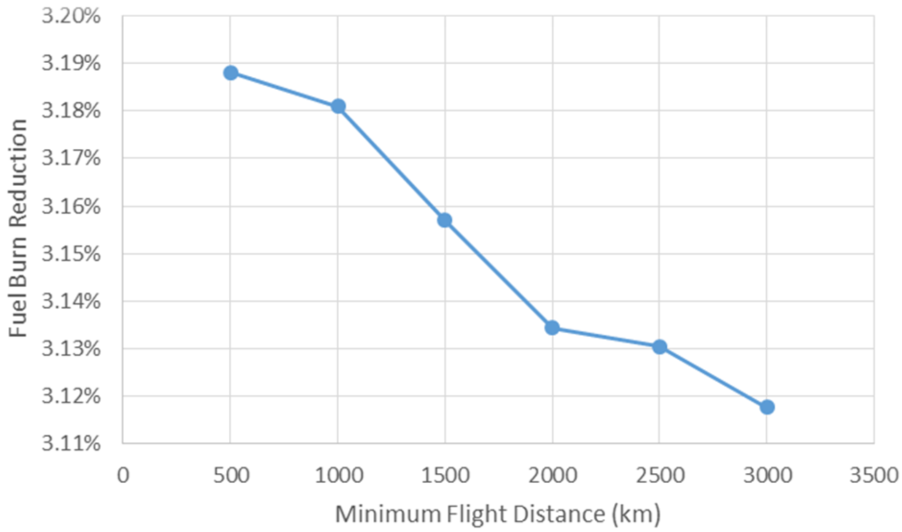

Figure 7: Lufthansa Formation Flight Fuel Burn Reduction based on Minimum Flight Distance

5 CONCLUSIONS

The analysis presented here extends the ability of researchers to study real world application of formation flight. This is enabled through the generation of fuel burn reduction response surface equations for general formation flight configurations based on easily measurable aircraft parameters, the formalization of a route pairing algorithm tailed to real air carrier operations, and most importantly the integration of these features into an established global air transportation cost-effectiveness model. As such, this work serves as not only a good first order approximation of the potential benefits of formation flight to real air carrier operations, but also as a platform for future studies of other air carriers throughout the world.

While it’s impossible to analytically consider the impacts of formation flight to air carrier scheduling using this analysis, it has been shown here that there are potential fuel burn benefits of formation flight in the 3-4% range, which is in line with previous research efforts. Further, these benefits do not increase significantly when shorter routes are included for formation flight considerations. Thus, one solution to prevent likely scheduling complications is to only consider formation flight for real air carriers on long haul routes. However, the frequency of formation flight inclusion in real air carrier operations is still highly uncertain, and warrants much more detailed analysis of airline specific scheduling constraints.

Finally, while it hasn’t been discussed here there are a number of other regulatory and safety concerns that will have to be addressed before this operational efficiency concept can be realized in commercial aviation. However, the fact that there are significant fuel burn reduction benefits realized even for a conservatively low use frequency and high minimum flight distance should serve as an important step in creating an impetus for the appropriate regulatory bodies to take up this issue.

REFERENCES

1. Thien, H., M. Moelyadi, and H. Muhammad, Effects of leaders position and shape on aerodynamic performances of V flight formation. arXiv preprint arXiv:0804.3879, 2008.
2. Brenci, T., Feasibility Study of the Optimization of Formation Flight Routes on Cargo Airlines. 2014, Aerospace Systems Design Laboratory: Atlanta, GA.
3. Antunes, N., A Methodology for Assessing the Cost Effectiveness of Formation Flight in Freighter Operations. 2014, Aerospace Systems Design Laboratory: Atlanta, GA.
4. Blauvac, J., Formation Flight for Cargo Air Carrier Service – Trajectory Optimization. 2013, Aerospace Systems Design Laboratory: Atlanta, GA.
5. Bancel, N., Formation Flight Cargo Air Carrier Service – Feasibility Assessment and Schedule Optimization. 2013, Aerospace Systems Design Laboratory: Atlanta, GA.
6. Humbert, M., A Methodology for Assessing the Cost and Performance Effectiveness of Formation Flight. 2013, Aerospace Systems Design Laboratory: Atlanta, GA.
7. Hummel, D., Aerodynamic aspects of formation flight in birds, Journal of Theoretical Biology, Vol. 104, No. 3, 1983, pp. 321–347.
8. Iglesias, S. and Mason, W. H., Optimum spanloads in formation flight, AIAA-2002-0258, 40th AIAA Aerospace Sciences Meeting & Exhibit, 2002.
9. Ning, A., Flanzer, T. C., and Kroo, I. M., Aerodynamic Performance of Extended Formation Flight, Journal of Aircraft, Vol. 48, No. 3, 2011, pp. 855–865.
10. Liu, Y., Risse, K., Franz, K., and Stumpf, E., Assessment of Potential Benefit of Formation Flight at Preliminary Aircraft Design Level, AIAA-2015-1907, 53rd AIAA Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, Jan. 2015.
11. Gerz, T., Holzäpfel, F., and Darracq, D., Commercial aircraft wake vortices, Progress in Aerospace Sciences, Vol. 38, 2002, pp. 181—208.
12. Risse, K., Lammering, T., Anton, E., Franz, K., and Hoernschemeyer, R., An Integrated Environment for Preliminary Aircraft Design and Optimization, AIAA-2012-1675, 8th AIAA Multidisciplinary Design Optimization Specialist Conference, April 2012.
13. Lewis, R.M. and V. Torczon, Pattern search algorithms for bound constrained minimization. SIAM Journal on Optimization, 1999. 9(4): p. 1082-1099.
14. CAEP, FESG CAEP/8 Traffic and Fleet Forecasts, in CAEP/8-SG/20082-IP/02. 2008, Committee on Aviation Environmental Protection: Seattle, Washington.