GENERAL AVIATION DEMAND FORECASTING MODELS AND A MICROSCOPIC NORTH ATLANTIC AIR TRAFFIC SIMULATION MODEL

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ABSTRACT

This thesis is focused on two topics. The first topic is the General Aviation (GA) demand forecasting models. The contributions to this topic are three fold: 1) we calibrated an econometric model to investigate the impact of fuel price on the utilization rate of GA piston engine aircraft, 2) we adopted a logistic model to identify the relationship between fuel price and an aircraft's probability of staying active, and 3) we developed an econometric model to forecast the airport-level itinerant and local GA operations. Our calibration results are compared with those reported in literature. Demand forecasts are made with these models and compared with those prepared by the Federal Aviation Administration. The second topic is to model the air traffic in the Organized Track System (OTS) over the North Atlantic. We developed a discrete-time event model to simulate the air traffic that uses the OTS. We proposed four new operational procedures to improve the flight operations for the OTS. Two procedures aim to improve the OTS assignments in the OTS entry area, and the other two aim to benefit flights once they are inside the OTS. The four procedures are implemented with the simulation model and their benefits are analyzed. Several implementation issues are discussed and recommendations are given.

Dedication

I would like to dedicate this work to my family. Their constant support and love has greatly strengthened me in the pursuit of my goals. I am grateful to them for their sacrifices that they have made that allowed me to pursue my ambitions. I would also like to thank all those that have taken their time to teach and encourage me as I have matured into the person I am today. I would like to especially thank my advisor, Dr. Trani, for his wise direction and mentoring that has greatly aided me in the fulfillment of this work and has greatly prepared me for the future I have before me.

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CHAPTER 1 INTRODUCTION

Section 1.1 Objective of the Thesis

The importance of demand forecasting models and simulation models has been well recognized by the air transportation community such as airliners, airport planners, and policy makers. This thesis is intended as a contribution to these two topics.

Section 1.2 Thesis Contributions

Subsection 1.2.1 Demand forecasting models for the General Aviation

General Aviation (GA) is the operation of civilian aircraft for purposes other than commercial passenger or cargo transport. More than 80% of the airports in the National Plan of Integrated Airport Systems primarily serve GA operations. According to the Terminal Area Forecast[1] prepared by the Federal Aviation Administration (FAA), the number of GA operations is almost three times as many as that of commercial aviation operations.

GA demand forecast plays an important role in aviation management, planning and policy making. For example, the forecast of GA activities is one factor used by the FAA to conduct benefit-cost analyses associated with airport development (GRA 2011) and to decide the allocation of construction/improvement grants among airports (Ghobrial 1997), the size of air traffic controller workforce, and the provision of navigation and communication services. GA demand forecast serves as a fundamental component in evaluating the new concepts and technologies suggested to the National Aeronautics and Space Administration to meet the national requirement for an improved air traffic management system (Wingrove, Jing et al. 2002). Forecasts of GA demand are also utilized by many local governments and airport planners to support operational planning and personnel requirements, make

[1] Statistics is obtained from TAF 2010. Operations reported as air carrier and air taxi/commuter is counted as commercial air services. Operations reported as itinerant and local GA is counted as GA

investment decisions related to the development of an airport and the community around it, and evaluate the need for additional aviation facilities.

For this topic, this thesis has three contributions.

1. We calibrated an econometric model to study the impact of fuel price on the utilization rate of GA piston engine aircraft.
2. We adopted a logistic model to identify the relationship between fuel price and an aircraft's probability of staying active.
3. We developed an econometric model to forecast the airport-level itinerant and local GA operations.

The model calibration results are compared with those reported in literature. Moreover, using these models, we made GA demand forecasts in three different future scenarios, and we compared our demand forecasts with those prepared by the FAA. We found that our "business-as-usual" demand forecasts generally are consistent with those provided by the FAA.

Subsection 1.2.2 Modeling the air traffic that use the Organized Track System over the North Atlantic

The air traffic between Europe and North America forms two major relatively concentrated unidirectional flows over the North Atlantic (NAT). To better serve this traffic, two Organized Track Systems (OTS) are created daily to increase the directional capacity. However, due to lack of surveillance and poor communication quality, the airspace over the NAT is usually congested at peak hours.

In recent years, more aircraft are equipped with advanced avionics. Those avionics have significantly enhanced the surveillance capability and communication quality over the ocean. As a result, it is possible to apply new procedures to improve the flight operations and adopt reduced separation minima in the OTS to further increase its capacity. The proposed new procedures and separation minima usually need to undergo some initial feasibility assessment to determine whether they could be practically and safely achieved. For such an assessment, simulation models usually considered a promising choice because they offer quick, inexpensive, and relatively realistic evaluations.

The second focus of this thesis is to model the air traffic that uses the OTS. We developed a discrete-time event simulation model, which simulates a transatlantic flight that uses the OTS from its origin airport to its destination airport. The model consists of three major components: a pilot routine, an Air Traffic Controller (ATC) routine, and a system update routine. The pilot routine controls each individual aircraft by simulating the behaviors of pilots. The ATC routine controls all the aircraft within an area by simulating the behaviors of ground controllers. The system update routine updates the status of all the units in the simulation (e.g., the status of each aircraft and the decisions of the ATC routine) as well as provides estimates for the pilot routine and ATC routine in their decision-making processes. The simulation model is applied to simulate the current flight operations in the OTS, and the simulation results are analyzed. In addition, we proposed four new operational procedures to improve the flight operations in the OTS. Two procedures are designed to improve the OTS assignments in the OTS entry area, and the other two are proposed to benefit flights once they are inside the OTS. The four procedures are implemented with the simulation model and their benefits are analyzed in terms of fuel savings. Several implementation issues are also discussed and recommendations are given.

Section 1.3 Thesis Organization

The thesis is organized as follows: in chapter 1, we introduce the objectives and contributions of this thesis. In chapter 2, we present two demand forecasting models for piston aircraft. In chapter 3, we present the airport-level demand forecasting models for itinerant and local GA operations. In chapter 4, we present the simulation model and four new operational procedures. In chapter 5, we summarize the findings of this thesis.

CHAPTER 2 THE IMPACT OF FUEL PRICE ON THE UTILIZATION OF PISTON ENGINE AIRCRAFT AND FUTURE PROJECTIONS[2]

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Section 2.1 Introduction

General Aviation (GA) is the operation of civilian aircraft for purposes other than commercial passenger or cargo transport. In the United States (US), piston engine aircraft account for 70%[3] of the total aircraft population. They play an important role in providing services to General Aviation (GA) users. For example, according to the 2010 General Aviation and Part 135 Activity Surveys (GA survey), about 77% of the hours flown for personal and business purposes are performed by piston engine aircraft. Besides their use as a mode of transportation, piston engine aircraft have an important role in serving many other purposes such as instructional, aerial observations, and agriculture spays. However, the piston fleet in the US has been declining during the past decade. According to the GA survey, from 2000 to 2010, the number of active piston engine aircraft dropped by about 8.9%. Meanwhile, the average utilization rate (i.e., average hours flown per aircraft) dropped by about 31%. Fewer piston engine aircraft flying in the National Airspace System (NAS) could have direct impacts in Aviation Trust Funds, ATC controller workforce and in the provision of navigation and communication services in the NAS.

The FAA believes that the current decline in the utilization of piston engine aircraft is partially due to the increasing fuel price (FAA 2010). The historical trend of GA fuel prices does support this hypothesis. Compared with that in 2000, the price of GA Avgas in 2010 increased by about 64% (price is adjusted for inflation). In 2000, the cost of purchasing 1000 gallons of GA Avgas accounted for about 10% of the

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[2] The content of this chapter is from the paper: Tao, L. and A. A. Trani (2013). Modeling the impact of fuel price on the utilization of piston engine aircraft. Integrated Communications, Navigation and Surveillance Conference (ICNS), 2013. DOI: 10.1109/ICNSurv.2013.6548555. Copyright © 2013 IEEE. Tao is one of the major contributors of the paper, and the research is done during his enrollment in Virginia Tech. The paper has been presented at the 4th Integrated Communications Navigation and Surveillance Conference and has been published as a conference proceeding. The paper received an honorable mention in the best student conference paper competition.

[3] Statistics is obtained from 2010 General Aviation and Part 135 Activity Surveys. The survey is conducted every year. It enables the FAA to monitor the GA fleet so that the demand for aviation infrastructures can be anticipated and met. The latest one available to the general public is the survey conducted in 2010.

disposable personal income per capita, however, this number increased to about 15% in 2010. The forecast from the Energy Information Administration (EIA) shows that fuel price could increase by 100% from 2010 to 2016 (EIA 2012). A possible ban on the low lead Avgas by the Environmental Protection Agency could further escalate the fuel price for piston engine aircraft. With an expectation of higher fuel prices in the future, aircraft owners, aircraft manufacturers, government agencies (e.g., FAA and DOT) and airport planners have raised concerns about the future of piston engine aircraft. A key step to address these concerns is to identify the impact of fuel price on the utilization of piston engine aircraft. An aircraft's operating cost usually includes fuel and oil cost, airframe, avionics, engine overhaul, maintenance cost and etc. Compared with the other costs, fuel cost is correlated with aircraft utilization. Moreover, fuel price is highly volatile and difficult to predict even in the short-term basis. From this point of view, identifying the impact of fuel prices on the utilization of piston engine aircraft is important to understand the future of such mode of transportation.

The objective of this chapter is to model the impact of fuel price on the utilization of GA piston engine aircraft. The contribution of this chapter is twofold: 1) it evaluates the impact of fuel price on the utilization rate (UR) of piston engine aircraft; 2) it identifies the relationship between fuel price and the probability for piston engine aircraft to stay active in the fleet (PSA) (i.e., in use). To provide more insight, model calibrations and analysis are done for single-engine piston (SEP) aircraft, multi-engine piston (MEP) aircraft and the combination of the two, respectively. Our study mainly focuses on the fixed-wing piston engine aircraft. They account for at least 75% of the total piston engine aircraft fleet in 2010 GA survey. Therefore, we believe that our study is representative of a large portion of the GA piston fleet.

Section 2.2 Literature Review

For the commercial aviation, historical data is relatively well documented. A significant body of research has been done on demand modeling. Considering the model outputs, demand models can be classified into two major categories: 1) demand models generate travel demand based on statistical techniques and gravity-based model formulations, see, for example, (Abed, Ba-Fail et al. 2001, Hsu and Wen 2003, Wei and Hansen 2003, Shen 2004, Wei and Hansen 2005, Wei and Hansen 2006, Grosche, Rothlauf et al. 2007, Marazzo, Scherre et al. 2010, Pitfield, Caves et al. 2010, Ryerson and Hansen 2010, Ryerson and Hansen 2011, Kopsch 2012), and 2) models to estimate the distribution (i.e., market share) of travel demand using discrete choice models, see, for example, (Proussaloglou and Koppelman 1995, Yoo and Ashford 1996, Proussaloglou and Koppelman 1999, Coldren, Koppelman et al. 2003, Coldren and Koppelman 2005, Georg, Thomas et al. 2006, Warburg, Bhat et al. 2006, Hess, Adler et al. 2007, Teichert, Shehu et al. 2008, Wen and Lai 2010).

For GA, historical data on GA activities is relatively limited. Demand modeling in GA is subject to data availability, and therefore relatively less research has been done. For the national level GA demand modeling, (Ratchford 1974) developed a theoretical model for measuring the quantity and price of the service flow obtained from a durable good. The model can be applied in cases where aircraft utilization rate varies over time, and operating costs are independent of the purchasing price. Further, using linear and translog models, (Ratchford 1974) studied the impact of disposable income and GA price (which is determined by operating cost and fixed cost) on the GA service quantity (which is a function of aircraft stock and utilization rate). It is concluded that the GA service quantity is sensitive to income and GA price changes. (Vahovich 1978) adopted semi-translog and double translog functions to study the impact of income and aircraft operating cost on the number of hours flown by individual owners (vs. companies). Some of the conclusions are: 1) for itinerant demand (hours flown), its elasticity with respect (w.r.t.) to income is less than one (about 0.1), which indicates that the demand is a necessity. 2) Variable cost is a significant determinant of hours flown. For local demand (hours flown), the elasticity w.r.t. variable cost is about -0.4. For itinerant demand, there exists a critical cost, beyond which the demand begins to decrease as cost increases. (Archibald and Reece 1977) used a hedonic price equation (i.e., a semi-logarithmic function) to describe the relationship between aircraft characteristics and price index. Their results support the hypothesis that the demand for fuel efficiency increases if there is an energy crisis (e.g., oil embargo).

Section 2.3 Data Sets

The General Aviation and Part 135 Activity Survey

This survey provides the FAA with a yearly snapshot of information on general aviation and on-demand part 135 aircraft activity. The latest survey (conducted in 2010) contains 15 aircraft types and collects information on aircraft characteristics, hours flown by aircraft type, etc. In the survey data currently available to the general public, hours flown are aggregated by several ways. We used two of them in this section: 1) hours flown aggregated by aircraft engine type, and 2) hours flown aggregated by flight purpose.

Aviation Research Group/US (ARG/US) Fuel Price Survey

This survey is conducted by the Aviation Research Group/US. It collects fuel prices from the fixed-based operators nationwide. The prices reported are full retail and include all taxes and fees. We investigated two types of GA fuel: Avgas and Jet-A. Avgas is mainly used by piston engine aircraft, and Jet-A fuel is mainly used by Jet engine aircraft. We found that their historical prices are highly correlated (the correlation coefficient is about 0.98). To avoid multicolinearity, we only considered the price of Jet-A throughout the thesis. It is the baseline fuel specification for commercial jet aircraft (Maurice, Lander, Edwards, & Harrison Iii, 2001).

Section 2.4 Models

In this section, we present two models describing the utilization of piston engine aircraft. The first model describes the impact of fuel price on the UR of piston engine aircraft. The second model, describes the relationship between the fuel price and the PSA. Before presenting them, we introduce how we select the explanatory variables for the models.

Subsection 2.4.1 Selection of explanatory variables

Table 2-1: Summary of Factors Investigated

	Variable	Data Source		Abbreviation	Reason for not being included in the model
		Historical	Forecast		
Cost Indicators	Fuel price (GA Avgas)	Fuel price survey conducted by Aviation Research Group/US	Estimated based on the fuel price projections from the EIA		Multi-colinearity (with F2I ratio)
	Ratio of the cost of purchasing 1000 gallons of fuel to disposable personal income per capita	Calculated by using the Fuel price and personal income	Calculated by using the Fuel price and personal income	F2I	-
	Service price index 2005 = 100	Bureau of Economic Analysis	EIA		Multi-colinearity
Economic, and personal income indicators	Disposable personal income per capita	Bureau of Economic Analysis	EIA		Estimated result is counterintuitive
	Gross Domestic Product	Bureau of Economic Analysis	EIA	GDP	Multi-colinearity
	GDP growth rate	Bureau of Economic Analysis	EIA	GDPGR	-
Demographic indicator	Number of student pilot	FAA Aerospace Forecasting	FAA Aerospace Forecasting	NSP	-
Dependent variable	Utilization rate	GA survey	UR model	UR	-
	Possibility of staying active	GA survey	PSA model	PSA	-

In addition to fuel price, we investigated several other factors that could have an impact on the utilization of piston engine aircraft. A summary of these factors and their data sources are presented in Table 2-1. The factors presented in the table can be classified into three categories: cost indicator (e.g., fuel price), economic and personal income indicator (e.g., personal income), and demographic indicator (e.g., number of student pilot). Those factors are chosen primarily based on the major usages of piston engine aircraft. Based on the GA survey 2010, about 93.4% of piston engine aircraft are used for three purposes: personal (73.4%), business and commercial (12.1%), and instructional (8%). Factors in the first two categories could have significant impacts on personal, business and commercial use. Factors in the third category could have significant impact on instructional use. Static models assume that GA makes immediate and complete adjustment to changes in factors such as fuel prices and income. However, this assumption is not always valid. In other words, there might be a lag effect in GA's reaction. Previous studies (see, for example, (Romero-Jordán, del Río et al. 2010, Li and Trani 2013)) introduced a lag term to capture this effect. To capture the possible lag in GA's reaction to changes in those factors, we investigated all the factors up to three-year lag. To select the explanatory variables for the models, we used the following rules:

1. **Principle of parsimony:** the model can explain the data with the least explanatory variables is preferred. This principle is especially important in GA studies as historical data is very limited for model calibration. In addition, models built with this principle are easy to use since they require less input data.
2. **Independence with other factors:** the explanatory variables included in the model should not be highly correlated with each other. A high correlation between explanatory variables (i.e., multi-colinearity) may result in inaccurate coefficient estimations. For example, we found that economic indicators such as GDP and durable goods price index are highly correlated. As a result, at most one of them is considered to be included in the final model.
3. **R-square and adjusted R-square**: R-square and adjusted R-square are introduced to measure how good the model fit the historical data. Explanatory variables that could significantly increase the value of R-Square and adjusted R-Square are preferred to those that could not. For example, we found that considering Fuel to Income Ratio (F2I) and GDPGR (one-year lag) could significantly increase the R-Square and adjusted R-Square, and therefore they are included in the final model.
4. **Statistical significance**: it is introduced to measure whether adding a variable could significantly increase the model's explanatory ability. In this study, we require that a variable included in the final model has to be statistically significant at 10% significance level.
5. **Consistency with common belief**: the estimated coefficient of explanatory variable should be consistent with common belief. For example, the coefficient of disposable personal income per capita is expected to be positive since it is believed that higher income will encourage GA aircraft

use. However, in our analysis, we found that the coefficient estimate for this factor is negative. In this case, this factor may not be considered to be included in the final model.

Subsection 2.4.2 Model to evaluate the impact of fuel price on the utilization rate of piston aircraft

To evaluate the impact of fuel price on the UR of piston engine aircraft, we adopted an econometric model similar to the one used in (Ghobrial 1997). This model can be considered as a simplified version of the models used in (Wei and Hansen 2003, Ryerson and Hansen 2011). The econometric model has the following form:

$$\mathrm{UR} = \left(\prod F_i^{\alpha_i}\right) \times e^{\beta_0 + \sum \beta_j E_j}$$

where F_i and E_j are explanatory variables, and α_i and β_j are model coefficients.

In economics, one important measurement of the quantitative responsiveness of a variable D (e.g., demand) to a change in another variable P (e.g., price) is the elasticity. More precisely, elasticity is defined as the percentage change in quantity of a variable D due to a percentage change in another variable P (the other variables are assumed to be constant). Elasticity is calculated by:

$$\text{elasticity} = \frac{\partial D}{D} \Big/ \frac{\partial P}{P} = \frac{P \partial D}{D \partial P}$$

The elasticity of GA operations with respect to (w.r.t.) the explanatory variable F_i is the variable's corresponding coefficient (i.e., α_i) in the model.

Applying the logarithmic function on both sides of the equation, we have

$$\ln(\mathrm{UR}) = \sum \alpha_i \ln(F_i) + \sum \beta_j E_j$$

Taking the derive with respect to F_i on both sides of the equation, we have,

$$\frac{1}{\mathrm{UR}}\frac{\partial \mathrm{UR}}{\partial F_i} = \alpha_i \frac{1}{F_i}$$

Rearranging the terms, we have,

$$\frac{F_i}{\mathrm{UR}}\frac{\partial \mathrm{UR}}{\partial F_i} = \alpha_i$$

The left hand side of the equation is elasticity of UR w.r.t. variable F_i, and is the coefficient of variable F_i in the econometric model (i.e., α_i).

Similarly, the elasticity of UR w.r.t. variable E_i is

$$\frac{E_i}{\mathrm{UR}}\frac{\partial \mathrm{UR}}{\partial E_i} = \beta_j E_j$$

The elasticity of UR w.r.t. variable E_j is not a constant. Instead, it is a function of variable E_j.

Subsection 2.4.3 Model to evaluate the impact of fuel price on an piston aircraft's probability of staying active

Let $\mathrm{P_a}$ be the probability of a piston engine aircraft staying active in the fleet. Then, the odds of a piston engine aircraft staying active is given by ${}^{\mathrm{P_a}}/_{1-\mathrm{P_a}}$. Odds can be considered as relative probabilities. We found that the coefficient of correlation between the log odds (i.e., $\ln({}^{\mathrm{P_a}}/_{1-\mathrm{P_a}})$) and the F2I ratio is about -0.65. In other words, a strong linear relationship exists between the two variables. Therefore, it is reasonable to assume the following relationship exists:

$$\ln({}^{\mathrm{P_a}}/_{1-\mathrm{P_a}}) = \sum \alpha_i \mathrm{F_i}$$

That is

$${}^{\mathrm{P_a}}/_{1-\mathrm{P_a}} = \exp(\sum \alpha_i \mathrm{F_i}) \qquad \textbf{(2.1)}$$

Further, from equation (2.1), we have

$$P_a = {}^{\exp(\sum \alpha_i \mathrm{F_i})}\Big/_{1+\exp(\sum \alpha_i \mathrm{F_i})}$$

This equation establishes a relationship between the probability of staying active and the explanatory variables (e.g., the F2I ratio). Based on equation (2.1), a ∇F_i change in variable $\mathrm{F_i}$ would change the odds of staying active by $\exp(\alpha_i \nabla F_i)$.

Subsection 2.4.4 Calibration results and analysis (utilization rate)

Table 2-2: Calibration Results for Utilization Rate

Utilization Rate							
Coefficient	Variables	Single-engine Piston		Mutli-engine Piston		Piston	
		Coefficient Estimation	P-value	Coefficient Estimation	P-value	Coefficient Estimation	P-value
β_0	Intercept	2.003	0.911	3.398	0.196	2.184	0.783
α_1	F2I Ratio	-0.665	0.000	-0.232	0.042	-0.603	0.000
β_1	GDP Growth Rate (one year lag)	1.898	0.063	4.027	0.001	2.307	0.019
α_2	Number of Student Pilot	0.264	0.093	0.215	0.118	0.260	0.068
	R-square/Adjusted R-Square	0.92/0.90		0.86/0.83		0.94/0.91	

The explanatory variables are carefully selected based on the rules described in Section 1.4. The final model for the UR has the following form:

$$\mathrm{UR} = \mathrm{F2I}^{\alpha_1} \times \mathrm{NSP}^{\alpha_2} \times \exp(\beta_0 + \beta_1 \times \mathrm{GDPGR(one\ year\ lag)})$$

In Table 2-1, we presented the reasons for the factors that are not included in the final model. The model is calibrated using the historical data collected from 2000 to 2010. The calibration results are presented in Table 2-2. It can be observed that the R-square and adjusted R-square are relatively high for all the three cases.

Based on its definition, the F2I ratio could be considered as the relative fuel price, that is, fuel price compared with personal income. We found that, in terms of R-square and adjusted R-square, the F2I ratio is a better factor to be included in the model than the fuel price alone.

For SEP aircraft, its elasticity w.r.t. the F2I ratio is about -0.665. This indicates that a 10% increase in the ratio would lead to a 6.7% drop in its UR. Its elasticity w.r.t. the NSP is estimated to be about 0.264. This suggests that a 10% increase in this variable could bring a 2.6% increase in its UR. However, the coefficient is only significant at the 10% significance level.

For MEP aircraft, its elasticity w.r.t. the F2I ratio is estimated to be about -0.232. It means that a 10% increase in the F2I ratio is expected to decrease its UR by 2.3%. Its elasticity w.r.t. the NSP is about 0.215. It indicates that a 10% increase in this factor could result in a 2.2% increase in its UR. However, the coefficient is not significant at the 10% significance level.

For piston engine aircraft as a whole, its elasticity w.r.t. the F2I ratio is about -0.603. It indicates that a 10% increase in this factor could decrease its UR by about 6.0%. Its elasticity w.r.t. the NSP is about 0.26. This suggests that a 10% increase in the variable could lead to a 2.6% increase in its UR. However, this factor is only significant at 10% significance level.

Our model suggests that the UR of SEP aircraft is more sensitive to the F2I ratio than that of MEP aircraft is. In other words, given income fixed, increase in the fuel price is expected to have more negative impact on the UR of SEP aircraft. One possible explanation for this is that many SEP aircrafts are used for personal purpose (i.e., purposes not related to business or commercial). According to the 2010 GA survey, the percentage of SEP aircraft used for personal purpose is about 76.1%; however, the corresponding number for MEP aircraft is only about 49.9%. Moreover, the UR of SEP aircraft is also more sensitive to the NSP than that of MEP aircraft is. We believe this can also be explained by comparing the number of aircraft used for instructional purpose between the two. According to the survey, about 8.3% of SEP aircraft is used for instructional purpose, and the corresponding number for MEP aircraft is about 5.6%. It is necessary to point that the percentage is relatively low for both aircraft types. This means that the usage for instructional purpose may have a relatively less impact on their overall UR. This could explain the relatively low statistical significance of the NSP's coefficient.

The elasticity of the UR w.r.t. previous year's GDPGR is not a constant in the econometric. However, a comparison is still possible to make. It can be observed that MEP aircraft is more sensitive to this factor. If there is an increase in the previous year's GDPGR, then the increase in its UR is about twice as much as that of SEP aircraft. Similarly, aircraft use could provide an explanation. Based on the survey, about 30% of MEP aircraft are used for business or commercial purpose, which is more sensitive to the economy conditions.

Subsection 2.4.5 Calibration Results and Analysis (probability of staying active)

Table 2-3: Calibration Results for PSA

Possibility of Staying Active							
Coefficient	Variables	Single-engine Piston		Mutli-engine Piston		Piston	
		Coefficient Estimation	P-value	Coefficient Estimation	P-value	Coefficient Estimation	P-value
α_0	Intercept	1.265	< 0.001	1.564	< 0.001	1.256	< 0.001
α_1	F2I Ratio	-1.925	< 0.001	-1.442	< 0.001	-1.800	< 0.001
α_2	GDP Growth Rate (one year lag)	1.794	< 0.001	5.202	< 0.001	2.194	< 0.001
α_3	Number of Student Pilot	0.002	< 0.001	-	-	0.002	< 0.001

Similarly, we select the explanatory variables using the rules presented in Section 1.4. In the final model, the PSA is calculated by the following function:

$$P_a = \frac{\exp(\alpha_0 + \alpha_1 \mathrm{F2I} + \alpha_2 \mathrm{GDPGR(one\ year\ lag)} + \ \alpha_3 \mathrm{NSP})}{1 + \exp(\alpha_0 + \alpha_1 \mathrm{F2I} + \alpha_2 \mathrm{GDPGR(one\ year\ lag)} + \ \alpha_3 \mathrm{NSP})}$$

To maintain consistency with the UR model, this model is also calibrated using the historical data collected between 2000 and 2010. The calibration results are presented in Table 2-3. We did not consider the Number of Student Pilots (NSP) in the model for MEP aircraft because its coefficient estimate is negative, which is counterintuitive.

In the following discussion, we investigate the change in the odds of stay active due to a change in the explanatory variables. If the F2I ratio increases by 0.01 (i.e., $\nabla \mathrm{F2I} = 0.01$), then the odds of staying active for SEP, MEP, and piston engine aircraft would drop by 1.91%, 1.43%, and 1.78%, respectively. This suggests that SEP aircraft is more sensitive to fuel price than MEP aircraft is. This result is consistent with the one observed in the previous section. In addition, if the previous year's GDPGR increases by 0.01 (i.e., $\nabla \mathrm{GDPGR} = 0.01$), then the odds of staying active for SEP, MEP, and piston engine aircraft is expected to increase by 1.81%, 5.34%, and 2.22%, respectively. This suggests that MEP aircraft are more sensitive to the economic conditions than SEP aircraft. This result is also consistent with the observation in previous section. Moreover, our model suggests that a unit increase (i.e., 1,000) in the NSP would increase the odds of staying active for SEP and piston engine aircraft by about 0.2%, respectively.

Section 2.5 Validation of the Two Models

As a model validation, we compared the total number of hours flown estimated by using our models with those reported in the GA survey. The comparison period is from 2000 to 2010. This comparison is meaningful since the statistics (i.e., total number of hours flown) are not used in the model calibrations. For a piston engine aircraft type, its total number of hours flown is estimated using the following equation:

$$\text{Total number of hours flown} = \text{total number of aicraft} \times \text{PSA} \times \text{UR} \tag{2.2}$$

where PSA and UR are estimated by using the PSA and UR model presented in Section 2.4, and the total number of aircraft for each piston engine aircraft type is obtained from the GA survey.

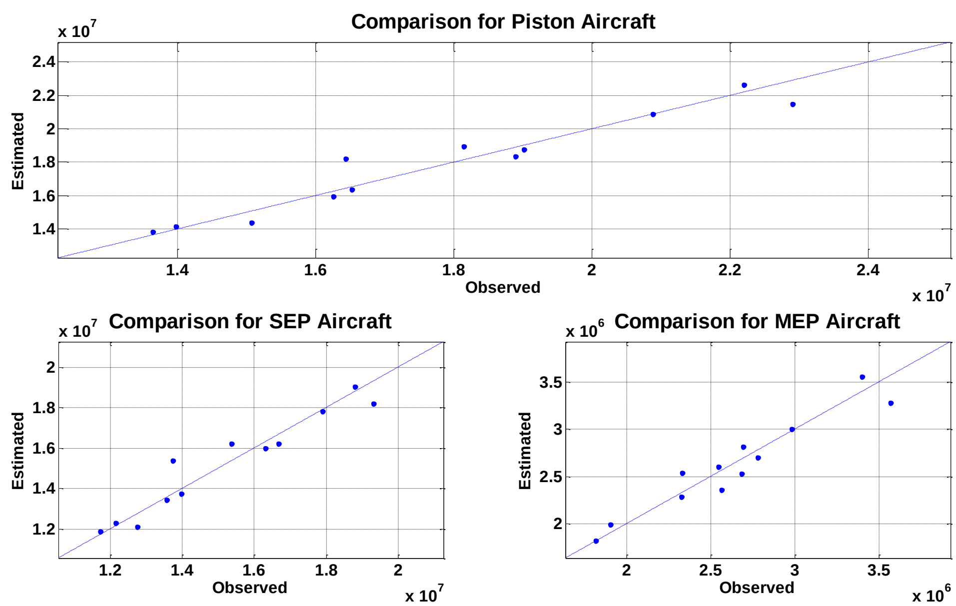

Figure 2-1: Comparison of estimated and observed (1999-2010) hours flown

The scatter plots in Figure 2-1 show the comparison between the estimated hours flown from our models and the observed ones from the GA survey. For each piston engine aircraft type, the scattered points lie close to the line $Y = X$, which indicates a good match between the two statistics. Further, the paired dependent t-test fails to detect any difference at the 5% significance level.

Section 2.6 Projections of the Acitivies of Piston Aircraft

In this section, we provide projections of PSA and UR of each piston engine aircraft type using our models. The projection period is from 2011[4] to 2032. As the first step, we present the projections of explanatory variables that are used as inputs to our models.

Subsection 2.6.1 Projection of explanatory variables

1. Projections of GA avgas price:

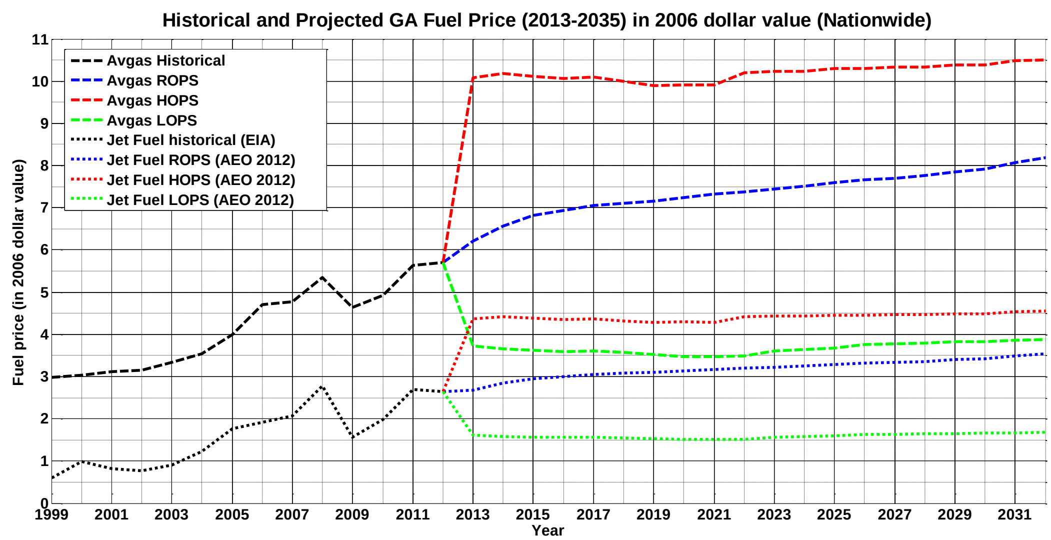

Figure 2-2: Projections of GA avgas price

Following (Macharis, Van Hoeck et al. 2010), we adopted the projections of fuel price given by the EIA in its Annual Energy Outlook (AEO) 2012. The projections are generated based on the results from the EIA's National Energy Modeling System. The projection period is from 2012 to 2032. To capture future uncertainties, the EIA gives multiple future scenarios. We adopted three of them: the high oil price

[4] 2011 GA survey has not been available to the general public as this chapter is finished. Statistics for this year is also estimated one in the FAA Aerospace Forecast FY 2012-2032.

scenario (HOPS), the low oil price scenario (LOPS), and the reference oil price scenario (ROPS). Each of the scenarios comes with a different expectation on oil supply and demand. The reference scenario is a "business-as-usual" trend estimate. The high oil price scenario can be considered as a pessimistic forecast. It assumes a higher demand and lower supply of oil in the future. On the contrary, the low oil price scenario can be considered as an optimistic forecast. It assumes a lower demand and higher supply of oil in the future.

However, the projections of fuel price from the EIA are for kerosene-type jet fuel[5]. To obtain the corresponding projections of GA Avgas fuel price, we assume the following relationship exists between the two prices:

$$\text{GA Avgas fuel price} = \alpha \times \text{Jet fuel price}$$

The coefficient α is estimated to be 2.31, and the R-square is about 0.9. The projections for the price of GA Avgas are presented in Figure 2-2. It can be observed the biggest uncertainty in price happens in 2013. In the HOPS for this year, the price is expected to be about 10 dollars per gallon (2006 dollar). In this year's low fuel price scenario, it is projected to be about 3.5 dollars per gallon. The fuel price in the high and low price scenarios stays relatively stable throughout the rest of projection period. The fuel price in the reference fuel price scenario, as consistent with the historical trend, is expected to increase steadily.

2. Projection of disposable income per capita and GDP growth rate:

[5] kerosene-type jet fuel is used for commercial and military turbojet and turboprop aircraft engines.

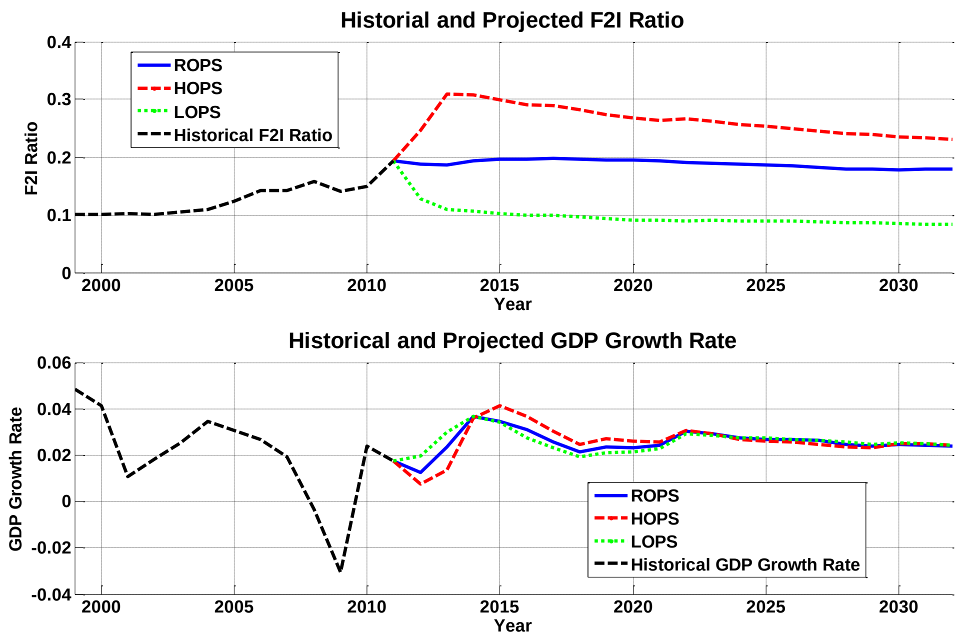

Figure 2-3: Historical and projected F2I ratio and GDP growth rate (1999-2032)

For each scenario, the EIA assumes a different disposable income per capita and GDP growth rate to capture the interactions between the economic conditions and fuel price. We also adopted those projections in this study to maintain consistency with the projections of fuel price. In Figure 2-3, we present the projected F2I ratio and GDPGR corresponding to the EIA's three-scenario projection. It can be observed that in all three scenarios the general trend of the projected F2I ratio is decreasing. In other words, the relative fuel price is expected to decrease in the long run. In addition, significant fluctuations in the GDPGR can be observed from 2013 to 2022.

3. **Projection of number of student pilots:**

Table 2-4: Long-term Economic and Fuel Cost Assumptions in AEO 2012 and FAA Aerospace Forecasting

	Long-term Annual Average GDP Growth rate			Long-term Annual Average Growth Rate of Fuel Cost (Crude Oil) (Dollars per Barrel)		
FAA Aerospace Forecasting	-			-		
	2.55%			2.97%		
EIA	Ref	High	Low	Ref	High	Low
	2.55%	2.59%	2.56%	2.72%	4.79%	-0.88%

EIA does not make projections of the NSP. Therefore, we adopted the one given in the FAA Aerospace Forecasting FY 2012-2032. Different from the EIA's multi-scenario projections, only one projected scenario is provided in the FAA Aerospace Forecasting. To make things clearer, we present a brief comparison of the long-term economic and fuel cost assumptions between the two forecasts[6] in Table 2-4. The forecast is made based on the discussions with industry experts conducted at industry meetings as well as suggestions from industry staff and aviation associations (FAA 2011). Therefore, we believe it represents the industry's prevailing expectation of a future GA scenario.

[6] The FAA uses world and individual country economic projections provided by IHS Global Insight, Inc.

Subsection 2.6.2 Projection of PSA

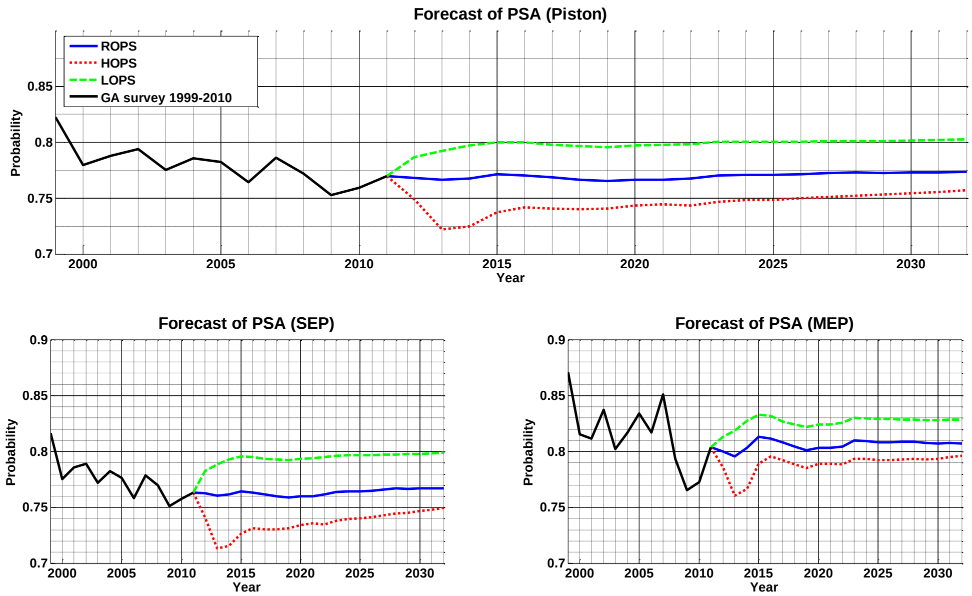

Figure 2-4: Historical and projected PSA (1999-2032)

Figure 2-4 shows the projections of the PSA by piston engine aircraft type. Three scenarios which correspond to the EIA's three-scenario fuel price projections are given. It can be observed that the projections of the PSA value for piston engine aircraft are similar to that of SEP in all the three scenarios. Therefore, for simplicity, we mainly focus our analysis on the projections of the PSA for SEP and MEP aircraft.

In the reference fuel price scenario, the average value of PSA for SEP aircraft from 2011 to 2032 is estimated to about 76.4%. During this period, its PSA is relatively stable, and a minor increasing trend can be observed after 2020. Its lowest PSA is expected to occur in 2019. It is mainly the result of a relatively high F2I ratio in that year and a relatively low GDPGR in the previous year. Compared with that of SEP aircraft, the PSA of MEP aircraft is expected to have more variations from 2012 to 2022. We believe this is mainly because of the variations in the GDPGR during this period. Its lowest PSA is expected to occur in 2013 because of the low GDPGR in 2012. Its highest PSA is projected to occur in

2015 due to the high value of GDPGR in 2014. Its average PSA from 2011 to 2032 is estimated to be about 80.6%.

In the high fuel price scenario, the value of the PSA for both SEP and MEP aircraft reach the lowest point in 2013 due to the high F2I ratio in this year and low GDPGR in 2012. A very mild recovery in their PSA can be observed from 2014 to 2016. This recovery is driven mainly by the high GDPGR in the forecast (from 2013 to 2015). Starting in the year 2018, the PSA of SEP aircraft is projected to have a long-term recovery until the end of forecast period. The recovery is driven mainly by the decreasing F2I ratio. During the same period, the PSA for MEP aircraft is expected to have several short-term declines and recoveries as the result of variations in GDPGR and decreasing F2I ratio. From 2011 to 2032, the average PSA for SEP and MEP is projected to be about 73.8% and 79%, respectively.

In the low fuel price scenario, the value of PSA for both SEP and MEP aircraft reaches a peak in 2015 due to the low F2I ratio in this year and high GDPGR in 2014. After this, both of them will experience a decline in the PSA caused by the slowdown in GDP growth. Starting in the year 2020, SEP aircraft will have a long-term recovery in its PSA driven by the decreasing F2I ratio. The PSA for MEP aircraft is also expected to recover between 2020 and 2024, and stay relatively stable for the remaining forecast period. Between 2011 and 2032, the average PSA for SEP and MEP aircraft is projected to be 79.3% and 82.6%, respectively.

Subsection 2.6.3 Projection of utilization rate

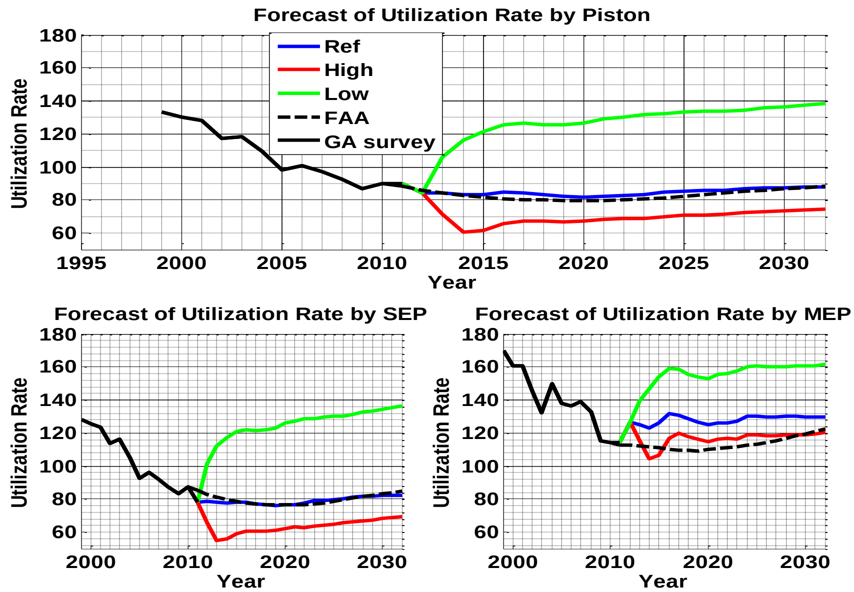

Figure 2-5: Historical and projected utilization rate by piston engine aircraft type

Figure 2-5 presents the projections of the UR by piston engine aircraft type from our UR model. Three future projections similar to those presented for PSA are given.

The FAA provides a forecast of total number of active aircraft and total number of hours flown in its FAA Aerospace Forecasting. We calculated the UR for each piston engine aircraft type using the two FAA forecasts. The forecast of UR by piston engine aircraft type from the FAA is also shown in Figure 2-5.

In our projections, it can be observed that the future trend of UR is similar to that of PSA. We believe this is reasonable because both models are driven by the same factors. Since a detailed analysis on the projections of PSA has been given in Section 2.6.2, in the following discussion we focus on comparisons between our projections with those performed by the FAA.

For SEP aircraft, it can be observed that the FAA's forecast is close to our projections under the reference fuel price scenario. From the perspective of the EIA's three scenarios, the FAA believes that the UR of SEP is going to be "business-as-usual" in the future. In the FAA's forecast, the average UR between

2011 and 2032 is about 80 hours per aircraft (in 2000 GA survey, the average UR in 2000 is about 126 hours per aircraft). This number is about 79 hours per aircraft from our projections in the reference fuel price scenario. Both the FAA and our model predict a long-term and very mild recovery in the UR of SEP aircraft beginning in 2020 until 2032.

For MEP aircraft, the FAA forecast is close to our projections under the high fuel price scenario. This indicates that the FAA is pessimistic about the UR of MEP in the future. The average UR between 2011 and 2032 in FAA's forecast is about 113 hours per aircraft (in 2000 GA survey, the average UR is about 161 hours per aircraft). The prediction from our UR model is about 117 hours per aircraft in the high fuel price scenario. FAA believes that a mild long-term recovery in the UR will start in 2020 until 2032. However, in our projections under the high fuel price scenario, the UR will experience several short-term declines and mild recoveries between 2011 and 2024, and then stay relatively stable at the end of the forecast period.

For piston engine aircraft, the FAA forecast is close to our projections under the reference fuel price scenario. Between 2011 and 2032, the average UR from our projections is about 85 hours per aircraft (in 2000 GA survey, the average UR in 2000 is about 130 hours per aircraft). The forecast from the FAA is about 83 hours per aircraft. Both our model and the FAA predict a very mild long-term recovery in the UR of piston engine aircraft beginning in 2020 until 2032.

Section 2.7 Conclusion

We have presented two models to evaluate the impact of fuel price on the utilization of piston engine aircraft. We found that fuel price does have a significant impact on their utilization. As the fuel price takes a larger portion of personal disposable income, both the utilization rate and PSA of piston engine aircraft will decrease. Our models suggest that SEP aircraft is more sensitive to fuel price than MEP aircraft. We also found that the growth of economy is another important factor that is positively correlated with the utilization of piston engine aircraft. In our models, this factor has more impact on MEP aircraft.

Using the two models, we estimated the utilization of piston engine aircraft under the EIA's three future fuel price scenarios. We compared our projections with those from the FAA. The comparison shows that the FAA forecast for SEP aircraft and piston engine aircraft is close to our projections under reference fuel price scenario, and the FAA forecast for MEP aircraft is close to our projections under high fuel price scenario.

Acknowledgement

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Disclaimer

The views and models presented in this chapter are the sole responsibility of the authors. This chapter does not reflect the views of the FAA or any other government office.

CHAPTER 3 A MODEL TO FORECAST AIRPORT-LEVEL GENERAL AVIATION DEMAND[7]

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Section 3.1 Introduction

General Aviation (GA) is the operation of civilian aircraft for purposes other than commercial passenger or cargo transport. In the literature, a significant amount of effort has been devoted to forecasting GA demand. This paper is intended as a contribution to this topic. GA demand forecast plays an important role in aviation management, planning and policy making. For example, the forecast of GA activities is one factor used by the Federal Aviation Administration (FAA) to conduct benefit-cost analyses associated with airport development (GRA 2011), and decide the allocation of construction/improvement grants among airports (Ghobrial 1997), the size of air traffic controller workforce, and the provision of navigation and communication services. GA demand forecast serves as a fundamental component in evaluating the new concepts and technologies suggested to the National Aeronautics and Space Administration (NASA) to meet the national requirement for an improved air traffic management system (Wingrove, Jing et al. 2002). Forecasts of GA demand are also utilized by many local governments and airport planners to support operational planning and personnel requirements, make investment decisions related to the development of an airport and the community around it, and evaluate the need for additional aviation facilities.

Subsection 3.1.1 Objective of this chapter

The objective of this paper is to develop an airport-level GA demand forecast model. In this study, airport-level GA demand refers to the number of GA operations (including both takeoffs and landings) at an airport. GA operations are classified into two types: local operations and itinerant operations. Local

[7] The content of this chapter is from the paper Li, Tao, and Antonio A. Trani: 'A model to forecast airport-level General Aviation demand', Journal of Air Transport Management, 2014, 40, (0), pp. 192-206. DOI: 10.1016/j.jairtraman.2014.07.003. Copyright © 2014 Elsevier Ltd. Tao is one of the major contributors of the paper, and the research is done during his enrollment in Virginia Tech.

operations refer to aircraft operating in the traffic pattern or within sight of the tower, or aircraft known to be departing or arriving from flight in local practice areas, or aircraft executing practice instrument approaches at the airport. Itinerant operations refer to operations of aircraft going from one airport to another. The FAA reports all aircraft operations other than local operations as itinerant.

Subsection 3.1.2 Literature review on GA demand models

GA demand models can be classified into two categories. Models in the first category focus on studying the macro-level relationship between GA demand and demand determinants (e.g., social-economic factors). (Ratchford 1974) developed a theoretical model for measuring the quantity and price of the service flow obtained from a durable good. It is concluded that the GA service quantity is sensitive to income and GA price changes. (Vahovich 1978) also found that income and aircraft operating cost have a significant impact on the number of hours flown by individual owners (vs. companies). (Archibald and Reece 1977) used a hedonic price equation (i.e., a semi-logarithmic function) to model the relationship between aircraft characteristics and price index. Their results support the hypothesis that the demand for fuel efficiency increases if there is an energy crisis (e.g., oil embargo). (Li and Trani 2013) showed that the relative fuel price - fuel price compared with disposable income per capita –is a significant determinant of the utilization of piston engine aircraft. In addition, their results suggest that the elasticity of the utilization rate with respect to the relative fuel price is about -0.6.

To effectively allocate limited resources among the diverse network of airports in the U.S. requires GA demand forecasts at county or airport level. However, models in the first category usually lack the capability to provide county or airport-level demand forecasts. From this point of view, models in the second category are more important because they are developed to model the microscopic relationship between county or airport-level GA demand and local demand determinants. (Baxter and Philip Howrey 1968) investigated the determinants of county-level GA operations. Their study shows that population, personal income, agriculture employment, number of airports and airport quality (e.g., the fraction of airports with runway lights and paved runway) could be significant determinants. (Wingrove, Jing et al. 2002) developed a top-down approach to forecast GA fleet and itinerant GA operations at an airport. The significant demand determinants they identified are similar to those reported by (Baxter and Philip Howrey 1968). (Ghobrial and Ramdass 1993, Wingrove, Jing et al. 2002) developed an econometric model to forecast demand at GA airports. (Ghobrial 1997) further extended the model by enhancing the model's structure and using a larger sample of GA airports for model calibration. In particular, their results show that supply factors (e.g., control tower and runway) are significant determinants of flight operations. (Hoekstra 2000) used a linear model to forecast the GA operation at small towered and non-towered airports. He found that the number of based aircraft at an airport, income per capita, and whether the airport is certificated for commercial services are among the important demand determinants. (GRA 2001) refined Hoekstra's model by considering more local variables (e.g. presence of a flight school at the airport) and more data in model calibration. (Dou, David et al. 2001) also developed a linear model to forecast GA demand by using local social-economic and demographic factors. However, their model has a low goodness of fit (i.e., low R-square). (Dou, David et al. 2001, Baik, Ashiabor et al. 2006) utilized gravity models to study the distribution of GA demand among airports. Both of their models show that the distance between airports is a particularly important factor for the distribution of GA demand.

The model presented in this paper can be considered an extension of the econometric model developed by (Ghobrial 1997). Our study departs from the previous one in the following three aspects:

1) The focus of the study in (Ghobrial 1997) is the aviation demand (i.e., the combination of commercial aviation and GA demand) at GA airports, while the focus of our study is the GA demand at any airport. In (Ghobrial 1997), itinerant operations and local operations are combined and modeled together (i.e., by one model).In our study, itinerant GA operations and local GA operations are modeled separately (by two different models). This means our study provides a more detailed GA demand forecast.

2) The impact of fuel price is considered in the modelling. It is well known that the GA demand in the U.S. has been declining over the past decade. This decline in GA activities cannot be completely explained by the country's economic conditions. The FAA believes that the decline is partially due to the high fuel price (FAA 2010). The historical trend of GA fuel prices supports FAA's belief. From 2000 to 2011, the price[8] of Jet-A fuel increased by about 120%. In 2000, the cost of purchasing 1000 gallons of Jet-A fuel accounted for about 8.5% of the personal income per capita; however, this number increased to about 13.7% in 2011. The survey conducted by (Kamala and R. John 2012) also supports this belief. In the survey, more than half of the responses indicated that costs were a significant reason for why they did not fly. However, to the authors' best knowledge, the effect of fuel price is not considered in the existing airport-level demand forecasting models. From this point of view, it is questionable that those models could adequately capture the impact of fuel price in their forecasts.

In commercial aviation and many other modes of transportation, fuel price has been studied as an independent factor, and its impact on travel demand and travel cost has been proved to be significant. For example, in the area of mass transit/transportation, the study in (Maghelal 2011) shows that fuel prices could significantly impact the U.S. transit ridership. The statistical model suggests that an additional one dollar increase to the average fuel cost could result in an increase in transit trips by 484%. (Macharis, Van Hoeck et al. 2010) used a GIS-based model to investigate the impact of fuel price on the competition between intermodal transport (e.g., rail and barge) and unimodal transport (e.g., road). They found that demand shifts to intermodal transport if the fuel price increases. In the area of personal vehicles, (Gallo 2011) found that a 22% increase in fuel price corresponds to a 2.56% decrease in demand for car use in Italy. Using data collected from 18 countries, (Clerides and Zachariadis 2008) found that the short-term elasticity of new car fuel consumption ranges from -0.08 to -0.21, and the long-term elasticity ranges from

[8]Statistics is obtained from Aviation Research Group/US (ARG/US) Fuel Price Survey.

-0.14 to -0.63. In the area of commercial air transportation, (Wei and Hansen 2003) used a translog model to study the operating cost of large commercial passenger jets. They showed that fuel cost is a significant part of operating cost. Their preferred model suggests that at the sample mean a 10% increase in the fuel cost could lead to a 2.4% increase in the operating cost. Further, (Ryerson and Hansen 2011) used a more advanced translog model to study the impact of fuel cost on the operating cost of commercial aircraft. They concluded that at the sample mean a 10% increase in the fuel cost would increase the operating cost by about 4%. (Ryerson and Hansen 2010) adopted the Leontief technology model to investigate the potential of turboprop aircraft in reducing the fuel consumption. Their model suggests that as fuel prices increase the turboprop offers a lower operating cost per seat over a wider range of distances than the jet aircraft does.

3) In addition, more statistical criteria are considered in the selection of the explanatory variables. The models are calibrated with more comprehensive data sets. This makes our results more representative. Furthermore, we compared our model projections with those provided in the Terminal Area Forecast (TAF). The comparison shows that, under the "business-as-usual" fuel price scenario, our projections of the total demand at the towered airports are within the acceptable error range (i.e., 10%) specified by the FAA.

The rest of the paper is organized as follows: in Section 2, we introduced the TAF. In Section 3, we presented our model and the potential determinants of airport-level GA demand. In Section 4, we presented the calibration results, and result analysis and comparison. In Section 5, we made projections of GA demand for the TAF airports using three fuel price scenarios prepared by the Energy Information Administration (EIA). We compared our model projections with those from the TAF. In Section 6, we summarized our study. In Appendix A, the data sets that are used in this paper are introduced. In Appendix

B, the table of correlation coefficients between the explanatory variables in our models is given. In Appendix C, the table of the abbreviations used in this paper is presented.

Section 3.2 Terminal Area Forecast (TAF)

The TAF is prepared to assist the FAA in meeting its planning, budgeting and staffing requirements. It contains historical and forecast information for enplanements, airport operations, tracon operations, and based aircraft. The data covers the 264 FAA towered airports, 248 federal contract tower airports, 31 terminal radar approach control facilities, and 2824 non-FAA airports. In the TAF, historical operation data of the towered airports are collected by the air traffic controllers; data at the non-towered airports represents their "best estimates." In the latest TAF (published in Mar 2013), historical data is available until 2011. There are eight operation categories in the TAF. We used two of them in this study: itinerant and local GA operations. They represent all the operations of all the civil aircrafts not classified as commercial. Based aircraft reported in the TAF are aircraft (mostly GA aircraft) that are permanently based at an airport. They are collected by the FAA inspectors, airport managers, and state aviation officials. There are five aircraft categories in the TAF: single engine, multiple engine, jet engine, helicopters and others.

Aviation activities forecasts in the TAF for towered airports usually undergo a systemic process by considering historical trends, and local and national factors that influence aviation activities (FAA 2010). Each estimate is examined for its reasonableness and consistency. Sometimes, other methods (e.g., regression and trend analysis) and forecasts from other sources (e.g., local authorities and master plan forecast) are considered to improve the estimate. However, the forecasts for many non-towered airports are held constant unless otherwise specified. Airport planning forecasts supplied by the airport sponsor have to be compared with the forecasts in the TAF by the FAA before they could be adopted into the TAF. In general, the FAA will find an airport planning forecast acceptable if the 5-year, 10-year, and 15-year forecast levels for the airport forecast and the TAF are within 10 percent of each other (GRA 2011, Kamala and R. John 2012).

The TAF is used by many state airport authorities and other aviation planners as a basis or benchmark for airport planning and improvements (GRA 2001). It is also one of the most used data sets for calibrating GA demand models (See, for example, (Dou, David et al. 2001) and (Wingrove, Jing et al. 2002)). Therefore, we also use the TAF for model calibrations.

It is necessary to point out that we did not consider GA air taxi operations in this study. In the TAF, GA air taxi operations and commercial commuter operations are reported in the same category; a separation between the two is not available. In the 2010 General Aviation and Part 135 Activity Survey (GA survey), the number of hours flown by operations other than GA air taxi[9] operations accounts for about 87% of the total number of hours flown by GA aircraft. Therefore, we believe that our study still covers the majority of the GA operations.

Section 3.3 Model and Potential Determinants of Airport-level GA Demand

Subsection 3.3.1 Model

In the literature, linear and translog functions are the two most used functions to model county and airport-level operations. (Baxter and Philip Howrey 1968) found that the translog model they used produced a better goodness of fit than the linear model did. In commercial aviation, translog models also have been adopted to study the impact of fuel cost on the operating cost of commercial aircraft (See, for example, (Wei and Hansen 2003, Ryerson and Hansen 2013)). Therefore, we adopted the translog function to model the airport-level GA demand and the function is given as follows:

$$\text{GA operations} = \left(\prod F_i^{\alpha_i}\right) \times e^{\beta_0 + \sum \beta_j E_j}. \qquad \textbf{(3.1)}$$

[9]It includes hours flown reported in category air taxi, air tour and air med in 2010 GA survey.

where F_i, E_j are the explanatory variables, and α_i,β_j are their coefficients. The function is similar to the one used in (Ghobrial 1997). In this sense, our study could be considered an extension of (Ghobrial, 1997)'s work. In economics, one important measurement of the quantitative responsiveness of a variable D (e.g., demand) to a change in another variable P (e.g., price) is the elasticity. More precisely, elasticity is defined as the percentage change in quantity of a variable due to a percentage change in another variable (the other variables are assumed to be constant). With the function given in equation (3.1), the elasticity of GA operations with respect to (w.r.t.) variable F_i is the variable's corresponding coefficient in the model. That is:

$$\text{elasticity of GA operations w.r.t. } F_i = \alpha_i. \tag{3.2}$$

If E_j is a binary variable (i.e., the value of E_j is either 0 or 1), then the percentage of change in GA operations due to a unit change in variable E_j is given by:

$$\Delta \text{ w.r.t.} E_j = \exp(\beta_j) - 1. \tag{3.3}$$

Subsection 3.3.2 Potential determinants of airport-level GA demand

Table 3-1 presents the factors we considered as the potential determinants of airport-level GA demand. Those factors are chosen based on results from previous studies, common beliefs, and data availability, and they are candidate variables from which the explanatory variables of our models are selected.

Table 3-1: Potential Determinants of Airport-level GA Demand Investigated in this Study

Variable Category	Variable definition	Expected impact on GA activities	Data sources
Local social economic and demographic factors	The total population of all the counties whose centers are within 20 miles of an airport	Population is expected to be positively correlated with GA demand	Woods & Poole Data**
	The weighted average (by population) income per capita of all the counties whose centers are within 20 miles of an airport	Personal income is expected to be positively correlated with GA demand	
	The number of farm industry employment of all the counties whose centers are within 20 miles of an airport	Farm and forestry industry may increase the demand on aerial applications and observations. These two factors may have positive impact on the number of local operations	Woods & Poole Data
	The number of forestry employment of all the counties whose centers are within 20 miles of an airport		
External social economic and demographic factors	The total gross state product of the counties whose centers are less than 500 miles but greater than 100 miles from the airport	These factors are expected to be positively related with GA activities.	Woods & Poole Data
	The total population of the counties whose centers are less than 500 miles but greater than 100 miles from the airport		
	The total employment of the counties whose centers are less than 500 miles but greater than 100 miles from the airport		
	The gross state product of the state where the airport is located		
	The total population of the state where the airport is located		
	The total employment of the state where the airport is located		
Fuel prices	Fuel price	High fuel price is expected to discourage GA demand.	Aviation Research Group/US (ARG/US) Fuel Price Survey**
	The weighted average (by population) of the ratio of the cost of purchasing 1000 gallons of fuel to the personal income per capita of the counties whose centers are within 20 miles of an airport	This factor can be considered as the relative fuel price. High relative fuel price is expected to discourage GA demand.	Woods & Poole Data and Aviation Research Group/US (ARG/US) Fuel Price Survey
Supply factors	Total number of runways at the airport	Availability of a supply factor is expected to have positive impact on GA activities.	NFDC airport data base**
	Presence of an airport control tower (*dummy variable**)		
	Availability of a concrete or asphalt runway at the airport (*dummy variable* *)		
	Availability of a runway with a runway length greater than 4000 ft. at the airport [1] (*dummy variable**)		
	Availability of a primary a runway with a runway length between 1000 ft. and 4000 ft. at the airport [2] (*dummy variable**)		
	Availability of an ILS at an airport (*dummy variable**)		
	Availability of an engine repair station (either minor or major) at the airport (*dummy variable**)		
	Availability of a fuselage repair station (either minor or major) at the airport (*dummy variable**)		
Number of based aircraft	Number of multiple engine aircraft based at the airport	These two factors are expected to have positive impact on GA activities. Based on GA survey, most of hours flown by these two aircraft type are itinerant in nature, their impact on itinerant operation may be more significant.	TAF
	Number of turbojet or turbofan aircraft based at the airport		
	Number of single engine aircraft based at the airport	These two factors are expected to have positive impact on GA activities. Based on GA survey, most of local hours flown is performed by single engine aircraft; their impact on local operation may be more significant.	
	Number of all the aircraft other than the three aircraft types given above (e.g., rotorcrafts and gliders)		
	Number of total based aircraft at the airport	This factor is expected to have positive impact on GA activities.	
Airport category [3]	Whether the airport is a primary commercial service airport (*dummy variable**)	Since scheduled commercial services usually compete with GA for resources (e.g., runway and air space) at an airport, this factor is expected to have negative impact on the GA demand (especially local GA demand).	NPIAS**
	Whether the airport is a reliever (*dummy variable**)	Since reliever is to provide GA access to surrounding area, an airport tends to have more GA operations if it is a reliever.	
Flight school	Whether there is a flight school based at an airport (*dummy variable**)	Since most of the instructional flights are local, this factor is expected to have positive impact on the number of local operations at an airport.	Retrieved from website (July 2013): http://www.flightschoollist.com/flight-schools.php

*the dummy variable is one if the factor is available; otherwise (i.e., if it is unavailable) 0.
**the data set is introduced in Appendix A
1,2 the runway lengths in the variable definitions are chosen by considering the results given in (Ghobrial 1997) and the criteria specified in (FAA 2005).
3 definitions of airport category are available in Appendix A.

Local and external social-economic and demographic factors:

Previous studies have shown that local social-economic and demographic factors around an airport play a significant role in generating and attracting GA demand. For example, (Ghobrial 1997) considered the population size of the county where the airport is located. (Dou, David et al. 2001, GRA 2001) considered the population size within a certain radius (e.g., 50 or 100 miles) of an airport. They concluded that the number of GA operations at an airport is positively correlated with the population size around the airport. Following the previous research, local social-economic and demographic factors are also considered in our study. In the National Plan of Integrated Airport Systems (NPIAS), an airport is considered to be particularly important to communities that have limited or no access to scheduled commercial services, and included in the NPIAS if it is at least 20 miles from the nearest NPIAS airport (FAA 2010). In other words, in the NPIAS, an airport is considered to primarily serve the communities within 20 miles around an airport. Following this, we considered the social-economic and demographic factors of all the counties whose center is within the 20 miles radius of an airport as the local social-economic and demographic factors around the airport.

Since GA is a medium and long distance travel tool, GA demand at an airport may also be subject to its “external environment” (e.g. economic conditions). To capture this, we also investigated the impact of an airport’s external social-economic and demographic factors. We considered two ways of defining the external factors for an airport. The first one is the social-economic and demographic factors of all the counties whose center is greater than 100 miles but less than 500 miles from the airport. The second one is the social-economic and demographic factors of the state where the airport is located.

Fuel prices:

We investigated two types of GA fuel: Avgas and Jet-A. Avgas is mainly used by piston engine aircraft, and Jet-A fuel is mainly used by Jet engine aircraft. Their historical prices are collected by the ARG/US fuel price survey. We found that their historical prices are highly correlated (the correlation coefficient is about 0.98). Considering both prices in the model may introduce multicolinearity. To avoid this, we only considered the price of Jet-A throughout the paper. Following (Li and Trani 2013), we also investigated the impact of the relative fuel price- fuel price compared with personal income.

An aircraft's operating cost usually includes fuel cost, oil cost, airframe, avionics, engine overhaul, maintenance cost, insurance cost etc. For GA demand modeling, operating cost is the ideal factor to be considered; however, information about airport-level operating costs is rarely available. As a result, many airport-level GA demand studies (e.g., those mentioned in the literature review) did not consider operating costs. For the same reason, we primarily consider fuel price in this study.

Supply (facilities, infrastructure and services) factors at an airport:

Supply factors refer to facilities (e.g., control tower and ILS), infrastructure (e.g., runways), and services (e.g., engine and body repair services, and charter flights services) provided at an airport. Supply factors are crucial for aviation activities. For example, the operations of large aircrafts usually require long runways and good runway pavement. (Baxter and Philip Howrey 1968) pointed out that the fraction of airports with paved runways could be one determinant of the number of GA operations in a county. (Ghobrial 1997) found that the presence of a control tower could increase the operations at an airport by about 253%, and availability of a runway with a runway length greater than 4000 ft. would increase the operations by 52%. In addition, as pointed out by the FAA (FAA 2010), the historical operations reported in the TAF were performed under constrained conditions at airports, that is, under the constraints of supply factors. Since our models are calibrated by using data from the TAF, it is necessary to consider the supply factors to capture those constrained conditions.

Number of based aircraft and presence of a flight school at an airport:

In the TAF, the correlation coefficient between the number of itinerant operations and the total number of based aircraft is about 0.75, which indicates that GA activities could be positively correlated with the number of based aircraft. (Wingrove, Jing et al. 2002) also concluded that a positive correlation exists between the number of based aircraft and the number of itinerant GA operations in a county.

Since most of the instructional flights are local, the presence of a flight school could significantly increase the number of local operations at an airport. Using a linear model, (GRA 2001) examined the impact of the presence of a flight school on the GA operations at small non-towered airports. In this study, we considered this factor as a potential determinant for local GA demand.

Competition from the commercial aviation:

GA and commercial aviation usually compete for resources (e.g., runway and air traffic controller). For example, large hubs (an airport category in NPIAS) primarily serve commercial aviation and therefore only allow for limited GA activities. Instructional training usually concentrates on GA airports such that the capacity at the commercial service airport can be preserved (FAA 2010). To capture the competition between commercial aviation and GA, (Hoekstra 2000) introduced a dummy variable to represent whether the airport is certificated for commercial services. In the NPIAS, one of the criteria to determine an airport's category is the commercial passenger enplanements at the airport. Therefore, we used an airport's NPIAS category to capture the impact of competition from the commercial aviation on the GA demand. We considered two NPIAS airport categories: primary commercial service airport and reliever. Primary commercial service airport is publicly owned airport that receives scheduled passenger service and has at least 10,000 passenger boardings each calendar year. Reliever airport is publicly or privately-owned airport that is primarily used to relieve congestion at commercial service airports and provide improved GA access to the overall community.

Section 3.4 Model Calibration and Results Analyses

Subsection 3.4.1 Variable selection and model calibration

Following (Dou, David et al. 2001, Long, D. Lee et al. 2001, Wingrove, Jing et al. 2002), we considered GA operations at both towered and non-towered TAF airports in the model calibrations. Though the information at non-towered TAF airports is relatively less accurate, we believe that it is necessary to consider them. GA operations at non-towered TAF airports account for about 60% of all the GA operations at the TAF airports. Excluding them could lead to parameter estimations biased to the towered airports.

Table 3-2: Statistical Criteria Used to Select Explanatory Variables

1. Principle of parsimony:	The model that can explain the data with the least explanatory variables is preferred. This principle is especially important for GA demand modeling as historical data is very limited for model calibration. Models built with this principle are relatively easy to use since they require less input data. The principle of parsimony is considered to be violated if adding a variable does not significantly increase the R-square/Adjusted R-Square and the model's forecasting ability.
2. Consistency with common belief:	The coefficient estimates of explanatory variables should be consistent with common belief.
3. Independence from other explanatory variables:	The explanatory variables included in the model should not be highly correlated with each other. A high correlation between explanatory variables (i.e., multicolinearity) may result in inaccurate coefficient estimates.
4. Goodness of fit:	To measure how good the model fits the historical data, we used two statistics: R-square/Adjusted R-Square and statistical significance. In this study, we require that the variables included in the final models be statistically significant at the 5% significance level.
5. Forecasting ability:	Goodness of fit only indicates how well the model fits the data that is used for model calibration. Since airport-level GA demand models are usually used for demand forecast, it is important to consider an explanatory variable's contribution to the models' forecasting ability. To do so, we reserved the operation data of 2010 and 2011 in the TAF as the test data sets for comparison with the models' forecast. An explanatory variable's contribution to models' forecasting ability is evaluated by comparing the model forecast with the operation data of 2010 and 2011 (by using paired dependent t-test with a 5% significance level).

We used the statistical criteria given in Table 3-2 to select the explanatory variables for the models. In addition, the comments and suggestions from the FAA Office of Policy and Plans (APO) are also considered. The APO has a particular interest in the impact of fuel price on airport-level GA demand since its impact is not adequately considered in the existing airport-level models. The selection of variables follows a stepwise forward try-and-error process: the variables related to the fuel price are the first to be evaluated for inclusion in the model, and followed by variables that have been investigated in previous studies (e.g., runway length and control tower), and the last to be evaluated for inclusion in the model are the other candidate variables listed in Table 3-1. If a criterion is violated after adding a variable, then all the variables that have been included in the model will be rechecked using the criteria given in Table 3-2 to decide the variable(s) to be deleted from the model.

Static models assume that GA demand makes an immediate and complete adjustment to changes in factors such as fuel prices and income. However, this assumption is not always valid. In other words, there might be a lag effect in the reaction of GA demand. Previous studies (see, for example, (Romero-Jordán, del Río et al. 2010, Li and Trani 2013)) introduced a lag term to capture this effect. Similarly, we also investigated the possible lag effect in fuel price and relative fuel price. However, the estimation results are counter-intuitive. In addition, the White's test suggests that the errors are heteroscedastic for both models at the 5% significance level. Standard estimation methods (e.g., ordinary least square) are inefficient when the errors are heteroscedastic. Since the form of the heteroscedasticity is unknown, we adopted the generalized method of moments (Hansen 1982) to calibrate the models. The method is implemented using SAS 9.3.

Subsection 3.4.2 Result analysis and comparison

Table 3-3: Calibration Results for Itinerant Operations

Itinerant operations (R-Square/Adj R-Sq:0.412/0.412)					
Parameter*	**Variable**	**Estimate**	**Std Error**	**t Value**	**Pr> |t|**
β_0	**Intercept**	**-8.657**	**2.397**	**-3.09**	**0.002**
α_1	**State gross product of the state where the airport is located (in trillions of 2005 dollars)**	**0.338**	**0.027**	**12.64**	**<.0001**
α_2	**Total population of the counties whose centers are within 20 miles of the airport (in thousands)**	**0.531**	**0.290**	**1.83**	**0.067**
α_3	**Total number of based aircraft at the airport**	**0.156**	**0.018**	**8.93**	**<.0001**
α_4	**Relative fuel price**	**-0.425**	**0.178**	**-2.39**	**0.0167**
β_1	**Availability of a concrete or asphalt runway at the airport**	**8.168**	**0.314**	**26.02**	**<.0001**
β_2	**Availability of a runway with a runway length greater than 4000 ft. ** **	**0.334**	**0.078**	**4.28**	**<.0001**
β_3	**Availability of a control tower**	**1.013**	**0.067**	**15.22**	**<.0001**
β_4	**Availability of an engine repair plant at the airport**	**1.243**	**0.067**	**18.60**	**<.0001**
β_5	**Whether the airport is a reliever**	**0.336**	**0.107**	**3.14**	**0.0017**

*Parameters correspond to those given in equation (1). The elasticity or percentage of change of demand w.r.t. each variable is given by equation (3.2) and (3.3).
** The dummy variable is 1 if the airport has a primary runway with a runway length greater than 4000 ft.; otherwise 0 (i.e., the airport does not have a runway longer than 4000 ft.).

Table 3-3 presents the calibration results for the model for itinerant operations. We compared the number of itinerant operations in 2010 and 2011 observed in the TAF with the one estimated by this model. The comparison is primarily focused on towered airports because their historical data is relatively accurate. For 2010, the paired dependent t-test does not detect any difference between the statistic from the TAF and our model estimates with a 5% significance level. However, the test suggests that a significant difference may exist for 2011. Our model estimate of the total number of itinerant operations is about 10% higher than the total number in the TAF.

The estimated coefficient for the relative fuel price is significant at the 5% significance level but not at the 1% significance level. Its coefficient is negative, which indicates that there will be less itinerant operations if the fuel price takes a larger portion of income. Given other factors fixed, a 10% increase in the relative fuel price would result in a 4.3% decrease in the number of itinerant operations. The population size around an airport has been considered in several studies. Its coefficient estimate in our study is 0.53. However, this factor is not included in the final model because its coefficient is not significant at the required significance level. In addition, our model suggests that a runway with a runway length greater than 4000 ft. is expected to increase the number of itinerant operations by 40%. An airport with a control tower could have about 170% more itinerant operations than an airport without one. A reliever is expected to have 40% more itinerant operations than a non-reliever.

Table 3-4: Calibration Results for Local Operations

Local operations (R-Square/Adj R-Sq:0.531/0.531)					
Parameter*	**Variable**	**Estimate**	**Std Error**	**t Value**	**Pr> |t|**
β_0	**Intercept**	**-12.921**	**1.516**	**-7.35**	**<.0001**
α_1	**State gross product of the state where the airport is located (in trillions of 2005 dollars)**	**0.330**	**0.036**	**9.26**	**<.0001**
α_2	**Total farm industry employment of the counties whose centers are within 20 miles of the airport (in thousands of jobs)**	**1.234**	**0.429**	**2.87**	**0.0041**
α_3	**Total number of based single engine aircraft at the airport**	**0.485**	**0.020**	**23.76**	**<.0001**
α_4	**Relative fuel price**	**-0.515**	**0.242**	**-2.13**	**0.0335**
β_1	**Availability of a concrete or asphalt runway at the airport**	**11.346**	**0.344**	**32.98**	**<.0001**
β_2	**Availability of a primary runway with a runway length between 1000 ft. and 4000 ft. ****	**0.538**	**0.073**	**7.38**	**<.0001**
β_3	**Availability of an engine repair plant at the airport**	**1.778**	**0.090**	**19.78**	**<.0001**
β_4	**Whether the airport is a primary commercial service airport**	**-1.241**	**0.127**	**-9.74**	**<.0001**
β_5	**Whether there is a flight school based at the airport**	**0.610**	**0.064**	**9.53**	**<.0001**

*Parameters correspond to those given in equation (1). The elasticity or percentage of change of demand w.r.t. each variable is given by equation (3.2) and (3.3).
** The dummy variable is 1 if the airport has a runway with a runway length between 1000 ft. and 4000 ft.; otherwise 0 (i.e., the airport has no runway longer than 1000 ft. or has a runway longer than 4000 ft.).

Table 3-4 presents the calibration results for the model for local operations. Similarly, we also compared the number of local operations of 2010 and 2011 observed in the TAF with the number estimated by this model. The paired dependent t-test does not detect any difference between the statistics from the TAF and our model estimates for both years.

The coefficient estimate for the relative fuel price is significant at the 5% significance level but not at the 1% significance level. The elasticity of local operations w.r.t. the relative fuel price is -0.52. Given other factors fixed, a 10% increase in the relative fuel price would cause a 5.2% decrease in the number of local operations. According to our estimation, local operations are elastic to local farm industry employment. A 10% increase in this factor would lead to a 12.3% increase in local operations. An airport with a primary runway with a runway length between 1000 ft. and 4000 ft. is expected to have 71% more local operations than an airport without a runway with a runway length greater than 1000 ft. or with a runway longer than 4000 ft. A possible explanation for the airports with a runway longer than 4000 ft. having relatively fewer local operations is that they may concentrate more on serving itinerant operations. Our estimation results also suggest that airports without commercial services could have about 80% more local operations than those with the services, and a based flight school would increase the number of local operations by about 84%.

Compared with itinerant operations, local operations are more sensitive to the relative fuel price (higher elasticity). A possible explanation for this is that a portion of local operations are for pleasure (e.g., sightseeing and air tours) and flight experience (e.g., practice). Based on our results, pavement condition plays a fundamental role for both itinerant and local operations, and the availability of an engine repair plant at an airport will also significantly increase the number of itinerant and local operations. Both itinerant and local operations are inelastic to the number of based aircraft. A 10% increase in the number of based aircraft will result in about a 1.6% increase in the number of itinerant operations. A 10% increase in the number of based single engine aircraft will lead to about a 4.9% increase in the number of local operations.

Table 3-5: Summary of Demand Elasticity w.r.t. Fuel Price (Cost)

Source	Independent Variable	Dependent Variable	Elasticity
(Wei & Hansen, 2003)	Fuel cost	Operating cost of large commercial jets	-0.24* (preferred model)
(Ryerson & Hansen, 2011)	Fuel cost	Operating cost of commercial aircraft	-0.4*
(Li &Trani, 2013)	Relative fuel price**	Utilization rate of piston aircraft	-0.6
(Li &Trani, 2013)	Relative fuel price**	Utilization rate of single-engine piston aircraft	-0.67
(Li &Trani, 2013)	Relative fuel price**	Utilization rate of multi-engine piston aircraft	-0.23
Our model	Relative fuel price	Number of itinerant operations	-0.43
Our model	Relative fuel price	Number of local operations	-0.52

*Elasticity is evaluated at the sample mean. ** Fuel is Avgas, and income is disposable income per capita.

Table 3-6: Comparison of Calibration Results

(Ghobrial 1997)		Our model (itinerant operations)		Our model (local operations)	
Availability of control tower	253%	Availability of control tower	170%	-	-
Availability of avionics services	119-203%	Availability of an engine repair plant	247%	Availability of an engine repair plant	490%
Availability of repair services	24-38%				
Availability of crop dusting and other related services	37-44%	-	-	Local farm industry employment (10% increase)	12.3%
Availability of a runway with a runway length greater than 4000 ft	57-61%	Availability of a runway with a runway length greater than 4000 ft.	40%	Availability of a runway with a runway length greater than 1000 ft. but less than 4000 ft.	71%
County population* (in thousands) (10% increase)	0.46%	Local population** (in thousands)	5.3%		
County employment (10% increase)	2.6-3.2%				

* County population is defined as the population of the county where the airport is located. ** This factor is not significant at the 5% significance level.

In Table 3-5, we summarized the elasticity of fuel price (cost) reported in some recent studies related to aviation. Since our study can be considered an extension of the model developed by (Ghobrial 1997), we also compared the estimation results for the factors shared by both studies in Table 3-6. It is necessary to stress that 1) in (Ghobrial 1997) airport-level demand includes flight operations (the combination of itinerant and local) of both commercial aviation and GA, and 2) the two models are calibrated using operation data of different airport sets.

Compared with those reported in (Ghobrial 1997), our results show that 1) itinerant GA operations are less sensitive (lower elasticity) to the availability of a control tower and a runway with a runway length greater than 4000 ft., and 2) the availability of repair services has a more important role for both itinerant and local GA operations. We believe that those differences are primarily because the operations of commercial flight are considered in (Ghobrial 1997) while they are not considered in our model calibration. Most of the commercial flight operations are performed by high-performance jets under Instrumental Flight Rules. They have higher requirements on the runway length and availability of a control tower. In addition, many carriers have their aircraft maintenance performed in house (Transport Workers Union of America 2011) or overseas, which may make commercial aviation aircraft less dependable on the repair services at other airports.

Section 3.5 Projections of the GA Demand for the Airports in the TAF

In this section, we will provide projections of GA demand for the airports in the TAF using our models. The projection period is from 2014 to 2035. Our projections are compared with those given in the TAF.

Subsection 3.5.1 Projections of explanatory variables

Projections of fuel price:

Compared with other operating cost, fuel price is highly volatile (Adams and Gerner 2012) and difficult to predict even in the short-term basis. To capture the uncertainties, many studies on the impact of fuel cost have considered three price scenarios in the analysis: “business-as-usual” price scenario, “worst/highest” price scenario and “best/lowest” price scenario. Those scenarios are created based on either the projections from reliable sources (e.g., EIA), or researchers’ own analysis and expectations (See, for example,(Gal 2006, Ryerson and Hansen 2013)). Following this practice in the literature, we also considered three future scenarios for the fuel price.

Following (Macharis, Van Hoeck et al. 2010, Li and Trani 2013), we adopted the projections of fuel price prepared by the EIA. The projections are made based on the results from the EIA’s National Energy Modeling System. In EIA’s Annual Energy Outlook (AEO) 2013, multiple fuel price scenarios are made by considering important areas of uncertainty for markets, technologies, and policies in the U.S. energy economy (EIA 2013). Among them, three are chosen for our study: the reference fuel price scenario (RPS), the high fuel price scenario (HPS), and the low fuel price scenario (LPS). According to the EIA, the RPS is a “business-as-usual” trend estimate. The scenario assumes that the current practices, politics, level of access, technology and technological and demographic trends will continue. The EIA used RPS as a starting point to create other alternatives. The HPS can be considered a pessimistic forecast. With the assumption of a higher demand for petroleum and other liquids in the non-Organization for Economic Co-operation and Development (OECD) nations, and more constrained supply availability, the projections of fuel prices in the HPS are higher than in the RPS. The LPS can be considered an optimistic forecast. With the assumption of a lower economic growth for the non-OECD nations and greater access to and production of petroleum liquids resources, the projections of fuel prices in the LPS are lower than in the RPS. Among all the scenarios, the projections of fuel price under HPS are the highest, and those under LPS are the lowest.

The fuel price projections from the EIA are given in terms of the kerosene-type jet fuel[10] for commercial aviation. To obtain the corresponding projections of Jet-A fuel price for the GA, we assume that the following relationship between the two prices exists:

$$\text{GA Jet A fuel price} = \alpha \times \text{Jet fuel price}$$

The coefficient α is estimated by using the historical data collected by the EIA and ARG/US survey. For national average fuel prices, the coefficient estimate is 2.21**,** and R-square/Adjusted R-square is about 0.97.

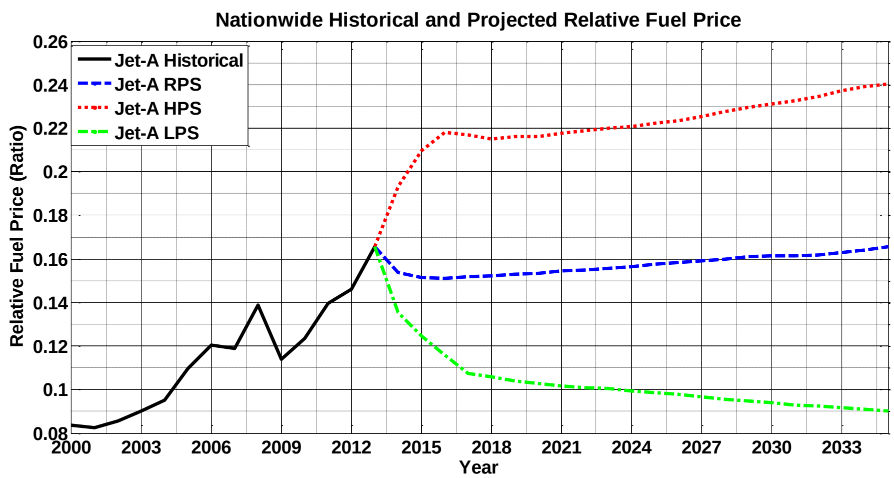


Figure 3-1: Projections of the relative fuel price

The projections of the relative fuel price are presented in Figure 3-1. In the RPS, the Jet-A price is projected to drop by about 5.4% in 2014 and increase slightly in 2015. This leads to a drop in the relative fuel price in those two years. From 2016 to 2035, the Jet-A price is projected to have a long-term increase with an average annual increase rate of 1.9%. As a result, the relative fuel price also increases in the same period. In the HPS, the Jet-A price is projected to increase significantly between 2014 and 2016 at about 11.3% per year. Because of this, the relative fuel price also increases significantly in this period. From 2017 to 2018, the increase in the fuel price is projected to continue but with a lower increase rate (about

[10]kerosene-type jet fuel is used for commercial and military turbojet and turboprop aircraft engines.

0.8%). Due to the growth in personal income, the relative fuel price is expected to decrease in those two years. From 2019 to 2035, the Jet-A price is projected to increase at about 2% per year, and the relative fuel price is also expected to increase during this period. In the LPS, the Jet-A price is projected to decrease at about 5.5% per year from 2014 to 2019. This leads to a significant decrease in the relative fuel price in this period. From 2020 to 2035, the Jet-A price is projected to have a long-term mild increase with an average annual increase rate of 0.52%. However, the relative fuel price is expected to decrease because personal income is expected to grow faster than the fuel price.

Projections of state/county-level social-economic and demographic factors:

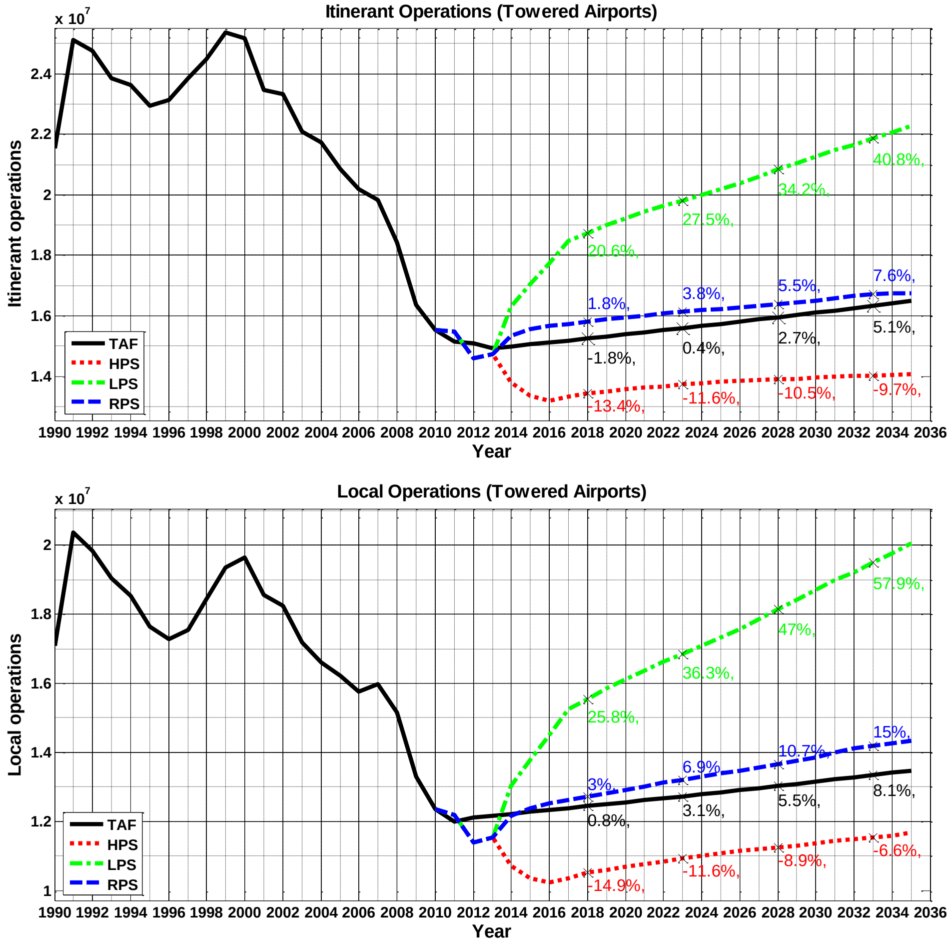
Since our models are calibrated by using the historical state/county-level data from the Woods & Poole data, we also adopted its projections of these factors to maintain consistency. The EIA uses different projections of social-economic factors (e.g., GDP and income growth rate) in different fuel price scenarios to capture the interactions between fuel price and social-economic factors. However, the projections of state/county-level social-economic and demographic factors corresponding to the three fuel price scenarios are not available to this study. Therefore, we used a top-down two-step approach to adjust the projections from the Woods & Poole data to account for the interactions between fuel price and state/county-level social-economic and demographic factors.

The first step is to distribute EIA's nation-level projections of social-economic and demographic factors for each year in each fuel price scenario among states/counties. The distribution is made by using the corresponding projections for states/counties in the Woods & Poole data. For factors related to employment and regional gross product, the EIA's projections are distributed among states/counties proportionally to the corresponding Woods & Poole's projections for states/counties. For the personal income per capita, the EIA's projections of total personal income and population are first distributed among counties proportionally to the corresponding Woods & Poole's projections for counties. The projections of the personal income per capita of a county are made by dividing the projections of its total personal income by the projections of its population. The second step is to make projections of social-economic and demographic factors for each state/county for each year in each fuel price scenario. For a state/county, the growth rates of its social-economic and demographic factors are estimated by using the projections made in the first step. With the growth rates and the historical data in 2012 as the baseline, the projections of social-economic and demographic factors for each state/county are made on a rolling basis.

Projections of the supply factors, flight schools and the number of based aircraft at the TAF airports:

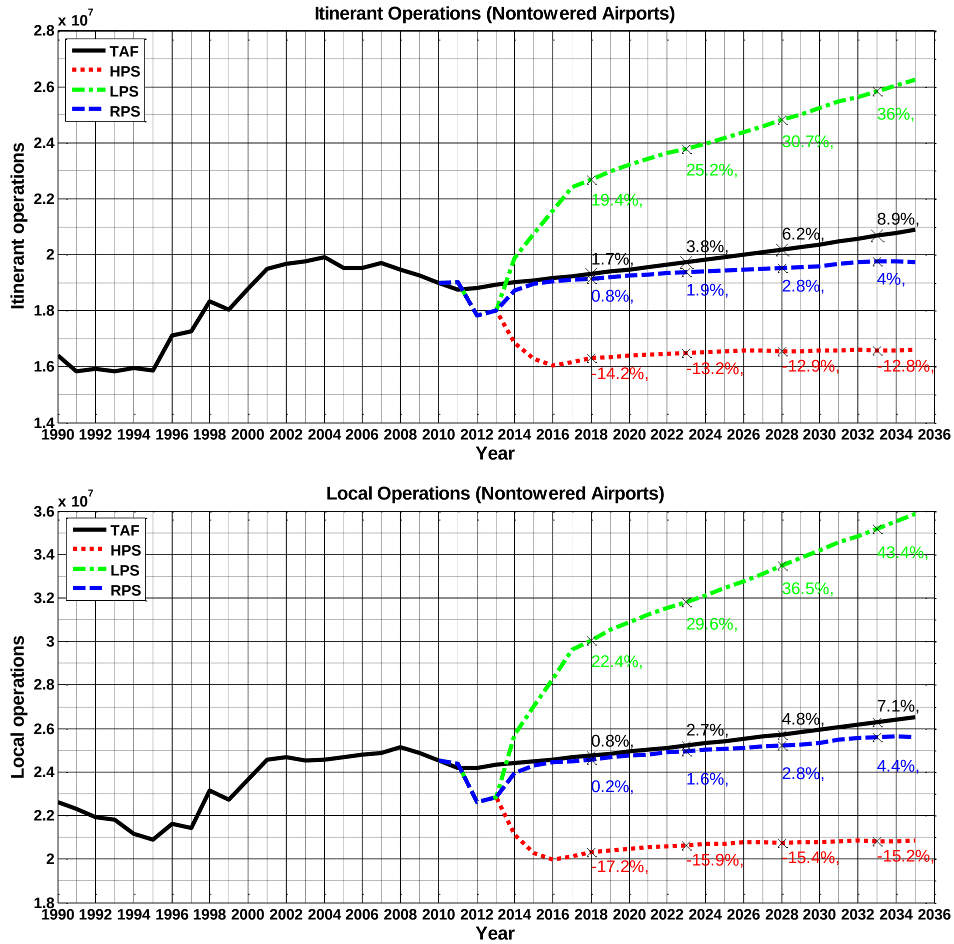
The supply factors and flight schools at the TAF airports are assumed to be constant throughout the projection period. This assumption will 1) make the impact of the fuel price easier to be identified, and 2) simplify our study by avoiding making projections of the supply factors and flight schools for every single TAF airport. For the projections of the number of based aircraft, we adopted those provided in the TAF.

Subsection 3.5.2 Projections and comparisons



The percentages on the curves represent the percentage of change in the number of operations in current year compared with that in 2010

Figure 3-2: Historical and projected itinerant and local operations at the towered TAF airports



The percentages on the curves represent the percentage of change in the number of operations in current year compared with that in 2010

Figure 3-3: Historical and projected itinerant and local operations at the non-towered TAF airports

The baseline year of our projections is 2010. To avoid model errors at the baseline year, our projections are made in a rolling horizon fashion using the growth rates estimated by our model. More specifically, with the historical operations data in 2010 as the starting point, the demand projection for the “next” year is made by applying the growth rate (estimated by our models) to the “current” year’s demand. Figure 3-2 and Figure 3-3 present our projections of the total number of GA demand under the EIA’s three fuel price scenarios for the TAF towered and non-towered airports, respectively. The projections from the TAF 2013 are also presented in the figures for comparison. Since projections from the TAF are relatively well prepared for the towered airports, the following analyses and comparisons are mainly focused on those airports.

Projections from the TAF (towered airports):

Based on the projections from the TAF, both itinerant and local operations at the towered airports are expected to recover after 2012 at about 0.45% per year. In 2022, the number of itinerant operations is expected to recover to the level observed in 2010. The number of local operations is projected to reach its level observed in 2010 in 2017. In 2035, the number of itinerant and local operations is predicted to be 6.2% and 9.1% higher than that observed in 2010, respectively.

Projections under the RPS (towered airports):

The drop in the relative fuel price from 2014 to 2015 would lead to an average annual recovery rate of 2.8% for itinerant operations, and 3.2% for local operations. In 2015, the number of itinerant operations would recover to the level seen in 2010. From 2016 to the end of the projection period, the number of itinerant operations is expected to have a long-term mild recovery with an average annual recovery rate of 0.37%. In 2035, the number could exceed the level observed in 2010 by 7.89%. The number of local operations is predicted to recover to the level seen in 2010 in 2015. Similar to the itinerant operation, the number of local operations would also have a long-term mild recovery with an average annual recovery rate of 0.73%, and the number will exceed that observed in 2010 by 16.2% in 2035. In our projections, the recovery of local operations is expected to be stronger than that of itinerant operations. Similarly, the TAF also predicts this. For both itinerant and local operations, our projections under the RPS are close to the projections from the TAF. The errors are within 10% error range.

In both projections, the GA demand is expected to have a mild recovery. Considering the historical trend of GA demand between 1990 and 2000 (shown in Figure 3-2), we believe that a recovery of GA demand in the future is possible. Some other studies also predict a mild recovery for the GA demand. For example, in addition to projections in the TAF, the FAA provides another forecast of GA activities in the FAA Aerospace Forecasting. The forecast is made based on the discussions with industry experts conducted at industry meetings (e.g., Transportation Research Board) as well as suggestions from industry staff and aviation associations (FAA 2013). Therefore, we believe the forecast represents the industry's prevailing expectation of a future GA scenario. In the FAA Aerospace Forecasting Fiscal Year 2013-2033, a mild recovery of GA activities is expected to start in 2012. (Li and Trani 2013) studied the impact of fuel price on the utilization of piston aircraft. Their study also adopted the three fuel price scenarios used in our study. They predicted that a mild recovery of the utilization rate of piston engine aircraft would start in 2020 under the RPS.

However, it is necessary to point out that, in addition to the GA demand factors discussed in this study, many other factors could also have significant impacts on GA activities. For example, (Thurber 2011) offered a discussion on the potential impacts of insurance cost, the cost of training pilots, the completion rate of new pilots, airport pressures (e.g., noise issues), safety issues, demographic changes in the age mix of the population, and the introduction of light sport aircraft. Since those factors are not included in our models, their impacts on future GA demand may not be sufficiently considered in our projections. Therefore, it is possible that the recovery of GA demand may be slower than our projections or may even not happen because of the impacts of those factors.

Projections under the LPS (towered airports):

Under this scenario, our models predict that the number of both itinerant and local operations will increase significantly between 2014 and 2019. This increase is primarily due to the projected low relative fuel price in this period.

Since the relative fuel price is expected to keep decreasing after 2019, the number of both operations is expected to continue growing with an average annual growth rate 0.99% for itinerant operations, and

1.48% for local operations. In 2035, the number of itinerant operations will grow by 43.45% compared with the one observed in 2010, and reach the level observed in 2003. The number of local operations is expected to reach the level seen in 2000 in 2033. In 2035, the number of local operations will exceed the level observed in 2010 by about 62.44%.

Projections under the HPS (towered airports):

From 2014 to 2016, the number of itinerant and local operations is expected to decline at an average annual rate of 3.56% and 3.92%, respectively. This decline is mainly because of the projected high relative fuel price during this period. In 2016, the number of itinerant operations would be 14.98% less than the level observed in 2010, and the number of local operations would be 17.2% less than the level observed in 2010.

The number of both operations is projected to have a long-term mild recovery beginning in 2017.The average recovery rate is about 0.34% per year for itinerant operations, and 0.7% per year for local operations. In 2035, the number of itinerant operations is predicted to be 9.3% less than the level seen in 2010, and the number of local operations is 5.5%less than the level observed in 2010.

Section 3.6 Summary and Suggestions for Future Study

Table 3-7: Comparison of Airport-level Demand Forecasting Models

Airport-level models	Definition of demand (dependent variable)	Demand function	Data used in model calibration	Explanatory variable related to									
				Fuel price	**Local social-economic factors (other than fuel price)**	**External social-economic factors**	**Availability of facilities and infrastructure**	**Availability of services**	**Based aircraft**	**Access to local attractions**	**Flight school**	**Airport category**	**Region category**
				e.g., fuel price and relative fuel price	e.g., population, income per capita, and employment	e.g., population and employment	e.g., control tower and long runway	e.g., engine repair, crop dusting, and charter flight	e.g., single engine, multiple engine, and jet engine	e.g., tourist/recreational area and urban area	e.g., presence of flight school and number of employees in the school	e.g., large hub and reliever	e.g., FAA region and state
(Ghobrial 1997)	The combination of itinerant and local operations performed by both GA and commercial aviation at GA airports	Translog	82 GA airports in the state of Georgia		Yes		Yes	Yes		Yes			
(GRA 2001)	The combination of itinerant and local operations performed at non-towered airports *	Linear	127 small towered and 105 non-towered airports		Yes		Yes		Yes		Yes	Yes	Yes
(Wingrove, Jing et al. 2002)	Itinerant GA operations	Linear	TAF airports (about 3300 airports)		Yes				Yes			Yes	
(Dou, David et al. 2001)	Itinerant GA operations	Linear	TAF airports (about 3300 airports)		Yes								
Models in this study	Itinerant and local GA operations (separate model)	Translog	TAF airports (about 3300 airports)	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	

*Not explicitly given, inferred based on the authors' best knowledge

GA is an essential part of the air transportation system in the U.S. Optimizing the distribution of limited resources among the country's diverse airport system is an important task. To achieve this goal requires high-fidelity forecasts of GA demand at the airport level. In this paper, we have developed an airport-level GA demand forecasting model. Table 3-7 presents a comparison between our models and the existing ones in terms of the definition of demand (i.e., dependent variable), demand function used, the explanatory variables considered in the model, and the data used for model calibration. Compared with the other studies, our study 1) considers the effect of fuel price, which is an important determinant of GA demand, and 2) provides more detailed forecasts in the sense that itinerant and local GA operations are modeled separately. Especially, our models suggest that a 10% increase in the relative fuel price could lead to a 4.3% and 5.2% drop in the number of itinerant and local GA operations, respectively. This result could be useful in making policies related to fuel prices such as fuel subsidies and fuel taxes.

It is necessary to point out that our models have a relatively low goodness of fit (i.e., R-square/Adjusted R-square). This indicates that more explanatory variables may be needed to better capture airport-level GA demand. Depending on data availability, we suggest the following factors be investigated in future studies:

1) Whether an airport provides access to local attractions (e.g., tourist and recreational areas), urban areas, remote communities, special events or medical centers. Due to data unavailability, this factor is not considered in this study. However, other studies have shown that this factor could significantly affect airport-level demand. For example, (Ghobrial 1997) showed that airports providing access to tourist and, recreational areas, or urban areas are expected to have 114% more aviation demand than those who do not provide.

2) Age mix and the primary use of the based aircraft at an airport. According to the 2010 GA survey, the average number of hours flown by the single engine piston aircraft that are 30 to 34 years old is only about half of those that are 0 to 4 years old. The average number of hours flown by the single engine piston aircraft for personal use is only about one-third of the number for corporate use. This suggests that the age mix and the primary use of the based aircraft could be significant determinants of the GA demand at an airport.
3) Number of student pilots and private pilots around an airport. (Li & Trani, 2013) have shown that the number of student pilots is an important determinant of the utilization rate of piston aircraft. Their results suggest that a 10% increase in the number could lead to a 2.6% increase in the utilization rate of piston aircraft. In particular, the number of student pilots around an airport could be a significant determinant of local GA operations because of the training and instructional flights performed by local student pilots.
4) Local weather and climate conditions such as temperature and level of precipitation.

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Disclaimer

The views and models presented in this paper are the sole responsibility of the authors. This paper does not reflect the views of the FAA or any other government office.

CHAPTER 4 A MICROSCOPIC SIMULATION MODEL FOR THE AIR TRAFFIC IN THE ORGANIZED TRACK SYSTEM OF THE NORTH ATLANTIC AIRSPACE

Section 4.1 Introduction

Background of the organized track systems over the North Atlantic region

Most of the commercial flights between Europe and North America will fly across the North Atlantic (NAT) region inside the Minimum Navigation Performance Specifications (MNPS) and Reduced Vertical Separation Minimum (RVSM) airspace.

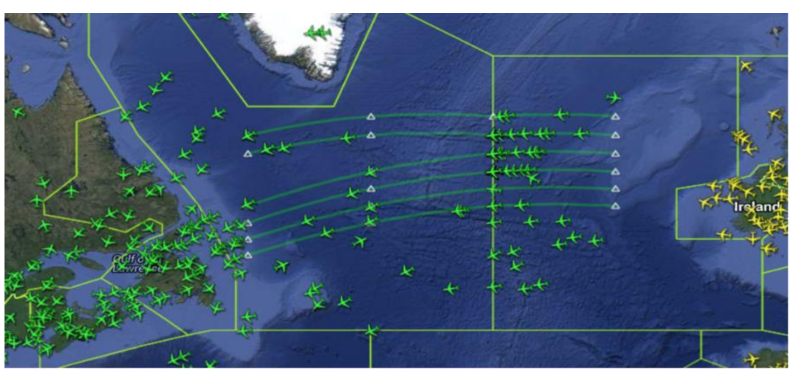
The MNPS is established to ensure that the risk of collision due to a loss of horizontal separation between aircraft would be contained within an agreed target level of safety. In the MNPS airspace, the minimum lateral separation between MNPS approved aircraft is designed to be 60nm or about one latitude degree. Considering the curvature of the earth, 'Gentle Slope Rules' are introduced to slightly adjust the minimum separation based on the altitude but never below 50.5 nm. The minimum longitudinal separation is usually expressed in clock time, and it could range from 5 minutes to 20 minutes depending on factors such as aircraft class and differences in Mach number.

The RVSM is established between flight level 29000 ft. and 41000 ft. to increase the airspace capacity while allow aircraft fly safely. In the RVSM airspace, the minimum vertical separation is 1000 ft.; in contrast to 2000 ft. in non-RVSM airspace. Usually, eastbound flights (Magnetic Track 000 to 179°) use odd thousands flight levels (FL) (i.e., FL 290, FL 310, FL 330, FL 350, FL 370, and FL 390), and westbound flights (Magnetic Track 180 to 359°) use even thousands flight levels (i.e., FL 300, FL 320, FL 340, FL 360, FL 380, and FL 400). This is also known as the 'hemispheric rule'.

In contrast to the operations in domestic airspace, operations over the NAT region cannot be continuously monitored by radar; and tracking operations over the NAT region primarily relies on communications between pilots and ground controllers. As a result, their operations over the NAT region need to follow offshore/oceanic procedures, in which separation minima are larger than those used in airspace with sufficient radar surveillance.

Due to the passenger demand, time zone differences and airport noise restrictions, the air traffic between Europe and North America forms two major relatively concentrated unidirectional flows over the NAT region: a westbound traffic departing from Europe to North America in the morning, and an eastbound traffic departing from North America to Europe in the evening. The peak of the westbound traffic crosses the 30W longitude between 1130 Coordinated Universal Time (UTC) and 1900 UTC, and the peak of the eastbound traffic crosses the 30W longitude between 0100 UTC and 0800 UTC.

Because of the large separation minima over the ocean, hemispherical rules, and a limited economical cruising altitude range (FL 310- FL 400) for commercial jets, the airspace over the NAT is congested at peak hours. The congestions could result in, for example, greater fuel consumption, more delays, higher Air Traffic Control (ATC) workload, and lower level of safety.



Westbound OTS on April 2nd. Source: http://radarbox24.com/ (AirNav Systems 2014) [fair use]

Figure 4-1: Westbound OTS on April 2nd

In order to better serve the two traffic flows, two Organized Track Systems (OTS) are created daily to accommodate as many flights as possible. They are located inside the MNPS and RVSM airspace. The eastbound OTS is designed by Gander Area Control Center and the westbound one is designed by Shanwick Oceanic Area Control Center. Figure 4-1 shows an example of the westbound OTS. The factors considered in the design of the OTS include:

1) Minimum time tracks of the flights and their optimal cruise altitudes.
2) Meteorological conditions such as weather and wind patterns. In particular, tracks are designed such that eastbound flights could make use of the prevailing tail wind (i.e., wind whose direction is the same as the flights' travel directions), and westbound flights could reduce their head wind (i.e., wind whose direction is opposite to the flights' travel directions).
3) The airlines' preferences, airspace restrictions, demand from opposite directions, and feedbacks from users.

The Track Message containing the information about the OTS is published daily (Federal Aviation Adminstration 2014). For the westbound OTS, the most northerly track is designated as Track 'A' at the origin point, and the next northerly track is designated as Track 'B' etc. For the eastbound OTS, the most southerly track is designated as Track 'Z' at the origin point, and the next southerly track is designated as Track 'Y' etc. Each track is at least about 60 nm apart to maintain the minimum lateral separation over the ocean.

Table 4-1: Track Definition

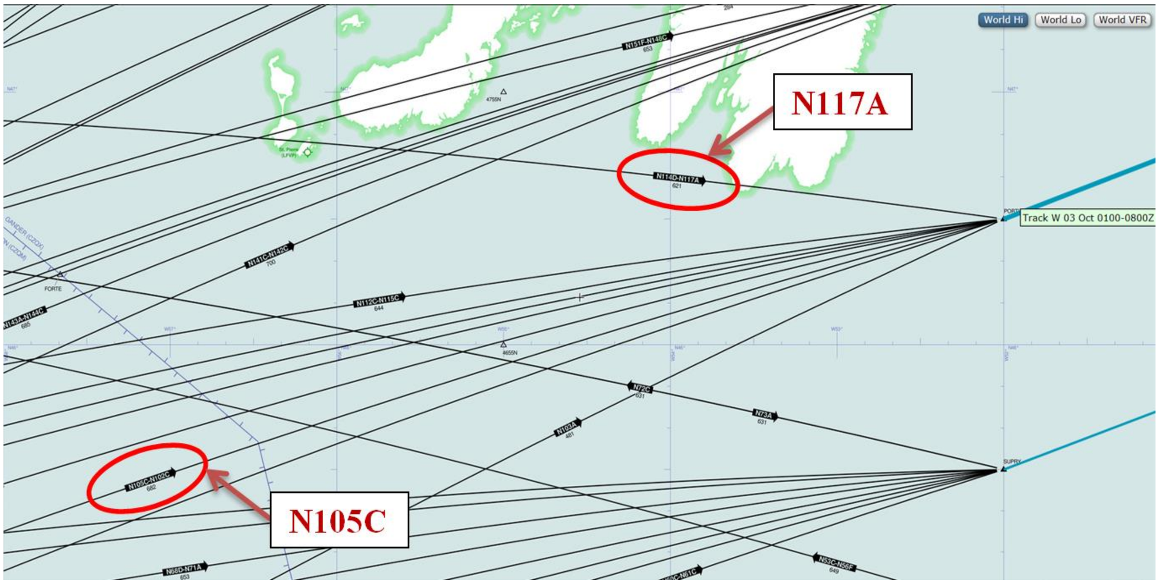
Track W PORTI 47/50 49/40 50/30 51/20 DINIM ELSOX	**Track B:** GOMUP 59/20 59/30 58/40 56/50 JANJO
AST LVLS 320 330 340 350 360 370 380 390 400	WEST LVLS 310 320 330 340 350 360 370 380 390
NAR N105C N117A-	EUR RTS WEST GINGA

A track is defined by a sequence of waypoints. Table 4-1 presents the waypoints used to define Track W. A waypoint is a point in space designated by latitude and longitude coordinates.

Sometimes, names are given to waypoints that are, for example, frequently used. The waypoints in the track definition could be given by their names (e.g., PORTI and ELSOX) or their actual latitudes and longitudes (e.g., 47/50 and 49/40). Aircraft that use a track need to travel each of the waypoints sequentially as specified in the definition. For example, aircraft that use track W need to start from PORTI (entry point) to 47/50 to 49/40 to 50/30 to 51/20 to DINIM to ELSOX (exit of the OTS).

Several flight levels will also be specified for each track in the track definition, and aircraft need to use one of the flight levels when they use the track. Usually, there is one flight level every 1000 ft. For example, for track W, nine flight levels, from FL 320 to FL 400, are specified.

The hemispherical rule may not be observed in the OTS since the vertical separation between traffic of the same heading is 1000 ft. (instead of 2000 ft. if the rule is observed). This doubles the airspace capacity for the directional flights that the OTS serves, and the minimum separations required in the MNPS and RVSM airspace are still maintained. In other words, the OTS increases airspace capacity without comprising safety. This could be achieved mainly because the two major alternating air traffic flows are concentrated on two peak time periods that have little overlapping.



Eastbound OTS on October 3th. Source: http://skyvector.com/ (SkyVector ARINC 2014) [fair use]

Figure 4-2: An example of routes leading to the entry point of an eastbound track

For each eastbound track, routes that lead to its entry point will be designated. For example, in Table 4-1, two routes (i.e., N105C and N117A marked by the red circles in Figure 4-2) are designated for aircraft that use track W. Aircraft that use track W need to follow one of the two routes to enter the track.

Westbound OTS on October 3th. Source: http://skyvector.com/ (SkyVector ARINC 2014) [fair use]

Figure 4-3: An example of waypoints leading to the entry point of a westbound track

For the westbound OTS, a waypoint will be designated for each track in the track message, which aircraft need to reach before entering the track. For example, in the table, waypoint GINGA (marked by the red circle in Figure 4-3) is designated for aircraft that use track B. Aircraft that use track B need to reach this waypoint and then travel to the entry of Track B.

The typical validity time of the OTS is as follows:

Daytime OTS: 1130 UTC to 1900 UTC at 30 W (westbound tracks)

Nighttime OTS: 0100 UTC to 0800 UTC at 30 W (eastbound tracks)

Track and flight level assignment

The use of OTS is not mandatory. Flights may fly on random routes which remain clear of the OTS or may fly on any route that joins or leaves an outer track of the OTS. According to (European and North Atlantic Office of ICAO 2012), about 50% of NAT flights use the OTS.

If a flight is planned to stay in the OTS from the oceanic entry point until the oceanic exit point, its operators should specify their intended track in the flight plan. The intended Mach number and flight level should be specified at either the last domestic reporting point prior to the entry of oceanic airspace or the organized track commencement point.

In February 2013, a data link mandate (Federal Aviation Adminstration 2012) is implemented, which creates an exclusive airspace covering the flight levels between FL 360 and FL390 inclusive on two tracks (called core tracks) of each OTS. The two core tracks and flight levels used to create the exclusive airspace will be specified in the track message. Only aircraft equipped with operating Automatic Dependent Surveillance-Contract (ADS-C) and Controller Pilot Data Link Communication (CPDLC) are eligible to use the exclusive airspace. Aircraft with the required equipment are also eligible to request tracks and flight levels not in the exclusive airspace. A new data link mandate which further expands the exclusive airspace will be implemented in 2015 (Federal Aviation Adminstration 2013).

ADS-C is a way of surveillance that relies on automatic reports (e.g., an aircraft's current position) from aircraft avionics to ground controllers via satellites. The reports are done in accordance with agreements between pilots and controllers. For example, the agreements could be that reports are sent to controllers if some events happen (e.g., a significant waypoint on the flight plan is reached) or a specific time interval (e.g., 10 or 20 minutes) is reached. Since the method does not rely on radar, it could provide accurate surveillance information even if aircraft are in remote and oceanic areas, which there is little or no radar coverage.

CPDLC is a data link application that allows text message communications between pilots and controllers via satellites. It improves the communication qualities and capabilities in remote and oceanic areas, where communications between pilots and controllers primarily relied on HF radio in the past.

Both ADS-C and CPDLC are satellite-based data link applications. ADS-C is primarily used for surveillances by ground controllers, and it requires little pilots' intervention. CPDLC is primarily used for communications between pilots and controllers, and it requires pilots to send messages to controllers and respond to the messages from the controllers. ADS-C could automatically send information from aircraft to controllers while allowing limited information to be sent from controllers to pilots. In contrast, CPDLC allows information to be sent between the pilots and controllers while the communications usually could not be done without pilots' involvement.

Pilots make requests when they are close to the OTS. The longitudinal separations in the OTS and flight-path clearance (from those that have been given clearance) are two important factors that controllers will consider when assigning tracks, flight levels, and Mach numbers (OTS assignment). If a flight’s preferred track and flight level is not available, controllers will consider other flight levels or tracks until one is found.

Operating aircraft inside the OTS

Flights inside the OTS are expected to follow their assigned tracks, flight levels, and Mach numbers to maintain separations. Any changes to those assignments need to be reported to and approved by controllers. In particular, operators may include step climbs for fuel efficiency inside the OTS in their flight plans. However, whether the step-climbs can be performed depends on the traffic conditions at the time when the climb request is made. Since there is littler radar coverage over the ocean, flights need to report their positions to controllers either via ADS-C or VHF radio. Though flights could send their position reports at any locations (e.g., every 10 or 20 minutes using ADS-C), they usually need to send one when they are at every 10 degrees of longitude (the reporting points are usually included in the flight plan).

Flights could be planned to fly cross the OTS; however, it is very likely that controllers will reroute those flights or make significant changes to their planned flight levels during most of the OTS traffic periods.

Section 4.2 Objective of This Chapter

The OTS has been providing a successful trade-off between capacity and operating efficiency (European and North Atlantic Office 2012). Considering the fact that some of factors (e.g., time zone differences and noise constraints) that lead to the relatively concentrated unidirectional traffic flows are unlikely to change, it is reasonable to believe that the need for the system is a long-term one.

In recent years, more flights are equipped with advanced avionics such as ADS-C/B (Broadcast) and CPDLC. Those avionics significantly improve the situational awareness of the pilots and controllers as well as the communications between them in remote and oceanic areas. Particularly, they make tracking flights over the NAT region easier. As a result, it is possible to apply new procedures and adopt reduced separation minima in the OTS to increase its capacity without undermining operational safety (Almira Williams, Stephane Mondoloni et al. 2005).

The proposed changes need to be carefully evaluated for their benefits and costs related to, for example, fuel consumption, flight time, controller workload, capacity and safety. Usually, they need to undergo some initial feasibility assessment to determine whether they could be practically and safely achieved before they can be put on expensive and time-consuming operational trials in real airspace (European and North Atlantic Office 2012). For such an assessment, simulation models usually considered a promising choice because they offer quick, inexpensive, and relatively realistic evaluations. The objective of this chapter is to develop a microscopic simulation tool to model the air traffic in the OTS. The simulation tool can be used to evaluate changes to policies, procedures, and technologies as well as to help the daily design of the OTS.

Section 4.3 Literature Review

(Stephanie Chung 2008) developed a North Atlantic Simulation model (NATSIM), which forecasts future demand and provides long-term operational and financial estimates resulting from policy and system change. However, NATSIM is a macroscopic model and therefore it offers relatively less details about the microscopic movements of the traffic in the OTS. From this point of view, it may not be able to sufficiently model the OTS assignment, conflict detection and resolution in details.

The Flight Cost Model (FCM) is developed under the sponsorship of the FAA to determine the potential fuel savings of proposed changes to NAT airspace separation standards due to future system improvements (G.J. Couluris 1981, Federal Aviation Adminstration 1998). The FCM is designed to model the 1979 NAT air system and is written in a discrete time simulation language called SIMSCRIPT II.5.

In the FCM, the aircraft is moved from node to node. Before the aircraft moves to the next node on its path in the domestic airspace, path clearance is checked to determine whether the path from current node to the next node is in conflict with the paths of other aircraft. If the path is clear, the aircraft moves to the next node and the arrival time is estimated. The processing of the aircraft is suspended until the system reaches its arrival time. If the path is not clear, a conflict-free path is determined. For the oceanic airspace, the system works in the same way as in the domestic airspace except that the path clearance may be checked for more than one node. For the climb request for fuel efficiency, the path clearance at the requested flight level is checked to determine its feasibility. If the flight path at the requested flight level is in conflict with the paths of other aircraft, then the aircraft stays at its current flight level; otherwise, it could climb.

Using a similar idea, (Christine M. Gerhardt-Falk 2000) developed a Flight Tracking Model (FTM), which moves an aircraft from its current waypoint to the next one, and calculates travel time and fuel consumption. One of the disadvantages of those two models is that if the distance between two waypoints (nodes) is large, some details may not be sufficiently captured (e.g., the traffic movements at the OTS entry and exit areas).

The North Pacific (NOPAC) Track system computer simulation model is developed by the FAA in 1984 to examine the safety impact of a new separation rule implemented in 1982 (Livingston 1984). The NOPAC is a discrete time model of the oceanic air traffic to provide comparative analysis of the total system burn, step-climb advantage, and route occupancy due to congestion influences. The model generates flight requests based on empirical data and determines the path assignment using probability distributions. Each choice is evaluated for conflicts before being allocated. Once a path is determined, information such as take-off time, aircraft type, path, direction, and take-off weights are kept. Step-climbs for fuel efficiency are also generated if they are conflict-free. In the simulation, a position update is made at the start of a flight or step-climb event to track the departure times, step-climbs, and weight changes of the aircraft. Fuel adjustments are calculated with altitude changes from step-climbs. The position updates are also used to calculate collision risk information. The major disadvantage of NOPAC is that it is developed for air traffic over the Pacific and therefore lacks the capability to model the traffic around/inside the OTS.

Transport Canada developed a North Atlantic Traffic Allocation Model (NATTAM) in 1991 to estimate the occupancy for the NAT airspace to evaluate the safety impact of new separation standards (International Civil Aviation Organization 1994). However, NATTAM does not generate economic measures (e.g., fuel consumptions), which are considered in many comparative analyses on the proposed changes for the OTS (see, for example, (Christine M. Gerhardt-Falk 2000), (Almira Williams 2006, Norma V. Campos 2013)).

The North Atlantic Track model is developed in 1988 by the CAA of the UK to estimate the congestion penalty (cost due to traffic volume conflicts causing deviations from optimal flight profiles) and level cruise penalty (cost due to the convention of flying on fixed flight levels as opposed to cruise-climbing). However, the model is primarily used to model westbound and random track traffic and does not consider meteorological conditions.

(Almira Williams 2006) developed a simulation model to assess the benefits of reduced separations in the OTS. Their model consists of four subroutines. The first one is the demand generation subroutine, which generates flights for the following routines as input. The second one is a fuel consumption subroutine, which evaluates fuel cost using two fuel consumption models. The first model determines the fuel consumption for a given flight profile (flight path, flight level and cruise speed). The second one determines the optimal flight profile (i.e., flight profile with the lowest fuel consumption) and the corresponding fuel consumption for each flight by flight profiles enumeration. For a given flight profile, both models estimate fuel consumptions by integrating backwards from the destination airport with appropriate landing weight to the origin airport. The third subroutine is a track selection model, which determines the OTS assignment using a flight path exhaustive algorithm. For a flight using the OTS, the model first enumerates all the possible flight paths using the OTS and evaluates their fuel costs. Then, a Monte Carlo simulation is used to calculate the probability of choosing each flight level of each track by assuming different departure times for the flight. In the Monte Carlo simulation, other flights are assumed to take the flight paths with the lowest cost. At last, an expected fuel cost is calculated for each track by weighting the fuel cost of the flight levels on the track with the probabilities of choosing those flight levels. The flight will pick up the track with the lowest expected fuel cost. The fourth subroutine is a discrete time simulation model, which adjusts the flight levels of the chosen flight paths to avoid conflicts and maintain optimal flight profiles.

Using a similar idea, (Aswin Kumar Gunnam 2012, Aswin, Antonio et al. 2014) evaluated the benefits of several more realistic reduced separation scenarios in the OTS. In essence the above two models are designed based on flight profile enumeration. Though they are efficient and could procedure estimates with acceptable accuracy, it is difficult to enumerate all the possible flight profiles for some cases where the degree of freedom is high (for example, climb inside the OTS and conflict resolution).

This chapter presents a new microscopic discrete-time event simulation model to simulate the air traffic using the OTS. In contrast to the previous models, our model is 1) closer to the flight operations in the real system, 2) more flexible in the sense that it could be easily adapted to model air traffic in other airspaces (e.g., Pacific airspace and domestic airspace). In particular, our model updates all the units (e.g., pilots, aircraft, and controllers) in the system from one time interval to the next one. In this case, all the aircraft in the air are considered simultaneously at each time interval and therefore, the interactions between aircraft are easier to capture.

In addition, we proposed four new operational procedures to improve the flight operations for the OTS. Two procedures aim to benefit flights once they are inside the OTS. One allows flights to climb inside the OTS for a better fuel efficiency and the other one allows flights to switch tracks to reduce travel time and therefore fuel consumption. The other two procedures aim to improve the OTS assignments in the OTS entry area. One allows controllers to adjust a flight's Mach number to increase the arrival time separation. The other one allows controllers to assign multiple flights simultaneously to achieve a better OTS assignment. The four procedures are implemented with the simulation model and their benefits are analyzed in terms of fuel savings. Several implementation issues are discussed and some recommendations are given.

Section 4.4 Methodology

The model developed in this study is a discrete-time simulation model, which updates the system from time n to time n+1. Particularly, the model updates three types of information in the simulation at the end of each time interval using three routines: pilot routine, ATC routine, and system updates routine.

Subsection 4.4.1 Pilot routine:

The first type of information is related to an aircraft's actions at time n+1. In this study, an aircraft's action is controlled by a pilot routine. The routine determines an aircraft's actions by using its flight plan, commands from the controllers, and the meteorological conditions around the aircraft. For example, if the aircraft is climbing to a new flight level assigned by the controllers, and has just reached the new flight level at time n, then the pilot routine will change the status of the aircraft to cruise at time n+1; otherwise, the pilot routine will keep the aircraft climbing at time n+1. Actions other than those specified by controllers and those to keep the aircraft flying in accordance with the cleared flight plan will need approval from the ATC. The pilot routine could also send requests to controllers. The two most important requests are OTS assignment request and flight-level-change request for fuel efficiency.

The OTS assignment request (e.g., track, flight level, and Mach number inside the OTS) is made by the pilot routine when the aircraft is close to the OTS (for example, 30-40 minutes away from the OTS). For a flight, we define the fuel consumption of using an OTS assignment as the total fuel consumption of flying from its origin airport to its destination airport using the assignment. For each flight, the fuel consumptions of using all possible OTS assignments are estimated by the simulation model developed by (Aswin Kumar Gunnam 2012). As explained in the literature review, Gunnam's model enumerates all the flight paths for a flight with all the possible OTS assignments that the flight could use, and calculates the fuel consumption for each flight path. In this study, we assume that the pilot routine will prefer and request the OTS assignment with the least fuel consumption. For simplicity, we call this OTS assignment the preferred assignment.

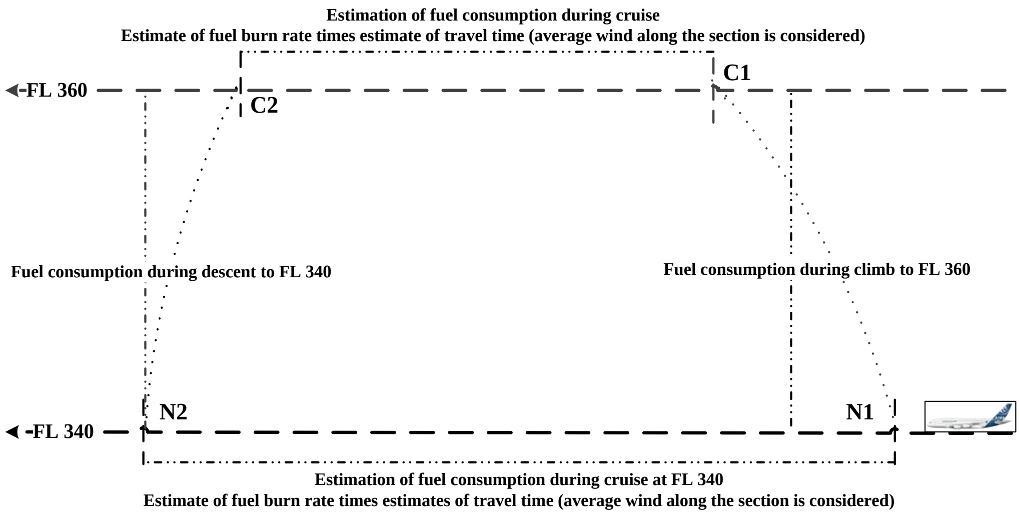


Figure 4-4: The decision-making process for making climb requests for fuel efficiency

To evaluate the need to change flight level for fuel efficiency, the pilot routine compares the fuel consumption of staying at the current flight level with those at other flight levels. A request for changing flight levels may be made only if staying at some other flight levels could offer a better fuel efficiency. In the following, we provide an example in Figure 4-4 to illustrate the decision-making process of making such a request.

The routine first needs to select a target waypoint on the flight plan. The target waypoint could be any waypoint on the flight plan whose associated flight level has been given clearance (i.e., the flight could stay at the flight level until that waypoint). In the figure, we assume that the target waypoint is N2, and its associated flight level is FL 340.

The routine estimates the fuel consumption from the aircraft's current position to the target waypoint by assuming that the flight level in the flight plan is followed. In the example presented in Figure 4-4, it is the fuel consumption of reaching waypoint N2 at FL 340 by cruising at FL 340 from N1.

The routine chooses several candidate flight levels other than the aircraft's current flight level. The candidate flight levels can be selected from the range of flight levels that the aircraft is capable of reaching and is eligible to reach. For example, the upper bound of the range could be determined by aircraft performance, and lower bound is the lower bound used to define the MNPS airspace (i.e., FL 290). For each candidate flight level, the routine estimates the fuel consumption if the candidate flight level is used to travel from the aircraft's current position to the target waypoint and its associated flight level. In the example, it is the fuel consumption of reaching N2 at FL 340 by cruising at FL 360 from N1. The fuel consumption estimate consists of three parts. The first part is the fuel consumption used to climb (or descend) to the candidate flight level. In the figure, this part is the fuel consumption used to climb from N1 to C1. The second part is the fuel consumption used to cruise to the point where the aircraft begin to descend (or climb) to the flight level associated with the target waypoint. This part is the fuel consumption used to cruise from C1 to C2 for the example in the figure. The third part is the fuel consumption used to descend or climb to the flight level associated with the target waypoint. In the figure, this part is the fuel consumption used to descend from C2 to N2.

If staying at the current flight level requires more fuel consumption, the pilot routine may send a climb or descent request to the candidate flight level with the least fuel consumption for fuel efficiency.

The pilot routine also could send request for changing flight levels without considering the fuel efficiency. Possible scenarios to trigger this decision could be severe weather, turbulence, or descend to destination. In addition, flight path conflict with other flights is not a major factor considered by the pilot routine when evaluating the need of a flight-level change. Instead, it would be considered by the ATC routine when evaluating the feasibility of a request for changing flight levels.

In Section 4.6, a new operational procedure is developed, which gives the pilot routine the ability to send requests for changing flight levels and switching tracks inside the OTS.

Subsection 4.4.2 ATC routine:

The ATC routine in this study is designed to simulate the behaviors of the ATC controllers, and it has two primary roles in the baseline scenario: the first one is to process OTS assignment requests, and the second one is evaluate the feasibility of the requests for changing flight levels.

Processing requests for OTS assignment

The routine considers two aspects to evaluate the feasibility of an OTS assignment request. Both of them are related to maintain minimum separations or avoidance of flight path conflicts.

The first aspect is to maintain the minimum longitudinal separation inside the OTS. In this study, the default minimum longitudinal separation inside the OTS is assumed to be10 minutes (about 50-60 nm separation by distance). A Mach number technique is introduced to adjust the minimum longitudinal separation based on the differences in aircraft speeds. The adjustment is made using the following formula:

$$\mathbf{minimum\ longitudinal\ separation} = \begin{cases} \mathbf{max(10+k_{open}(S_L-S_F),5), for\ openning\ case}\ (\mathbf{S_L \geq S_F}) \\ \mathbf{max(10+k_{close}(S_L-S_F),5), for\ closing\ case}\ (\mathbf{S_L < S_F}) \end{cases} \quad \textbf{(4-1)}$$

where $\mathrm{k_{open}} = -100$ and $\mathrm{k_{close}} = -300$, $\mathrm{S_L}$ and $\mathrm{S_F}$ are the speed (in terms of Mach number) of the leading and following aircraft, respectively.

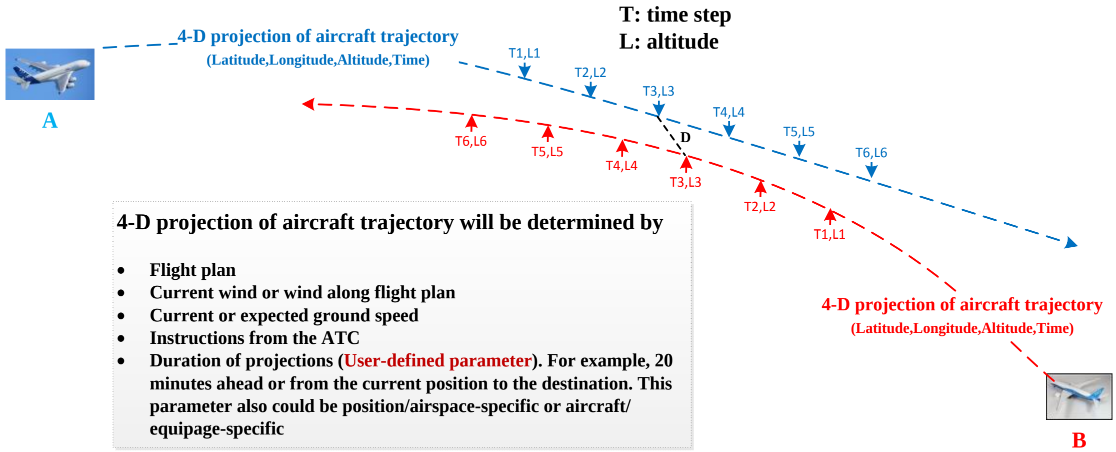


Figure 4-5: Conflict detection

The second aspect is the flight-path clearance; that is, whether there would be flight-path conflicts between flights. For a flight that has sent its OTS assignment request, the ATC routine makes a 4-D projection (latitude, longitude, altitude, and time) of its flight path (as shown in Figure 4-5). When making the projection, the ATC routine considers the OTS assignment being evaluated, the flight's flight plan, wind, speed, and instructions from the ATC routine. The projection is from the flight's current position to the entry point of the OTS assignment being evaluated for the flight.

Rules specified in the Air Traffic Organization Policy (U.S.Department of Transportation 2011) for areas with sufficient radar coverage will be considered when the routine checks potential conflicts in the projected flight paths. In particular, the following two separation minima are applied:

1) The vertical separation of the projected flight paths should be no less than 1000 ft., or
2) The lateral and longitudinal separation of the projected flight paths should be no less than 5 miles.

For example, for the projected flight paths of flight A and B in the figure, the routine will examine the separations between the two at each time step. If the difference in altitudes (i.e., L) of the two aircraft is less than 1000 ft., for example, at time T3, then the routine continues to examine the lateral distance (e.g., the distance D at T3) between the two. If the distance is less than 5 miles at the time step, then the two flights will be considered to have flight-path conflicts with each other.

Whether two flights have flight-path conflicts, to some extent, depends on how the ATC routine makes their flight paths projections. In the OTS assignment process, projecting a flight's flight path is flexible in that the controllers could assume that the flight starts to climb/descend a flight at any time that is feasible. Since the controllers must accommodate an OTS assignment request within a limited time period, it will be helpful if the controllers could consider multiple projections of a flight's flight path. This could reduce a flight's probability of getting a flight path conflicts. In our study, the ATC routine will make multiple projections of a flight's flight path by assuming different times to start to climb/descend to the flight level being considered, and the flight path to an OTS assignment is considered to be clear as long as one of those projections is clear.

An OTS assignment may be given to a flight only if there is the minimum longitudinal separation inside the OTS will be maintained and its projected flight path to the assignment is clear; otherwise, the ATC routine will consider other assignments for the flight.

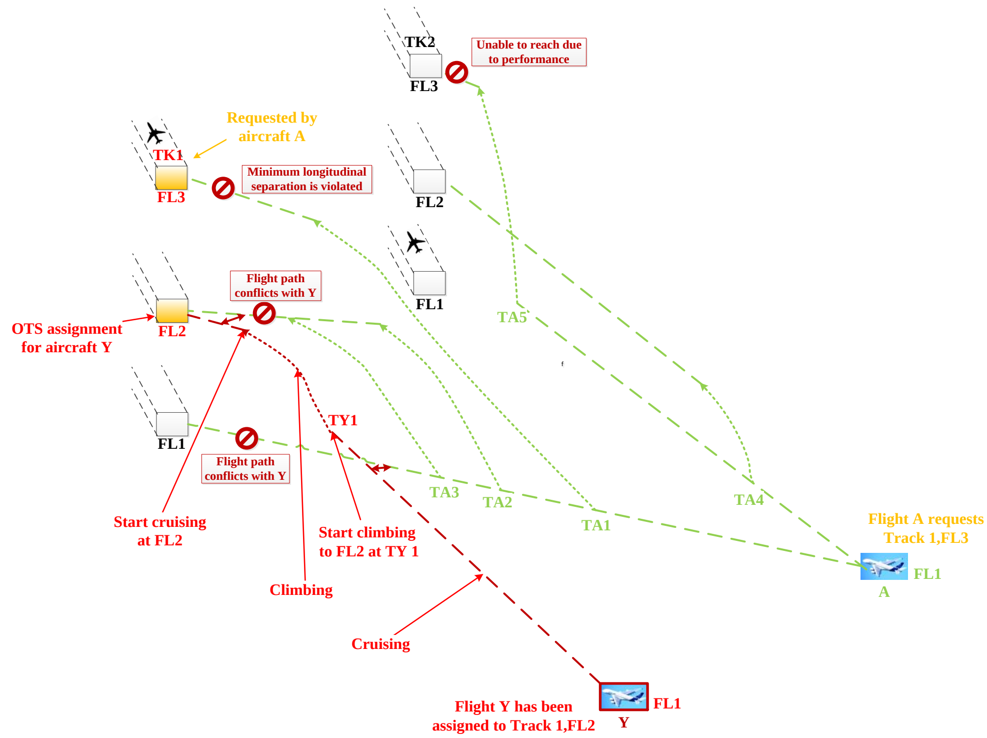


Figure 4-6: Illustration of the OTS assignment process

Figure 4-6 presents an example of the OTS assignment process performed by the ATC routine. In the figure, flight Y has been assigned to track TK1 and flight level FL2, and the red line is its projected flight path from its current position to the entry of its assignment. Flight A requested track TK1 and flight level FL3. For this request, the ATC routine estimates its arrival time at the assignment, and evaluates the longitudinal separations between flight A and the flights that have been given the assignment using Eq (4-1). In this case, the assignment is infeasible because the minimum longitudinal separation will not be maintained. The routine continues to consider flight level FL2 on the same track. For this assignment, the minimum longitudinal separation inside the OTS will be maintained. The routine will proceed to examine the flight-path clearance by searching conflicts in the projected flight paths between flight A and those that have been given assignments.

In this example, for simplicity, the routine makes two flight path projections for flight A: one is made based on the assumption that it starts to climb to FL2 at TA2, and the other with the assumption that it starts to climb at TA3. However, for both projections, there are conflicts with that of flight Y. As a result, this assignment is infeasible for flight A. Similarly, flight level FL 1 on track TK1 is also infeasible. Since flight level FL1 and the flight levels below it on track TK1 are all infeasible for flight A, the routine begins to examine flight level FL3 on track TK2. In this example, flight level FL3 on track TK2 is infeasible due to possible limitations in aircraft performance; that is, the aircraft may be too heavy to reach the flight level when it arrives at the entry. The routine continues to examine flight level FL2. For this assignment, the minimum longitudinal separation will be maintained, and there are no conflicts in the projected flight paths between flight A and those that have been given assignments. Therefore, track TK2 and flight level FL2 will be given to flight A as its OTS assignment. This assignment deviates from its preferred one by one track and one flight level.

Once a feasible OTS assignment is found, the ATC routine will send the assignment and instructions to reach the assignment to the pilot routine. The pilot routine follows the instructions to reach the assignment. For example, the pilot routine will start to climb or descend the aircraft to the assigned flight level according to the time specified by the ATC routine.

Processing requests for flight-level changes outside the OTS:

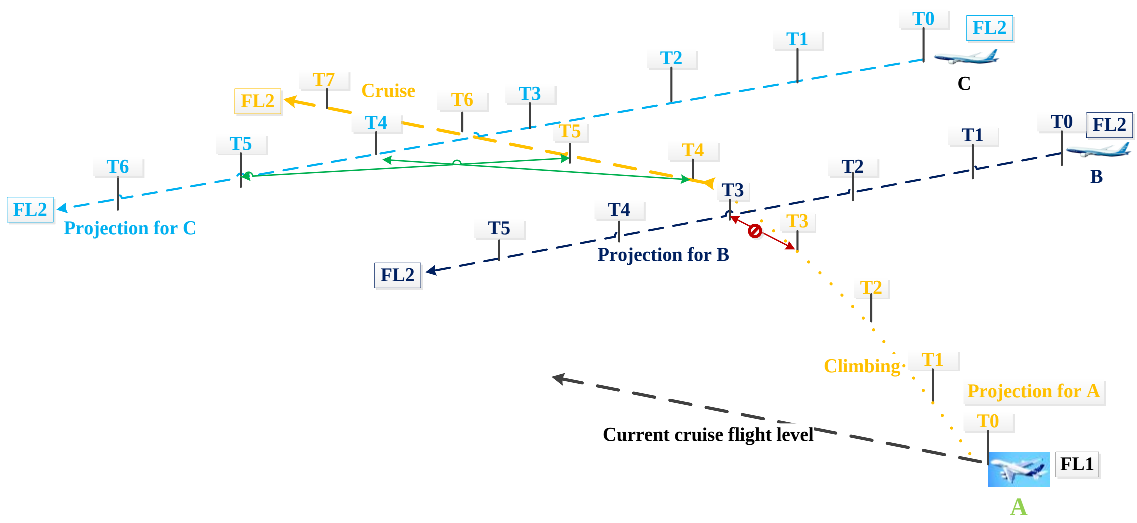


Figure 4-7: Processing flight-level-change requests

For flights that use the OTS, we assume that there is sufficient radar coverage when they are outside the OTS. To evaluate the feasibility of a request for changing flight levels outside the OTS, the primary factor that the ATC routine considers is to maintain the minimum separations between flights at the requested flight level and flight levels that the climb will traverse.

Methods similar to those used to detect flight-path conflicts in the OTS assignment will be used except that the projection is given in terms of time period (e.g., 20 minutes from now). The request for changing flight levels would be approved only if the minimum separations will be maintained at the requested flight level and flight levels that the climb will traverse; otherwise the request will be denied.

Figure 4-7 presents an example of how a request for changing flight levels is processed by the ATC routine. In the example, flight A has sent a request to climb from flight level FL1 to flight level FL2, and two flight (B and C) are cruising at flight level FL2. For simplicity, we assume that there is no flight level between the two flight levels.

The ATC routine first makes flight-path projections for the three flights: flight A (orange), B (dark blue line) and, C (light blue line) from time T0 to T7. The flight-path projection for flight A is made based on the assumption that flight A starts climbing at time T0. For each time step, the routine examines the position projections of the three flights for violations of minimum separations. For example, at time T0, there are no violations since flight A is vertically separated from the other two flights, and flights B and C are laterally separated. There are no violations of minimum separations between flights A and B at any time step. For flight A and B, the minimum separation at time T3 may be violated since the vertical separation between the two is less than 1000 ft. and the lateral separation is less than 5 miles. As a result, the request for changing flight levels is infeasible and will be denied. The ATC routine will send the decision to the pilot routine of flight A, and the pilot rountine will keep the aircraft at its current flight level. However, if flight B does not exist, then the request may be approved.

In Section 4.6, two new procedures are developed for flights inside the OTS. One is flight-level change for fuel efficiency; the other one is track switch. The processes of evaluating the requests for performing those two procedures by the ATC routine will be introduced in the corresponding section.

Conflicts detection:

In this study, one of the most important functionalities that the ATC routine has is the detection of flight-path conflicts. Each time a flight sends a request for changing flight levels, track switch or OTS assignment, a conflict detection will be performed by the ATC routine to evaluate the feasibility of the request. However, because of the focus of modelling efforts, the conflict detection procedure is implemented differently in different phases of a flight.

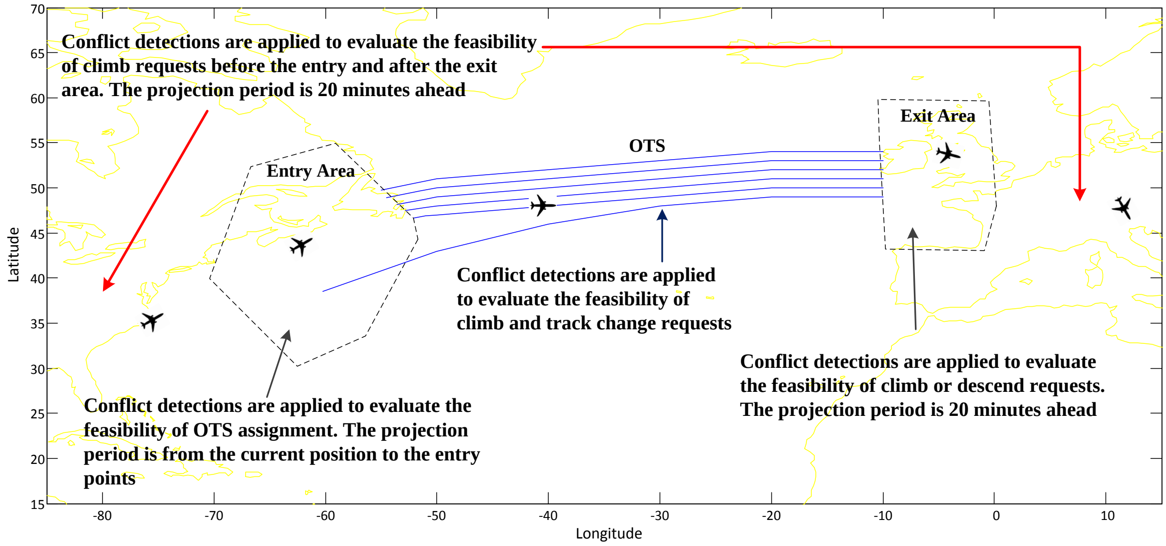


Figure 4-8: Conflict detection in different phases of a flight

As shown in Figure 4-8, a transatlantic flight that uses the OTS could by divided into five phases: 1) from its origin airports to the entry area, 2) in the entry area of the OTS, 3) inside the OTS, 4) in the exit area of the OTS, and 5) from the exit area to its destination airports.

In the OTS entry area, there is sufficient radar coverage, and the conflict detection is applied to determine the feasibility of an OTS assignment. Two types of conflicts will be inspected. The first one is the violation of minimum longitudinal separation between flights inside the OTS. The second one is the flight-path conflicts between flights in the OTS entry area. To detect conflicts of this type, the ATC routine creates multiple flight-path projections from a flight's current position to the entry of the OTS assignment.

Once flights are inside the OTS, the minimum lateral and vertical separations are expected to be maintained by the design of the OTS, and the longitudinal minimum separation is maintained by using appropriate OTS assignments. Therefore, conflict detections are not applied for flights that cruise inside the OTS. However, the conflict detection will still be applied to evaluate the feasibility of requests for changing flight levels or switching tracks inside the OTS (more details are presented in Section 4.6).

In the OTS exit area, there is sufficient radar coverage, and conflict detections are used to determine flight path clearance for climb/descent requests for fuel efficiencies, following hemispheric rule, and changing headings. Rules similar to those used in the entry area will be applied to detect conflicts; however, the projection period is 20 minutes ahead.

The other phases (i.e., 1 and 5) of a flight are not of significant concern to this study, for simplicity, the conflict detection is only implemented to evaluate the feasibility of requests for changing flight levels.

Subsection 4.4.3 System updates routine:

System updates routine is responsible for determining the position and the weights of each aircraft, and the meteorological conditions around each aircraft at time n+1. In addition, this routine also provides estimates of aircraft performance (e.g., estimate of travel time and fuel consumption between two points or two flight levels) that are used in the decision-making processes of the pilot routine and the ATC routine.

Aircraft position update:

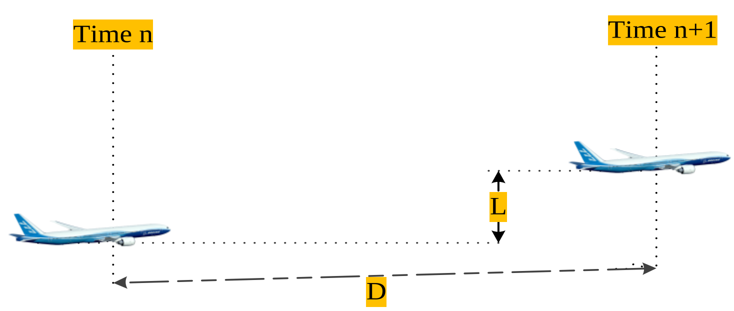


Figure 4-9: Position update

As shown in Figure 4-9, to determine the position of an aircraft at time n+1, the model calculates the distance travelled on a horizontal surface from time n to time n+1 (i.e., the distance D) and the change in altitude L from time n to time n+1.

L is equal to the rate of climb (ROC)/ rate of descent (ROD) times the length of step time Δ, where ROC/ROD is determined by the pilot or ATC routine.

To calculate D, the aircraft's groundspeed speed (i.e., speed relative to the ground) (V_{GS}) is first estimated. The ground speed is determined by the aircraft's True Air Speed (TAS) (V_{TAS}) and the surrounding wind. V_{TAS} is calculated as follows:

$$V_{TAS} = V_M \times V_{sound},$$

where V_M is the aircraft's Mach number, and V_{sound} is the speed of sound at the aircraft's geo-potential altitude.

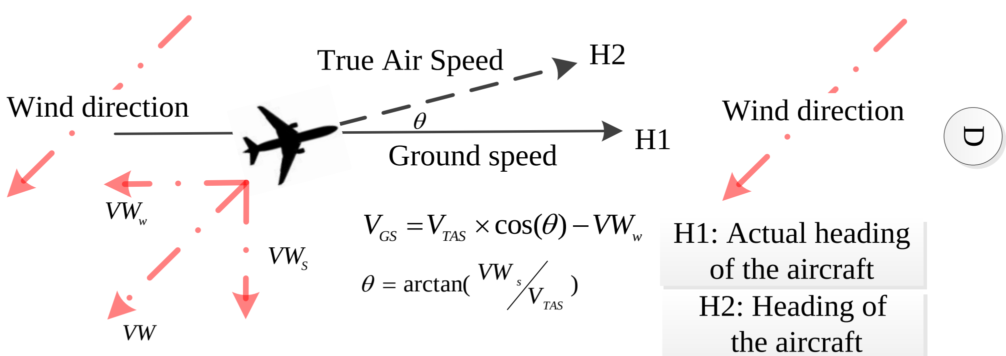


Figure 4-10: Impact of the wind

Wind is another important factor that affects the ground speed. Figure 4-10 illustrates the impact of the wind on an aircraft's ground speed and heading. In the figure, the aircraft is heading to point D, and the wind has a component (VW_w) opposite to the direction of travel and a component perpendicular to the direction of travel (VW_s). The component VW_w reduces the aircraft's ground speed towards D, and the component VW_s makes the pilots set the heading (i.e., the direction of the aircraft's TAS) as H2 to gain an actual heading of H1 (i.e., the direction of the aircraft's ground speed). As a result, aircraft ground speed is given as

$$V_{GS} = V_{TAS} \times \cos(\theta) - VW_w,$$

where θ is the angle difference between H1 and H2. The distance travelled in one step time Δ is given as

$$D = V_{GS} \times \Delta$$

Weight update:

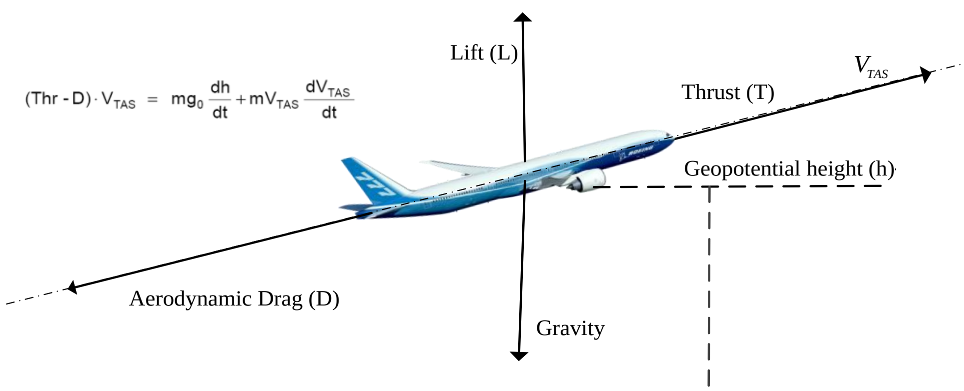


Figure 4-11: Weight update

The second update is the weight of an aircraft due to fuel consumption. To do so, the fuel flow rate at time n is calculated using the Base of Aircraft Data (BADA) user manual (Eurocontrol Experimental Centre 2008). BADA is an aircraft performance model developed and maintained by EUROCONTROL through cooperation with aircraft manufacturers and airlines (Eurocontrol Experimental Centre 2014). The information and data in BADA is designed for use in aircraft trajectory simulations in air traffic modelling. Each BADA aircraft type has its own parameters and coefficients specifying the characteristics (such as dimensions and mass) and performances (such as thrust) of the aircraft that it represents. In BADA, fuel flow rate of a jet engine aircraft (most of the commercial aircraft are jet engines) is a function of thrust (T) and TAS V_{TAS}. Based on the status (i.e., climb, descent or cruise) of an aircraft, it is calculated as follows:

- Nominal fuel flow rate f_{nom} (kg/min) for phases except idle descent and cruise: $f_{nom} = \eta \times T$,
- Cruise fuel flow f_{cr} (kg/min) for cruise: $f_{cr} = \eta \times T \times C_{fcr}$,
- Minimum fuel flow f_{min} (kg/min) for idle thrust descent conditions: $f_{min} = C_{f_3} \times \left[1 - \frac{H_p}{C_{f_4}}\right]$,

where $\eta = C_{f_1} \times \left[1 + \frac{V_{TAS}}{C_{f_2}}\right]$, H_p(ft.) is the geopotential pressure altitude, C_{f_1}, C_{f_2}, C_{f_3}, C_{f_4}, and C_{fcr} are coefficients specific for the aircraft type. Thrust T is estimated by using the total energy model:

$$(T - D) \times V_{TAS} = mg\frac{dH}{dt} + mV_{TAS}\frac{dV_{TAS}}{dt},$$

where m is the aircraft mass, H is the geopotential altitude, g is the gravitational acceleration, and D is the aerodynamic drag, which is given by:

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

where S is the wing reference area (m^2), ρ is the air density (kg/m^3), and $C_D = C_{D0,CR} + C_{D2,CR} \times (C_L)^2$, where $C_L = \frac{2mg}{\rho(V_{TAS})^2 S\cos(\varphi)}$ is the lift coefficient corrected for bank angle φ, $C_{D0,CR}$, and $C_{D2,CR}$ are aircraft specific drag coefficients. For a discrete time model with step time Δ, the above equation could be rewritten as

$$(T - D) \times V_{TAS} = mgR\Delta + mV_{TAS}a\Delta,$$

where R is the rate of altitude change (climb/descent), and a is the acceleration of the TAS. We assume that the fuel flow rate is constant from time n to time n+1. This is a reasonable assumption if the time interval is sufficiently small. The fuel consumption from time n to time n+1 is calculated by multiplying the fuel flow rate by the length of step time Δ. The fuel consumption is subtracted from the weight at time n to get the weight at time n+1.

Meteorological conditions update:

The system updates routine updates the meteorological conditions around an aircraft based on the aircraft's position at time n+1. If the meteorological conditions are not available at the position, the conditions at the positions that are in close proximity to the aircraft's position or interpolation results will be used as the estimates.

Aircraft performance estimates:

The system updates routine also provides aircraft performance estimates that are used in the decision-making processes of the pilot routine and the ATC routine. The estimates can be classified into four types:

1) Estimate of the travel time between two points:

The travel time is estimated by dividing the distance between the two points by the average ground speed. The average ground speed is calculated by using the ground speed formula, in which the wind is the average wind between the two points. The travel time estimate is used to, for example, calculate the fuel consumption between two points, evaluate the need of switching tracks, evaluate the feasibility of a track-switch request, and create flight-path projections.

2) Estimate of the fuel consumption of cruising between two points:

The fuel consumption is estimated by multiplying the fuel flow rate by the travel time estimate of cruising between the two points. The estimate of fuel consumption is used to, for example, evaluate the need of changing flight levels for fuel efficiency and estimate an aircraft's the maximum operational altitude.

3) Estimates of the fuel, time, and distance needed to climb/descend between two flight levels:

Table 4-2: The Climb Profile of BADA Aircraft Type B763 with the Nominal Mass

Time (Seconds)	0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400	420
Distance (nm)	0	1	2	3	4	5	6	8	9	11	12	14	16	18	20	22	24	26	28	30	33	35
Flight level (ft.)	0	745	1,482	2,242	3,007	3,860	4,820	5,822	6,843	7,852	8,838	9,826	10,817	11,794	12,738	13,657	14,550	15,419	16,264	17,084	17,880	18,652
Fuel (kg)	0	86	171	256	339	422	504	586	667	747	825	903	980	1,056	1,130	1,204	1,275	1,346	1,415	1,483	1,550	1,616

For each BADA aircraft type, the BADA provides three typical climb/descent profiles corresponding to three weight scenarios: high mass, low mass, and nominal mass. Each profile specifies the fuel, time, and distance needed by the aircraft that the BADA aircraft type represents to climb/descend to a flight level with the corresponding weight. The fuel, time, and distance needed to climb/descend between two flight levels are estimated as the differences between those needed to climb/descend to each of the flight level. For example, Table 4-2 shows the climb profile of the BADA aircraft type B763 with the nominal mass. According to the table, the fuel, time and distance needed to climb from 745 ft. to 1482 ft. for the aircraft type with the nominal mass is 85 (171-86) kg, 20 (40-20) seconds, and one (2-1) nm, respectively. If the estimates corresponding to a flight level are not available in the BADA, interpolation of the profile will be used to create the estimates for the flight level. Estimates of the fuel, time, and distance needed to climb/descend between two flight levels are used, for example, to evaluate the need of changing flight levels for fuel efficiency, and to make flight-path projections.

4) The maximum operational altitude that an aircraft could reach at a position:

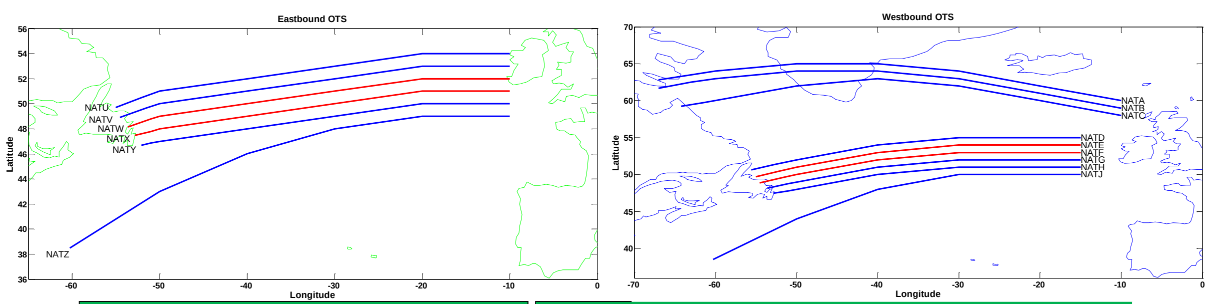
The BADA provides the maximum operational altitude that every BADA aircraft type could reach with several different weights. The routine estimates the maximum operational altitude that an aircraft could reach at a position by first estimating the aircraft's weight at the position, and then finds the altitude corresponding to the weight in the BADA. If the maximum operational altitude corresponds to the aircraft's estimated weight is not available in the BADA, then interpolation is used to estimate the altitude. The maximum operational altitude is used, for example, in the OTS assignment process and to evaluate the need of a request for changing flight levels.

All the estimates presented above are only used in the pilot routine and ATC routine's decision-making processes. The actual aircraft performance (e.g., travel times and fuel consumptions) are generated by the simulation.

Section 4.5 Baseline Scenario[11]

The baseline scenario is created based on the current structure of the OTS and operational procedures. The new procedures are evaluated by comparing with this scenario.

Track systems and OTS assignment:



Eastbound Tracks

Flight Level	NATU	NATV	NATW	NATX	NATY	NATZ
39000						
38000						
37000						
36000						
35000						
34000						
33000						
32000						
31000						

Westbound Tracks

Flight Level	NATA	NATB	NATC	NATD	NATE	NATF	NATG	NATH	NATJ
39000									
38000									
37000									
36000									
35000									
34000									
33000									
32000									
31000									

Light orange flight levels are open to all aircraft. Yellow flight levels are exclusive to equipped aircraft

Figure 4-12: Configurations of the OTS in baseline scenario

We use the two OTS systems (one for eastbound and one for westbound) published on July 26-27 2008 in our study. Figure 4-12 shows the configurations of their tracks and flight levels. There are six tracks in the eastbound OTS and nine tracks in the westbound OTS. Each track has nine flight

[11] Some of the modeling efforts in this section has been presented at the 2014 INFORMS annual meeting, the 26th and 27th Europe Technical Coordination Meeting, and the 2014 ICNS conference.

levels from FL 310 to FL 390. There are two core tracks (red lines in the figure) in each OTS (Tracks W and X for the eastbound OTS, Tracks E and F for the westbound OTS). An exclusive airspace exists between FL 360 and FL 390 inclusive on the two core tracks of each OTS (yellow cells in the figure). Only aircraft equipped with ADS-C and CPDLC could fly inside the exclusive airspace. Though the actual OTS changes from day to day, these two track systems are representative enough in terms of track structures that are currently being used.

In the baseline scenario, flights are not allowed to change flight levels for fuel efficiency outside the OTS; however, they are allowed to change their flight levels to reach the OTS assignments in the OTS entry area, and to follow the hemispherical rule once they exit the OTS. Once inside the OTS, they are expected to maintain their assigned tracks, flight levels, and Mach numbers until they reach the OTS exit points. Changing flight levels for fuel efficiency inside the OTS is not allowed either.

For the OTS assignment, the ATC routine follows the assignment procedure described in Section 4.4. Particularly, the following specific rules are used:

1) Flights send their OTS assignment requests when they are about 250 nm away (about 30-40 minutes) from their preferred assignments.
2) When the ATC routine inspects the flight levels on a track for a flight, it starts from the flight's preferred flight level. If the flight's preferred flight level is not feasible on the current track, the ATC routine will inspect three flight levels below the flight's preferred flight level on the current track before it begins to inspect flight levels on other tracks.
3) When making flight-path projections for a requesting flight, the ATC routine creates multiple projections by assuming that the flight climbs/descends to the flight level being considered at every one minute interval. For example, a requesting flight is currently at FL

310 and 30 minutes away from the entry point, and the ATC routine is inspecting the feasibility of FL 320 for it. The routine will make 30 projections of its flight path by assuming that the flight starts to climb to FL 320 one minute later, two minutes later,…, and 30 minutes later. The routine will assign the earliest feasible climb time (if the assignment is available) to the requesting flight.

4) Based on the statistics from the Gander control center and the interview of the controllers in the New York oceanic control center, we decide that the ATC routine does not adjust a flight's preferred Mach number for the OTS assignment in the baseline scenario.

Demand and flight plans:

To create the demand (flights) for the OTS, 3517 flights that could possibly use the OTS are considered first. These flights can be classified into two types: commercial flights (i.e., passenger and cargo flights) and the other flights (general aviation and military).

The commercial flights are obtained from the Official Airline Guideline (OAG) 2008. The other flights are obtained from the ETMS data of the same year. The OAG and ETMS data contain information about the origin, destination, departure time, and aircraft type of these flights. Their equipage (a factor used to determine whether they are eligible to use the OTS) is randomly assigned based on the FAA's survey on the equipage levels of some typical aircraft. In the baseline scenario, about 90% of the flights have the appropriate equipage to operate inside the exclusive airspace. The take-off weights of the flights are generated by using some empirical take-off-weight distribution from the Airlines for America.

Table 4-3: Distribution of Preferred Tracks and Flight Levels

Eastbound								Westbound										
Flight level	NATU	NATV	NATW	NATX	NATY	NATZ	Total	Flight level	NATA	NATB	NATC	NATD	NATE	NATF	NATG	NATH	NATJ	Total
39000	5	10	0	2	8	0	25	39000	0	0	2	4	0	0	2	0	0	8
38000	26	43	4	17	10	0	100	38000	0	0	1	11	8	6	0	0	0	26
37000	37	78	14	59	42	6	236	37000	0	0	5	106	36	18	1	3	1	170
36000	17	46	4	29	17	7	120	36000	0	0	9	72	37	22	1	1	4	146
35000	13	30	2	24	25	11	105	35000	0	0	6	55	15	7	0	2	16	101
34000	7	17	2	18	36	9	89	34000	0	0	15	34	11	11	2	1	7	81
33000	0	10	0	9	26	1	46	33000	0	0	9	21	4	2	1	0	18	55
32000	0	2	0	1	4	0	7	32000	0	0	4	10	5	0	0	0	4	23
31000	0	0	0	0	1	0	1	31000	0	0	1	4	1	0	0	0	0	6
Total	105	236	26	159	169	34	729	Total	0	0	52	317	117	66	7	7	50	616

Not all those flights will use the OTS. In other words, some of those flights will be random flights. To determine whether a flight will use the OTS, a quick assessment of the fuel consumption and the arrival time at 30W of all possible flight paths are made using the model developed by (Aswin Kumar Gunnam 2012). Based on the assessment, 1345 flights will use the OTS, which account for about 38.2% of the total flights considered. Among them, 729 are eastbound flights, and 616 are westbound flights.

Table 4-3 shows the distribution of the preferred tracks and flight levels of the OTS flights. For the eastbound flights, Tracks U, V, X, Y, and flight levels FL 350 – FL 380 are the most preferred. For the westbound flights, Tracks D and E, and flight levels FL 350 – FL 370 are the most preferred. As shown in the table, there are no requests for Track A and B in the westbound OTS; however, flights still may be assigned to those two tracks due to congestion.

For those that will use the OTS, flight plans are made based their preferred tracks and flight levels of the OTS. The optimal cruise Mach number and cruise altitude are determined by using their characteristics in the BADA. In particular, waypoints in their flight plans are generated by using the coordinates of origin and destination airports as well as the significant waypoints of their preferred tracks. Flights are expected to fly great circle paths between waypoints. A detour factor of 5% will be added to account for possible deviations from the great circle path due to, for example, navigation needs, wind conditions, or traffic congestions.

It is also worthwhile to mention that the core tracks in each direction are not the most preferred tracks. This seems to be counter-intuitive since the core tracks usually offer better fuel efficiency. This could be because of the following reasons:

1) Data and model inconsistencies:

The information (e.g., meteorological conditions) and models that are used by carriers to generate flight plans might be different from those used in our study. Especially, in the simulation, the wind conditions at many locations of the OTS are estimated using the wind data available to this study, and those estimates might not be accurate enough.

2) Simplifications of the real operations

When flights are outside the OTS, for simplicity, they are assumed to fly great circle paths between two waypoints with a 5% detour factor. This simplification is due to lack of the information on traffic conditions in domestic airspace. However, it could introduce relatively large errors into the estimations of fuel consumption and therefore estimations of flight's preferred OTS assignments. In addition, we assume that flights always prefer OTS assignment with the least fuel consumption; however, in real operations, many other factors such as weather, turbulence, and probability of getting the assignment may also be considered when flights choose their preferred OTS assignments.

Aircraft characteristics and performance:

Table 4-4: Number of Aircraft by BADA Type and Its Equipage Level

Eastbound			Westbound		
Aircraft BADA type	Number of aircraft belonging to this type	Percentage of equipped	Aircraft BADA type	Number of aircraft belonging to this type	Percentage of equipped
B763	155	96.77%	B763	155	97.42%
B772	125	100.00%	B772	111	100.00%
B744	76	100.00%	B744	67	100.00%
B752	56	67.86%	B752	46	78.26%
A333	136	95.59%	A333	104	98.08%
A346	41	92.68%	A346	49	95.92%
MD11	32	100.00%	MD11	21	100.00%
A388	5	100.00%	A388	3	100.00%
B764	43	100.00%	B764	27	100.00%
B762	1	0.00%	B762	1	0.00%
A320	7	100.00%	A320	10	90.00%
A310	16	0.00%	A310	10	0.00%
FA7X	2	50.00%	FA7X	1	100.00%
B773	2	100.00%	B773	2	100.00%
B77W	3	100.00%	B77W	2	100.00%
B77L	18	100.00%	B77L	4	100.00%
CL60	11	0.00%	CL60	3	0.00%
Total	729	91.63%	Total	616	94.64%

We adopted the aircraft characteristics and performance specified in the Base of Aircraft Data (BADA) 3.9 (Eurocontrol Experimental Centre 2008). The aircraft that used by the OTS flights are categorized into 17 BADA aircraft types. Table 4-4 presents the distribution of the aircraft used by the 1345 flights among the 17 aircraft BADA types and the percentage of equipage for each BADA aircraft type.

Meteorological conditions:

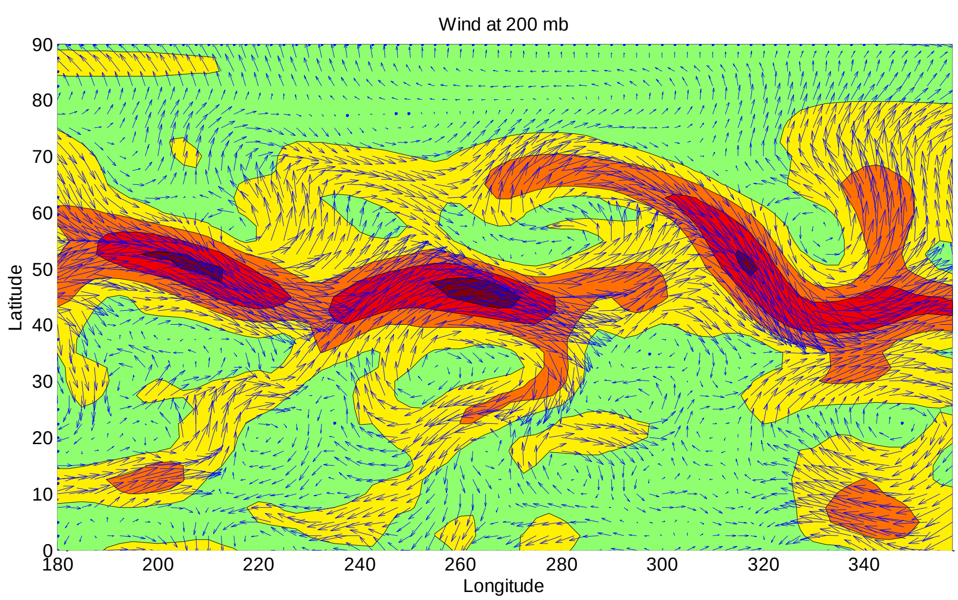
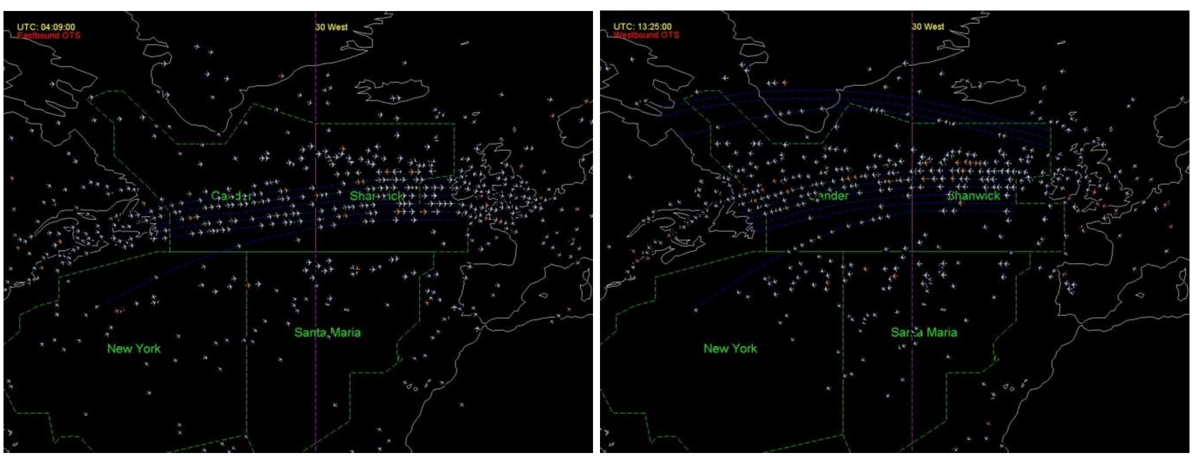


Figure 4-13: An example of wind vector at 200 mb (about 40000 ft) from the NCAR model

This study adopts the wind data from the National Center for Atmospheric Research (NCAR) Reanalysis model (NOAA/ESRL/PSD 2014) developed by Earth System Research Laboratory Physical Science Division (Kalnay et al. 1996). The data provides the magnitude and direction of the wind every 2.5 latitude and longitude degrees at 17 predefined geopotential heights. Figure 4-13 shows the wind vector at 200 mb (about 40000 ft) over the NAT region. As can be observed in the figure, westbound flights over the NAT usually experience headwinds; and eastbound flights usually experience tailwinds. As a result, eastbound flights usually have shorter travel times and less fuel consumption than those of westbound flights.

In addition, we assume that International Standard Atmosphere (ISA) conditions apply over the NAT region. For simplicity, we assume that there are no severe weather conditions that could affect flights inside the OTS in this study.

Simulation results for the baseline scenario:



The blue lines represent the OTS; green lines mark the territories of the four major control centers (i.e., New York, Shanwick, Gander, and Santa Maria) controlling the traffic over the NAT, and the white lines represent the coast lines.

Figure 4-14: Examples of simulated airspace

The simulation is performed using Matlab 2012b. The simulation step size is five seconds, that is, the system is updated every five seconds. The computation time is about 4 hours for the OTS flights only and 8 hours for all the flights (i.e., random flights are included in the simulation). Two snapshots of the simulated flights (both OTS and random flights) over the NAT are presented in Figure 4-14. The left hand side one is for the eastbound flights and the right hand side one is for the westbound flights.

Table 4-5: Distribution of the Flights over the OTS (Assigned Tracks and Flight Levels)

Eastbound							
Flight level	NATU	NATV	NATW	NATX	NATY	NATZ	Total
39000	5	9	0	2	7	0	23
38000	18	26	8	13	12	0	77
37000	27	40	20	35	24	5	151
36000	23	38	17	26	22	8	134
35000	16	36	9	29	18	10	118
34000	15	28	6	28	31	11	119
33000	2	21	3	15	26	1	68
32000	0	4	0	7	16	0	27
31000	0	1	0	3	8	0	12
Total	106	203	63	158	164	35	729

Westbound										
Flight level	NATA	NATB	NATC	NATD	NATE	NATF	NATG	NATH	NATJ	Total
39000	0	0	2	4	0	0	2	0	0	8
38000	0	0	1	10	9	6	0	0	0	26
37000	0	0	3	50	31	16	4	3	1	108
36000	0	0	10	46	38	18	1	2	4	119
35000	0	1	4	45	29	15	0	1	12	107
34000	0	1	13	42	23	11	2	1	10	103
33000	0	0	9	33	16	7	1	0	11	77
32000	0	0	5	22	11	1	0	1	7	47
31000	0	0	3	10	4	0	0	0	4	21
Total	0	2	50	262	161	74	10	8	49	616

Table 4-6: Success Rate of the Track and Flight Level Requests

Eastbound						
Flight level	NATU	NATV	NATW	NATX	NATY	NATZ
39000	100.00%	90.00%	-	100.00%	87.50%	-
38000	69.23%	58.14%	100.00%	76.47%	100.00%	-
37000	59.46%	44.87%	71.43%	55.93%	54.76%	66.67%
36000	82.35%	41.30%	100.00%	55.17%	70.59%	85.71%
35000	92.31%	66.67%	100.00%	54.17%	56.00%	81.82%
34000	71.43%	76.47%	100.00%	72.22%	66.67%	100.00%
33000	-	90.00%	-	88.89%	53.85%	100.00%
32000	-	50.00%	-	-	75.00%	-
31000	-	-	-	-	100.00%	-

Westbound									
Flight level	NATA	NATB	NATC	NATD	NATE	NATF	NATG	NATH	NATJ
39000	-	-	100.00%	100.00%	-	-	100.00%	-	-
38000	-	-	100.00%	90.91%	100.00%	100.00%	-	-	-
37000	-	-	60.00%	45.28%	63.89%	83.33%	100.00%	66.67%	100.00%
36000	-	-	100.00%	37.50%	56.76%	68.18%	100.00%	100.00%	100.00%
35000	-	-	66.67%	45.45%	60.00%	85.71%	-	50.00%	75.00%
34000	-	-	73.33%	52.94%	63.64%	81.82%	100.00%	100.00%	100.00%
33000	-	-	66.67%	61.90%	100.00%	100.00%	100.00%	-	55.56%
32000	-	-	75.00%	70.00%	100.00%	-	-	-	75.00%
31000	-	-	100.00%	75.00%	100.00%	-	-	-	-

The success rate is calculated as the percentage of flights that are assigned their preferred assignment.

Table 4-5 shows the distribution of assigned tracks and flight levels. The average success rates for the requests are presented in Table 4-6. A success request refers to the case where a flight gets its preferred track and flight level. As shown in the table, the most requested assignments have the lowest success rates (e.g., 37.5% for Track D and FL 360 in westbound OTS) and the least requested assignment have the highest success rates (e.g., 100% for Track C and FL 390 in westbound OTS). The average success rate is about 63.7% for the eastbound flights and about 60.9% for the westbound flights.

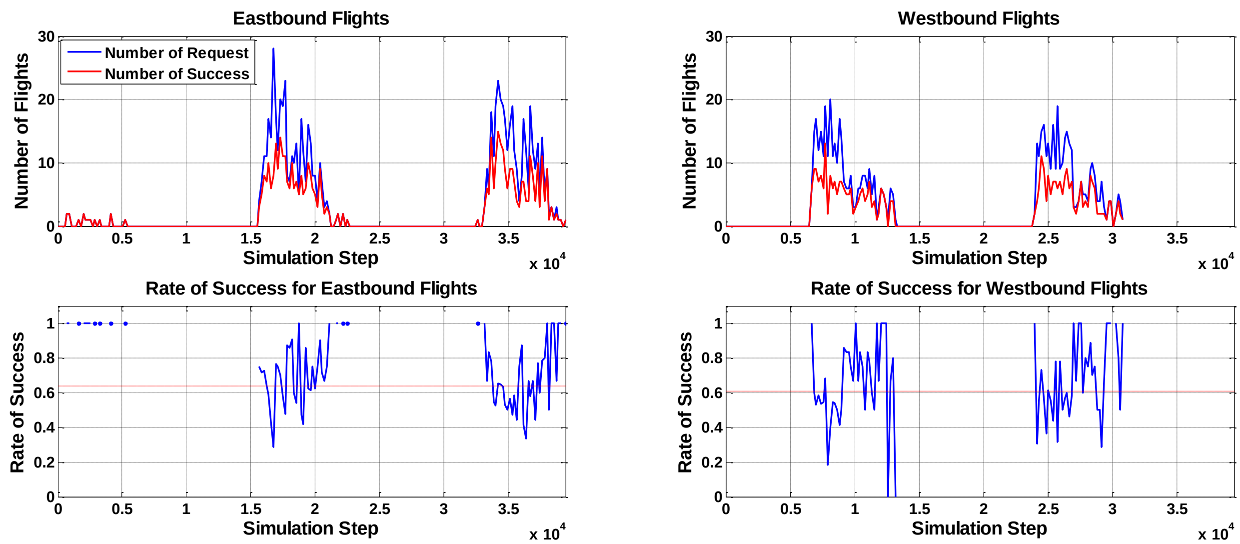
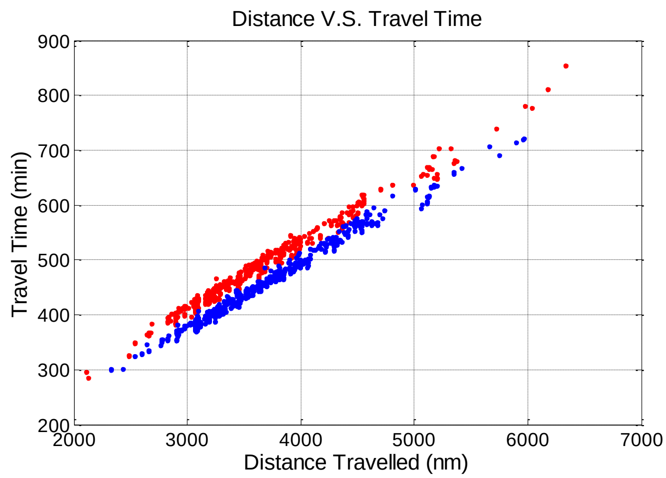


Figure 4-15: Number of assignment requests and success rate over simulation time

The success rate and number of assignment requests over simulation time is shown in Figure 4-15. Since the flights between North American and Europe are relatively concentrated, two peaks in the number of assignment requests can be observed for each direction. At each peak period, the success rate fluctuates significantly around the average success rate and is almost negatively correlated with the number of requests. Since the requests are made within a relatively small entry area, more requests would lead to higher probabilities of violating the minimum longitudinal separation inside the OTS or flight-path conflicts. Therefore, the observation of negative correlation between the two is reasonable. In addition, the peaks at the eastbound OTS are higher than those at the westbound OTS, which indicates that the traffic flow of the eastbound OTS is more concentrated during the peak hours than that that of the westbound OTS is.



Eastbound flights are marked by blue dots, and westbound flights are marked by red dots.

Figure 4-16: Distance travelled V.S. travel time

Figure 4-16 shows the relationship between the travel time and the distance travelled for the OTS flights. As has been explained, westbound flights over the NAT usually would experience headwinds, which reduce their ground speeds, while eastbound flight would experience tailwinds, which increase their ground speeds. This explains the trends observed in the figure; that is, to travel the same distance, the westbound flights need more time than the eastbound flights do. Based on our simulation, the average travel time per flight for the westbound flights is about 7% and higher than that of the eastbound flights, and the average fuel consumption per flight for the westbound flights is 6.5% higher.

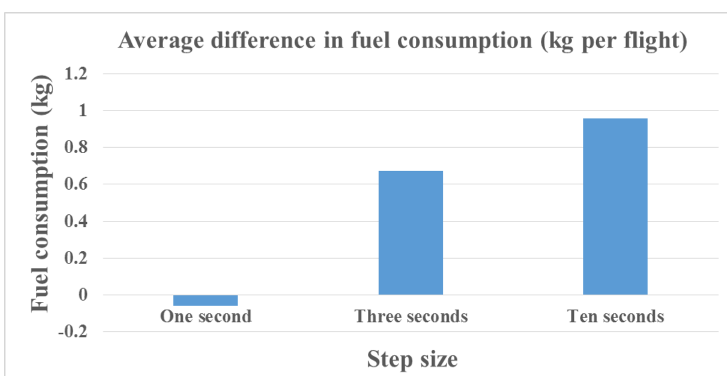


Figure 4-17: The sensitivity of fuel consumption to the simulation step size

We evaluated the sensitivity of the fuel consumption to the simulation step size by using three different step sizes: one second, three seconds, and ten seconds. The average fuel consumptions per flight of the three step sizes are compared with that of the five-second step size. Figure 4-17 presents the comparison, and it can be observed that the differences are less than 1 kg per flight. Compared with the average fuel consumption per flight, the differences are less than 0.01%.

Section 4.6 New OTS Procedures

The flights between Europe and North America usually fly over the NAT airspace in relatively concentrated time periods. In the past, due to lack of sufficient surveillance and poor communication quality over the ocean, relatively conservative procedures (e.g., large separation minima) are used to ensure the safety, which usually leaded to congestion. As a result, many flights need to follow flight paths or flight levels that have large deviations from their optimal ones. This could lead to, for example, delays and greater fuel consumption.

In recent years, as more flights are equipped with advanced avionics, controllers' capabilities of surveillance and communication with pilots in remote and oceanic areas are greatly improved. As a result, it is possible to apply new procedures to improve the operations of the OTS. Especially, with the implementation of the DLM, some of those new procedures are already practical in the exclusive airspace.

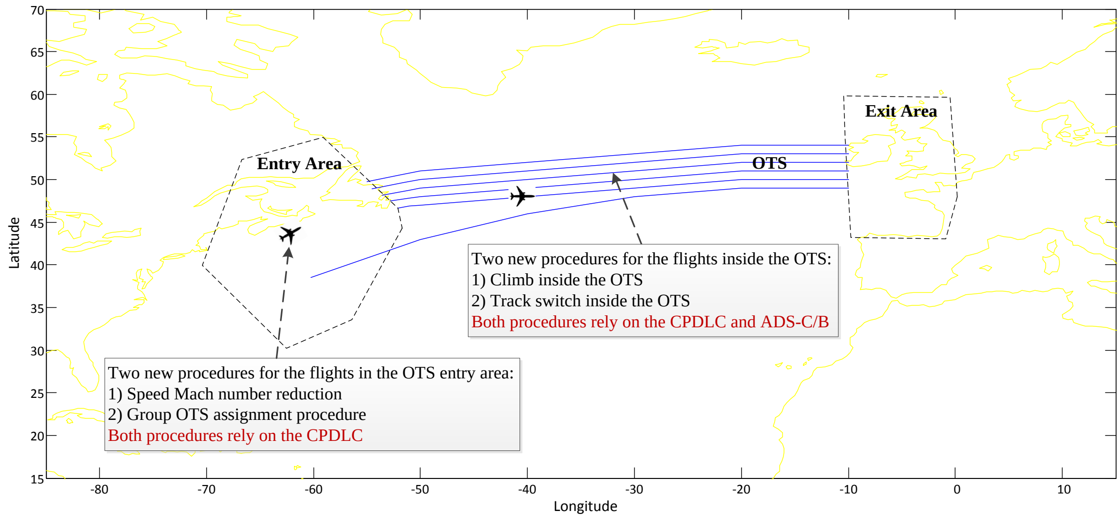


Figure 4-18: Flight stages where the four new procedures are designed to apply

In the following, we will develop four such new procedures. As shown in Figure 4-18, each new procedure is designed to be applied in a stage of a transatlantic flight and has certain requirements on the avionics.

The first two procedures are climbing for fuel efficiency and track switch inside the OTS. Since a large portion of the OTS is in the remote oceanic area, the two procedures require flights equipped with ADS-C/B and CPDLS to provide ground controllers sufficient capabilities of surveillance and commination with pilots. In addition, controllers need to ensure clearance between the flights that request to climb or switch track and those around them. This requires that controllers have sufficient capabilities of surveillance and commination within a certain airspace. Two most frequently used position reports from the ADS-C/B are time-based position report and event-based position report. With the first one, a position report is sent to the ground controllers at every given time interval (e.g., 10 or 20 minutes). The time interval may not be the same for different flights. With the second one, a position report is sent if a predefined event happens (e.g., approaching or passing a significant waypoint on the flight plan). For the equipped flights inside the OTS, this means that their position reports will be sent at the significant waypoints of the OTS (e.g., ten degree of longitude). Therefore, we suggest that 1) the two procedures be applied within the exclusive airspace, where all the flights are equipped with the required avionics, and 2) the requests to perform the procedures be made at the significant waypoints.

The last two procedures are speed Mach number reduction technique and group OTS assignment procedure. They are designed to be applied in the OTS entry area to improve the OTS assignment. Since a sufficient radar surveillance is expected to be available in the entry area, the application of the two procedures mainly requires flights equipped with avionics (e.g., CPDLC) that can provide high-quality communication between the controllers and pilots.

Subsection 4.6.1 Climb inside the OTS for fuel efficiency[12]

We have shown that an aircraft's fuel consumption rate is a function of its thrust T when it is in cruise. Based on the total energy model, the thrust is equal to the aerodynamic drag D, which is proportional to the air density ρ at the cruising altitude. In general, the air density reduces as the cruising altitude increases. This means that the fuel consumption rate is smaller (i.e., better fuel efficiency) if the cruising altitude is higher. Since flights will cruise inside the OTS for about 2-3 hours, it is possible that a significant amount of fuel is consumed to allow for climbs for fuel efficiency. This new procedure also could be useful for flights that are not given their optimal flight levels.

[12] Some of the modeling efforts in this subsection has been presented at the 2014 INFORMS annual meeting and the 27th Europe Technical Coordination Meeting.

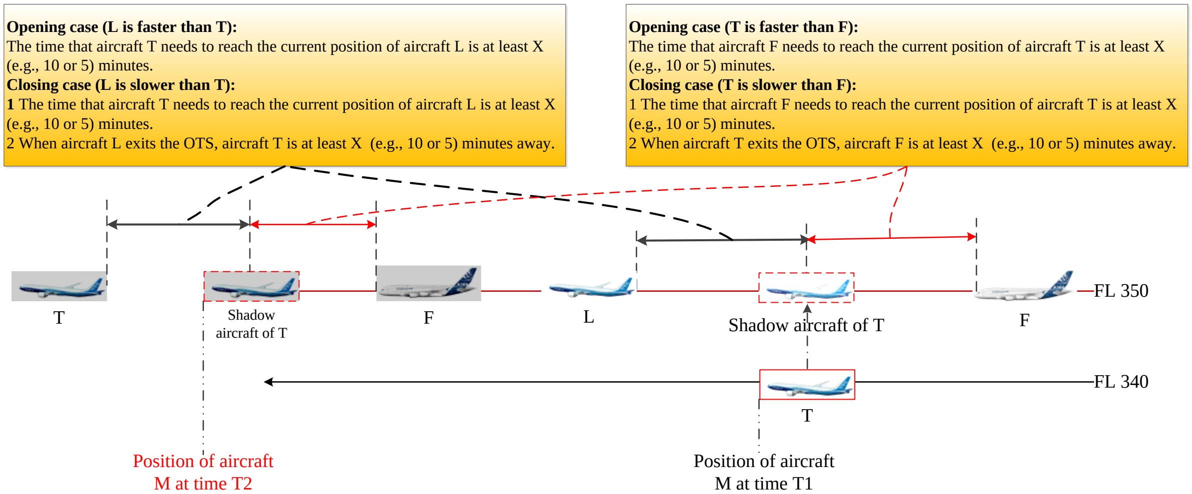


Figure 4-19: Climb inside the OTS

In this study, two decision making processes are modelled for climbing inside the OTS. One is how the pilot routine makes the decision to request a climb; the other one is how ATC routine evaluates the feasibility of a climb request.

For the pilot routine, the process of evaluating the need of climbing for fuel efficiency inside the OTS is similar to the one developed for changing flight levels outside the OTS. However, it is worthwhile to point out that, since flights inside the OTS usually have their flight-level clearance until the OTS exit, we suggest using the OTS exit as the target waypoint when estimating fuel consumption. In addition, the candidate flight levels for a flight should be selected from the flight levels that are the flight's current track and the flight is eligible to use.

To process the climb request, the primary factor that the ATC routine will consider is to maintain the minimum longitudinal separation at the requested flight level and the flight levels that the climb will traverse. This is different from the factors considered in evaluating the feasibility of requests for changing flight levels outside the OTS in that, inside the OTS, the minimum lateral and vertical separations between aircraft will be maintained by the design of the OTS.

In the following, an example is presented in Figure 4-19 to illustrate how a climb request inside the OTS is evaluated by the ATC routine. There are two flight levels (FL 340 and FL 350), and three aircraft. Two aircraft (L and F) are on FL 350, and one is on FL 340. Aircraft T requests to climb from FL 340 to FL 350.

To evaluate the feasibility of the request, the ATC routine will check whether the minimum longitudinal separation between aircraft L and T, T and F will be maintained on FL 350 if the request is approved. The routine will first create a shadow aircraft of aircraft T on FL 350 by projecting aircraft T onto FL 350. The ground speeds of aircraft T and its shadow aircraft may be different because of the difference in the sound speed and wind speed at the two different flight levels. Therefore, the ATC routine will estimate the shadow aircraft's ground speed and arrival time at the OTS exit. Then, the routine will check longitudinal separations between aircraft L and the shadow aircraft, aircraft F and the shadow aircraft at the current time as well as at the estimated time when the shadow aircraft leaves the OTS. If any of the longitudinal separations violates the minimum (e.g., 5 or 10 minutes), the ATC routine will decline the request. If no violations are found at the two time points, it is unlikely that such violations would happen between the two time points since the three aircraft (aircraft L, F, and the shadow aircraft) will maintain their current Mach number and experience similar meteorological conditions (e.g., wind) between the two time points. Therefore, the climb request will be approved. When the aircraft T is climbing to FL 350, we assume that the segment between aircraft L and F will be blocked by the ATC routine to prevent other flights from getting in.

Subsection 4.6.2 Switching tracks for fuel efficiency

With the current procedures, flights are expected to follow their assigned tracks until they exit the system even if the assigned tracks are not their preferred ones. Allowing track switching would give the flights that are not assigned their preferred tracks an opportunity to switch to their preferred tracks and therefore save their fuel and travel time. Those that are assigned their preferred tracks could also benefit from switching tracks. The OTS tracks are designed based on many factors other than flights' preferred flight paths. As a result, for many flights, even their preferred tracks are not necessarily close to their optimal ones. By switching tracks, flights could get closer to their optimal flight paths or avoid adverse conditions (e.g., weather).

Similar to the previous procedure, two decision making processes are modelled for switching tracks inside the OTS. One is how the pilot routine makes the decision to make a track-switch request; the other one is about how ATC routine evaluates a track-switch request.

The primary factor considered by the pilot routine when evaluating the need of a track switch is whether the switch could lead to a reduction in travel time. Reduction in fuel consumption may be a more ideal factor to be considered; however, compared with the fuel consumption, travel time is easier to estimate and therefore less computationally expensive.

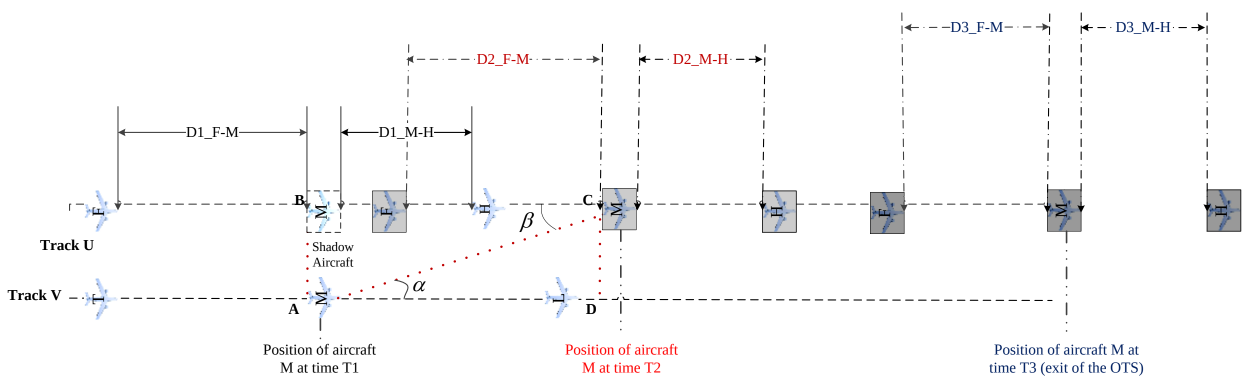


Figure 4-20: The decision making processes for a track switch

An example is presented in Figure 4-20 to illustrate the two decision making processes. In the example, there are two tracks (i.e., Tracks U and V). There are three aircraft (T, M, and L) on Track V and two aircraft (F and H) on Track U. Aircraft M is the aircraft considering the need to switch to Track U.

In the following discussion, we assume that an aircraft is only allowed to switch to its adjacent tracks. We define the aircraft that has sent the track-switch request as the requesting aircraft, and the track to which the aircraft requests to switch as target track.

The pilot routine first evaluates the travel time from Point A to the destination using its current track (i.e., Track V). Then, for each target track, the routine estimates the travel time to the destination if aircraft M switches to the track. The travel time includes two parts: the travel time spent during the track switch (e.g., from Point A to Point C) and the travel time from its joining position on the target track (e.g., Point C on track U) to the destination.

To estimate this travel time, an angle to leave the current track (e.g., α) and an angle to join the target track (e.g., β) need to be determined. Large angles could reduce the time spent on the transition of tracks; however, they could also significantly reduce the aircraft's speed along tracks, which could lead to violation of minimum separations with other aircraft on its target track during the transition. On the contrary, small angles could result in less reduction in speed along tracks; however, they could increase the time spent on transition, which may result in more uncertainties.

In reality, those two angles could be determined by the pilots and/or controllers. For simplicity, in this study, they are assumed to be the same (i.e., $\alpha = \beta$), and determined by the pilot routine as part of the track-switch request sent to the ATC routine.

If switching to an adjacent track could lead to a significant time saving, then a track-switch request would be sent; otherwise, no request will be sent. Note that whether switching tracks could result in violation of minimum separations with other flights is not a factor considered by the pilot routine. Instead, it will be considered by the ATC routine when evaluating the feasibility of a track-switch request.

The primary factor considered by the ATC routine to evaluate the feasibility of a track-switch request is to maintain the minimum longitudinal separations on the target track if the request is approved. The evaluation process is similar to the one used in evaluating the feasibility of a climb request inside the OTS.

To evaluate the feasibility of a track-switch request, the ATC routine first creates a shadow aircraft of the requesting aircraft on the target track by projecting the aircraft onto its target track. The shadow aircraft is at the same flight level as the requesting aircraft. For example, in the figure, aircraft M on Point A on track U is the shadow aircraft of aircraft M on track V, and both aircraft are on the same flight level. Then, the routine inspects the longitudinal separations between the aircraft behind and in front of the shadow aircraft, that is, aircraft F and H. If the minimum longitudinal separation between any of them is violated, then the track-switching request will be denied.

The above step seems to be unnecessary since the requesting aircraft will not be on its target track until it joins the track (e.g., aircraft M will not be on track V between Point B and C). However, when the requesting aircraft leaves its current track to join its target track, its speed along the tracks would reduce, and the aircraft on the target tracks would approach the requesting aircraft more quickly. In addition, as the requesting aircraft travels from its current track to its target track, the minimum lateral separation between the requesting aircraft and the aircraft on the target track might no longer be maintained via the design of tracks, especially when the distance of the two tracks is at the minimum lateral separation. As a result, without this step, it is possible that the minimum lateral or longitudinal separations between the requesting aircraft and some aircraft around the requesting aircraft on the target track might be violated.

If the request is not denied in the above step, the ATC routine proceeds to estimate the arrival time (e.g., time T2 in the figure) of the shadow aircraft at the joining point (e.g., Point C in the figure), and its OTS exit time (time T3 in the figure) on the target track. Then, the ATC routine identifies the aircraft that will be behind and in front of the shadow aircraft after it joins its target track. For example, in the figure, the aircraft that would be behind and in front of the shadow after it joins Track V are aircraft F and H. Then, the routine inspects the minimum longitudinal separations between the three aircraft at the time point when the requesting aircraft joins the target track and the time point when the shadow aircraft leaves the OTS. If any violation is found, then the request will be denied; otherwise, the request would be approved. As has been explained in evaluating the climb request, if no violation of minimum longitudinal separations is found at the two time points, it is unlikely that a violation could happen in between the two points. Similar to the case of climbing inside the OTS, the segment between the shadow aircraft and the joining point on the target track will be blocked to prevent other aircraft from getting into the segment when the requesting aircraft is traveling from its current track to its target track.

It is necessary to point out the following:

- When evaluating the feasibility of a track-switch request, the minimum longitudinal separations between aircraft on the current track of the requesting aircraft are not considered. This is primarily because the minimum longitudinal separations are expected to be maintained (via OTS assignment) at least before the requesting aircraft begins to leave the current track. After the requesting aircraft begins to leave its current track, the minimum separations between the requesting aircraft and the aircraft behind it might be violated due to the reduction in the requesting aircraft's speed along the current track. However, it might not be a significant concern since they are on diverging courses, i.e., they are moving away from each other. For the aircraft that is ahead of the requesting aircraft on its current track, it is easy to verify that it is unlikely that the minimum separations between them would be violated during the process of track switch.

- Though our study only allows aircraft to switch to their adjacent tracks, switching to non-adjacent tracks could be achieved by switching to adjacent tracks multiple times.

Subsection 4.6.3 A new speed technique in the OTS entry area

The Mach number technique currently being used for the OTS assignment is to maintain the minimum longitudinal separations inside the OTS. Usually the assigned Mach numbers should not be more than 0.01 M faster or 0.02 M slower than the requested ones. Flights are expected to follow their assigned Mach numbers during the entire trip inside the OTS.

An OTS assignment is considered infeasible for a requesting flight if assigning it to the flight will violate the minimum longitudinal separation. This violation is mainly because the estimated arrival time of the requesting flight is too close to the arrival time of a flight that has been given the same assignment. In this case, the requesting flight needs to be assigned to other assignment, which could result in greater fuel consumption or longer travel time.

Our goal is to apply a new speed technique in the OTS entry area. With the new procedure, the controllers could assign slower Mach numbers to postpone the arrival time of a requesting flight and hence reduce its probability of violating the minimum longitudinal separation with those that have been given assignments. In other words, this procedure could give a flight more chances of getting its preferred assignments or getting an assignment with smaller deviation from its preferred one. This procedure is different from the Mach number technique currently used in the OTS assignment procedure in that the Mach number assigned by this new procedure is only applicable at the OTS entry area. That is, flights that are given reductions in Mach numbers by this procedure could use their preferred Mach numbers once they are inside the OTS.

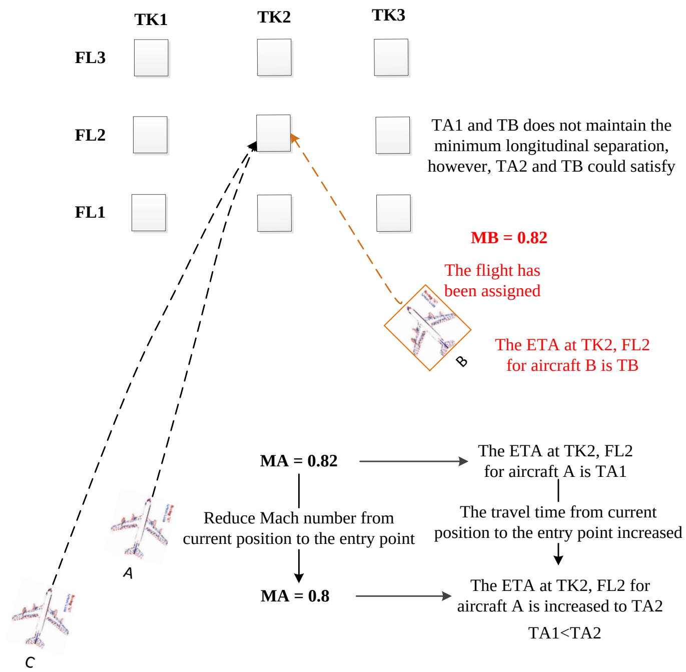


Figure 4-21: Illustration of applying Mach number technique at the entry area

In the following, we use the example in Figure 4-21 to illustrate how this procedure benefits a flight. In the example, flight B has been assigned Track TK2 and flight level FL2, and flight A and C have requested the same assignment. For flight C, its longitudinal separation from flight B inside the OTS would be above the minimum if it is given the same assignment. With the current Mach number (e.g., 0.82 M) of flight A, its estimated arrival time at the entry point would be TA1, and its longitudinal separation from flight B inside the OTS would be below the minimum if it is given the assignment. Therefore, it cannot be given the assignment. However, if flight A could postpone its arrival time to TA2 by reducing its Mach number (e.g., from 0.82 M to 0.8 M), then its longitudinal separation from flight B would be at the minimum, and therefore it could get the assignment if the flight path is clear.

If the minimum longitudinal separation between a requesting aircraft's assignment and the last aircraft given to the assignment is not maintained, the ATC routine will calculate the minimum reduction in the requesting aircraft's current Mach number. The minimum reduction is calculated based on the minimum additional time needed to main the minimum longitudinal separation. Assuming that the distance and estimated arrival time to an assignment are T and D, and the additional time to maintain the minimal longitudinal separation is ΔT, with the notations and equations used to calculate the ground speed in Section 4.4, the minimum reduction to an aircraft's Mach number ∇V_M to obtain the minimum additional time is given as follows:

$$\boldsymbol{\nabla V_M} = \left(\frac{\boldsymbol{D}}{\boldsymbol{T}} + \boldsymbol{VW_W}\right)/(\mathbf{V}_{\boldsymbol{sound}}\mathbf{cos}\,\boldsymbol{\theta}\Big) - \left(\frac{\boldsymbol{D}}{(\boldsymbol{T}+\Delta\boldsymbol{T})} + \boldsymbol{VW_W}\right)/(\mathbf{V}_{\boldsymbol{sound}}\mathbf{cos}\,\boldsymbol{\theta}) \qquad \textbf{(4-2)}$$

In some cases, ∇V_M is relatively large, which could result in unrealistic reduction in Mach number. To avoid this, we suggest that this procedure be applicable only if ∇V_M is no more than a user-specified upper bound (e.g., 2 or 5 minutes).

It is also necessary to point out that this procedure does not increase the capacity of the OTS but its benefits come from redistributing the OTS assignment. As a result, some flights might not be able to get their preferred assignment with this procedure. For example, if flight A gets the assignment by reducing its Mach number, then flight C might not be able to get the assignment because it cannot maintain the minimum longitudinal separation inside the OTS from flight A. To reduce this possibility, we suggest that this procedure applies only when a flight's preferred assignment is inspected for availability. In other words, this procedure does not apply if the assignment being considered in not a flight's preferred one.

Subsection 4.6.4 Application of an optimization technique to improve OTS assignment

The current OTS assignment procedure is similar to a first-request-first-assigned method. This procedure is easy to implement for the controllers in the sense that it does not require controllers' efforts to optimize the assignment. For uncongested period, this procedure could produce OTS assignments close to the optimal ones (i.e., most of flights could be assigned their preferred tracks, flight levels, and Mach number). However, during congestion period, it is questionable that this procedure could produce satisfactory assignments.

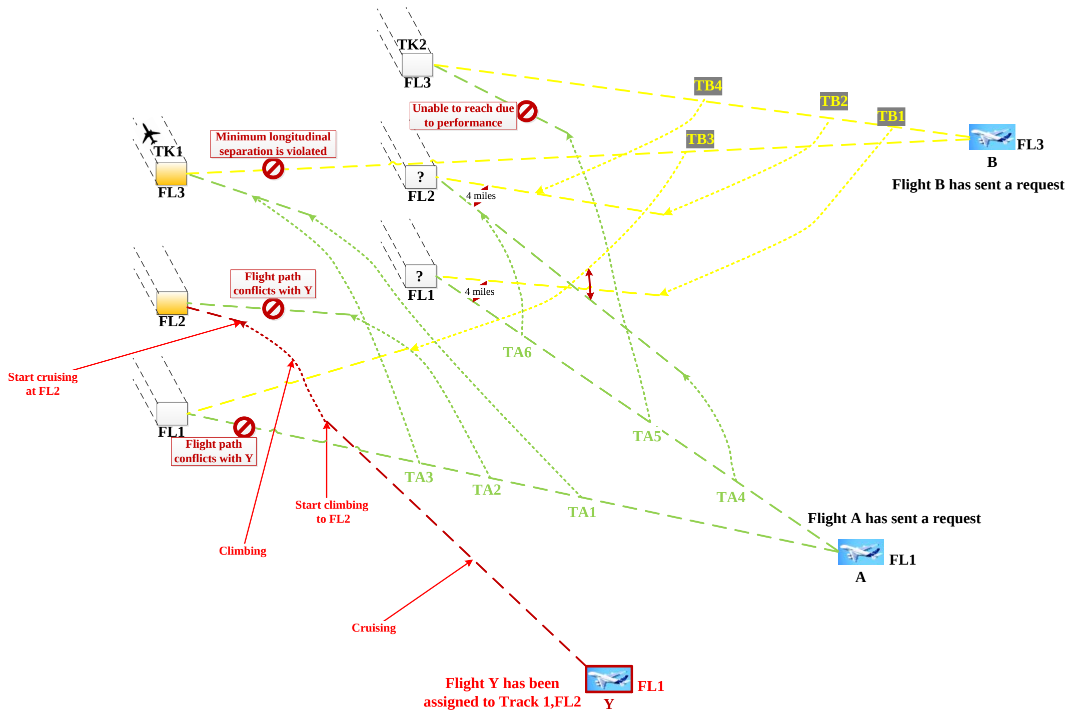


Figure 4-22: Collective decision making process

In this section, we design a new procedure to improve the OTS assignment. Instead of only considering one flight in each assignment, the new procedure improves the assignment by considering a group of flights that have sent their OTS assignment requests within a certain time period (e.g., every 2 or 5 minutes). To differentiate the assignment procedure currently being used, we call the new procedure Group Assignment Procedure (GAP) and the current procedure Individual Assignment Procedure (IAP).

In Figure 4-22, we provide an example to demonstrate the GAP. This example is an extension of the example given in Figure 4-6 in that flight B is added as another requesting flight. The GAP is applied with flights A and B in the group. The ATC routine first performs two preprocessing steps. The first one is to search for all the feasible assignment for each requesting flight in the group by only considering the flights that have been given their OTS assignments. For simplicity, we call the flights that have been given their OTS assignments intermediate flights. The second one is to detect possible violations of the minimum longitudinal separation inside the OTS among the requesting flights, and the conflicts in the projected flight paths of all the requesting flights.

Preprocessing step 1:

Assume that there are N requesting flights in the group assignment, that is, N flights have sent their OTS assignment requests and are waiting for their assignment. For each requesting flight, the routine enumerates all the feasible assignments (e.g., all combination of tracks, flight levels, and Mach number). The rules used to determine the feasibility of an assignment are similar to those used in the IAP. That is, 1) whether the minimum longitudinal separations in the OTS will be maintained with those have been given the OTS assignments, and 2) whether the projected flight paths of the requesting flight to the assignment has no conflicts with the projected flight paths of those that have been given the OTS assignments. It is necessary to stress that 1) and 2) are inspected only against those that have been given their OTS assignments in this step.

This preprocessing step is different from the one used in the IAP in that the latter one inspects the possible assignments sequentially according to an order and stops as long as a feasible one is found; however, this preprocessing step does not stop until all the feasible assignments for a requesting flight are found. For example, for flight A in the figure, the IAP will determine track TK2 and flight level FL2 (as illustrated in Figure 4-6) as its assignment and stop inspecting other assignments. The GAP will also determine this assignment feasible for flight A but it will continue to inspect other assignments (e.g., track TK 2 and flight level FL 1) until all the possible assignments are inspected.

The difference between the two is primarily due to the fact that multiple flights are considered and assigned simultaneously in the GAP, and finding one feasible assignment for each flight might not guarantee that all will be assigned because conflicts may exist between them. For example, as shown in the figure, track TK 2, flight level FL 2 is a feasible assignment for both flight A and flight B; however, assigning both to this assignment may create flight path conflicts between the two because their projected flight paths are too close to each other (i.e., 4 nm as shown in the figure) at the entry point.

Preprocessing step 2:

Since multiple requesting flights are assigned simultaneously, another step is required to guarantee that the minimum longitudinal separations are maintained inside the OTS and their flight paths are cleared from each other.

In this step, the rules used to identify possible conflicts between two requesting flights are similar to those used in the first step except that they are only applied to the requesting flights.

This additional step is unnecessary in the IAP since it only assigns one flight each time. Unlike the case in the first step, flight path conflicts or violations of the minimum longitudinal separations between two requesting flights in this step do not mean that none of them could be given their corresponding assignments. Instead, it means that at most one of the two could be given the corresponding assignment. For example, if a conflict exists in the projected flight paths of flight A and flight B to track TK 2, flight level FL 2, then at most one of them could be given this assignment.

After performing the two preprocessing steps, an optimization model is formulated to determine the optimal assignment for the N requesting aircraft. In the following, we introduce the notations that will be used in the model.

Notations:

$\boldsymbol{G}$: set of all the requesting flights in the group assignment.

$\boldsymbol{A}$: index of the requesting flight in G.

$\boldsymbol{R}$: index of the tracks in the OTS.

$\boldsymbol{F}$: index of the flight levels available (including both exclusive and non-exclusive ones) in the OTS.

$\boldsymbol{R_A}$: index of the tracks in the OTS available for flight A.

$\boldsymbol{F_A}$: index of the flight levels in the OTS available for flight A.

$\boldsymbol{M_A}$: index of the feasible Mach number inside the OTS for flight A.

$\boldsymbol{T_A}$: set of expected times (in minutes) to start to climb/descend to a flight level for flight A.

$\boldsymbol{PR_A}$: the preferred track of flight A.

$\boldsymbol{PF_A}$: the preferred flight level flight A.

$\boldsymbol{PM_A}$: the preferred Mach number flight A.

$\boldsymbol{FS_A}$: set of all the feasible assignments for flight A. This set is created during the first preprocessing step. Each element in this set is a 1×4 vector (R_A, F_A, M_A, T_A), which specifies the feasible track R_A, flight level F_A, Mach number M_A, and the time T_A to start to climb/descend to the flight level F_A.

$\boldsymbol{X_{A,R_A,F_A,M_A,T_A}}$: binary variable, which indicates whether flight A is assigned to track R_A, flight level F_A, Mach number M_A, and is expected to start climbing to the flight level at T_A. It is 1 if flight A is given this assignment; 0, otherwise. This variable is created for each of the element in set FS_A.

$\boldsymbol{XR}$: a function, which takes X_{A,R_A,F_A,M_A,T_A} as the input, and returns the track of the assignment X_{A,R_A,F_A,M_A,T_A} corresponding to as the output.

$\boldsymbol{XF}$: a function, which takes X_{A,R_A,F_A,M_A,T_A} as the input, and returns the flight level of the assignment X_{A,R_A,F_A,M_A,T_A} corresponds to as the output.

$\boldsymbol{XM}$: a function, which takes X_{A,R_A,F_A,M_A,T_A} as the input, and returns the Mach number of the assignment X_{A,R_A,F_A,M_A,T_A} corresponds to as the output.

$\boldsymbol{C_{A,R_A,F_A,M_A}}$: the cost of giving flight A the assignment (R_A, F_A, M_A, T_A). In this study, we use the deviation from a flight's preferred assignment to determine C_{A,R_A,F_A,M_A} with the following function:

$$\boldsymbol{C_{A,R_A,F_A,M_A} = WR_A \times \left|XR(X_{A,R_A,F_A,M_A,T_A}) - PR_A\right| + WF_A \times \left|XF(X_{A,R_A,F_A,M_A,T_A}) - PF_A\right| + WM_A \times \left|XM(X_{A,R_A,F_A,M_A,T_A}) - PM_A\right|}, \quad \textbf{(4-3)}$$

where WR_A, WF_A, and WM_A are weights associated with the deviations from flight A's preferred assignment. In addition, we assume that the expected time to start to climb/descend to the assigned flight level is not a significant determinant of cost.

$\boldsymbol{FS_N}$: set of assignments that could have conflicts. This set is determined in the second preprocessing step. Each element in the set is a 1×10 vector $(A, R_A, F_A, M_A, T_A, B, R_B, F_B, M_B, T_B)$, which specifies two assignments (for two aircraft) that are considered to have conflicts. The first five components of the element specify the flight index (e.g., flight A) and the assignment for the first flight (e.g., R_A, F_A, M_A, T_A), and last five for the second flight.

$\boldsymbol{Y_A}$: a binary variable introduced for flight A. It is one if no assignment is available for flight A; otherwise,0.

Formulations:

The optimization model is formulated as an integer programming with the following form:

$$\min \sum_{A\in G,(R_A,F_A,M_A,T_A)\in FS_A} (C_{A,R_A,F_A,M_A} \times X_{A,R_A,F_A,M_A,T_A}) + M \times (\sum_{A\in G} Y_A)$$

$$\boldsymbol{s.t.} \quad \sum_{(R_A,F_A,M_A,T_A)\in FS_A} \boldsymbol{X_{A,R_A,F_A,M_A,T_A} + Y_A = 1}, \forall\, \boldsymbol{A} \in \boldsymbol{G}, \quad \textbf{(4-4)}$$

$$\boldsymbol{X_{A,R_A,F_A,M_A,T_A} + X_{B,R_B,F_B,M_B,T_B} \leq 1}, \forall\, \boldsymbol{(A, R_A, F_A, M_A, T_A, B, R_B, F_B, M_B, T_B)} \in \boldsymbol{FS_N}, \textbf{(4-5)}$$

X_{A,R_A,F_A,M_A,T_A}, and Y_A are binary variables, $\forall\, A \in G, (R_A, F_A, M_A, T_A) \in FS_A$,

where M is a sufficiently large number so that Y_A could be one only if there is no assignment available for flight A.

The objective of the model is to minimize the total cost of the group assignment. If the cost of an assignment is positively correlated with its deviation from a flight's preferred one, then the objective could be considered as minimizing the total deviations from the flights' preferred assignments. Constraint (4-3) requires that flight A is assigned to one and only one of its feasible assignments. If no assignment is available for the flight, then it would be assigned to the dummy assignment (i.e., $Y_A = 1$). This means that the model cannot determine a feasible assignment for the flight. In this case, the flight could be assigned, for example, separately by the ATC routine or wait to be included in the next group assignment. Constraint (4-4) requires that, if the feasible assignments of two flights have conflicts, at most one of the flights could be given its feasible assignment (as has been illustrated by the previous example).

Determining the weights in the cost function (equation (4-1)):

Those weights could be additional costs such as fuel consumption or travel time caused by the deviations from the preferred assignments. They could be provided by the operators/carriers or estimated during the OTS design process by using, for example the model developed by (Aswin Kumar Gunnam 2012, Aswin, Antonio et al. 2014).

The weights could also be determined based on the preferences of the pilots/carriers. In this case, they do not necessarily have any physical meanings. In particular, if an operator has a list of preferred assignments with for example, a decreasing degree of preference, separate weights could be selected for each of the assignments in the list such that the cost for each assignment is negatively correlated with its degree of preference, and the weights of the other assignments could be selected such that their cost is greater than any of the assignments in the list.

The size of the optimization model:

The total number of decision variables in the optimization model is given by:

$$\sum_{A \in G}(|FS_A| + 1),$$

where $|*|$ represents the total number of elements/index in a set. It is bounded by the following number:

$$\sum_{A \in G}(|FS_A| + 1) \le |G| \times |R| \times |F| \times \max_{A \in G}(|M_A|) \times \max_{A \in G}(|T_A|) + |G|.$$

$\max_{A \in G}(|M_A|)$ and $\max_{A \in G}(|T_A|)$ do not have strong dependency on the number of flights in G. $|R|$ and $|F|$ are determined by considering the total number of flights (note that it is not the same as $|G|$) (i.e., the number of tracks and flight levels in the OTS are determined by considering the total demand instead of the number of flights in G). However, due to factors such as the limit of airspace, they do not increase exponentially with the demand. Therefore, the number of decision variables could be considered be bounded by a polynomial function of $|G|$.

The total number of equality constraints in the optimization model is the same as the number of flights. Therefore, it is a polynomial function of $|G|$.

The total number of inequality constraints in the optimization model is $|FS_N|$, which is determined by the number of conflicts in the projected flight paths between two flights. Its upper bound is given by:

$$|FS_N| \le C(|G|, 2) \times (|R| \times |F| \times \max_{A \in G}(|T_A|))^2,$$

where $C(|G|, 2) = \frac{|G|\times(|G|-1)}{2}$, and it is the total number of flight pairs needed to be inspected for conflicts. $|R| \times |F| \times \max_{A\in G}(|T_A|)$ is the upper bound for the number of unique elements in set FS_A without considering the component M_A. In this study, the number of projected flight paths for flight A does not depend on $|M_A|$. Therefore, $|R| \times |F| \times \max_{A\in G}(|T_A|)$ is also the upper bound of the number of projected flight paths for flight A. This upper bound is also a polynomial function of $|G|$.

In summary, the size of the optimization model is bounded by a polynomial function of the number of flights in the group.

Section 4.7 Results and Analysis

The simulations of the four new procedures are also performed by using Matlab 2012b. For the first three new procedures, we compare their results with those from the baseline scenario. However, for the last new procedure, some simplifications are made to control the size of the integer optimization problem. To have comparable results, some settings in the baseline scenario are revised, and the results of the last new procedure are compared with those in the revised baseline scenario.

The benefit of the new procedures is evaluated primarily using reductions in fuel consumption. In particular, we present the reductions in fuel consumption for those that performed the new procedures as well as for all the flights in the system.

It is necessary to point out that, for a flight, a reduction in fuel consumption means an increase in its payload as well as a reduction in emissions. Those benefits are not considered in the analysis. In addition, safety issues associated with those new procedures are not evaluated in this study.

Subsection 4.7.1 Climb inside the OTS for fuel efficiency

Settings for the pilot routine:

- A climb must be made in the exclusive airspace or into the exclusive airspace.

- When evaluating the need of a climb request, the pilot routine uses the exit point of the OTS on its flight plan as the target waypoint. A climb is considered necessary as long as it could result in a fuel saving.
- A climb request must be made at one of the ten degree longitudinal waypoints. The climb should be no more than 2000 ft.; that is, the requested climb should be either 1000 ft. or 2000 ft.
- If the request from a flight is approved and the climb is performed, the flight is not eligible to make another request. If the request from a flight is denied, the flight could make a request again. That is, a flight is allowed to make only one climb but multiple requests.
- If the request is approved, the pilot routine will maintain the Mach number and climb the aircraft with all the remaining thrust.

Settings for the ATC routine:

- A request will be considered only if the climb will be performed inside the exclusive airspace or into the exclusive airspace (i.e., from the flight levels in non-exclusive airspace to the flight levels in the exclusive airspace).
- When projecting the flight path of a requesting flight, the ATC creates one flight-path projection by assuming that the requesting starts to climb at current time. Note that since the requesting flight and flights at its target flight level are on the same track, creating multiple flight-path projections might not be able to significantly increase the flight's probability of getting approved.
- To evaluate the feasibility of a request, the ATC uses 10 minutes as the minimum longitudinal separation between two flights.

- If a 2000 ft. climb request is infeasible, the ATC routine will consider a 1000 ft. climb. If both are infeasible, the climb request will be denied. If a 1000 ft. climb request is infeasible, the climb request will be denied.

Simulation results:

Since this procedure applies after flights enter the OTS, it does not affect the OTS assignments, which are made before flights enter the OTS. As a result, the simulation model produces the same OTS assignment results as those given in Section 4.5.

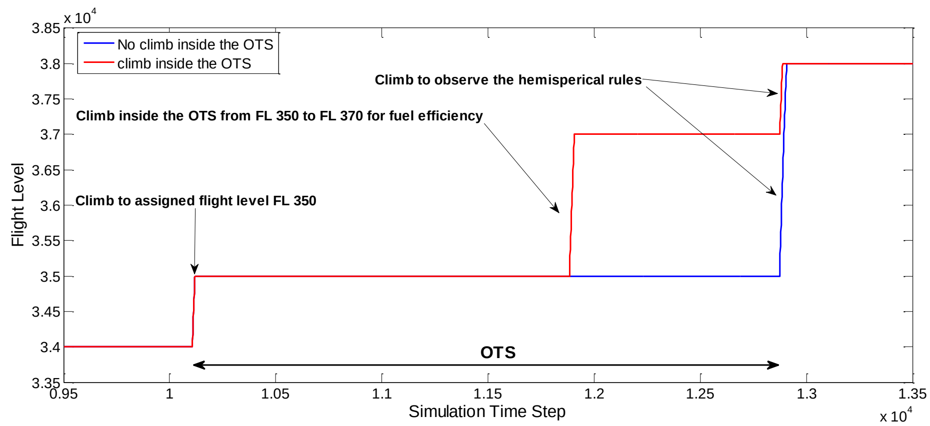


Figure 4-23: An example of a 2000 ft. climb inside the OTS

Figure 4-23 shows the flight path of a westbound flight that performs a 2000 ft. climb inside the OTS. The flight is assigned to Track E and flight level FL 350. The climb is made about 2 hours after it entered the OTS. Compared that of the baseline scenario, this flight has a net fuel savings of about 114 kg (about $114 dollars[13]) for its trip inside the OTS due to this climb.

It is also worthwhile to point out that a climb inside the OTS may also result in fuel savings outside the OTS. In our simulation, flights near the OTS exit need to request their desired flight levels after they exit the OTS. For most flights, their desired flight levels are higher than their current ones. In this case, for flights at high flight levels, the difference between their desired

[13] 1 kg of jet-A is equivalent to 0.33 gallon, and the price jet-A is assumed to be 3 dollars per gallon.

flight levels and their current ones are smaller than those at low flight levels. This gives an advantage to flights at high flight levels because, for example, their requests are less likely to be denied because of conflicts, and they need less fuel to climb to their desired flight levels.

For example, as shown in the figure, the flight make another 1000 ft. climb (from FL 370 to FL 380) after it exits the OTS. However, in the baseline scenario, it makes a 3000 ft. climb (from FL 350 to FL 380) since it does not climb inside the OTS. Based on the simulation results, the climb of an additional 2000 ft. in the baseline scenario requires 54 kg additional fuel consumption. Therefore, the total fuel savings for this flight due to its climb inside the OTS is about 168 kg. In addition, a climb request from FL 370 to FL 380 is more likely to be approved than a climb request from FL 350 to FL 380 because the latter will traverse more flight levels, and therefore is more likely to have conflicts with other flights on higher flight levels.

However, we found that not every climb inside the OTS would lead to a fuel saving. In other words, some climbs would lead to greater fuel consumption. We believe that this is primarily because the need of a climb is determined based on the estimations, in which errors may exist.

Table 4-7: Some Statistics about Climbs Made inside the OTS

Eastbound							
Total requests	**Total approved requests**	**Flight levels**		**Average fuel saving per flight inside the OTS**		**Average fuel saving per flight of the trip**	
		1000 ft.	**2000 ft.**	**For flights climbed**	**For all the flights**	**For flights climbed**	**For all the flights**
385	**139**	132	7	**81.7 (kg)**	**15.6 (kg)**	**132.6 (kg)**	**25.3 (kg)**

Westbound							
Total requests	**Total approved requests**	**Flight levels**		**Average fuel saving per flight inside the OTS**		**Average fuel saving per flight of the trip**	
		1000 ft.	**2000 ft.**	**For flights climbed**	**For all the flights**	**For flights climbed**	**For all the flights**
306	**142**	123	19	**51.5 (kg)**	**11.9 (kg)**	**90.9 (kg)**	**20 (kg)**

More results about the climbs made inside the OTS are presented in Table 4-7. In the eastbound OTS, the total number of climb requests is 385 (about 0.53 request per flight), and 139 requests are approved. The average success rate is about 36.1%. Among the approved requests, 132 requests are given a 1000 ft. climb, and 7 requests (about 5.04%) are given a 2000 ft. climb. In addition, 45 climbs are from nonexclusive flight levels to exclusive flight levels. Compared with the baseline scenario, the average fuel savings per flight for those climbed is about 81.7 kg inside the OTS and 132.6 kg for their whole trips. The average fuel savings per flight for all the eastbound flights is about 15.6 kg inside the OTS and 25.3 kg for their whole trips.

For the westbound flights, the total number of climb requests is 306 (about 0.50 request per flight), and 142 requests are approved. The average success rate is about 46.4%. Among the approved requests, 123 requests are given a 1000 ft. climb, and 19 requests (about 13.38%) are given a 2000 ft. climb. Moreover, 47 climbs are from nonexclusive flight levels to exclusive flight levels. Compared with the baseline scenario, the average fuel savings per flight for those climbed is about 51.5 kg inside the OTS and 90.9 kg for their whole trips. The average fuel savings per flight for all the westbound flights is about 11.9 kg inside the OTS and 20 kg for their whole trips.

The success rate of climb requests for the westbound flights is higher than that of the eastbound flights. In particular, the number of 2000 ft. climbs is almost three times as many as that of the eastbound flights. One possible explanation for is that, as shown in Table 4-5, more westbound flights are assigned to the lower flight levels of the exclusive airspace than the eastbound flights, which makes climbs easier for westbound flights at the lower flight levels because there would be fewer conflicts with the flights on higher flight levels.

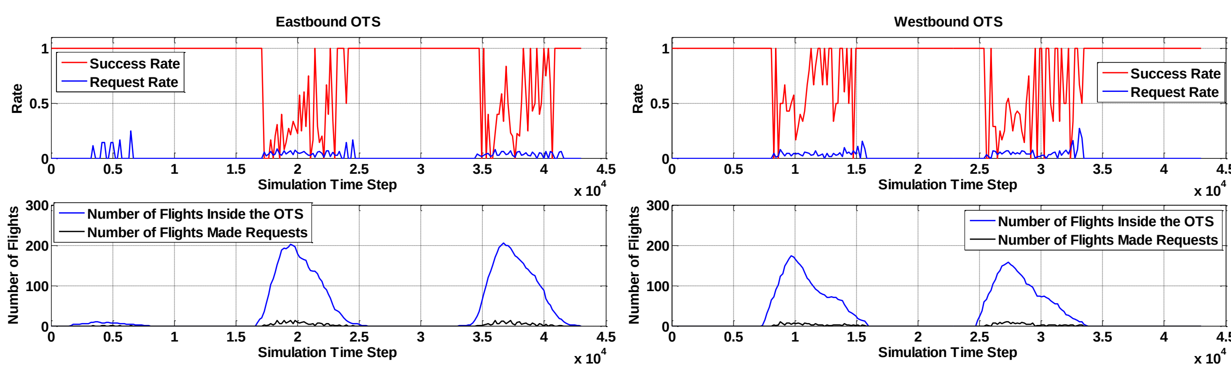


Figure 4-24: The number of climb requests over time

Figure 4-24 shows the success rates of the climb requests over time. Intuitively, the success rates would decrease when the number of flights in the OTS is high. The success rates shown in the figure are generally consistent with this. However, as can be observed, the success rates begin to fluctuate significantly when the number of flights inside the OTS is high. In other words, the success rate is not proportional to the number of flights inside the OTS. This is reasonable since whether a climb request could be approved also depends on the positions of flights on the target flight level.

Subsection 4.7.2 Switching tracks for fuel efficiency

Settings for the pilot routine

- The track switch must be made within the exclusive airspace or into the exclusive airspace.
- When evaluating the need of a request, the pilot routine uses the destination as the target waypoint. A track switch is considered necessary as long as it could result in time savings.
- A request must be made at one of the ten degree longitudinal waypoints.
- If the request from a flight is approved and the switch is performed, the flight is not eligible to make another request. If a request from a flight is denied, the flight could make a request again. That is, a flight is allowed to make only one track switch but multiple track-switch requests.
- If a request is approved, the pilot routine will maintain the Mach number and flight level, and leave its current track and join the target track with 15 degree angles (i.e., $\alpha = \beta = 15$).

Settings for the ATC routine

- A request will be considered only if the switch is within the exclusive airspace or into the exclusive airspace.
- When projecting the flight path of a requesting flight, the ATC creates one flight-path projection with the information (e.g., angles of leaving current track and joining the target track) provided by the requesting flight.
- To evaluate the feasibility of a request, the ATC uses 10 minutes as the minimum longitudinal separation between two flights.

Simulation results:

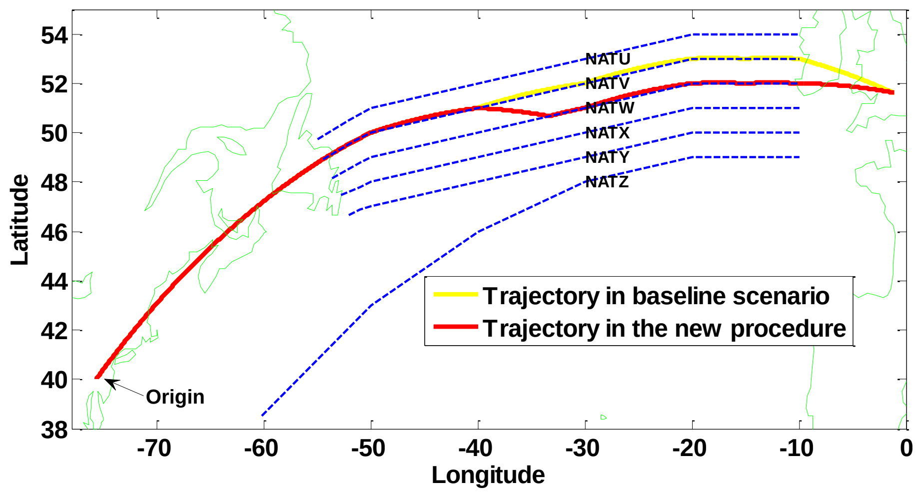


Figure 4-25: An example of track switch inside the OTS

Figure 4-25 shows the flight path of an eastbound flight that switches from Track V to Track W. The flight is assigned to Track V and flight level FL 370. The switch is made about 72 minutes after it enters the OTS. Due to this switch, it saves about 26.5 kg of fuel and 0.5 minute of travel time for the whole trip.

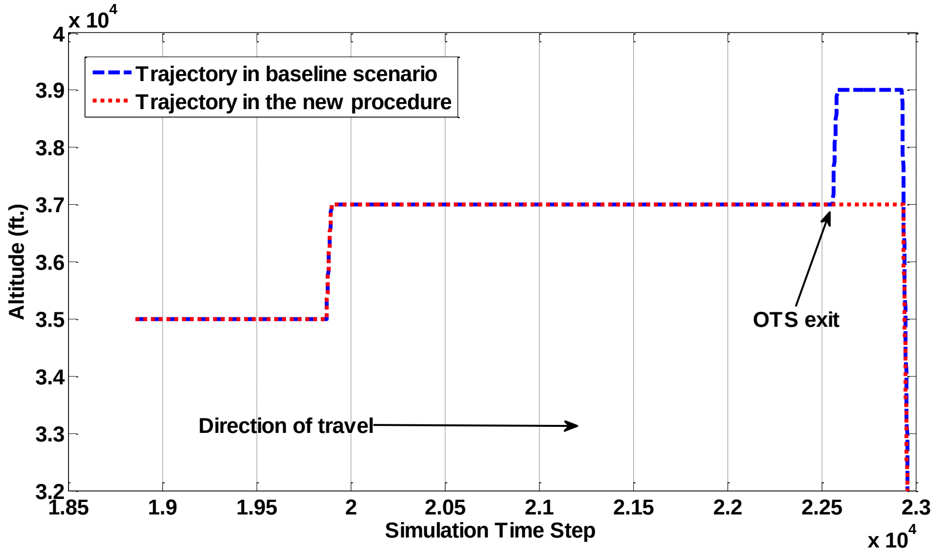


Figure 4-26: The altitude profile of an eastbound flight that switched track inside the OTS

However, a track switch does not necessarily result in fuel or time savings for a flight's trip inside the OTS. This is because the need of a track switch is evaluated based on the saving in the travel time of the whole trip. In other words, it is not based on the time or fuel savings inside the OTS. In our simulation, the majority of flights that switch their tracks would consume more fuel inside the OTS. For example, the flight in Figure 4-26 consumes 39.5 kg of more fuel and 0.75 minute of additional travel time inside the OTS after the track switch. Note that using the OTS exit as the target waypoint to evaluate the need of a track switch may not be reasonable in the sense that traveling on a target track to the OTS exit will probably take a longer travel time than traveling on a flight's current track to the exit because of the transition between tracks. Moreover, a track switch does not necessarily always lead to fuel saving for the whole trip. In addition to the fact the track switch decision is not made based on fuel consumption, whether flights that switch tracks inside the OTS could get their optimal flight levels after exit the OTS is also an important factor.

Figure 4-26 shows the altitude profiles of an eastbound flight. The flight is able to get its preferred assignment (Track W and flight level FL 370) in the baseline scenario and is able to perform a track switch to Track W with the new procedure. The flight is assigned FL 390 after it exits the OTS track V in the baseline scenario, and it maintains the flight level until the end. However, it is unable to get the same flight level after it exits the OTS Track W with the new procedure due to conflicts, and the flight maintains flight level FL 350 until the end. The flight still saves about 0.16 minute due to the track switch; however, because of the lower cruise altitude after the OTS, the entire trip consumes about 57 kg more fuel.

Table 4-8: Some Statistics about the Track Switches Made Inside the OTS

Eastbound							
Total requests	Total approved requests	Average fuel increase per flight inside the OTS (kg)		Average fuel saving per flight from the OTS exit to the destination (kg)		Average fuel saving per flight of the whole trip (kg)	
234	80 (34.2%)	For flights that switch tracks	For all the flights	For flights that switch tracks	For all the flights	For flights that switch tracks	For all the flights
		104 kg	11.4 kg	186 kg	20 kg	82 kg	9 kg

Westbound							
Total requests	Total approved requests	Average fuel increase per flight inside the OTS (kg)		Average fuel saving per flight from the OTS exit to the destination (kg)		Average fuel saving per flight of the whole trip (kg)	
10	1 (10%)	For flights that switch tracks	For all the flights	For flights that switch tracks	For all the flights	For flights that switch tracks	For all the flights
		224 kg	0.4 kg	320 kg	0.5 kg	95 kg	0.2 kg

Some statistics about the track switches inside the OTS are presented in Table 4-8. In the eastbound OTS, 234 track-switch requests are made by 144 flights. 186 track-switch requests made by 122 flights are from non-core Track V to core Track W. Among those 122 flights, 85 are assigned their preferred OTS assignments, and 36 are assigned their preferred tracks but not preferred flight levels. 48 requests made by the other 22 flights are from core Track W to core Track X. Among the 22 flights, three are assigned their preferred OTS assignments, and one is given its preferred track but not preferred flight level. The rest of them are not given their preferred tracks, in particular, twelve prefer Track V but are assigned to Track W, and six preferred Track X but assigned to Track W. 80 requests (about 34.2%) are approved. 75 switches are from non-core Track X to core Track W, and five switches are from core Track W to core Track X.

For the trip inside the OTS, the average additional fuel consumption caused by the track switch is about 104 kg per flight for those switch tracks and about 11.4 kg per flight for all the eastbound OTS flights. For the trip from the OTS exit to the destinations, the average fuel savings is about 186 kg per flight for those switch tracks and about 20 kg per flight for all the eastbound OTS flights. For the whole trip, the average fuel savings caused by the track switch is about 82 kg per flight for those switch tracks and 9 kg per flight for all the eastbound flights.

For the westbound OTS flights, 10 track-switch requests are made by 8 flights. Three requests are from non-core Track D to core Track E, one is from core Track E to core Track F, five are from core Track F to core Track E, and one is from non-core Track G to core Track F. One track-switch request (about 10%) is approved. The flight switches from non-core Track G to Track F. The additional fuel consumption inside the OTS caused by the track switch is about 224 kg for the flight, and about 0.4 kg per flight for all the westbound OTS flights. From the OTS exit to the destination, the flight saves about 320 kg fuel, and the average fuel savings for all the westbound OTS flights is about 0.5 kg per flight. For the whole trip, the fuel savings is about 95 kg for the flight that switches track and 0.2 kg per flight for all the westbound flights.

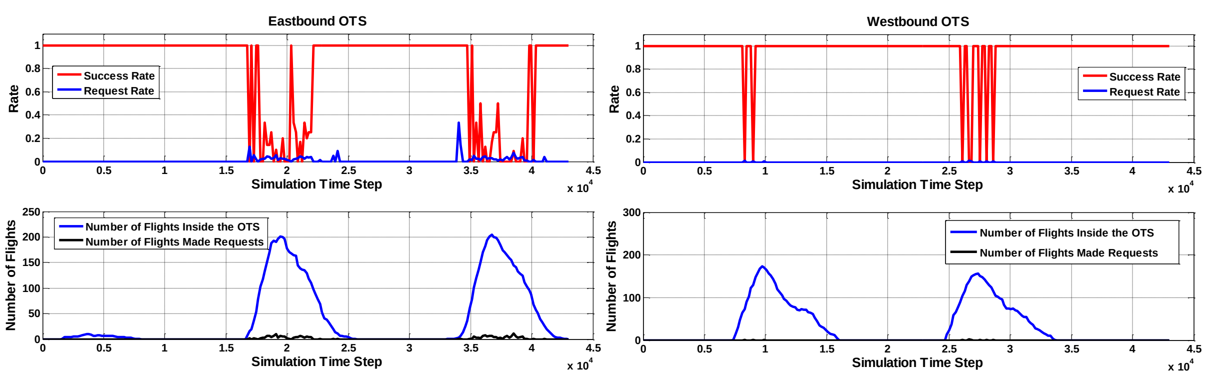


Figure 4-27: Track-switch requests over time

Figure 4-27 shows the success rates of track-switch requests over time. Similar to the climb requests over time presented in Figure 4-24, the success rates are expected to decrease when the number of flights in the OTS is high. The success rate shown in the figure is generally consistent with this. However, as can be observed, the success rates begin to fluctuate when the number of flights inside the OTS is high. In other words, the success rate is not proportional to the number of flights inside the OTS since whether a track-switch request could be approved also depends on the positions of the flights on the target track.

Subsection 4.7.3 Application of speed technique in the OTS entry area

Settings for the pilot routine:

There are no additional settings for the pilot routine for this procedure except that the pilot routine needs to follow the new Mach number when the flights are in the entry area of the OTS.

Settings for the ATC routine:

- For a flight, the procedure only applies to its preferred assignment, and the maximum additional waiting time ΔT in Equation (4-2) is no more than 2 minutes.

Simulation results:

Table 4-9: Changes in the Success Rate Compared to Those in the Baseline Scenario

Eastbound						
Flight level	NATU	NATV	NATW	NATX	NATY	NATZ
39000	0.00%	10.00%	-	0.00%	0.00%	-
38000	0.00%	2.33%	0.00%	0.00%	-10.00%	-
37000	2.70%	-2.56%	0.00%	3.39%	0.00%	0.00%
36000	5.88%	6.52%	0.00%	3.45%	5.88%	0.00%
35000	0.00%	0.00%	0.00%	8.33%	4.00%	0.00%
34000	0.00%	0.00%	0.00%	0.00%	8.33%	0.00%
33000	-	0.00%	-	0.00%	7.69%	0.00%
32000	-	0.00%	-	-	25.00%	-
31000	-	-	-	-	0.00%	-

Westbound									
Flight level	NATA	NATB	NATC	NATD	NATE	NATF	NATG	NATH	NATJ
39000	-	-	0.00%	0.00%	-	-	0.00%	-	-
38000	-	-	0.00%	0.00%	0.00%	0.00%	-	-	-
37000	-	-	0.00%	2.83%	2.78%	-5.56%	0.00%	0.00%	0.00%
36000	-	-	0.00%	1.39%	8.11%	0.00%	0.00%	0.00%	0.00%
35000	-	-	0.00%	10.91%	0.00%	14.29%	-	0.00%	6.25%
34000	-	-	20.00%	11.76%	18.18%	9.09%	0.00%	0.00%	0.00%
33000	-	-	11.11%	14.29%	0.00%	0.00%	0.00%	-	11.11%
32000	-	-	0.00%	10.00%	0.00%	-	-	-	0.00%
31000	-	-	0.00%	25.00%	0.00%	-	-	-	-

The percentage in each cell is the success rate of the new procedure minus that of the baseline scenario

Table 4-9 presents the differences in the success rates of assignment requests between the new procedure and the baseline scenario. Significant changes in the success rates for some tracks and flight levels can be observed. For example, Track Y and flight level FL 320 has a 25% increase in the success rate while Track Y and flight level FL 380 has a 10% drop in the success rate. Those changes could be explained by the fact that the procedure redistributes the OTS assignments. The average success rate is about 66.1% for the eastbound flights and about 66.2% for the westbound flights, both of which are higher than those in the baseline scenario (the statistics are 63.7% and 60.9% in the baseline scenario).

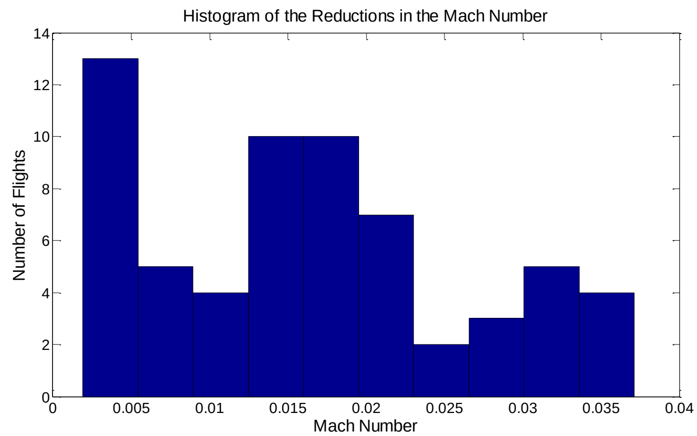


Figure 4-28: Histogram of the reductions in the Mach number in the OTS entry area

The histogram of Mach number reductions by the new procedure is presented in Figure 4-28. The average reduction in the Mach number is about 0.016, the highest reduction is about 0.04[14], and the standard deviation is about 0.01.

[14] For the Mach number technique applied inside the OTS, the reduction in a flight's preferred Mach number inside the OTS is usually no more than 0.02. The speed Mach number technique developed in this study reduces a flight's Mach number within the OTS entry area only, that is, the flight could use its preferred Mach number when it is inside the OTS.

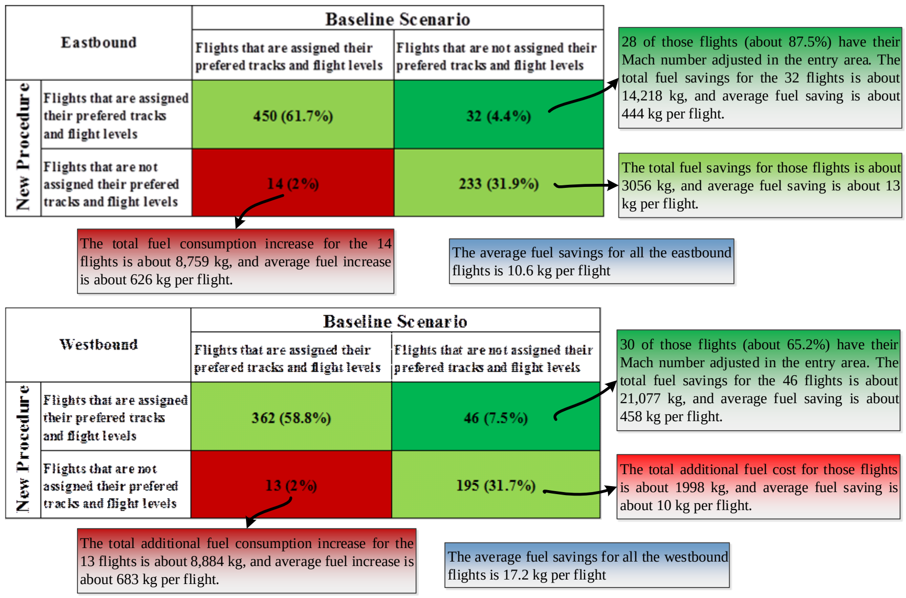


Figure 4-29: Comparison of some statistics between the two scenarios

In Figure 4-29, we compare some the simulation results in the baseline scenario with those in the new procedure. 32 (about 4.4%) eastbound flights that are unable to get their preferred OTS assignments in the baseline scenario are assigned their preferred ones with the new procedure. As has been explained, the new procedure does not increase the capacity but redistributes the OTS assignments to benefit flights. Among them, 28 flights are given Mach-number reductions in the entry area. The other 4 flights are not given any Mach-number reductions, which mean they are benefited by the redistribution of the OTS assignments. The average fuel savings for those 32 flights is about 444 kg per flight. For the westbound flights, 46 (about 7.5%) flights that are unable to get their preferred OTS assignments in the baseline scenario are assigned their preferred ones with the new procedure. 30 flights are given reductions in their Mach numbers in the entry area, and the others achieve this because of the redistribution of the OTS assignments. The average fuel savings for those 46 flights is about 458 kg per flight.

However, as pointed in Section 4.6, some flights that can be assigned their preferred tracks and flight levels in the baseline scenario might not be able to get their preferred ones with the new procedure. In our simulation, this happens to 14 eastbound flights, and 13 westbound flights. The average additional fuel consumption is 626 kg per flight for those eastbound flights and 683 kg per flight for those westbound flights. In addition, due to the redistribution of the OTS assignments, flights that are unable to get their preferred tracks and flight levels in both scenarios also experience fuel consumption changes. Those in the eastbound OTS have an average fuel saving of 13 kg per flight; however, those in the westbound OTS have an average additional fuel consumption of 10 kg per flight.

In summary, with the new procedure, the average fuel saving is 10.6 kg per flight for all the eastbound OTS flights, and 17.2 kg per flight for all the westbound OTS flights.

Subsection 4.7.4 Application of an optimization technique to improve OTS assignment

Settings for the pilot routine:

- The pilot routine requests its preferred flight level as well as reports the highest flight level the aircraft could achieve at the OTS entry point. In contrast, in the IAP, the routine only specifies its preferred flight level.
- The pilot routine may need to spend extra time in waiting for the ATC routine to gather enough flights to perform a GAP. To account for the extra waiting time, the pilot routine sends its request when the flight is 350 nm (40-50 minutes) away from its preferred OTS assignment.

Settings for the ATC routine:

- For each flight in the group, the routine also makes multiple projections of its flight paths by assuming that the flight climbs/descends to the flight level being considered at every one minute interval. However, we found that considering all those projections could make the size of the problem too large for the integer programming solver in Matlab to handle.

To control the size, we assume that the routine only uses at most 10 projections that have the least conflicts with the flight-path projections of the other flights in the group.

- The above setting could increase the possibility of formulating an infeasible problem because fewer choices for the time to start to climb/descend are given to the requesting flights. To avoid this, when searching for all the feasible OTS assignments for a flight, the routine 1) starts from the highest level the flight could reach at the entry point, and 2) adjusts the flight's Mach number inside the OTS by adding 0.01 M, -0.01 M, and -0.02 M to its preferred Mach number. In contrast, in the IAP, the routine starts from the preferred flight level of the flight and does not adjust its preferred Mach number inside the OTS.
- The routine performs a GAP if there are already 5 requesting flights in the group or if there is at least one requesting flight and it has been more than 5 minutes since the last GAP is performed, whichever happens first.
- In Eq (4-2), we tentatively set $WR_A = 2$, $WF_A = 1$, and $WM_A = 0.5$. With this setting, if a flight's preferred OTS assignment is not feasible, the ATC routine tends to assign the flight by changing its preferred Mach number first, then preferred flight level, and preferred track the last.
- The integer optimization problem is solved using the mixed-integer linear programming solver in Matlab 2014a (MathWorks 2014).
- If a flight cannot be assigned in the current group assignment, the ATC routine includes the flight in the next group assignment.

Revised baseline scenario:

Compared with the IAP used in the baseline scenario, some differences exist in the settings of the GAP. Some of those differences give a requesting flight more opportunities to get their preferred tracks and flight levels while some reduce such opportunities. For example, the ATC routine adjusts a flight's Mach number when searching for feasible assignments. This gives the flight more opportunities to get its preferred track and flight level. However, the routine only uses at most 10 projections of flight paths for the flight. This reduces the flight's opportunities to get its preferred track and flight level.

Because of those differences, we believe that the results (e.g., success rates and fuel consumption) from the GAP and those from the baseline scenario are not always comparable. However, the most important difference between the IAP and the GAP is the number of flights considered in each assignment. Therefore, to have comparable results, we created a Revised Baseline Scenario (RBS), in which the ATC routine performs the GAP as long as it receives one OTS assignment request. That is, the GAP is performed with only one flight in the group in the RBS. We will compare the results from the GAP with the results from the RBS.

Simulation results:

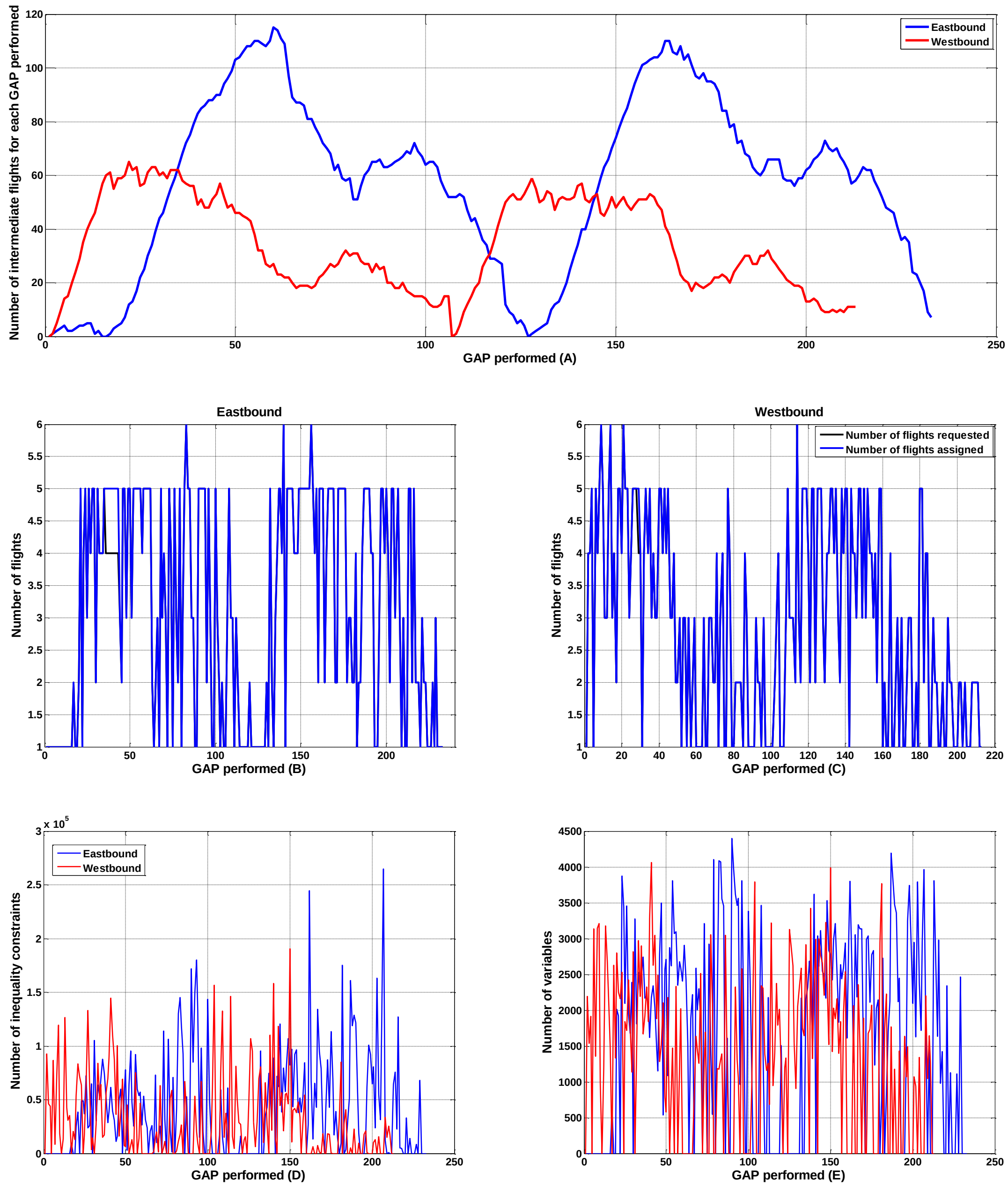


Figure 4-30: GAP performed over time

233 GAP are performed in the eastbound OTS, and 213 are performed in the westbound OTS. Figure 4-30 shows some statistics about the GAP performed over the simulation time.

Part A presents the number of the intermediate flights. The intermediate flights are considered in preprocessing step 1 by the ATC routine when searching for feasible assignments for the requesting flights. For each direction, two peaks in the number of intermediate flights could be observed, which corresponds to the peaks in demand shown in Figure 4-15. It is also worthwhile to note that the peaks in the eastbound OTS are almost twice as high as those in the westbound OTS. The average number of intermediate flights considered in each assignment is 57 in the eastbound OTS and 34 in the westbound OTS. They suggest that the entry area of the eastbound OTS is more congested than that of the westbound.

Parts B and C show the number of requesting flights and the number of flights that are given assignments in each GAP performed. It can be observed that several GAP are performed with more than five flights in the group. This is because multiple flights can send their OTS assignment requests at the same time step. There are three GAP performed in the eastbound OTS and four in the westbound OTS with more than five requesting flights in the group. In the simulation settings, the ATC routine will include a flight in the next assignment if it cannot be assigned in the current one. In the simulation, this happens to one eastbound flight and one westbound flight. The eastbound flight is included in eight consecutive GAP before it is given an assignment, and its total waiting time is about 25 minutes. The westbound flight is included in two consecutive GAP before it is given an assignment, and its total waiting time is about five minutes.

Part D and Part E show the total number of decision variables and inequality constraints in each assignment. The number of decision variables for a requesting flight is determined in preprocessing step 1. The total number is positively correlated with the number of requesting flights in the group with a correlation coefficient of 0.8. However, we found no strong negative correlation between the total number of decision variables and the number of intermediate flights. A possible explanation is that the intermediate flights' flight paths, arrival times at the entry, and separations from the requesting flights could also play a role in determining the number of decision variables. The number of inequality constraints is determined in preprocessing step 2 by avoiding possible violations of minimum separations or flight path conflicts between the requesting flights. We found that this number is also positively correlated the number of requesting flights in the group with a correlation coefficient of 0.7.

Table 4-10: Comparison of Results between Revised Baseline Scenario and the New Procedure

Eastbound				
Overall	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0824	1.2616	0.0043	0.6173
New procedure	0.0954	1.1767	0.0041	0.6118
Total flights	729	Fuel saving per flight		35.7 kg
5 flights or more	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0928	1.3351	0.0042	0.5550
New procedure	0.1031	1.2371	0.0038	0.5550
Total flights	436	Fuel saving per flight		42.78 kg
4 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0769	1.1538	0.0044	0.5568
New procedure	0.0732	1.0488	0.0051	0.5341
Total flights	88	Fuel saving per flight		20 kg
3 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.1905	0.9048	0.0048	0.7308
New procedure	0.1667	1.2500	0.0046	0.6923
Total flights	78	Fuel saving per flight		-24 kg
2 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0000	1.0769	0.0054	0.7903
New procedure	0.0000	1.0000	0.0050	0.8065
Total flights	62	Fuel saving per flight		38.7 kg
1 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0000	1.1538	0.0038	0.8030
New procedure	0.0769	0.8462	0.0038	0.8030
Total flights	66	Fuel saving per flight		54.1 kg

Westbound				
Overall	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0406	0.5162	0.0020	0.5974
New procedure	0.0455	0.4903	0.0021	0.6023
Total flights	616	Fuel saving per flight		4.3 kg
5 flights or more	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0738	0.6352	0.0022	0.5287
New procedure	0.0820	0.5369	0.0022	0.5492
Total flights	244	Fuel saving per flight		23.6
4 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0161	0.5645	0.0025	0.5403
New procedure	0.0323	0.5565	0.0026	0.5403
Total flights	124	Fuel saving per flight		4 kg
3 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0256	0.5214	0.0018	0.6154
New procedure	0.0085	0.6154	0.0021	0.5983
Total flights	78	Fuel saving per flight		-40 kg
2 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.0135	0.3243	0.0018	0.7162
New procedure	0.0270	0.2703	0.0015	0.7162
Total flights	74	Fuel saving per flight		7 kg
1 flights	**Track**	**Flight level**	**Mach number**	**Success rate**
Revised baseline scenario	0.1000	0.8000	0.0050	0.8276
New procedure	0.1000	1.0000	0.0070	0.8276
Total flights	58	Fuel saving per flight		8.6 kg

The comparisons of average deviations from the flights' preferred assignments and the fuel consumption between those in the GAP and those in the RBS are given in Table 4-10.

For the eastbound flights, the GAP produces smaller average flight-level and Mach-number deviations but higher average track deviation than those produced in the RBS. The average success rate with the GAP is slightly lower than that of RBS. However, this does not mean that the GAP is inferior to the IAP in the RBS since the objective of the GAP is not to maximize the success rate. Compared with the RBS, the average fuel savings per flight with the GAP is about 35.7 kg. We believe that the fuel saving mainly comes from the smaller deviation from a flight's preferred flight levels and Mach numbers.

For the westbound flights, the GAP produces smaller average flight-level deviation but slightly higher track and Mach-number deviations than those produced in the RBS. In addition, the success rate with the GAP is slightly higher than that produced in the RBS. Compared with the RBS, the average fuel savings per flight with the GAP is about 4.3 kg. We believe that the fuel savings are primarily a result of the smaller deviations from a flight's preferred flight levels as well as the higher success rate.

The breakdown of the comparisons by the number of requesting flights in the group is also presented in Table 4-10. The following observations can be made:

1) Flights assigned by the GAP performed with 5 or more flights in the group (GAP5+):

   The number of the GAP5+ accounts for about 35.6% of the total GAP performed in the eastbound OTS and 19.7% in the westbound OTS. The number of flights assigned by the GAP5+ accounts for 60% of the total eastbound flights and 40% of the westbound flights. With the simulation settings, most of the GAP5+ should be performed during congestion period. This suggests that the level of traffic in the eastbound OTS is higher than that of the westbound. It is consistent with the observation shown in Part A of Figure 4-30; that is, the entry area of the eastbound OTS is more congested than that of the westbound during peak hours. For both directions, flights assigned by GAP5+ have fuel savings higher than the overall average.

2) Flights assigned by the GAP performed with one flight in the group (GAP1):

   The percentage of the GAP1 is about 28.3% in the eastbound OTS and 27.2% in the westbound OTS. The number of flights assigned by the GAP1 accounts for less than 9.5% for both directions. Based on the simulation settings, assignments performed by GAP1 are expected to be the same as those produced by the IAP in the RBS since the GAP1 is equivalent to the IAP. However, it can be observed that the flights assigned by the GAP1 also have fuel savings compared with their fuel consumption in the RBS. This is probably because the GAP1 is performed among the GAP with more than one flight, which make the traffic conditions (e.g., the assignments of the intermediate flights) different from those when the IAPs are performed in the RBS. As a result, the fuel savings produced by the GAP1 may be not a result of a better assignment for the flight in the group but because of the better assignments of other flights (i.e., flights assigned by the GAP with more than one flight).

3) Flights assigned by the GAP with more than one but less than five flights:

   For both directions, flights assigned by the GAP with two or four flights in the group also have fuel savings; however, the savings are less than those assigned by the GAP5+. The flights assigned by the GAP with three flights in the group (GAP3) actually consume more fuel. We believe that the additional waiting time for the GAP to be performed may provide an explanation for those observations.

   In the RBS, a flight's waiting time for the IAP to be performed is negligible. However, with the GAP, a requesting flight needs to wait for the conditions to perform the GAP to be satisfied. In our simulation, the requesting flights are assumed to fly toward their preferred assignments while waiting for their assignments. If the waiting time is long, the requesting flights may travel a significant distance such that they are all close to the OTS entry as well as to each other. This could increase the probability of flight-path conflicts with intermediate flights as well as among the requesting flights themselves, which could reduce the requesting flights' chances to get their preferred assignments.

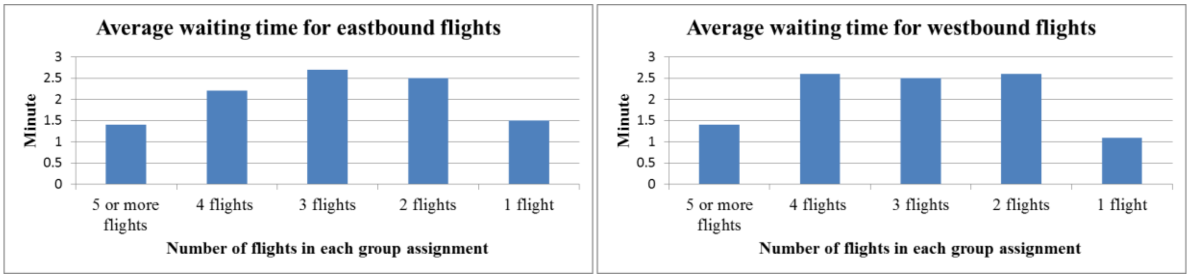


Figure 4-31: Average waiting time per flight

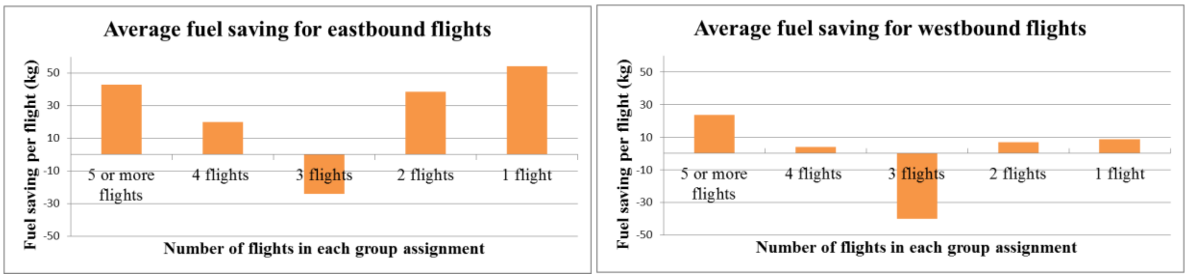


Figure 4-32: Average fuel savings per flight

A GAP performed with less than five flights in the group (GAP5-) must be performed no earlier than five minutes after the last one is performed. This means some requesting flights assigned by GAP5- might experience long waiting times (e.g., could be as long as five minutes). Figure 4-31 and Figure 4-32 show the average waiting times and fuel savings of the requesting flights assigned by the GAP with the same number of flights in the group. It can be observed that the requesting flights assigned by the GAP5+ and GAP1 have relatively shorter waiting times and greater fuel savings than those assigned by the GAP performed with 2-4 flights. In addition, the bar plots in the two figures suggest that a negative correlation exists between the additional waiting time and fuel savings; that is, the longer the waiting time is, the less the fuel savings is. In particular, the eastbound requesting flights assigned by the GAP3 experienced the longest waiting time and the least fuel savings (in fact, they consume more fuel than they do in the RBS).

4) As can be observed, the GAP produces more fuel savings for the eastbound flights than it does for the westbound OTS. Though many factors such as the differences in the OTS

structure and fleet mix could contribute to this, an important possible explanation worth mentioning is the advantage of the GAP over the IAP. The GAP has an advantage over the IAP in that it optimizes the assignment of multiple requesting flights. Intuitively, this advantage could be more significant as the traffic becomes more congested since the average number of requesting flights in the group would be higher. We have shown that the degree of congestion in the eastbound OTS is higher than that of the westbound. For example, the average number of intermediate flights considered in the GAP performed for the eastbound flights is almost twice as many as that in the GAP for the westbound flights. The percentage of the GAP5+ performed in the eastbound OTS is almost twice as high as that of the westbound OTS. The higher traffic flow in the eastbound OTS could make the GAP produce more benefits than it does for the westbound OTS.

CHAPTER 5 SUMMARY OF FINDINGS

Section 5.1 Summary of Findings for Chapters 2 and 3

Subsection 5.1.1 Demand forecasting models for piston aircraft

We found that the relative fuel price (that is, fuel price compared with personal income), GDP growth rate (one year lag), and the number of student pilots are significant determinants of the utilization rate and the probability of staying active for piston aircraft.

A 10% increase in the relative fuel price would lead to about 6.7%, 2.3%, and 6% drop in the utilization rate of single engine piston, multi-engine piston, and piston aircraft, respectively. A 10% increase in the number of student pilots could bring a 2.6%, 2.2%, and 2.6% increase in the utilization rate of single engine piston, multi-engine piston, and piston aircraft, respectively. In addition, due to the difference in the primary usage, the previous years' GDP growth rate has more impact on the utilization rate of multi-engine aircraft than it has on single engine piston aircraft.

If the relative fuel price increases by 0.01, then the odds of staying active for single engine piston, multi-engine piston, and piston would drop by 1.91%, 1.43%, and 1.78%, respectively.

If the previous year's GDP growth rate increases by 0.01, then the odds of staying active for single engine piston, multi-engine piston, and piston is expected to increase by 1.81%, 5.34%, and 2.22%, respectively.

If the number of student pilots increases by 1000, then the odds of staying active for single engine piston and piston aircraft will increase by about 0.2%, respectively.

Subsection 5.1.2 Airport-level demand forecasting models for itinerant and local GA operations

We found that the social-economic and demographic factors around an airport, the availability of supply factors, the competition from the commercial aviation, the number of based aircraft, and the presence of a flight school at an airport are significant determinants for the airport-level GA demand.

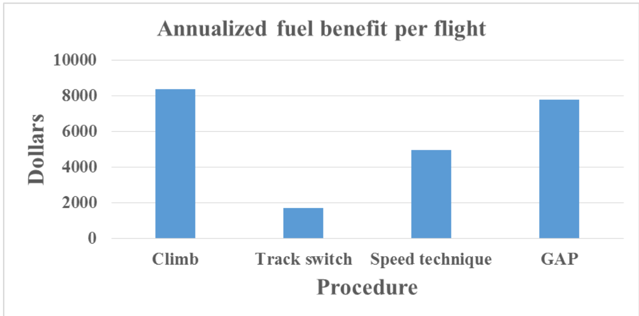
For itinerant GA operations at an airport, a 10% increase in the relative fuel price would result in a 4.3% decrease in the number of itinerant operations. The availability of a runway with a runway length greater than 4000 ft. is expected to increase the number of itinerant operations by 40%. An airport with a control tower could have about 170% more itinerant operations than an airport without one. A reliever airport is expected to have 40% more itinerant operations than a non-reliever.

For local GA operations at an airport, a 10% increase in the relative fuel price would result in a 5.2% decrease in the number of local operations. Local GA operations are elastic to local farm industry employment. A 10% increase in this factor may lead to a 12.3% increase in local operations. An airport with a primary runway with a runway length between 1000 ft. and 4000 ft. could have 71% more local operations than an airport without a runway with a runway length greater than 1000 ft. or with a runway longer than 4000 ft. In addition, airports without commercial services is expected to have about 80% more local operations than those with the services, and a based flight school could increase the number of local operations by about 84%.

Pavement condition and the availability of an engine repair plant will significantly increase the number of itinerant and local operations at an airport. Both types of operations are inelastic to the number of aircraft based at an airport. A 10% increase in the number of based aircraft will result in about a 1.6% increase in the number of itinerant operations. A 10% increase in the number of based single engine aircraft will lead to about a 4.9% increase in the number of local operations

Section 5.2 Discussions, Conclusions, and Recommendations for Chapter 4

Subsection 5.2.1 Annualized fuel benefits and the sensitivity of the fuel benefits to the stimulation step size



We assumed that the fuel price is one dollar per kg and a flight flies 365 times in a year with conditions (e.g., traffic and meteorological) similar to those used in this study

Figure 5-1: Annualize fuel benefit per flight

The annualized fuel benefits per flight of the four procedures are summarized in Figure 5-1. In this study, climbing inside the OTS produces the highest annual fuel benefit (about $8000 per flight per year), and switching tracks produces the least annual fuel benefit (about $2000 per flight per year).

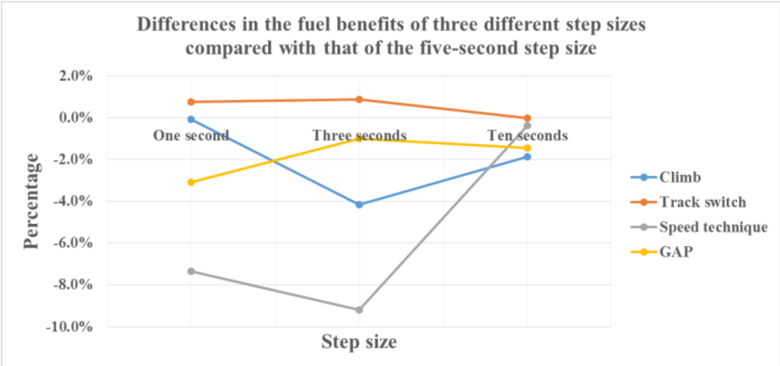


Figure 5-2: Sensitivity of the fuel benefits of the four procedures to the simulation step size

In addition, we evaluated the sensitivity of the fuel benefits of the four procedures to the simulation step size. The evaluation is done by comparing the fuel benefits produced by the four procedures with three different step sizes (i.e., one second, three seconds, and ten seconds) with that of the five-second step size. In other words, for each procedure the average fuel benefits per flight produced by the three step sizes are compared with that of the five-second step size. Figure 5-2 shows the comparison in terms of the differences in fuel benefit with respect to the fuel benefit produced by the five-second step size. In other words, the differences are given as their percentages in the fuel benefit produced by the five-second step size. For the climbing inside the OTS, switching tracks inside the OTS, and the GAP, it can be observed that the differences in fuel benefit between the three step sizes and the five-second step size are less than 5%. For the Mach speed technique, the differences are less than 10%.

Subsection 5.2.2 Climb and track change inside the OTS

1) About their benefit estimates and possible improvements

We have observed that climbing inside the OTS will generally lead to fuel saving both inside and outside the OTS. The fuel savings are primarily because of the lower fuel consumption rate at higher flight levels. In addition, this procedure not only benefits those that performed the climb but also all the flights in the system as a whole.

We believe that the benefit estimates for this procedure are relatively conservative because of the restrictions in the simulation settings. For example, a flight is only allowed to make a no more than 2000 ft. climb once; however, in reality, flights are allowed to make multiple climbs, and the target flight levels could be any feasible flight level. In addition, we assume that the procedure is performed only at significant waypoints since all the flights are expected to send position reports at those waypoints because of the event-based position reports. However, the procedure could be performed at any position if the time interval of reports in the time-based positon reports is sufficiently short. Moreover, the minimum longitudinal separation is assumed to be 10 minutes even in the exclusive airspace. As the surveillance capability is improved, this minimum could be reduced to, for example, 2 or 5 minutes. At last, the ATC routine handles the requests from flights that are not given their preferred OTS assignments and those that are the same in this study. However, the former ones might be benefited more if they could get closer to their preferred assignments. Therefore, we suggest that priorities be given to those that are not given their preferred OTS assignments.

Our results also show that switching tracks inside the OTS usually will result in savings in fuel and travel time for the whole trip. The fuel savings are mainly due to the reduction in travel time. However, for flights that perform the procedure, the fuel consumption and travel time inside the OTS could increase due to the transition between tracks. Similar to climbing inside the OTS, this procedure not only benefit those that performed the switch but also all the flights in the system as a whole.

Similar to the previous procedure, the benefit estimates for the track-switch procedure are also relatively conservative. In addition to the restrictions used in the previous procedure, we assume that the angle of leaving current tracks and angle of joining target tracks are 15 degrees. In reality, the two angles could be determined by minimizing the travel time on target tracks or avoiding flight-path conflicts with flights on target tracks to increase the success rate.

2) Scenarios to be applied

Both procedures are developed to benefit flights in terms of fuel or travel time when they are inside the OTS; however, they could also be applied in other scenarios such as avoiding turbulence or severe weather. In addition, the two procedures are not mutually exclusive in the sense that they could be applied simultaneously with each other.

However, due to some of their differences, there could be some scenarios in which it may be more beneficial to implement one procedure instead of the other. In particular, we would like to point out the following scenario, which is related to controllers' practice used to make the OTS assignments.

In this study, if a flight's preferred flight level is not available, the ATC routine would first inspect three flight levels below its preferred one before inspecting other tracks. With this practice, flights are more likely to get their preferred tracks than their preferred flight levels. In this case, climb inside the OTS would be a more appropriate procedure to be implemented since it allows flights to get closer to their preferred flight levels. However, if controllers first inspects the flight's preferred flight level on other tracks before inspecting other flight levels, then track switch inside the OTS may be more appropriate to be implemented.

3) Pilots' and controllers' familiarity with the new procedures

Both procedures require pilots to evaluate the need of a request and the ground controllers to evaluate the feasibility of a request. Though the two procedures are relatively new for the flight operations inside the OTS, they are not completely new to pilots and ground controllers in that procedures that are similar to the two are already being used outside the OTS. For example, climb for fuel efficiency and flight-level change due to traffic are two procedures relatively common for flights in domestic airspace and random flights over the NAT or Pacific. These two procedures are comparable to the procedure of climbing for fuel efficiency inside the OTS in their decision-making processes are similar to those of the two new procedures. Flight-path deviations due to weather or traffic is also a relatively common procedure for flights in domestic airspace and random flights over the NAT or Pacific. This procedure is comparable to the procedure of track switch inside the OTS because of their similarities in the decision-making process. From this point of view, pilots and ground controllers should be relatively familiar with those two procedures.

4) Workload for the controllers

During congestion period, more flights may not be able to get their preferred OTS assignments, and therefore are more likely to request climb or track switch once they are inside the OTS. As a result, the number of requests for implementing the two procedures could be high during peak hours. This could significantly increase controllers' workload, especially when flights are allowed to implement the procedures multiple times. However, we believe that this issue could be addressed by restricting the number of requests a flight is allowed to make or the time period when a flight is allowed to make the requests. Those restrictions could be specified in the Track Message.

5) Safety

The safety issues related to the two procedures are not investigated in this study. However, a conflict detection routine is applied to detect and avoid flight-path conflicts when the feasibility of requests are evaluated. The minimum longitudinal separation which is one of the most critical minimum separations inside the OTS used by the routine is 10 minutes. This minimum is relatively conservative in that it is for traveling the entire OTS while the requests are usually expected to be sent when flights have travelled a significant distance inside the OTS. Though it is still imperative to evaluate whether implementing the two procedures could maintain the target level of safety inside the OTS, we believe that, if applied properly, those two procedures would not cause significant safety issues inside the OTS.

6) Conclusion for the two procedures

Based on the analysis of the simulation results and the above discussion, we conclude that implementing the two procedures would benefit all the flights using the OTS, and would not cause any significant issues for the pilots and controllers in terms of workload and safety.

Subsection 5.2.3 Speed Mach number technique and the group assignment procedure

1) About their benefit estimates and possible improvements

We have shown that the Speed Mach number technique could lead to fuel saving for those that perform the procedure. This is primarily because those flights could obtain their preferred OTS assignments for their entire trip inside the OTS. From this viewpoint, the benefit of performing this procedure is higher than that of performing the previous two procedures in that the previous two are performed after a part of the OTS has been travelled.

However, this procedure only redistributes the OTS assignments to benefit flights. As a result, we also have observed that some flights that do not perform the procedure could experience greater fuel consumption. This is because they cannot get their preferred OTS assignments because of those that perform the procedure. From this viewpoint, the negative impact of performing this procedure could also be significant. Though in this study a benefit for all the flights in the system is also observed for this procedure, it is not clear to us that this could always happen.

The procedure only assigns lower Mach numbers to increase the arrival time separations. An improvement could be to also assign higher Mach numbers to decrease the arrival time separations. This improvement would be useful for the cases where the arrival time separations are much more than enough to maintain the minimum. Intuitively, it would give flights that arrive later a greater chance of getting their preferred OTS assignments.

For the GAP, our results show that it does benefit flights in terms of deviations from their preferred OTS assignments and fuel consumption. Those benefits are mainly due to a better OTS assignment made by considering a group of flights simultaneously. However, we also observed that the fuel savings could be significantly different depending on the traffic condition. In addition, we found that the fuel savings could have a negative relationship with the waiting time for the procedure to be performed, that is, the longer the waiting time, the less the fuel savings.

In this study, all the flights are assigned by the GAP. In the conditions to perform the GAP, a fixed time interval (i.e., 5 minutes) and a fixed threshold (i.e., 5 flights) for the number of flights in the group are used. The GAP is performed only if one of them is satisfied. However, the simulation results show that those settings might not be optimal if the traffic flow is relatively low in that they might cause a longer waiting time. We suggest the following improvements:

- Using a dynamic threshold for the number of flights in the group based on the number of assignment requests received within a time period (e.g., last 5 minutes). If the number of assignment requests received within a time period increases, then a higher threshold could be used; otherwise, a lower threshold could be adopted. This improvement could include more flights in the GAP when the traffic is congested because of the increased threshold and it could reduce the average waiting time for the procedure to be performed when the traffic flow is relatively low because of the reduced threshold. Therefore, we believe this improvement could produce more fuel savings than the current GAP.
- Using the GAP or the IAP depending on the traffic condition. Using the GAP to make the assignment if the number of assignment requests received within a time period exceeds a threshold; otherwise, using the IAP to make the assignment.

2) Scenarios to be applied

Both procedures are developed to benefit flights by improving the OTS assignment process. The speed Mach number technique actually could be incorporated into the GAP by introducing another degree of freedom, that is, Mach number in the OTS entry area. However, doing this could increase the size of the optimization problem.

Similar to the previous procedures, there are some scenarios in which it may be more beneficial to implement one procedure instead of the other. The GAP could produce fuel savings and smaller deviations from flights' preferred assignment when the traffic is congested, and therefore it should be used in this case. Since the GAP may cause a long waiting time and sometimes greater fuel consumption if traffic flow is relatively low, it may be more beneficial to use IAP and the speed Mach technique in this case.

3) Pilots' and controllers' familiarity with the new procedures

Applying both procedures mainly requires the efforts of ground controllers. Similar to the previous ones, the two procedures are not completely new to controllers either. The speed Mach number technique is essentially the same as adjusting a flight's speed Mach number to avoid flight-path conflicts or for fuel efficiency, which is relatively common for the flights in domestic airspace and the random flights over the NAT or Pacific. The GAP is not significantly different from the current practice used to make the OTS assignments (i.e., the IAP) except the additional steps that are introduced to assign multiple flights simultaneously. To perform those steps on a real-time basis, a computer software will be needed, for example, to formulate and solve the optimization problem. The computer software could significantly reduce controllers' involvement in the assignment process. In this case, controllers mainly need to prepare the inputs for the software and send theassignments to pilots. Therefore, it should be relatively easy for controllers to become familiar with the two procedures.

4) Workload for the controllers

In contrast to the previous procedures, these two procedures will be applied, at most, once for each flight at the entry area. The speed Mach number technique, if applied, only requires one additional step to estimate the reduction in the Mach number when a flight's preferred OTS assignment is being inspected for availability, and the GAP is expected to be handled with the assistance of a computer software, which could significantly reduce controllers' workload. As a result, it is reasonable to believe that these two procedures would not significantly increase controllers' workload.

5) Safety

The safety issues related to the two procedures are not investigated in our study. However, the two procedures are to be implemented at the OTS entry area, where sufficient radar surveillance and communication capability are expected to be available to ensure safety. Moreover, the two procedures are designed to be applied with the same measures currently being used to ensure the safety of flight operations. Though evaluating whether implementing the two procedures could maintain the target level of safety at the OTS area is still a necessary step, we believe that, if applied properly, those two procedures would not cause significant safety issues.

6) Conclusion for the two procedures

Based on the analysis of the simulation results and the above discussion, we conclude that implementing the two procedures would improve the OTS assignment process and would not cause any significant issues for the pilots and controllers in terms of workload and safety.

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