Fleet Level Environmental Evaluation of Emission Taxing Scheme and Biofuel: A Combined Optimization and Multi-Actor Approach

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By Hsun Chao

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Fleet Level Environmental Evaluation of Emission Taxing Scheme and Biofuel: A Combined Optimization and Multi-Acrotr Approach

For the degree of Master of Science in Aeronautics and Astronautics

Is approved by the final examining committee:

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Chair

Dr. Buyung Agusdinata

Dr. William A. Crossley

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Approved by Major Professor(s): Dr. Daniel A. DeLaurentis

Approved by: Dr. Weinong Wayne Chen 07/25/2016

Head of the Departmental Graduate Program Date
FLEET LEVEL ENVIRONMENTAL EVALUATION OF EMISSION TAXING SCHEME AND BIOFUEL: A COMBINED OPTIMIZATION AND MULTI-ACTOR APPROACH

A Thesis

Submitted to the Faculty

of

Purdue University

by

Hsun Chao

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Aeronautics and Astronautics

August 2016

Purdue University

West Lafayette, Indiana
This work dedicated to my family, who unreservedly and generously support my dream.
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SYMBOLS

Area_{i,m} \quad \text{Land area used to cultivate crop } i \text{ in state } m

a \quad \text{Intercept of linear regression results}

BF_l \quad \text{Biofuel consumption in state } l

BF_{l}^{pred} \quad \text{Predicted biofuel consumption in state } l

BH_{k,j} \quad \text{Block hours of aircraft type } k \text{ on route } j

b \quad \text{Slope of linear regression results}

C_{free} \quad \text{Free carbon emission quota}

C_i \quad \text{Unit production cost of feedstock } i

C_{k,j} \quad \text{Direct Operating Cost (DOC) of aircraft } k \text{ on route } j

C_{k,j}^{\text{non-fuel}} \quad \text{DOC excludes fuel cost}

CO_2 \quad \text{Carbon emissions}

Comp_{i,l} \quad \text{Composition of feedstock } i \text{ in state } l

Cost_{\text{carbon}} \quad \text{Carbon Emission Charge}

Cost_{\text{fuel}} \quad \text{Fuel Cost}

Cost_{\text{no change}} \quad \text{Airlines’ Expenses on fuel and emission with fixed biofuel usages}

Crop_{i,m,l} \quad \text{Equivalent biofuel of feedstock } i \text{ import from state } m \text{ to state } l

cap_k \quad \text{Capacity of aircraft type } k

dem_j \quad \text{Total passenger market demand on route } j

dem_{i,m}^{\text{crop}} \quad \text{Crop demand of feedstock } i \text{ in state } m

E_p \quad \text{Unit carbon emission per pound of conventional Jet A fuel}

E_{i}^{\text{bio}} \quad \text{Unit carbon emission per pound of biofuel in state } l

E_{\text{old}}^{\text{bio}} \quad \text{Average unit carbon emission per pound of biofuel in previous year}

E(f) \quad \text{Expectation of stochastic variable } f

F_C \quad \text{Carbon emission charges per pound of carbon dioxide emissions}
Number of aircraft type $k$ in the airline fleet
Fuel Consumption of aircraft type $k$ on route $j$
GDP growth rate
Set of routes connect to state $l$
Marginal land area in state $m$
Maximum equivalent biofuel production of land competition feedstocks in state $m$
Maximum equivalent biofuel production of feedstock $i$ in state $m$
Maintenance hours of aircraft type $k$ on route $j$
Net Present Value of cultivating crop $i$
Number of new observation of interested variable $f$
Ticket price of type $k$ aircraft on route $j$
Biofuel Price in state $l$
Average biofuel Price in previous year
Adjusted prediction of total fuel consumption
Passenger on aircraft type $k$ on route $j$
Fuel consumption portion in state $l$
Suitability of feedstock $i$ in state $m$
Daily biofuel supply in state $l$
Turnaround time
Variance of stochastic variable $f$
Number of trips of aircraft type $k$ on route $j$
Yield per acre of feedstock $i$
Prior degree of freedom of variable $f$
Posterior degree of freedom of variable $f$
Mean of a normal variable $f$
Prior mean of $\mu_f$
Posterior mean of $\mu_f$
Prior scale of $\sigma_f^2$
\( \nu_f \)  
Posterior scale of \( \sigma_f^2 \)

\( \sigma_f^2 \)  
Variance of a normal variable \( f \)

\( \sigma_{f_0}^2 \)  
Prior variance of \( \mu_f \)

\( \sigma_{f^*}^2 \)  
Posterior variance of \( \mu_f \)
## Abbreviations

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<th>Description</th>
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<tr>
<td>ASCENT</td>
<td>The Aviation Sustainability Center</td>
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<tr>
<td>BI</td>
<td>Bayesian Inference</td>
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<tr>
<td>BTS</td>
<td>Bureau of Transportation Statistics</td>
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<tr>
<td>CDM</td>
<td>Cleaning Development Mechanism</td>
</tr>
<tr>
<td>CER</td>
<td>Certified Emission Reduction</td>
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<tr>
<td>CO₂e</td>
<td>Carbon Dioxide Equivalent</td>
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<tr>
<td>DOC</td>
<td>Directed Operating Cost</td>
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<td>EAG</td>
<td>Environment Advisory Group</td>
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<td>EEA</td>
<td>European Economic Area</td>
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<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
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<tr>
<td>ETS</td>
<td>Emission Trading Scheme</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>EUA</td>
<td>European Emission Allowance</td>
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<td>FLEET</td>
<td>Fleet-Level Environmental Evaluation Tool</td>
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<tr>
<td>FLOPS</td>
<td>Flight Optimization System</td>
</tr>
<tr>
<td>FT-Synthesis</td>
<td>Fischer-Tropsch-Synthesis</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>GLADS</td>
<td>Global Aviation Dialogues</td>
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<tr>
<td>GMBM</td>
<td>Global Market-Based Measure</td>
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<tr>
<td>GNI</td>
<td>Gross National Income</td>
</tr>
<tr>
<td>HLM-GMBM</td>
<td>High-Level Meeting on a Global Market Scheme</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transportation Association</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
</tr>
<tr>
<td>JI</td>
<td>Joint Implementation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>LTO NO\textsubscript{x}</td>
<td>Landing and Takeoff Nitrogen Oxides</td>
</tr>
<tr>
<td>MIP</td>
<td>Mixed Integer Programming</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>RPNMI</td>
<td>Revenue Passenger Nautical Miles</td>
</tr>
<tr>
<td>SOC</td>
<td>Soil Organic Carbon Sequestration</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>SFW</td>
<td>Subsonic Fixed Wing</td>
</tr>
<tr>
<td>SRWC</td>
<td>Short Rotation Woody Crop</td>
</tr>
<tr>
<td>VER</td>
<td>Voluntary Emission Reduction</td>
</tr>
<tr>
<td>WWLMINET</td>
<td>Worldwide Logistics Management Institute Network Queuing Model</td>
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ABSTRACT


The Fleet Level Environmental Evaluation Tool (FLEET) can assess environmental impacts of various levels of technology and environmental policies on fleet-level carbon emissions and airline operations. FLEET consists of different models to mimic airlines’ behaviors and a resource allocation problem to simulate airlines’ aircraft deployments on their networks. Additionally, the Multiactors Biofuel Model can conduct biofuel life-cycle assessments and evaluate biofuel developments and assess the effects of new technology on biofuel production costs and unit carbon emissions as well.

In addition, the European Union (EU) initiated an Emission Trading Scheme (ETS) in the European Economic Area, while International Civil Aviation Organization (ICAO) is designing a Global Market-Based Measure (GMBM) scheme to limit civil aviation fleet-level carbon emissions after 2021. This work integrates the FLEET and the Multiactors Biofuel Model together to investigate the interactions between airline operations, biofuel production chains, and environmental policies. The interfaces between the two models are bio-refinery firm profit maximization problem and farmers’ profits maximization problem. The two maximization problems mimic the bio-refinery firms and farmers behaviors based on environmental policies, airlines performances, and biofuel developments.

In the current study, limited impacts of biofuels on fleet-level emissions due to the inconsistency between biofuel demand and feedstock resource distributions and feedstock supplies were observed. Furthermore, the main driving factor for biofuel developments besides newer technologies was distinguished. Conventional jet fuel prices have complex impacts on biofuel developments because conventional jet fuel
prices increase biofuel prices and decrease potential biofuel demands at the same time. In the end, with simplified EU ETS and ICAO GMBM models, the integrated tool represents that EU ETS model conducts lower emissions in a short term, while the ICAO GMBM model has greener long-term effects.
1. INTRODUCTION

Mark W. Maier [1] has defined a system of systems (SoS) as follows:

A system-of-system is an assemblage of components which individually may be regarded as systems, and which possesses two additional properties:

- Operational Independence of the Components: If the system-of-system is disassembled into its component systems the component systems must be able to usefully operate independently. That is, the components fulfill customer-operator purposes on their own.

- Managerial Independence of the Components: The component systems not only can operate independently, they do operate independently. The component systems are separately acquired and integrated but maintain a continuing operational existence independent of the system-of-systems.

According to Maier’s definition, the aviation industry can be regarded as a SoS. In this system, airlines, aircraft manufacturers, government sectors, and fuel suppliers are not only geographically distributed but also operating and achieving their objectives independently. Additionally, they try to include latest technologies or policies to, by their means, cope with some unexpected emergent behaviors, like air traffic conjunctions, environmental pollution or diseases transmission. These characteristics make the system evolve constantly. The properties of the system components are diverse, and the future states of the systems are not well defined. Hence, many agencies including National Aeronautics and Space Administration (NASA), the International Civil Aviation Organization (ICAO), and the European Union (EU) fund
many projects to improve make aviation industry in the future and gain an exhaustive understanding of it from different perspectives, e.g. NASA’s Subsonic Fixed Wing Project.

Global warming presents a challenge to many industries, and aviation is no exception. Although the portion of carbon emissions from aviation is only 2% of total carbon emissions, it is expected to have 3-4% growth per year due to the rapid demand growth rate [2]. Therefore, the International Air Transportation Association (IATA) set up an ambitious goal to keep total carbon emissions in 2020 with 2005 emissions level and reduces to 50% of 2005 emissions level in 2050. Besides, NASA, EU, and ICAO have tried to tackle the challenges with different approaches.

The following two sections provide a brief introduction to the recent research about performances of future aircraft and the policies to regulate greenhouse gas (GHG) emission from aircraft operators.

1.1 FUTURE AIRCRAFT PERFORMANCE

According to NASA’s Subsonic Fixed Wing (SFW) project, the future aircraft should satisfy not only the increasing passenger demand but also have lower GHG and noise emissions. The SFW project has set different environmental goals for aircraft in consecutive generations based on the variance in the level of technology. The “N” generation aircraft is the aircraft with highest production rate in 2005 while the next generation aircraft is “N+1” aircraft which are expected to be available in 2015. The latter features 60% decrements of landing and takeoff nitrogen oxides (LTO NO$_x$) from CAEP/6 level, 33% fuel consumption reduction compared with 2005 aircraft level, and 32 dB noise reduction from Stage 4 level. With the possible technologies in 2020, the “N+2” generation aircraft should have 75% reduction in LTO NO$_x$ from CAEP/6 level, 50% fuel consumption reduction with 2005 aircraft level, and 42 dB noise reduction from Stage 4 level. Moreover, the “N+3” generation aircraft which are expected to be available in 2025 with more than 75% LTO NO$_x$ from CAEP/6 level,
more than 70% fuel consumption decrements, and 71 dB noise reduction from Stage 4 level. The goals for each generation aircraft with environmental factors appear in Table 1.1.

Although the NASA SFW project defines the future aircraft-specifics to achieve the CO\textsubscript{2}, LTO NO\textsubscript{x}, and noise reductions, those reduction goals cannot ensure to mitigate fleet-level environmental impacts. While average economics is growing, aviation passenger demands and aircraft operations are growing as well. The overall environmental impact may increase due to the economic growth even if the individual aircraft becomes greener and greener.

### 1.2 CARBON EMISSION TRADING SCHEME

The European Union Emission Trading Scheme (EU ETS) for international aviation and the ICAO Global Market-Based Measure (GMBM) scheme are the two most well-known environmental policies in the world. The EU ETS has been implemented in the European Economic Area since 2012, and the GMBM will be initiated globally.

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<th>Technology Benefits</th>
<th>Technology Generations (Technology Readiness Level = 4-6)</th>
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<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
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<tr>
<td>LTO NO\textsubscript{x} Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)</td>
<td>-33%</td>
</tr>
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Table 1.1.. NASA SFW Project Goals [3]
by 2021. Both schemes try to reduce the fleet-level carbon dioxide equivalent (CO₂e) and are briefly introduced in the following sections.

1.2.1 EUROPEAN UNION EMISSION TRADING SCHEME

European Union Emission Trading Scheme (EU ETS) aims to limit GHG emissions from various industries in European Economic Area (EEA). In July 2008, the EU Council decided to extend the EU ETS to involve international aviation. This decision would influence both European and third-country airlines that have flights takeoff or landing on airports in the EEA. Additionally, to keep airlines providing service on important routes with low capacities and opportunities for rapid growth or new in airlines, exemptions are granted to the routes, flights, and aircraft operators which match either of the following points [4]:

- routes which have capacities lower than 30,000 seats per year;
- aircraft operators with fewer than 243 flights per four-months period for one year;
- flights with total CO₂e emissions less than 10,000 tonnes per year;
- carbon emissions from flights which have maximum take-off weight less than 5,700 kg, perform under visual flight rules, or are rescue missions.

The emissions which do not get the exemption have to be included in the following calculations. Moreover, the EU ETS is designed to assign the emission allowances to the participating aircraft operators. Furthermore, aircraft operators have the obligations to have the CO₂e emission less than their allowances, but they can get the extra allowance by two means. First, they can auction the extra allowances from governmental emission allowance markets. Second, they can join in the project-based Kyoto instruments and be rewarded for emission allowances. The total emission allowances
are 97% average historical CO$_2$e emissions level from 2004 to 2006, and the rest of 3% emission is preserved for emergent situations and new or fast growth aircraft operators. Subsequently, the 85% of the total allowances is allocated to aircraft operators for free with the benchmark method, and the remaining 15% of the total allowances is preserved for allowance auction markets [4].

In the allowance assigning procedure, the benchmark method has three major steps. First, the free allowances, Free Allowance$_{2012}$, subtracts the share of allowances preserved for auction markets from the total allowance. Second, in Eq. 1.1, the remaining allowances are divided by the total verified revenue tonnes-kilometers, which are reported by all aircraft operators in the monitoring year 2010. Third, the amount of free allowances for an aircraft operator, Free Allowance$_{Operator}^{2012}$, equals to the benchmark multiplying with its reported tonnes-kilometers in the monitoring year, which is shown in Eq. 1.2.

$$\text{Benchmark}_{2012} = \frac{\text{Free Allowance}_{2012}}{\text{Reported RTK}_{2010}}$$

$$\text{Free Allowance}_{Operator}^{2012} = \text{Benchmark}_{2012} \times \text{Reported RTK}_{Operator}^{2010}$$

Due to the intervention from government sectors of third-countries, European governing institute activated “stop-the-clock” provision to grant exemptions to third-countries airlines from 2013 to the end of 2016. The compromise deal not only eased oppositions from third-countries to the scheme but also provided extra time to the ICAO for designing a global mechanism to limit global CO$_2$e emissions.

1.2.2 ICAO GLOBAL MARKET-BASED MEASURE SCHEME

In the 38th Session of the Assembly in 2013, the ICAO and its member states decided to develop a Global Market-Based Measure scheme to achieve the neutral carbon growth after 2020. The ICAO also conducted two rounds of Global Aviation
Dialogues (GLADS) and came up with the primary considerations for the design of a GMBM. The primary considerations were administrative simplicity, environmental integrity, cost effectiveness, differentiation/non-discrimination, and avoiding excessive cost or administrative burdens. Additionally, in January 2015, the Environment Advisory Group (EAG) meeting recommended that a high-level meeting on a Global MBM scheme (HLM-GMBM) have to be established. In the draft Assembly Resolution text which was considered by EAG, it not only mentioned details of the GMBM but also provided a schedule to guide the implementation of the GMBM by 2021. In May 11th to 13th, the HLM-GMBM held a meeting to discuss and share ideas about the GMBM in preparation for the 39th Session of the ICAO Assembly [5].

The scheme has two phases to mitigate the impacts from the GMBM on developing countries. The first and the second phases are going to start in 2021 and 2026, respectively. The State members are categorized into the two phases according to their Gross National Income (GNI) per capita from the World Bank in 2018 and their International Aviation Activities in Revenue Tonnes Kilometers (RTKs) in the same year. In the first phrase, states either are classified as high-income States regarding GNI, have 1% of total RTK shares, or have a cumulative share in the list of States from the highest to the lowest amount of RTKs reaches to 80%. In the second phase, states either are classified as upper-middle income regarding GNI, have 0.5% of total RTK shares, or have a cumulative share in the list reaches to 95%. Finally, the emissions from the operator on the routes connecting the states in phases mentioned above have to be included in and reported by the operators to ICAO [5].

The ICAO GMBM allocates the required offsets which can reach neutral carbon growth to aircraft operators. First, in year \( t \), the ICAO calculates the sector growth rate which is shown in Eq. 1.3. Then, the amount of required carbon offset for aircraft operator \( x \) in year \( t \) equals to the total emissions from the aircraft operator in the same year multiply with the sector growth rate, which is shown in Eq. 1.4.

\[
\text{Sector Growth}_t = \frac{\text{Total Emission}_t - \text{Total Emission}_{2020}}{\text{Total Emission}_t} \tag{1.3}
\]
\[
\text{Amount Offset}_{x,t} = \text{Emission}_{x,t} \times \text{Sector Growth}_t
\]  

(1.4)

Subsequently, aircraft operators have to compensate the assigned carbon offset with offset credits which can be gotten from two ways. They can join in the Cleaning Development Mechanism (CDM) or the Joint Implementation (JI) and earn the Certified Emission Reduction (CER) and the Voluntary Emission Reduction (VER) under the Kyoto Protocol. Buying allowance from emission trading schemes, like European Emission Allowances (EUA) and California units, is another option for the aircraft operators. In 2013, even though the GMBM was not initiated, Delta airline accomplished neutral carbon growth compared to 2012 levels by acquiring offset units [5].

1.3 OBJECTIVE

Previous works investigated the aviation carbon emissions with different levels of new technologies, various alternative fuels from diverse feedstock resources, and global environmental policies. For example, Fleet-Level Environmental Tool (FLEET) [6] and Aviation Environmental Portfolio Management Tool (APMT) [7] are capable of studying how new levels of technologies influence the fleet-level carbon emissions. Several studies have looked at the impact of biofuels and the EU ETS on the commercial aviation from economic and environmental perspectives. These studies can demonstrate the impacts of one or two factors on aviation, but research about how aviation industry simultaneously evolves with levels of new technologies, biofuel from various resources, and initiation of certain environmental policy is still required.

One of the objectives of this dissertation is to study the U.S. air transportation system with biofuel production chains, aircraft manufacturers, and global level environmental policies. First, the current research focuses on the environmental impacts of the three diverse industries on the U.S. commercial airlines. Due to the implemen-
tation of new policies, airlines will have extra costs or limitations from using their fleets, which would create demands for more advanced aircraft and biofuel. Then, aircraft manufacturers would use higher levels of technologies on upcoming aircraft to help airlines mitigate the extra cost or limitations. Similarly, the demand would also drive biofuel production chains from farmers or feedstock suppliers to airlines. The interactions between these actors conduct the higher level environmental impacts from the future air transportation system.

This dissertation intends to come up with a framework to integrate two existing tools, which are FLEET and Multiactors Biofuel Model. FLEET has the capabilities to model the U.S. air transportation system with upcoming and more advanced aircraft. Multiactors Biofuel Model can assess the carbon life cycle of biofuel from different feedstock resources. This framework with a combined multiactors and optimization approach can model the biofuel industry development and farmers’ behaviors in each state, represent the risk-attitude of the bio-refinery firms, demonstrate the feedstock transportation in the United States. Hence, this framework can not only provide junctions for both models to pass information back and forth but embrace the mechanism of a given environmental policy in the decision-making of each actor. The successful work can achieve the needs of modeling impacts from biofuel production chain, aircraft manufacturers, and government sectors on the U.S. air transpiration system together.

In the end, this dissertation intends to design a biofuel module that can integrate into more tools to help policy makers develop environmental schemes and assess biofuel production impacts on aviation. Although this dissertation uses FLEET to demonstrate the capabilities of the model, this biofuel module can combine with other tools or models with total fuel consumption and distributions, e.g. APMT and Hierarchical Decision-Centric Model [8]. Also, this biofuel module can include more feedstock models from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model [9] to investigate the development competition between
feedstocks. Finally, the module intends to help the policymakers in analyzing the impacts of new policies on aviation and biofuel production chains.
2. PREVIOUS WORKD

The Fleet Level Environmental Evaluation Tool (FLEET) assesses environmental impacts of aviation and does model-based simulation for airline decision-making about fleet operations along with an evaluation of passenger demand and airline fleet mix and technology level simultaneous. Also, the Multiactors Biofuel Model is capable of executing the life cycle assessment (LCA) for biofuel from five potential feedstocks, which are camelina, algae, corn stover, switchgrass, and short rotation woody crops (SRWCs). At the same time, different stakeholders and decision makers get involved into the biofuel development process. The integration of both models can provide a holistic capability to assess the environmental impacts of aviation, model airlines operations about fleet deployments along with levels of technologies and mandatory environmental policy, and simulate biofuel development from fields to wheels. The parts which are essential to both models are introduced in the next two sections.

2.1 FLEET LEVEL ENVIRONMENTAL EVALUATION TOOL

The core of FLEET is a resource allocation optimization problem to model the airlines’ aircraft usage, along with several models to represent other airlines decisions, such as assigning ticket prices and deciding aircraft acquisitions and retirements. The interactions between each model are shown in Figure 2.1. In preparation for the author’s work, following sections introduce the FLEET setup and the resource allocation optimization problem.
2.1.1 FLEET SETUP AND MODEL ASSUMPTION

There are several abstractions to simplify the U.S. air transportation system in FLEET. At the airport level, FLEET models the airports in Worldwide Logistics Management Institute Network Queuing Model (WWLMINET) 257 airports list, which includes the busiest airports worldwide. At the route level, FLEET includes those routes which have flights takeoff or landing at the U.S. airports and have more than 10 passengers per day. The passenger demand network is generated according to historical data from Bureau of Transportation Statistics (BTS) DB1B Database in 2005. After filtering, in the model, there are 2134 routes, which cover 65% of all passenger flights and 80% of all passengers traveled.

Figure 2.1. System dynamics-like representation of FLEET [6].
At the aircraft level, the real world aircraft fleet is categorized into six classes by aircraft seat capacities and four technology groups. The technology groups are representative-in-class, best-in-class, new-in-class, and future-in-class. The aircraft with highest operation numbers in 2005 belongs to representative-in-class, while the aircraft with the most recent entry-in-service date in each class is categorized as the best-in-class. The new-in-class aircraft are either concept aircraft that incorporate technology improvement or currently under development. Similarly, future-in-class aircraft are currently under development and expected to enter into service in the further future. The aircraft used in FLEET are listed in Table 2.1 according to its technology group and class.

Regarding aircraft performance of the representative-in-class and best-in-class aircraft, FLEET uses the Flight Optimization System (FLOPS) to size the existing aircraft. FLOPS is used to estimate the sizes and performance of new-in-class and future-in-class concept aircraft, which, regarding aircraft environmental impacts reduction, should be consistent with other NASA models of advanced technology aircraft. For the aircraft without a reasonable conceptual model, FLEET uses the existing aircraft models and adjusts aircraft fuel burn, LTO NOx emissions, and noise to meet NASA goals; hence the “magic wand” labels in Table 2.1. Besides, FLOPS can simulate various mission with different load factors and ranges, and create aircraft performance tables such as fuel burn, Direct Operating Cost (DOC), etc. Theses tables are applied to estimate the performance of aircraft on the abstract airline network.

2.1.2 RESOURCE ALLOCATION PROBLEM FORMULATION

A resource allocation problem is the core of FLEET, and it is formulated and solved as a mixed integer programming problem by using GAMS software package [10]. The problem consists of an airline profit equation and various aircraft operation constraints. The mathematical model searches for the most optimal solution to put the fleet on each route in the network without violating all constraints. A more
<table>
<thead>
<tr>
<th>Class</th>
<th>Seats</th>
<th>Representative-in-Class</th>
<th>Best-in-Class</th>
<th>New-in-Class</th>
<th>Future-in-Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20-50</td>
<td>Canadair RJ200 / RJ440</td>
<td>Embraer ERJ 145</td>
<td>Small Regional Jet</td>
<td>“Magic Wand” CRJ200</td>
</tr>
<tr>
<td>2</td>
<td>51-99</td>
<td>Canadair RJ700</td>
<td>Embraer 170</td>
<td>CS100</td>
<td>“Magic Wand” CRJ700</td>
</tr>
<tr>
<td>3</td>
<td>100-149</td>
<td>Boeing 737-300</td>
<td>Boeing 737-700</td>
<td>Boeing 737-700 Re-engined</td>
<td>Purdue Small ASAT with N+1 / N+2 level technology</td>
</tr>
<tr>
<td>4</td>
<td>150-199</td>
<td>Boeing 757-200</td>
<td>Boeing 737-800</td>
<td>Boeing 737-800 Re-engined</td>
<td>D-8 “double Bubble”</td>
</tr>
<tr>
<td>5</td>
<td>200-299</td>
<td>Boeing 767-300</td>
<td>Airbus A330-200</td>
<td>Boeing 787</td>
<td>“Magic Wand” Boeing 767</td>
</tr>
<tr>
<td>6</td>
<td>300+</td>
<td>Boeing 747-400</td>
<td>Boeing 777-200ER</td>
<td>Large Twin Aisle</td>
<td>“Magic Wand” Boeing 777</td>
</tr>
</tbody>
</table>
detailed mathematical equation set is shown in Eqs. 2.1 - 2.5.

Maximize:
\[
\sum_{k=1}^{K} \sum_{j=1}^{N} (pax_{k,j} \times P_{k,j}) - \sum_{k=1}^{K} \sum_{j=1}^{N} (x_{k,j} \times C_{k,j}) \tag{2.1}
\]

Such that:
\[
\sum_{j=1}^{J} 2 \times (x_{k,j} \times (BH_{k,j} + MH_{k,j} + t)) \leq 24 \times 3 \times fleet_k, \forall k \tag{2.2}
\]
\[
\sum_{k=1}^{K} pax_{k,j} \leq dem_j, \forall j \tag{2.3}
\]
\[
\sum_{k=1}^{K} pax_{k,j} \geq 0.2 \times dem_j, \forall j \tag{2.4}
\]
\[
pax_{k,j} \leq x_{k,j} \times cap_k, \forall j, k \tag{2.5}
\]

The integer variables \( x_{k,j} \) represents the number of trips served by aircraft \( k \) on route \( j \), while the variable \( pax_{k,j} \) shows the number of passengers carried by aircraft type \( k \) on route \( j \). Equation 2.1 is the profit function, which is the total revenue minus the total operating cost. The total revenue equals the summation of the number of passengers, \( pax_{k,j} \), multiplied by ticket price, \( P_{k,j} \), on each route and each type of aircraft. Additionally, the total operating cost is the summation of DOC, \( C_{k,j} \), multiplied by the number of trips, \( x_{k,j} \), operated by each type of aircraft on each route. This formulation assumes that the passenger demands are perfectly symmetric, and the airline would deploy the round trip with the same type aircraft. Therefore, the problem can be simplified with only two variables, \( x_{k,j} \) and \( pax_{k,j} \), to represent the round trips aircraft usages and the passengers flows on each route.
The constraint in Eq. 2.2 ensures that total aircraft usages do not exceed its possible fleet usages. On the left-hand side of Eq. 2.2, the total time of each one-way trip consists of three components, the block time $BH_{k,j}$, the maintenance time $MH_{k,j}$, and the turnover time $t$ of aircraft $k$ on route $j$. Since the formulation assumes the number of trip variable, $x_{k,j}$, represents the round trips of the flight, the total one-way aircraft operation time should be doubled on the left-hand side of Eq. 2.2. Subsequently, because the longest flight in the model has total round trips operation time more than 52 hours, FLEET models a three days aircraft operations. On the right-hand side of Eq. 2.2, the total possible aircraft usage time equals to three days, 72 hours, times number of aircraft $k$ in the airline fleet.

The constraints in Eq. 2.3 and Eq. 2.4 show the upper bound and lower bound of demand. Out of concern for the total simulation time, this study is set up with the constraints of 100% available demand upper bound and 20% lower bound. These settings can provide good quality results in a reasonable time. The constraint in Eq. 2.5 shows that the total passenger carried by aircraft $k$ should be less than the total seats the flights can provide.

The resource allocation optimization problem can be regarded as a mixed integer programming (MIP) problem because the design variables involved integer and continuous variables concurrently. FLEET uses the CPLEX [11] to solve the MIP problem. Readers can read from Refs. [6, 12–15] for a more detailed explanation of the system dynamics models which can represent the ticket price assigning, the price-demand elasticity, and aircraft production, acquisitions, and retirements.

2.2 LIFE CYCLE ASSESSMENT OF BIOFUEL WITH MULTIACTORS APPROACH

Previous work of the biofuel model can represent the biofuel production chain developments from cultivation and collections of five potential feedstocks. The Multiactors Biofuel Model contains a system dynamics model to represent the intertwined
relationships between farmers, bio-refinery factory firms, and airlines. The model can estimate biofuel production costs and unit GHG emissions based on various biofuel production chains. Also, there are two refinery processes in the model, along with five feedstocks are the input materials for the two refinery process [16]. Following sections introduce the properties and assumptions of the five potential feedstocks, two oil refinery processes, and the decision-making criteria of bio-refinery factory firms and farmers.

2.2.1 FEEDSTOCKS AND REFINERY PROCESSES

Out of concern for the competitions between biofuel feedstocks and food crops, the model only includes Camelina, Algae, Corn Stover, Switchgrass and Short Rotation Woody Crops (SRWCs) as the raw materials because they can either cultivate on marginal lands or will not cause land competitions with food crops. Additionally, because the model is capable of estimating the system level interactions between actors, it uses the operating costs and the yields from U.S. average data to simplify the real world cultivation processes. The five feedstocks and their abstractions are introduced in following paragraphs.

**Camelina:**

The model includes camelina-based biofuel because camelina-based biofuel has been produced and used on commercials airlines experimentally even though it is not the most popular one. According to field tests and consultations from experts, this model assumes that camelina yields on marginal land have 50% to 70% yields in field tests. Due to initiated crop production improvement strategies, the model assumes that the yield could increase significantly over years without increasing fertilizer usages. Also, the glucosinolate content in camelina meal limits its usage as animal feed, so the model assumes that most of the meals will be used as fuel to replace mill residues. The mill residues price is assumed to be $20/tonne. The preprocessing and
farming parameters for camelina are given in Ref. [16].

**Algae:**

Algae can be produced via two approaches, the open pond and the photobioreactors. Even if photobioreactors can have relatively higher productivity than the open pond, it requires much higher capital investments, operating costs, and have higher GHG emissions as well. Therefore, the model only includes the algae from open pond approach. Referring to the EPA report, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis* [17], it shows algae achievable yield, lipid content, lipid production cost, and GHG emission in three cases, base, aggressive, and maximum cases. The base case represents a challenging but achievable objective by 2022, while an aggressive case shows a near optimum growth rate and lipid content. The maximum case assumes algae yield and lipid content reach theoretical maximum based on photosynthetic efficiency [17]. The Multiactors Biofuel Model uses the prediction, along with the operational data, to extrapolate the algae lipid content and yield through the simulation period [18]. The algae cultivation parameters are listed in Ref. [16].

**Corn Stover:**

Corn Stover is assumed to reach up to 50% collection rate without soil erosion. Also, corn stover yields are assumed to be as the same as grain yield. We use historical average grain yield data from 1995 to 2009 to extrapolate stover yields through the simulation years. Additionally, soils need to be replenished with nutrients after corn stover collections, which increases fertilizer usages. Besides, the transportation cost of stover is adjusted to correspond to the difference of plant sizes between the research and EIA report [17], which is 4000 tonnes/day. In this study, the plant size is 2000 tonnes/day. Finally, the collection cost of corn stover can also be reached from Ref. [16].

**Switchgrass:**

Switchgrass is assumed to be harvested once per year and has the reduction of fertilizer usage over time. Also, the stands can keep producing for next 10 years
after the establishment. Due to the improvement of species, the timing of fertilizer application, and field management, the model assumes that the future switchgrass yield will keep increasing. Regarding fertilizer, previous research shows that the yield responds to N application rate linearly till maximum yield at 112 kg N/ha. Although P and K do not influence switchgrass yield, they are applied to keep soil nutrient level. Then, the required P and K are calculated based on per pound of residue removed. The cultivation parameters are given in Ref. [16].

**Short Rotation Woody Stock (SRWC):**

SRWC is assumed to harvest only from marginal land. There is a little data published on SRWCs yields, so the model assumes that the yield is the same as the one grows in a natural forest, which is from 1 to 3.8 tonnes/ha. The study also assumes that the yield will be doubled in 2030 with constant fertilizer usages because of scientific improvements. The cultivation parameters of SRWC are given in Ref. [16] as well.

**Two Refinery Processes:**

There are two refinery processes to produce biofuel. The first process, Hydrotreating/hydrocracking process, produces biofuel from oil-based feedstocks, like camelina oil and algae lipid. The production capacity of the plant based on the process is assumed to be 350,000 m$^3$/year. Furthermore, the other process, gasification followed by Fischer-Tropsch(FT)-Synthesis and Syncrude upgrading, produces biofuel from lignocellulosic feedstocks, like corn stover, switchgrass, and SRWC. Out of concern the feedstock transportation cost and the economics of scale, the plant based on FT-synthesis and Syncrude upgrading is assumed to deal with 2000 tonnes feedstock per day. The bio-refineries parameters based on two processes are given in Ref. [16]

**2.2.2 REFINERY FACTORY FIRM AND FARMERS**

Policy makers, airlines, bio-refinery firms, and farmers/feedstock suppliers are the four major actors in the model. The interactions between the four actors compose
U.S. air transportation system and biofuel production chains. This section introduces the decision-making processes of bio-refinery firms and farmers/feedstock suppliers. Because a new policy makers model is adopted to the research and the research replaces the airline model with FLEET, the description of the two actors is ignored in this section.

**Bio-refineries:**

Three criteria influence bio-refinery firms to decide to build up a factory with a certain refinery biofuel procedure. First, the bio-refinery factory firms require that the projected biofuel demands should be more than a certain percentage of the refinery factory production capacity. Then, the firms test the Net Present Value (NPV) and Internal Rate of Return (IRR) of building a plant for a 15-year window. If the NPV and IRR exceed the thresholds, the new factories would build up. In addition, the operation costs decrements from a learning curve and demand/supply time delay would influence the detailed calculation. The operation cost of new refinery factories would decrease with increments of existed factories due to the learning curve. Moreover, the time delay between biofuel demand prediction and actual supply creates the inertial in biofuel productions. The delay time corresponds to the cultivation and plant construction time, which would result in zero revenue and construction costs on the cash flow.

The model includes the risk attitudes of bio-refinery firms as well. Three fuel price scenarios are set up in this model, low oil, reference oil, and high oil price scenarios. Furthermore, the risk-attitudes of bio-refinery firms are assumed to follow with those fuel price scenarios. Refinery factory firms have increased risk attitude when the fuel price is higher. For the time delay between supply and demand, low oil, reference oil, and high oil prices scenarios are assumed to be 3, 2, and 1 years, respectively. Then, the IRR threshold is assumed to be 15%, 10%, and 7.5% that are listed in the same order as the scenarios, receptively. Finally, the required percentages of biofuel demand to factory capacity are assumed to be 1.0, 0.9, and 0.75, respectively.

**Farmers/Feedstock Suppliers:**
Whenever there is a crop demand from refinery factories, farmers cultivate or collect the feedstocks. To minimize the impacts of biofuel on food, the model assumes camelina, switchgrass, and SRWC can only be cultivated on marginal land. The suitability factors are applied to represent the differences in soils, climate conditions, and crop properties in each state. The factors are defined as the portions of marginal land which are suitable for every crop. Also, regarding corn stover, the total collection is currently 75 million dry tonnes/year and is assumed to be 169.7 million dry tonnes/year in the long term. Furthermore, yields of algae are limited by the availability of solar radiation, large stationary sources of CO$_2$, and saline ground water.

The model assumes that farmers’ decisions are profit-driven, so the feedstock competitions should involve a new income source for farmers from soil organic carbon (SOC) sequestration. The SOC sequestration is 800 and 1860 kg/C/ha/year for switchgrass and SRWCs, respectively. Furthermore, there is no evidence for sequestration for camelina. In the end, the SOC price is $72 per metric tonne CO$_2$, which is from EPA’s projection. For more detailed descriptions of bio-refinery firms and farmers, readers are encouraged to refer to Ref. [19].
3. MODEL DESCRIPTION

The integration of FLEET and the Multiactors Biofuel Model can extend FLEET's capabilities to model biofuel development, production, and usage. The biofuel production chain only affects the model flows in the right bottom corner of Figure 2.1. Figure 3.1 shows the part of the modified system dynamics-like representation of FLEET. Biofuel production chains have both environmental and economic impacts on the U.S. air transportation system. Bio-refinery factory firms predict future fuel demands according to airlines' conventional jet fuel and biofuel usages. With a given environmental policy, refinery firms predict biofuel demands and decide prices based on the environmental policy and airline operations. Since the airlines' emission charges can be reduced by using biofuel, the strategy of feedstock compositions, which determine biofuel production cost and unit carbon emissions, influences the airlines' biofuel usages and profits of refinery firms. Finally, the integrated model can represent bio-refinery's strategies in each state. The following sections introduce the structure of the integration of FLEET with the Multiactors Biofuel Model.

3.1 INFORMATION FLOWCHART

With the life-cycle assessments for biofuels from the Multiactors Biofuel Model, the author rearranges the information flow between stakeholders to integrate the Multiactors Biofuel model and FLEET together, which is shown in Fig. 3.2. In the beginning, the airlines module in FLEET is adopted to represent the behaviors of a single profit-driven airline. Subsequently, based on the biofuel and conventional jet fuel usages, the refinery firm tries to predict future total fuel demand. Next, a profit-driven refinery factory firm decides its strategies and predicts biofuel demands based on a given environmental policy and airline operations. The strategies include
targeted biofuel prices, biofuel production quantities, and feedstock compositions in each state. Because the feedstocks distribute unevenly in the U.S., the firm also concerns about feedstock transportation and land suitability for feedstocks. Subsequently, according to the predicted biofuel demands and the targeted biofuel prices, the firm evaluates the profitability to construct a new refinery factory with a certain refinery process, which subsequently creates the feedstock demands if the factory was built up.

In the next stage, farmers and feedstock suppliers satisfy the feedstock demands. The corn stover and algae suppliers produce feedstocks as long as there is any demand. If the feedstock demands of algae and corn stover exceed their maximum productions, the unsatisfied demands for both feedstocks shift the demands to camelina, switchgrass, and SRWC. Due to land competition, profit-driven farmers maximize their profits based on crop demands, land availability, and land suitability of crops in each
Finally, the refinery firm produces biofuel based on the feedstock supplies. Also, the feedstock supply compositions determine the final biofuel unit carbon emissions.

In the last step, the model updates the parameters of the airline, economic environment, refineries, and farmers. FLEET has models to represent the evolution of economic environments. It has models to show the airline’s decision-making processes to acquire and retire its aircraft and decide ticket prices. Besides, the new Multiactors Biofuel Module would update the economics, bio-refinery operation, and farmers operation parameters, such as labor costs, crop yields, and fertilizer usages. Subsequently, the policy maker updates fuel regulations and the environmental policy.
to regulate the blending ratios of drop-in fuel and the fleet-level carbon emissions. Finally, those updated parameters pass to FLEET for the following year simulations.

### 3.2 FLEET: MODIFIED RESOURCE ALLOCATION PROBLEM

The modified airline resource allocation problem has additional terms and constraints to embed biofuel usages and emission costs. According to EU ETS and ICAO GMBM, airlines are assigned with free emission allowances, which is called free quota. Airlines have to buy emission allowances or carbon credits for the emissions beyond their free quota. Both real world schemes are summarized in Table 3.1. Furthermore, because the soil condition and climates differ from each state, the biofuel properties are also different. In this modification, the conventional jet fuel price is the same in every state, but the biofuel price can be different.

<table>
<thead>
<tr>
<th></th>
<th>EU ETS</th>
<th>ICAO GMBM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phase II: 2026 [5]</td>
</tr>
<tr>
<td><strong>Total Free</strong></td>
<td>82.45% Average Emissions Level from 2004-06 [4]</td>
<td>100% Emission Level in 2020 [5]</td>
</tr>
<tr>
<td><strong>Emission Quota</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Carbon Price</strong></td>
<td>$7.52 - $11.79 [20]</td>
<td>Unknown</td>
</tr>
<tr>
<td>$/tonnes CO₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The formulation of the allocation problem is shown in Eqs. 3.1 - 3.9 and followed with explanations.

Maximize:

\[ \sum_{k=1}^{K} \sum_{j=1}^{N} (2px_{k,j} P_{kj} - \sum_{k=1}^{K} \sum_{j=1}^{N} (2x_{k,j} C_{kj}^{\text{non-fuel}}) - Cost_{\text{carbon}} - Cost_{\text{fuel}} (3.1) \]

Where:

\[ Cost_{\text{fuel}} = P_p \sum_{k=1}^{K} \sum_{j=1}^{J} (2x_{k,j} fuel_{kj}) + \sum_{l=1}^{L} (P^{bio}_l - P_p) BF_l (3.2) \]

\[ Cost_{\text{carbon}} = F_C \times \text{Max} \left( E_p \sum_{k=1}^{K} \sum_{j=1}^{J} 2x_{k,j} fuel_{kj} + \sum_{l=1}^{L} (E^{bio}_l - E_p) BF_l - 3C_{\text{free}}, 0 \right) \] (3.3)

Subject to:

\[ \sum_{j=1}^{J} \left( x_{k,j} \times (BH_{kj} + MH_{kj}) \right) \leq 72 \times fleet_k, \forall k \] (3.4)

\[ \sum_{k=1}^{K} pax_{k,j} \leq dem_j, \forall j \] (3.5)

\[ \sum_{k=1}^{K} pax_{k,j} \geq 0.2dem_j, \forall j \] (3.6)

\[ pax_{k,j} \leq x_{k,j} \times cap_k, \forall j, k \] (3.7)

\[ BF_l \left( \sum_{k=1}^{K} \sum_{j \in J_l} x_{k,j} \times fuel_{kj} \right) \leq \frac{1}{2} \forall l \] (3.8)
The DOC $C_{k,j}$ in the profit function in Eq. 2.1 is split into three terms in Eq. 3.1. The first term, $\sum_{k=1}^{K} \sum_{j=1}^{J} 2x_{k,j} \times C_{k,j}^{\text{non-fuel}}$, represents the operating costs which are not related to fuel cost, while the second term, $Cost_{carbon}$, shows the emissions charges (carbon costs) for emissions beyond the free quota. Then, the third term, $Cost_{fuel}$, shows the fuel costs which include both biofuel and conventional jet fuel, which is shown detailed in Eq. 3.2. The first part in Eq. 3.2 is the conventional fuel cost, $P_{p}$, multiplied by total fuel consumption, which includes biofuel and conventional fuel. Then, due to biofuel usages in each state, $BF_{l}$, the second terms add back the price difference between biofuel price, $P_{l}^{\text{bio}}$, and conventional jet fuel prices. In this formulation, the total conventional jet fuel usages are calculated from network routes, while the total biofuel consumption is from each state. So that, the first term, which is related to network routes, needs to be doubled to ensure the consistency of round trips assumption.

In addition, this article assumes that airlines cannot sell their remaining free quota to other industries, which is shown in Eq. 3.3. The first part in the maximum function is the extra emission beyond the free quota, $C_{free}$, while the second part ensures positive extra carbon emissions if the total emissions are less than the free quota. The first term of the extra emission is the total fuel consumption times the unit carbon emission of conventional jet fuel $E_{p}$, while the second term adds multiplication of biofuel usages, $BF_{l}$, and the unit emission difference of biofuel, $E_{l}^{\text{bio}}$, and conventional jet fuel, $E_{p}$, in each state. Subsequently, the carbon emission costs equal to the extra emission multiply by carbon prices $F_{C}$. In the end, since Eq. 3.3 is a nonlinear equation, the modification splits the equation into two inequality constraints, Eqs. 3.10 and 3.11, to keep the linearity of the formulation.
\[ \text{Cost}_{\text{carbon}} \geq 0 \quad (3.10) \]

\[ \text{Cost}_{\text{carbon}} \geq F_C \times \left( 2 \times E_p \sum_{k=1}^{K} \sum_{j=1}^{J} \text{fuel}_{k,j} \times x_{k,j} + \sum_{l=1}^{L} (E_{l}^{\text{bio}} - E_p) BF_l - 3 \times C_{\text{free}} \right) \quad (3.11) \]

Equations 3.4 to 3.7 represent the airlines operation constraints, which have been described in Section 2.1.2. Moreover, the research assumes all of the biofuels would be used as a form of drop-in fuel. To meet the current aviation turbine fuel specifications, the blending ratio of biofuel to conventional jet fuel is up to 50%. The constraint in Eq. 3.8 limits the biofuel usages in each state to meet the regulation requirement. The route \( j \) which has flights takeoff or landing at airports in the state \( l \) needs to be included in set \( J_l \). Furthermore, because aircraft only refuels in the origin airport when it conducts a flight, the fuel consumption term in the denominator of Eq. 3.8 should not be doubled. The constraint in Eq. 3.9 shows the daily biofuel supply in state \( l \). The daily biofuel supply, \( \text{Supply}_l \), in state \( l \) times three to ensure consistency with the three days assumptions.

### 3.3 FUEL DEMAND PREDICTION: BAYESIAN INFERENCE FOR FUEL CONSUMPTION

Bayesian Inference (BI) is a statistical method to update the knowledge of a certain parameter when more information becomes available. Furthermore, the method can model the knowledge propagation between agents [21] in an agent-based model. The agent can update its understanding based on its previous knowledge and historical data about interested parameters, which is analogous to the experience learning processes of human beings. Previous research [21] proved that BI can model the information diffusion between farmers. Additionally, BI is applied to an agent based modeling [22] to model farmers’ decision-making with different risk attitudes, which
conducts a high fidelity result. In this research, the author adopts BI to represent the risk-attitude of a bio-refinery firm toward the future total aviation fuel demands.

This dissertation assumes that the bio-refinery factory firm has the perceptions that the airlines’ fuel consumption, \( f \), should follow a normal distribution. With historical data, its previous knowledge, and its risk-attitude, the firm predicts the fuel consumption in the following year along with the uncertainty of the prediction. By observing airlines’ fuel consumption in the next year, the firm uses the new information and its previous predictions to forecast the airlines’ fuel consumption in the following year with a new uncertainty. Furthermore, since the fuel consumption is related to the GDP growth rate, the refinery firm adjusts the prediction with the uncertainty and the GDP growth rate to have a better result.

This dissertation assumes that the prior distribution of \( f \) follows a normal-inverse-\( \chi^2 \) distribution with a variance \( \sigma^2 \) because the total fuel consumption \( f \) follows a normal distribution. The normal-inverse-\( \chi^2 \) distribution has four parameters, \( \mu_{f0} \), \( \sigma_{f0}^2 \), \( \kappa_{f0} \), and \( \nu_{f0} \). \( \mu_{f0} \) is the mean of \( \mu_f \), while \( \frac{\sigma_{f0}^2}{\kappa_{f0}} \) is the variance of \( \mu_f \). And, \( \kappa_{f0} \) and \( \nu_{f0} \) are the degrees of freedom and scale of \( \sigma_{f}^2 \). Then, the posterior distribution is the same as the prior distribution with the updated four parameters, \( \mu_{f^*} \), \( \sigma_{f^*}^2 \), \( \kappa_{f^*} \), and \( \nu_{f^*} \), which are the functions of prior distribution parameters and are shown in Eq. 3.12 - 3.15 [22].

\[
\mu_{f^*} = \frac{\kappa_{f0}}{\kappa_{f0} + n_f} \mu_{f0} + \frac{n_f}{\kappa_{f0} + n_f} m_f \tag{3.12}
\]

\[
\kappa_{f^*} = \kappa_{f0} + n_f \tag{3.13}
\]

\[
\nu_{f^*} = \nu_{f0} + n_f \tag{3.14}
\]
\[
\sigma_{fg}^2 = \frac{1}{\nu_{fg}^*} \left( \nu_{fo} \sigma_{fo}^2 + s_f^2 (n_f - 1) + \frac{\kappa_{fo} n_f}{\kappa_{fo} + n_f} (m_f - \mu_{fo})^2 \right) \tag{3.15}
\]

In these equations, \( n_f \) is the number of new observation, while \( m_f \) and \( s_f^2 \) are the observation mean and variance, respectively. In Eq. 3.12, the posterior mean is merely the weighted summation of the prior mean and the observation mean. Then, the posterior degrees of freedom and scale are the prior degree of freedom and the scale plus the number of observation, which are shown in Eqs. 3.13 and 3.14. In Eq. 3.15, the posterior variance is the summation of three weighted variances, namely the prior variance \( \sigma_{fo}^2 \), the observation variance \( s_f^2 \), and the difference of the prior and observation means \((m_f - \mu_{fo})^2\).

The mean and variance of a normal distribution variable \( f \) can be conducted from the posterior normal-inverse-\( \chi^2 \) distribution with a Student-\( t \) distribution with degrees of freedom \( \nu_{fg}^* \) and scale \( \kappa_{fg}^* \), which is shown in Eq. 3.16 and Eq. 3.17 [22].

\[
E(f) = \mu_{fg}^* \tag{3.16}
\]

\[
\text{Var}(f) = \frac{\nu_{fg}^*}{\nu_{fg}^* - 2} \left( 1 + \frac{1}{\kappa_{fg}^*} \right) \sigma_{fg}^2 \tag{3.17}
\]

Subsequently, the airlines’ fuel consumption prediction from the refinery firm is adjusted with the GDP growth rate in the next year:

\[
F_{pred} = E(f) + \text{Var}(f) (a + b \times GDP) \tag{3.18}
\]

In the next step, the prior degrees of freedom \( \kappa_{fo} \) and the prior scale \( \nu_{fo} \) are fixed through the simulation since they define the characteristics the refinery factory firm. Additionally, the number of observation \( n_f \) is one because the refinery firm has only one piece of new information, the annual total fuel consumption. Subsequently, this dissertation uses BTS P-12(a) database to build up the characteristics of the refinery.
firm and find the constant \( a \) and \( b \) in Eq. 3.18. BTS P-12(a) database contains the U.S. airlines' quarterly fuel consumption in domestic or international market. Furthermore, the adjustment process is objective, so we arbitrarily choose a setting that has magnitudes of prediction errors less than one-half of standard deviations for most of the data points. Since the BI prediction completely depends on historical data, the GDP growth rate adjustment can help the firm improve its predictions. The comparisons between adjusted fuel consumption prediction and historical data from 1990 to 2014 are shown in Figure 3.3.

![Figure 3.3. BI Adjusted Fuel Consumption Prediction and Historical Data](image-url)
3.4 REFINERY FACTORY: BIOFUEL DEMAND PREDICTION & REFINERY PROFIT OPTIMIZATION

The decision-making process of bio-refinery factory firm consists with two part. In the first part, with biofuel and conventional jet fuel usages across the U.S., total fuel consumption prediction, and environmental policy, the refinery factory firm predicts the possible biofuel demands and decides feedstock compositions and biofuel prices in each state.

In the second part, with the predicted biofuel demands, the feedstock compositions, and the target biofuel prices, the refinery firm decides whether to build a refinery factory of a certain refinery process or not. This dissertation keeps the original NPV and IRR thresholds of Multiactors Biofuel Model to evaluate the profitability of constructing a new refinery factory. The detailed descriptions about refinery construction decision making are discussed in Section 2.2.2.

For the first part of the bio-refinery decision-making process, this article assumes that the refinery factory firm is a profit-driven company, so the firm would try to occupy the benefits of airlines using biofuel. Its strategies which decide the biofuel properties should not increase airlines expenses on carbon emission charges and fuel costs. In addition, because geographical crop and biofuel demand distributions are not consistent, the author assumes that the refinery firm in one state can only import feedstock from its touching neighboring states. The profit optimization problem is shown in Eqs. 3.19 - 3.29.

Maximize:

$$\max L \prod_{l=1}^{L} \left( P_{l}^{\text{bio}} - \sum_{i=1}^{I} C_{i} \cdot \text{Comp}_{i,l} \right) BF_{l}^{\text{pred}}$$

(3.19)

Subject to:

$$\frac{BF_{l}^{\text{pred}}}{F_{\text{pred}} \times R_{\text{State}_{l}}} \leq \frac{1}{2}, \forall l$$

(3.20)
\[ BF_{l}^{\text{pred}} = \sum_{m=1}^{M} \sum_{i=1}^{I} \text{Crop}_{i,m,l}, \forall l \] (3.21)

\[ \text{Comp}_{i,l} = \frac{\sum_{m=1}^{M} \text{Crop}_{i,m,l}}{\sum_{i=1}^{I} \sum_{m=1}^{M} \text{Crop}_{i,m,l}}, \forall i, l \] (3.22)

\[ \text{Crop}_{i,m,l} \times \text{Crop}_{i,l,m} = 0, \forall l \neq m \] (3.23)

\[ \sum_{l=1}^{L} \text{Crop}_{i,m,l} \leq \text{MaxYield}_{i,m}, \forall i, m \] (3.24)

\[ \sum_{i}^{\text{land}} \sum_{l=1}^{L} \text{Crop}_{i,m,l} \leq \text{MaxCompeteYield}_{m}, \forall m \] (3.25)

\[ \text{Cost}_{\text{no change}} = F_{C} \text{Max} \left( F_{\text{pred}} \left( (1 - BR) E_{p} + E_{\text{bio}}^{\text{old}} BR \right) - C_{\text{free}}, 0 \right) \]
\[ + F_{\text{pred}}^{\text{bio}} P_{\text{old}} BR + (1 - BR) F_{\text{pred}} P_{p} \] (3.26)

\[ 0 \leq CO_{2} \] (3.27)

\[ E_{p} F_{\text{pred}} + \sum_{l=1}^{L} BF_{l}^{\text{pred}} \times \sum_{i=1}^{I} (\text{Comp}_{i,l} E_{i}^{\text{bio}} - E_{p}) - C_{\text{free}} \leq CO_{2} \] (3.28)

\[ F_{C} CO_{2} + F_{\text{pred}} P_{p} + \sum_{l} BF_{l}^{\text{pred}} (P_{l}^{\text{bio}} - P_{p}) \leq \text{Cost}_{\text{no change}} \] (3.29)
The continuous variables $P_{l}^{bio}$ and $Comp_{i,l}$ represent the target fuel price and feedstock composition in state $l$, while the continuous variable $BF_{l}^{pred}$ shows the predicted biofuel demand in the same state. Equation 3.19 is the total profit function of the refinery firm, which is the unit profit, price of biofuel $P_{l}^{bio}$ minus the multiplication of the average production cost $C_{i}$ of feedstock $i$ and the feedstock compositions, $Comp_{i,l}$, in state $l$, and times the predicted demand $BF_{l}^{pred}$. Then, the biofuel supplies and usages are limited by the blending ratio constraint, Eq. 3.20, the imported feedstock from neighboring state constraints, Eqs. 3.21 - 3.25, and the requirement of keeping airlines operation cost the same, which is shown in Eqs 3.28 - 3.29.

The blending ratio constraint in Eq. 3.20 shows one-half should be larger than the blending ratio in state $l$, which is the ratio of biofuel demand $BF_{l}^{pred}$ to the predicted total fuel consumption, $F_{pred} \times RState_{l}$, in state $l$. Also, $RState_{l}$ represents the portion of fuel consumed in state $l$ from FLEET resource allocation problem results in the previous simulation run. Equation 3.21 ensures that biofuel demands $BF_{l}^{pred}$ in each state equals to the equivalent imported biofuel $Crop_{i,m,l}$ of feedstock $i$ from state $m$. The equivalent imported biofuel, $Crop_{i,m,l}$, of feedstock $i$ is the quantity of imported feedstock which is converted to the amount of biofuel that feedstock can
produce. Similarly, Eq. 3.22 ensures the feedstock composition, $\text{Comp}_{i,t}$ equals to the ratio of the total imported equivalent biofuel of feedstock $i$ to the total imported equivalent biofuel from every feedstock. Subsequently, Eq. 3.23 limits one direction feedstock flow between two states.

The article assumes that the firm can perfectly predict the maximum yield of feedstock $i$ in each state. Equation 3.24 shows the maximum possible equivalent biofuel of feedstock $i$ exporting from state $m$. Because of land competition between some crops, Eq. 3.25 shows the equivalent biofuel of feedstock $i$ should be lower than the possible maximum equivalent biofuel productions, while the set $I_{\text{land}}$ indicates which between feedstocks have land competition. The maximum equivalent biofuel production is according to that farmers cultivate feedstocks with the order of the highest to lowest yield.

The constraints in Eqs. 3.26 - 3.29 shows that the airlines’ expenses on carbon emission allowances and fuels should be less or equal to the costs when airlines used the old type of biofuel with old biofuel prices. If the refinery firm kept the same strategies as previous simulation year but with new information, the airline’s expense is shown in Eq. 3.26. The old strategies of bio-refinery firm include unit carbon emission of biofuel, $E_{\text{bio,old}}$, biofuel price $P_{\text{bio,old}}$, and average blending ratio $BR$. The new information involves the predicted total fuel consumption, $F_{\text{pred}}$, the carbon price, $F_{C}$, and the new free quota for the airline, $C_{\text{free}}$. Similarly, because airlines cannot sell their remaining free quota, this part uses the same technique as in Section 3.2 to convert the maximum function of carbon emission into two inequality constraints, which are shown in Eqs. 3.27 and 3.28.

The first inequality constraint in Eq. 3.27 ensures the positive carbon emission while the total emission is less than the free quota, whereas second inequality constraint in Eq. 3.28 evaluates the free quota, $C_{\text{free}}$, subtracts from the total carbon emission using the new biofuel. The total carbon emission consists of two terms. The first term is the predicted total fuel consumption multiplied by the unit carbon emission of conventional jet fuel. The second term is the multiplication of total biofuel
consumption in each state and the difference of unit carbon emission between biofuels and conventional jet fuel. And, the average biofuel unit emission is the feedstock compositions, \( \text{Comp}_{i,l} \), multiplied by unit biofuel consumption, \( E^{\text{bio}}_{i} \), from feedstock \( i \). Finally, the constraint in Eq. 3.29 shows that the airlines expenses, with the new biofuel prices and new unit fuel carbon emissions, should be less or equal to the expense with the old type biofuel and old prices.

The constraint in Eq. 3.30 limits the price variance between states \( l \) and \( m \). In the real world, there are many refinery firms producing biofuel or conventional fuel. Hence, the fuel and biofuel prices should not have very large differences due to competitions. Therefore, the constraint can avoid the strategy that the firm arises the biofuel price in certain states but have much lower prices in the other to satisfy the constraint in Eq. 3.26.

Next, the refinery firm should also keep its factories running when the factories build up. Hence, the constraints in Eqs. 3.31 and 3.32 ensure that the total biofuel production lower bound is 80% of total biofuel production from existing factory in state \( l \) with either refinery processes. The production capacity of factories converting oil-based feedstock in state \( l \) is \( \text{Prod}^{\text{existing}}_{\text{oil},l} \), while the one converting lignocellulosic feedstock in state \( l \) is \( \text{Prod}^{\text{existing}}_{\text{lign},l} \). Moreover, the set of oil-based and lignocellulosic feedstocks is \( I_{\text{oil}} \) and \( I_{\text{lign}} \), respectively.

The bio-refinery firm profit maximization problem is distinguished as a non-linear problem. Also, depending on the coefficients in the problem, the problem could be a non-convex problem. Since BARON [23] is a multi-starting points solver, this article uses the BARON to search for the global optimum solution.

### 3.5 Farmers’ Profit Optimization & Biofuel Production

Feedstock suppliers intend to satisfy all feedstock demands from the refinery firm. Since algae and corn stover have no land competition with others, feedstock suppliers satisfy their feedstock demands first. If there are unsatisfied demands from both
feedstocks, their demands are redistributed to other feedstocks based on feedstock compositions and feedstock’s properties. The unsatisfied demand for algae adds up to camelina demand because both of them can go through the same refinery process. Similarly, the unsatisfied corn stover demand is redistributed to switchgrass and SRWC demands based on the relative composition between the two feedstocks because FT-Synthesis can convert the three feedstocks into biofuel.

Camelina, Switchgrass, and SRWC can only cultivate on marginal lands, so farmers have to find the most profitable cultivation composition of the three crops. Hence, the work formulates a NPV optimization problem to find the most profitable land compositions for each crop in each state, which is shown in Eqs. 3.33 - 3.36.

Maximize:

$$\sum_{i=1}^{I} \sum_{m=1}^{M} NPV_i \times Area_{i,m}$$

Equation 3.33 shows the total NPV function. Because the growth time and harvest period of the crops are different, the author assumes that farmers tend to use the strategies with highest total NPV, which sums up mul-

The continuous variable $Area_{i,m}$ represents the land area which is used to cultivate feedstock $i$ in state $m$. Equation 3.33 shows the total NPV function. Because the growth time and harvest period of the crops are different, the author assumes that farmers tend to use the strategies with highest total NPV, which sums up mul-
multiplications of cultivation area, $\text{Area}_{i,m}$, and the average NPV of feedstock $i$ per acre $NPV_i$.

The constraint in Eq. 3.34 restricts that the cultivation area should be less than the total marginal land area, $\text{MarginLand}_{m}$, in state $m$, while constraint in Eq. 3.35 limits cultivation area of each crop should be less than the multiplication of total marginal land area and crop suitability, $\text{Suit}_{i,m}$. $\text{Suit}_{i,m}$ represents the portion of marginal land in state $m$ which is suitable for cultivating crop $i$. The author assumes that farmers can predict the crop demands perfectly and only the refinery firm can create crop demands out of concern the competitions between the refinery firm and other industries. Then, the constraint in Eq. 3.36 limits the total crop yields less than the refinery firm crop demands.

If there is any unsatisfied feedstock demand from the three land competition crops, the unsatisfied feedstocks demand would redistribute to corn stover and algae based on feedstock properties if algae or corn stover had available production capacities. If either algae or corn stover has nonzero feedstock composition, the unsatisfied camelina demand can be added up to algae demands, while the unsatisfied switchgrass and SRWC demands can go into corn stover demand. Subsequently, if farmers could not satisfy all of the feedstock demands, the yields of feedstocks are distributed proportionally to the customer factories according to the feedstock flow of the refinery firm in different states. This logic corresponds to the competition between refinery factories in neighboring states. Finally, the farmers NPV optimization problem is a linear programming problem, which is solved with CPLEX solver.

Based on the feedstock supplies from each state, the refinery firm calculates the feedstock supply composition. The unit carbon emission of biofuel in each state is based on the feedstock supply composition. Finally, the quantities of biofuel supplies, the unit carbon emissions of biofuel, and the targeted biofuel prices in each state are passed back to FLEET and are used to solve FLEET’s resource allocation problem for next simulation year.
4. CASE STUDY AND DISCUSSION

This chapter shows the environmental and economic impacts of conventional jet fuel and carbon prices on aviation industry if either EU ETS or ICAO GMBM schemes were applied to U.S. touching flights. There are three price scenarios for conventional jet fuel and carbon emissions. The carbon price scenarios are shown in Table 4.1. Also, the fuel price scenarios, along with prescribed GDP growth rate, are introduced in the following sections.

4.1 SCENARIO SETUP

With the huge set of possible studies, this research focuses on various conventional jet fuel and carbon prices scenarios and environmental schemes. The aircraft performances, the airline network structure, the airline initial fleet composition, and passenger demands in 2005 are fixed in all scenarios. Also, the environmental schemes include simplified EU ETS and ICAO GMBM models. The fuel prices from 2005 to 2050 are prescribed as high fuel price, reference fuel price, and low fuel price scenarios. Similarly, the emission price from 2012 to 2050 are defined as high price, reference price, and low price scenarios.

4.1.1 ENVIRONMENTAL SCHEME

The study intends to implement the simplified EU ETS and ICAO GMBM models in the U.S. air transportation system to study policy impacts. First, although FLEET is capable of handling the scheme which only covers parts of the network routes, the study assumes that carbon emissions from the whole network should be included. Moreover, the study prescribes three carbon prices to avoid to model the supply and
demand curve of emission allowances. The two simplified schemes are summarized in Table 4.1.

Table 4.1.. Modeled Emission Trading/Taxing Schemes

<table>
<thead>
<tr>
<th></th>
<th>EU ETS Model</th>
<th>ICAO GMBM Model</th>
</tr>
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<tbody>
<tr>
<td><strong>Initiation Time</strong></td>
<td>2012</td>
<td>2021</td>
</tr>
<tr>
<td><strong>Free Emission</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Quota</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. 82.45% of Emissions Level in 2005 by 2020.</td>
<td></td>
<td>100% Emission Level in 2020</td>
</tr>
<tr>
<td>2. Linear decrement to 41.23% of 2005 Emissions Level by 2050.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Policy Boundary</strong></td>
<td>FLEET network</td>
<td></td>
</tr>
<tr>
<td><strong>Carbon Prices</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$/(\text{tons CO}_2)$</td>
<td>Low Price Scenario: $7.48$ from 2012 to 2050</td>
<td>Ref. Price Scenario: $10.29$ in 2012 with $0.48$ annual increments</td>
</tr>
<tr>
<td></td>
<td>High Price Scenario: $11.79$ in 2012 with $0.60$ annual increments</td>
<td></td>
</tr>
</tbody>
</table>

In the EU ETS model, this article assumes that the free quota from 2012 to 2020 equals to 82.45% of the emissions level in 2005. And, the free quota decreases linearly from 82.45% to 41.23% the emissions level in 2005 from 2020 to 2050, which corresponds to IATA’s emissions goals to reduce total carbon emission in half by 2050. On the other hand, the ICAO GMBM model is initiated in 2021 and keeps the free quota constant from 2021 to 2050.

The three carbon price scenarios are developed and implemented into the two scheme models by the author based on Schaefer et al. [4], and adjusted with historical auction data from European Emission Exchange (EEX) [20]. The low carbon price scenario has a constant carbon price, $7.48$, from 2012 to 2050, while the reference carbon price scenario has an initial average price $10.29$ by 2012 with constant price growth rate, $0.48$ per year, to 2050. And, the high carbon price scenario has higher average initial price $11.79$ by 2012 with higher price growth rate, $0.60$ per year, to 2050.
4.1.2 FUEL PRICE SCENARIO & GDP GROWTH RATE

Since fuel cost is a averaged quarter of airline’s total expenses [24], fuel prices have large impacts on the air ticket prices and fleet usages. Ticket prices influence the passenger demands, and the fleet usages affect the time of new aircraft penetration. Both passenger demands and levels of technology in airlines’ fleets have direct impacts on fleet-level carbon emissions. Moreover, fuel cost is hard to predict due to its volatility. Hence, the work tries to study the impacts from levels of fuel prices on fleet-level emissions instead of the accurate price predictions. The author sets three fuel price scenarios, high, reference, and low fuel prices, to represent the levels of fuel price impacts.

The three fuel price scenarios are based on the predictions from Energy Information Administration (EIA) and historical data from EIA [25]. From 2005 to 2015, the research uses historical conventional jet fuel prices, and the EIA predictions are adopted after 2016. The predictions include three different price scenarios, while, in the low price scenario, fuel prices decrease slightly from 2015 to 2017, but increase linearly to about 200 cents/gallon by 2050. In the reference fuel price scenario, fuel prices increase from 2015 to 2050 to about 400 cents/gallon by 2050, and the fuel prices increase to over 650 cents/gallon by 2050 in the high fuel price scenario. The three scenarios are shown in Figure 4.1.

In this study, the conventional jet fuel prices are the same in each state even though the biofuel prices are different. Due to lack of understanding and data about the driving factors of conventional jet fuel price in each state, this article adopts the same average prices across the United States. However, the feedstock availability has large impacts on biofuel production costs; this dissertation sets the different biofuel prices in each state to correspond to the uneven feedstock distribution.

Due to the difficulties to predict the long-term U.S. GDP growth rate, this study prescribes a GDP growth rates scenario from 2005 to 2050. The article adopts historical data from 2005 to 2014 and builds up the GDP growth rate scenario after
2015 based on a geometric Brownian Motion stochastic model [26]. According to Don Harding et al. [26], in the quarter year period, the logarithm of GDP can be modeled with a constant shift superimposed with a random walk model, which can be regarded as the geometric Brownian Motion as well. Based on the properties of geometric Brownian Motion, the ratio of GDP between two consecutive periods follows a log-normal distribution. The research uses historical data from 1961 to 2014 from World Bank [27] to build up the log-normal model and uses the stochastic model to construct the GDP growth rate scenario, which is shown in Figure 4.2. The scenario has highest GDP growth rate 6.3% by 2028 and average annual growth rate 2.24%.

Figure 4.1. The three fuel price scenario in FLEET
4.2 EU ETS MODEL

This section shows the effects if the EU ETS happened in the U.S. domestic and international commercial aviation market. The work models the scheme with nine economic scenarios involved the combinations of two factors, which are conventional fuel prices and carbon prices. Additionally, there are baseline scenarios to show the results without environmental scheme initiation and available biofuel. The scenarios with scheme model but without available biofuel represent impacts only from envi-

Figure 4.2. The GDP growth rate scenario in FLEET
ronmental policy on the whole system. In the end, the scenarios with available biofuel and initiated scheme show the biofuel impacts on the aviation industry.

The results are categorized into two types. The first part is the fleet-level air transportation metrics, which includes the fleet-level carbon emissions and the revenue passenger nautical miles (RPNMI). The second part is the state-level biofuel metrics. The metrics consist of total biofuel productions from both refinery processes, the geographical distribution of feedstocks activities, and the prices of conventional jet fuel, average carbon costs, and average biofuel prices. Discussions are followed with the simulation results.

4.2.1 FLEET-LEVEL METRICS

The fleet-level carbon emissions of each scenario are normalized with emission level in 2005, as shown in Figure 4.3. The scenarios from left to right columns are low, reference, and high carbon price scenarios, respectively, while the scenarios from bottom to top rows are low, reference, and high conventional jet fuel price scenarios. Taking the upper left corner sub-figure as an example, it shows results of the scenarios with high conventional jet fuel and low carbon prices. Each sub-figure consists of four lines. The solid blue line represents the scenario where biofuel is not available. The red dash-dot line shows the same scenario where biofuel is available; the yellow dash line is the baseline scenario, which has no environmental policy initiation and no available biofuel, and the purple dot line is the free quota that is given to the airline.

The results demonstrate that the trends of carbon emissions in every scenario are similar. However, higher carbon emission reductions between baseline and other scenarios happen in the high fuel prices and both reference and high carbon prices scenarios. In the other scenarios, the EU ETS model can not effectively reduce fleet-level carbon emissions. Furthermore, the biofuel can conduct lower fleet-level carbon emissions results as well. In Table 4.2, the carbon emissions in 2050 from scenarios
with biofuel usages have 0.118% to 4.566% emission reduction from the scenario without available biofuel.

Table 4.2. EU ETS percentage emissions reductions by 2050 due to available biofuel.

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<tr>
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<tr>
<td>High Fuel Price</td>
<td>3.924%</td>
<td>4.566%</td>
<td>3.251%</td>
</tr>
<tr>
<td>Reference Fuel Price</td>
<td>2.825%</td>
<td>3.300%</td>
<td>2.587%</td>
</tr>
<tr>
<td>Low Fuel Price</td>
<td>0.118%</td>
<td>0.218%</td>
<td>0.000%</td>
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The Figure 4.3 represents how conventional jet fuel and carbon prices influence fleet-level emissions as well. The normalized carbon emission profiles with the scheme initiation from each scenario become lower and lower from left to right in each row, while the carbon price profiles increase with the same order. Obviously, the fleet-level carbon emissions decrease with the increment of carbon prices. Similarly, the fleet-level carbon emissions profiles decrease from bottom to top in each scenario, while the conventional jet fuel price profiles increase with the same order. This result shows that the fleet-level emissions decrease with increasing fuel prices. In addition, the results demonstrate that conventional fuel price has stronger carbon emission reduction effects than the carbon price.

Regarding the scheme performance, the results show that the carbon emissions from air transportation system cannot reach carbon neutral growth by 2020 in 2005 emission level. Also, it cannot reduce the fleet-level carbon emission to half emission level in 2005. The passenger demand growth shadows the efforts from the higher levels of technology, biofuel usages, and the emission schemes to reduce carbon emissions.
Figure 4.3. The normalized carbon emissions. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. The carbon emissions are normalized with carbon emission level in 2005. The solid blue lines show the fleet-level normalized carbon emissions without biofuel, while the red dash-dot lines represent the results with biofuel. Moreover, the yellow dash lines show the baseline scenarios, while the purple dot lines represent the normalized free quota.
In Figure 4.4, with the same scenario layout as Figure 4.3, the blue lines are the normalized RPNMI from scenarios without biofuel usages, the red dash lines show the normalized RPNMI from scenarios with biofuel usages, and the yellow dash lines demonstrate the normalized RPNMI without scheme initiation and available biofuel. The normalized RPNMI trends are almost the same in every scenario. The percentage increments of normalized RPNMI in 2050 between the scenarios with and without available biofuel usages are shown in Table 4.3. The results indicate that, concerning airline performance, the usage of biofuel has no significant effect on RPNMI.

Figure 4.5 shows the normalized satisfied demand of each scenario. The figure has the same scenario layout and color codes as previous figures. The results reveal, in most cases, the airline can achieve the similar level of demand satisfied as baseline scenarios. However, in high carbon and conventional jet fuel price scenario, the airline has lower demand satisfied in the scheme initiation scenarios than in the baseline scenario.

In Figures 4.3 to 4.5, in each scenario, the normalized emission, the normalized RPNMI, and the normalized demand satisfied profiles are similar, but the carbon emission growth rates are smaller than the RPNMI and demand satisfied growth

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<tr>
<td>High Fuel Price</td>
<td>0.044%</td>
<td>0.189%</td>
<td>0.098%</td>
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<tr>
<td>Reference Fuel Price</td>
<td>0.028%</td>
<td>0.040%</td>
<td>0.045%</td>
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<tr>
<td>Low Fuel Price</td>
<td>0.000%</td>
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<td>0.000%</td>
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Figure 4.4. The normalized RPNMI of each scenario. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. All of the RPNMI is normalized with the RPNMI value in 2005. The solid blue lines show the fleet-level normalized RPNMI without biofuel available, while the red dash-dot lines represent the results with biofuel available. Finally, the yellow dash lines show the baseline results, which have no scheme initiation and available biofuel.
Figure 4.5. The normalized demand satisfied of each scenario. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. All of the demand satisfied is normalized with the value in 2005. The solid blue lines show the fleet-level normalized demand satisfied without biofuel available, while the red dash-dot lines represent the results with biofuel available. Finally, the yellow dash lines show the baseline results, which have no scheme initiation and available biofuel.
rates. Taking the low fuel prices and low carbon prices scenario as an example, the
normalized carbon emissions, and the RPNMI are about 2.4 and 4.4, respectively.
Although the RPNMI increases significantly by 2050, the airline can still mitigate the
carbon emission growth by acquiring higher levels of technology aircraft in its fleet.
In addition, the similarities between RPNMI and demand satisfied profiles imply that
the airline has the similar strategies as baseline scenarios.

4.2.2 BIOFUEL PERFORMANCE

The global environmental policies would commoditize carbon dioxide and drive
related industries, such as biofuel and aircraft productions chains. Figure 4.6 shows
the normalized biofuel production capacity based on the two refinery processes, which
have the same scenario layout as previous result figures. The solid blue lines and
red dot-dash lines represent the biofuel production capacities from oil based and
lignocellulosic feedstocks, respectively. From bottom to top in each column, the
biofuel from both processes starts to be produced earlier and earlier. However, there
is no clear relationship between biofuel production and carbon prices.

Table 4.4. EU ETS highest accumulative biofuel consumption state.

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<tr>
<td>High Fuel Price</td>
<td>California</td>
<td>California</td>
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<tr>
<td>Reference Fuel</td>
<td>California</td>
<td>California</td>
<td>California</td>
</tr>
<tr>
<td>Low Fuel Price</td>
<td>Nevada</td>
<td>Nevada</td>
<td>No Biofuel Usage</td>
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Figure 4.6. The normalized biofuel production from both refinery processes in each scenario. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. All of the biofuel production are normalized with the airlines fuel consumption in 2005. The solid blue lines show the biofuel productions from oil-based feedstock, while the red dot-dash lines represent the biofuel production with FT-synthesis process.
The feedstock flows map in Figure 4.7 can represent where feedstock supplies and biofuel consumption are in scenarios with available biofuel. The states which are highlighted in yellow have the highest accumulative biofuel consumption from 2005 to 2050, as listed in Table 4.4. The flows of different feedstocks are shown with different colors. Blue and red represent camelina and algae, respectively, while cyan, green, and magenta are corn stover, switchgrass, and SRWC.

The feedstock demand and supply distribution affect the geographical distribution of feedstock flows. The major feedstock flows in great lakes and southeast regions are switchgrass, while SRWC is the major feedstock in New England region. Furthermore, camelina is the main feedstock in rocky mountain, southwest, and far west regions. In addition, the highest biofuel consumption happens in the states where are close to feedstock supplies and have large populations. For example, the airports in California have highest accumulative biofuel consumption from lignocellulosic feedstocks in reference and high conventional fuel price scenarios. In low conventional price scenarios, airports in Nevada consume biofuel from an oil-based feedstock, camelina.

Figure 4.8 shows the conventional price, average carbon prices, and average biofuel price in each carbon and conventional jet fuel prices scenario. Since the airline is assigned with free quota, the average carbon price is defined as total carbon costs divided by total fuel consumption. Similarly, the average biofuel price is total biofuel costs divided by total biofuel consumption to correspond to different biofuel prices in each state. If airlines have no biofuel consumption, average carbon and biofuel prices are defined as zero.

Figure 4.8 shows general trends of average biofuel prices and average carbon costs in various carbon and conventional fuel prices scenarios. In the scenarios with higher conventional jet fuel prices, the biofuel production happens earlier and the average carbon costs decrease. In the higher carbon prices, the average carbon costs increase. Additionally, the biofuel prices increase when either conventional jet fuel or carbon prices increase.
Accumulative Feedstock Flow

Figure 4.7. The map shows the accumulative feedstock flows. The scenarios from left to right columns are low, reference, and high emissions allowance prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. The state highlighted in yellow shows which state has highest accumulative biofuel consumption. In addition, camelina and algae flows are shown with blue and red arrows, respectively. Corn stover, switchgrass, and SRWC represent with cyan, green, and magenta arrows.
Out of concern the interchangeability of biofuel and conventional jet fuel and their production capacities, conventional jet fuel should be the main driving factors for future fuel prices. Also, due to the technology improvements, biofuel production happens whenever the unit production costs and conventional fuel prices are close enough, which results in an earlier biofuel production in higher conventional prices scenarios.

The potential biofuel demand would also affect biofuel price as well. Both carbon and conventional jet fuel prices would affect ticket fares and total passenger demands. Moreover, the total passenger demand would encourage the airline to have more flights, which results in higher total fuel demand and higher carbon emissions. In the reference conventional fuel prices scenarios, because the airline still gets emission reduction benefits by using biofuel, the airline is willing to pay the premium for biofuel. However, in the high conventional jet fuel prices scenarios, total fuel consumption decrease due to the higher fuel prices and ticket fares and decrease in passenger demand. The reduced total fuel demand limits the emission reduction benefits by using biofuel, which also decrease the biofuel demand and limits the biofuel prices.

4.3 ICAO GMBM MODEL

ICAO GMBM scheme is the most likely upcoming environmental scheme in the international commercial aviation market. Although the drafted ICAO GMBM scheme assigned the emission offsets instead of free emission quota to airlines, the mechanism can be regarded as a modified EU ETS with different baseline and initiated years. Hence, the work simulates that the ICAO GMBM model on the domestic and international market in the United States.
Figure 4.8. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. The convention jet fuel price is shown in solid blue lines, while red dot-dash lines represent the average biofuel prices. The average carbon prices with and without biofuel available are shown in yellow dash lines and purple dot lines, respectively.
4.3.1 FLEET-LEVEL METRICS

The fleet-level carbon emissions are also normalized with the emission level in 2005, as shown in Figure 4.9. The scenarios without available biofuel are shown with solid blue lines, while the ones with available biofuel are represented with red dot-dash lines. The yellow dash lines are the baseline scenarios which have no initiated environmental scheme and no available biofuel, and the purple dot lines are the free quota for the airline. The free quotas differ by 2021 in different fuel price scenarios because lower ticket prices deduce higher demand by 2020, which would conduct more aircraft operations and result in higher fuel consumption and carbon emissions.

Although the trends between fleet-level carbon emissions and conventional fuel and carbon prices in ICAO GMBM model are similar to EU ETS model, the ICAO GMBM can limit the fleet-level carbon emission more efficiently. Comparing Figures 4.3 and 4.9, the fleet-level emissions in ICAO GMBM model are equal or lower than the same scenario which EU ETS model are initiated. Besides, the results in the ICAO GMBM model show higher emission reductions when biofuel is available to the airlines. Hence, the results imply higher biofuel usages in ICAO GMBM model. Next, the emission reductions between scenarios with and without available biofuel by 2050 are listed in Table 4.5.

Figure 4.10 shows the normalized RPNMI with the similar scenario layouts as previous figures. The solid blue lines represent the scenarios without available biofuel, the red dot-dash lines show the simulation results with available biofuel, and the yellow dash lines are the baseline scenarios without initiated environmental scheme and available biofuel.

The simulation results also show that the airline does not sacrifice its aircraft operations for emission reductions. In each conventional fuel and carbon prices scenarios, the RPNMIs from the scenario with environmental scheme initiation are almost the same as the baseline scenarios results; however every scenario results in different fleet-level emission. Furthermore, Table 4.6 shows the percentage RPNMI increments
Figure 4.9. The normalized carbon emissions of each scenario. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. All of the carbon emissions are normalized with carbon emission level in 2005. The solid blue lines show the fleet-level normalized carbon emissions without available biofuel, while the red dash-dot lines represent the scenarios with available biofuel. And, the yellow dash lines show the baseline results, while the purple dot lines represent the normalized free quota.
between biofuel available and unavailable scenarios by 2050. The negligible differences in each scenario show that the optimal strategies for the airline cannot provide more services by using biofuel to reduce its operating costs.

Figure 4.11 shows the normalized satisfied demand of each scenario. The figure has the same scenario layout and color codes as previous figures. The results represent the airline has lower demand satisfied in scenarios with either high conventional jet fuel or carbon prices than baseline scenarios. In the other scenarios, the satisfied demands are close to results from baseline scenarios.

Comparing Figures 4.10 and 4.11, the airline has the similar RPNMIs as baseline scenarios, while its satisfied demands are lower. In the scenarios with either high conventional jet fuel or carbon prices, although the total satisfied demand decrease, the airline tends to provide more service on longer routes to keep the similar total RPNMI performances. The strategies shifting from shorter to longer routes correspond to the fuel efficiency of various size class aircraft, which have higher fuel efficiency for larger aircraft.

The ICAO GMBM model has stronger impacts on satisfied demand than EU ETS model. The results in Figures 4.5 and 4.11 show that the airline with ICAO

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<tr>
<td>High Fuel Price</td>
<td>4.701%</td>
<td>6.077%</td>
<td>4.727%</td>
</tr>
<tr>
<td>Reference Fuel Price</td>
<td>3.102%</td>
<td>3.177%</td>
<td>4.791%</td>
</tr>
<tr>
<td>Low Fuel Price</td>
<td>0.240%</td>
<td>0.086%</td>
<td>0.249%</td>
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Figure 4.10. The normalized RPNMI of each scenario. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. All of the RPNMI is normalized with the RPNMI in 2005. The solid blue lines show the fleet-level normalized RPNMI without available biofuel, while the red dash-dot lines represent the results with available biofuel. Moreover, the yellow dash lines represent the baseline scenario results, which have no initiated environmental scheme and no available biofuel.
Table 4.6. ICAO GMBM percentage RPNMI increments by 2050 due to available biofuel

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<tr>
<td>High Fuel Price</td>
<td>0.160%</td>
<td>0.053%</td>
<td>0.185%</td>
</tr>
<tr>
<td>Reference Fuel Price</td>
<td>0.040%</td>
<td>0.045%</td>
<td>0.056%</td>
</tr>
<tr>
<td>Low Fuel Price</td>
<td>−0.001%</td>
<td>0.000%</td>
<td>0.000%</td>
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GMBM model has lower or equal satisfied demand. The demand satisfied in ICAO GMBM decreases more than EU ETS while either conventional jet fuel or carbon prices increase. However, the lower demand satisfied in ICAO GMBM model results in a lower carbon emission as well, which is shown in Figures 4.3 and 4.9.

### 4.3.2 BIOFUEL PERFORMANCE

The normalized biofuel productions through the two refinery processes are shown in Figure 4.12 with the same scenario layout as previous figures. The results show that biofuel productions start earlier when the conventional jet fuel prices rise. Moreover, there are biofuel productions happen in low conventional fuel and high carbon prices scenarios, which do not happen in EU ETS model. By comparing the biofuel production between the two environmental models in Figures 4.6 and 4.12, the production capacity profiles are similar. The results conclude that schemes are not the main driving force to influence the biofuel production capacity.

The supply and demand maps in Figure 4.13 shows that the feedstock flow distributions are similar to the results from EU ETS model in Figure 4.7. States with
Figure 4.11. The normalized demand satisfied of each scenario. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. All of the demand satisfied is normalized with the value in 2005. The solid blue lines show the fleet-level normalized demand satisfied without biofuel available, while the red dash-dot lines represent the results with biofuel available. Finally, the yellow dash lines show the baseline results, which have no scheme initiation and available biofuel.
Figure 4.12. The normalized biofuel production from both refinery processes in each scenario. The scenarios in the left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios in the bottom to top rows are low, reference, and high fuel price scenarios, respectively. All of the biofuel production are normalized with the airlines fuel consumption in 2005. The solid blue lines show the biofuel productions from oil-based feedstock, while the red dot-dash lines represent the biofuel production with FT-synthesis process.
the highest biofuel consumption in each scenario are the same as the results from the EU ETS model as shown in Table 4.7. These are because the feedstock supplies only depend on climate, soil conditions in different locations, and crop properties instead of the scheme or aviation industry behaviors.

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<td>High Fuel Price</td>
<td>California</td>
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<tr>
<td>Reference Fuel Price</td>
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<td>California</td>
<td>California</td>
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<tr>
<td>Low Fuel Price</td>
<td>Nevada</td>
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The biofuel demand is driven by the conventional fuel price, biofuel unit production cost from each feedstock, and feedstock supplies around a certain state. For example, only camelina biofuel demands are in low conventional fuel price scenarios because the unit production cost of camelina biofuel is lower enough to compete with petrol jet fuel. Furthermore, the highest biofuel consumption state is California in reference and high conventional jet fuel price scenarios because there has high fuel demand and the refinery factory in Camelina can get enough feedstock from neighboring states.

The conventional jet fuel prices, average biofuel prices, and average carbon prices are shown in Figure 4.14. The biofuel usages happen earlier with higher prices while the conventional fuel price increase. In high fuel price scenarios, the average biofuel prices are equal or lower than the conventional jet fuel prices. On the other hand, in low and reference conventional fuel price scenarios, biofuel prices can become higher than the conventional jet fuel prices. Finally, comparing the two environmen-
Accumulative Feedstock Flow

Figure 4.13. The map shows the accumulative feedstock flow. The scenarios from left to right columns are low, reference, and high carbon price scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. The state highlighted in yellow shows which state has highest accumulative biofuel consumption in each scenario. And, camelina and algae flows are shown with blue and red arrows, respectively. And, corn stover, switchgrass, and SRWC represent with cyan, green, and magenta arrows.
tal schemes, the average carbon costs are lower in ICAO GMBM model than EU ETS model. The higher free emission quota in ICAO GMBM model can reduce the airline expenses on emission allowances and fleet-level carbon emissions as shown in 4.9.

The biofuel price premiums have complex relationships with conventional jet fuel prices and emission reduction demands. In Figure 4.9, for high conventional jet fuel price scenario and without available biofuel, the airline can keep the similar emission level by changing strategies to deploy its fleet. This action reduces the benefits of using biofuel. As a result, the biofuel prices are constrained by the conventional jet fuel prices, so refinery firms can only lower the biofuel price to keep it competing with conventional jet fuel. On the other hand, the airline can reduce carbon cost by using biofuel with premium in reference and low conventional jet fuel prices scenarios.

Furthermore, a huge biofuel price fluctuation happens in reference conventional jet fuel and high carbon prices scenario from 2035 to 2045. This fluctuation is due to the optimistic strategies of bio-refinery firms. Since the bio-refinery firm tries to maximize its profit at the national level, it tends to rise the biofuel prices in the states with high production capacities; however, the single huge airline tends to use the biofuel from the lowest price states if the prices were lower than a certain threshold. During that fluctuating period, the bio-refinery has the biofuel price in every state higher than the threshold in one year and has the biofuel price in some states lower in the following year. This behavior results in average biofuel prices oscillate between zero and certain prices.
Figure 4.14. The scenarios from left to right columns are low, reference, and high carbon prices scenarios, respectively. Similarly, the scenarios from bottom to top rows are low, reference, and high fuel price scenarios, respectively. The convention jet fuel prices are shown in the solid blue lines, while the average biofuel prices are represented by the red dot-dash lines. The average carbon prices with and without available biofuel are shown in yellow dash lines and purple dot lines, respectively.
5. CONCLUSIONS AND FUTURE WORKS

The structure of FLEET and the Multiactors Biofuel Model has been built up. The work has extended FLEET’s capabilities to evaluate the developments of biofuel from potential feedstocks. Subsequently, the discussion about the case studies and future works are included in the following sections.

5.1 CONCLUSIONS

_Airline Performance and Biofuel Usages:_

In both environmental scheme models, the carbon emissions can be regarded as a commodity or another form of fuel tax at the same time, which can convert to average carbon costs on per pound of fuel. The results show that the average carbon cost is lower than fifty cents per pound of fuel even in the high carbon price scenarios. The low average carbon cost limits the biofuel premium that the airline is willing to pay and diminishes the effectiveness of environmental schemes to mitigate fleet-level carbon emissions.

Although the results show that the conventional jet fuel and carbon prices can create a sound economic condition for biofuel developments, the high fuel and carbon prices can have downside impacts on biofuel production chain as well. Since the biofuel production always happens after scheme initiation, high fuel and carbon prices raise ticket fares and reduce the passenger demand growth rates. Subsequently, the total fuel growth rates also decrease. The lower fuel demands lower the average carbon costs and reduce the potential biofuel demands. As a result, the bio-refinery firm can do nothing except lowering the biofuel price to compete with conventional jet fuel.

With the initiation of ICAM GMBM model and high conventional jet fuel prices, the airline can reach relatively lower fleet-level emissions with biofuel, but the total
RPNMI does not increase as much as the magnitude of emission reductions. The economic inertia drives the airline continuing its previous strategies even after the biofuel happens in the market. Even though biofuel has lower unit carbon emissions than conventional jet fuel, the prices or supplying quantities cannot benefit the airline enough to provide more flights.

The airline is more willing to pay for the carbon emissions instead of changing its strategies to provide services in every scenario except high fuel or carbon price scenarios. Since the biofuel production capacity is less than 10% of fuel consumption level in 2005, this demonstrates that the airline can achieve the effective emissions control without large biofuel usages. However, the simulation reveals that the airline does not have aggressive behavior to reduce the carbon emissions. The carbon costs are cheaper than stopping services and losing money.

**Driving Forces for Biofuel Developments:**

Without any subsidy from government sectors to aviation or biofuel industries, the biofuel development is mainly driven by conventional jet fuel prices and airline operations. Higher conventional jet fuel prices can increase the biofuel sale prices, so the selling prices and production costs can get closer enough to make biofuel production happens earlier. However, it also decreases the airline operations, which would decrease the potential biofuel demand. The lower airline operation reduces the demand for carbon emissions and total biofuel. As a result, the airline is reluctant to pay for the biofuel more than the convention jet fuel prices.

Feedstock resource distributions limit biofuel productions. The biofuel production capacity is about 10% of 2005 total fuel consumption level in 2050. However, the fuel consumption increases to 200% to 205% of 2005 fuel consumption level by 2050. Due to the inconsistency between feedstock resource and biofuel demand distributions, the refinery firm should have more advanced technologies to acquire feedstocks from further distances with lower prices and less emissions. They should find a new feedstock with large supply capacity and similar distributions as biofuel demand.
Environmental Policy Impacts:

Even though the fleet-level emissions by 2020 in scenarios with ICAO GMBM model was higher than scenarios with EU ETS model, the fleet-level emissions by 2050 from scenarios with ICAO GMBM model is lower than the ones with EU ETS model. Additionally, the RPNMI profile of scenarios with either scheme initiation is almost the same. The results show that ICAO GMBM model can guide the airline to use its fleet in a greener way in a longer term. Furthermore, ICAO GMBM model can reach the carbon neutral growth in higher conventional jet fuel and carbon prices scenarios but reach a lower satisfied passenger demand. In conclusion, the GMBM has greener impacts on the U.S. air transportation system than EU ETS with the similar airline operations. However, further investigations are required to verify the route-wise influences.

Comparison between this work and related research:

The Aviation Sustainability Center (ASCENT) is a research organization led by Washington State University and the Massachusetts Institute of Technology and is funded by the NASA, FAA, Transport Canada, the Department of Defense, and the Environmental Protection Agency. The objective of ASCENT is to create science-based solutions for the challenges of the U.S. air transportation system.

The ASCENT 1 project, one of ASCENT projects, studies the future sustainable fuel production chains, which include feedstock resources, land usages, biofuel converting processes, locations of factories, and means of products transportation. Although the project is still going on, the previous results have represented the possible future feedstocks and biofuel converting processes in different regions. Furthermore, the project is more focused on water qualities, farmers’ cultivation behaviors, and feedstock supplies. Subsequently, the project will work on future scenarios of alternative fuel productions and properties in each region and their impacts on environmental, economics, and social sustainability.

The ASCENT 1 project has a sound biofuel production database and the FLEET with the Multiactors Biofuel Module is capable of handling environmental and opera-
tional policies in strategies decisions of bio-refinery firms and farmers. The ASCENT 1 project and this research complements each other very well as both deal with similar problems. This work can serve as an interface between the simulations from both air transportation and biofuel production domains.

5.2 FUTURE WORK

The structure of the integration between FLEET and Multiactors Biofuel Model has been done. Additionally, the biofuel module is capable of integrating with other fleet-level evaluation tools if the tools can provide the required input data, such as Aviation Environmental Portfolio Management Tool and Hierarchical Decision-Centric Model [8]. However, it is still required to validate and verify the model and improve its fidelity.

5.2.1 SHORT-TERM

In short-term, further research should be done to enhance the capabilities of the integrated model more, as listed:

- building up more feedstocks models, like municipal solid waste;
- building up the distance matrix to describe the feedstock transportation distance between one state to the other in the refinery profit optimization problem;
- building up the market-based carbon price model;
- executing a sensitivity analysis to analyze the impacts from the uncertainties of feedstock properties and future aircraft performances.

5.2.2 LONG-TERM

To make the model more realistic, there is a need to address the competition between different industries. The integration of the Multiactors Biofuel Module and
Argonne the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) can reduce the difficulties to organize feedstocks and refinery process database [28]. Besides, FLEET has the capability to model airline competition with a two-airline model. However, there are some difficulties in integrating the Multiactors Biofuel Module and two-airline model in FLEET together. In summary, the long-term goals include:

- distributing biofuel to two airlines;
- deciding the biofuel price for a duopoly market where the biofuel quantity is limited;
- modeling the competition between airlines with the emission allowances;
- creating an interface to access the database of Argonne GREET.
REFERENCES


