Abstract: This paper provides the future projection of CO\textsubscript{2} emission from international aviation, considering changes of international network structure and fleet size. The network structure includes two common types, namely the hub-and-spoke system and the point-to-point system, and two other in-between network cases are assumed. Also regarded is the more use of smaller aircraft for more efficient and more frequent flight services. The two cases for fleet size include the use of current size fleet and smaller size fleet. The future aviation demand and CO\textsubscript{2} emission is projected under six scenarios, built by the combination of these cases. The result suggests that the utilization of smaller aircraft induces less amount of CO\textsubscript{2} emission. Also, the point-to-point system has the effect of CO\textsubscript{2} emission reduction to some extent.

Key Words: International Aviation, CO\textsubscript{2} Emission Projection, Network, Fleet Size

1. INTRODUCTION

Aviation is the second largest source of carbon dioxide (CO\textsubscript{2}) emission in transport sector, responsible for 13\% of total emission (Kim et al., 2005). Further increase of air traffic demand is expected due to the growth of population and economy, as well as ongoing globalization (Airbus Industrie, 2006; Boeing, 2006). Facing problems on exhaustion of energy resources and global warming, CO\textsubscript{2} emission from aviation will be one of the increasingly critical global issues.

Several analyses on calculations and predictions of fuel use and CO\textsubscript{2} emission from aviation are conducted mainly in the United States and Europe. Pioneering researches conducted by the National Aeronautics and Space Administration (NASA) provide basic but comprehensive insights on the amount of fuel use and emissions by scheduled civil aviation in 1992 and 1999 (Baughcum et al., 1996; Sutkus et al., 2001). Emissions such as nitrogen oxide (NOx) and carbon monoxide (CO) are targeted in these studies and CO\textsubscript{2} emission is not originally considered; however, CO\textsubscript{2} emission factor of 3.155 CO\textsubscript{2}-g per fuel-g (Kim et al., 2005; Gardner, 1998) suggests that the total CO\textsubscript{2} emission from worldwide aviation market was 404Tg, or 404 million metric-tons, in 1999 (Sutkus et al., 2001). Projection for 2020 is also carried out (Sutkus et al., 2003). Calculation with the emission factor implies the total amount of CO\textsubscript{2} emission in 2020 to be 1,096Tg. Federal Aviation Administration (FAA) of the United States and several other institutions in Europe also conducted similar analyses (Kim et al., 2005; Gardner, 1998; Eyers et al., 2004). Suzuki et al. (2009) recently updated the current amount of worldwide CO\textsubscript{2} emission from aviation to be 630.3Tg in 2005. The paper also
attempted to predict long-term CO$_2$ emission growth toward 2050; however, we have to keep in mind that the results of long-term prediction is apt to be influenced by changes in anticipated conditions, such as economic situation and security considerations, as well as changes in aviation industry itself (Olsthoorn, 2001). Projection results by these studies toward 2030 are summarized in Figure 1.

Airbus Industrie, a major aircraft manufacturer, predicts in their market forecast report (Airbus Industrie, 2006) that the hub-and-spoke network system with stronger hub airports and larger aircrafts will constitute the future aviation network. The Boeing Company, the counterpart to Airbus in the United States, insists that the future aviation network will be point-to-point, utilizing greater number of smaller aircrafts (Boeing, 2006). Differences in the standpoint of two companies are reflected on their aircraft production. Airbus is promoting the largest-ever commercial aircraft A380 series, while Boeing is now at the final stage of the development of middle-sized long-range aircraft B787 series.

A number of large “legacy” airline companies already adopted the hub-and-spoke network system, for more efficient operation and meeting restrictions in airport slots and airspace. On the other hand, some newly established low cost carriers (LCCs) adopted the point-to-point network system. Recently, the average fleet size is generally becoming smaller and rich in variety despite the growth of air traffic demand (Kilpi, 2007; Swan, 2002). Also, especially in Europe the importance of hub airports is declining, though long distance flights still depend on them (Burghouwt et al., 2001). The potential of utilizing smaller aircrafts is also discussed in Japan, where we can find relatively rigid slot and space restrictions (Yai et al., 2002; Hino et al., 2001). Hiramatsu et al. (2003) also discusses the applicability of small-sized regional jets to international markets within Asia.

These differences in the network structure and fleet size may affect the amount of CO$_2$ emission, as well as the convenience of air travel and aircraft operation efficiency. A research in Europe (Peeters et al., 2001) revealed a slight trend that concentrating more flights at fewer hub airports will induce more fuel use, while increase in the number of direct flights will bring the opposite. It is also pointed out that restricting the number of air routes may lead to the growth of fleet size (Peeters et al., 2001). Therefore we can say that fleet size, network structure and fuel use are interacting among each other. However, in their study CO$_2$ emission
is not predicted and the region is limited to Europe; further researches on the CO$_2$ emission prediction regarding global network structure and changes in fleet size is necessary.

The notion of the CO$_2$ emission can be decomposed as shown in Figure 2. Regardless of the network structure, efficiency is expected to be improved as the result of technology advances (Greene, 1992). The hub-and-spoke network forces passengers to stop by hub airports for transfer, making the journey longer than using direct flights (Burghouwt et al., 2001). Average fleet size in the hub-and-spoke network will be larger since more passengers will concentrate on fewer links and flights (Airbus Industrie, 2006). Flights will be less frequent when larger fleet is utilized (Hiramatsu et al., 2003) The point-to-point network has the opposite characteristics; however, the fleet size may be arguable. In one way, traffic dispersion to numerous routes enables fleet to be smaller (Boeing, 2006). In the other way, long-haul point-to-point markets may demand longer-range fleets, which are dominated by larger aircrafts (Swan, 2002).

This paper first calculates the amount of CO$_2$ emission in 2005 from the international aviation market. Then we project CO$_2$ emission toward 2050 under several scenarios considering changes in network structure and fleet size. Differences in projected CO$_2$ emission among scenarios are then discussed. Domestic aviation market is ignored in this study.

2. METHODOLOGY

2.1 Calculating CO$_2$ Emission in 2005
First the total amount of CO$_2$ emission from international aviation market in 2005 is calculated, utilizing the Official Airline Guide (OAG) Worldwide Timetable (2005) covering all worldwide scheduled commercial flights in 2005. This amount is used not only to grasp the current amount of emission, but also as the reference to the future projection.

The first step of the calculation is to acquire the origin, destination, flight distance and duration, fleet type, seat and cargo volume, and flight frequency of every international flight from the OAG timetable. Each flight is divided into five phases, as depicted in Figure 3. The cruise phase refers to the situation where an aircraft flies over the altitude of 3,000 feet, or 1,000 meters. Under this altitude, a flight consists of four phases, namely takeoff, climbout, approach and idle. Generally, duration of each phase may depend on location, fleet types and weather conditions. In this research, however, a unified duration of each phase, determined by International Civil Aviation Organization (ICAO), is applied to all flights, that is: 45 seconds for takeoff, 132 seconds for climbout, 240 seconds for approach and 1,560 seconds for idle.

\[
\text{CO}_2 \text{ emission (CO}_2\text{-g/year)} = \text{Efficiency (CO}_2\text{-g/km)} \times \text{Distance per person (km/person)} \times \text{Fleet size (person/flight)} \times \text{Number of flights (flights/year)}
\]

Figure 2 Decomposed elements of CO$_2$ emission
The duration of cruise phase is calculated by subtracting the total duration of these four phases, 1,977 seconds, from the flight duration indicated on the timetable. If a flight is shorter than the total of four phases, the flight is considered to last 1,977 seconds and the cruise phase to be 0 seconds. Possible delays and flight cancellations are ignored.

Then, the engine type applied to each fleet type is specified. Some fleet types are equipped with several types of engines: in such cases, the most common engine type is selected. For each engine type, the amount of fuel flow is calculated with engine emission databases, which record the per-second fuel flow and emission ratio of a wide range of aircraft engine types. Fuel flow per engine per second for four phases under the altitude of 3,000 feet is drawn directly from three engine emission databases (ICAO, 2007; Swedish Defense Research Agency, 2007; Swiss Federal Office of Civil Aviation, 2007). Fuel flow for cruise phase is not shown in these databases. Therefore, 36% of fuel flow in the takeoff phase is treated as the flow for cruise phase. This proportion is drawn from the database provided by Eurocontrol (2004), which is not rich in variety of engine types but covers fuel flow for cruise phase. The sum of the multiplication of fuel flow and duration of each flight phase, further multiplied by the number of engines and frequency, gives the total fuel use per flight per year. This process is done for all international flights and summed up to find the total fuel use in 2005. Finally, the amount of CO$_2$ emission is calculated by multiplying the amount of fuel use by 3.155. The calculation model is described in Equation (1).

\[ Q = F \times \sum (N \times E \times W_p \times T_p), \]  
\[ (1) \]

where  
- \( Q \): Total CO$_2$ emission (g/year)  
- \( F \): CO$_2$ emission factor (3.155 CO$_2$-g/fuel-g)  
- \( N \): Flight frequency (flights/year)  
- \( E \): Number of engines (engines/flight)  
- \( W \): Fuel flow (fuel-g/second, engine)  
- \( T \): Duration (seconds)  
- \( p \): Flight phase

2.2 Air Traffic Demand Forecast toward 2050
The air traffic demand for every five years from 2005 to 2050 is estimated first. International aviation network assumes inter-country links with each country having only one representative node. In 2005, 223 countries and equivalent regions (hereafter “countries”)
served scheduled commercial flights. However, the following countries are merged into another country, making up the total of 219 countries because of the data limitations: Christmas Island, Cocos Islands and Norfolk Island into Australia, and Mayotte into Comoros. All 219 countries served scheduled international passenger flights, while scheduled international cargo flights covered 214 countries. This coverage is assumed to be unchanged in the future. The following projection process is done separately for passenger and cargo demand. The fact that most of passenger flights share some space to cargo service is also considered.

First, the international link network is built for each projection year. This is done by judging whether any two countries are directly linked or not in a given year. Population (United Nations Population Division, 2008; United States Census Bureau, 2007), GDP (United Nations Statistics Division, 2008), and distance between two countries are incorporated into the model shown in Equation (2) to predict the probability of direct linkage between two countries. The future GDP growth rate is assumed to be the same to that of the 1990-2005 average. Distance between two countries is calculated by the spherical trigonometry and the location coordinates. The city with an airport which has the largest international passenger volume in the country represents the location of the country. In most cases the capital cities are the representative nodes; some of exceptions include Frankfurt, Germany, Johannesburg, South Africa and New York City, the United States, all of which are not capitals but representative. Parameter $\beta_4$ in Equation (2) denotes the dummy parameter whether given two countries include China or India, since they have a prominent volume of population.

$$L_{ij} = \frac{\exp(A)}{\exp(A) + 1}$$

$$A = \beta_1 \ln(P_i P_j) + \beta_2 \ln(G_i G_j) + \beta_3 D_{ij} + \beta_4$$

where

- $L_{ij}$: Probability of countries i and j directly linked
- $P_i, P_j$: Population of country i, j
- $G_i, G_j$: GDP of country i, j (USD/capita)
- $D_{ij}$: Distance between countries i and j (km)
- $\beta_1 - \beta_4$: Parameters to be determined

The 2005 population, GDP, distance and existence of direct links gives the value of parameters $\beta_1$ to $\beta_4$, and $L_{ij}$ which best reproduces the actual link network in 2005. The result was $L_{ij}=0.5$ for both passenger and cargo networks. Next, future population and GDP data together with parameters estimated above are thrown into Equation (2) and, if the calculated $L_{ij}$ is 0.5 or greater, the two countries get the direct link. This is done to all country pairs to build up the future international flight network. As a supplement, if any two countries are actually linked in 2005, then they are automatically linked in the future network, regardless of the results of Equation (2).

The next step is to estimate the OD traffic volume between all country pairs and to assign it to the links. The estimation model is shown in Equation (3). The probability, or proportion, of OD traffic between given two countries passing through a certain link, expressed as $C_{ABij}$, is first calculated with the Dial’s method (Sheffi, 1985). Then the total OD volume, divided by the probability, is assigned to each link. Repeat this for all OD pairs to obtain the total traffic volume of a link. Flight duration is employed as the travel cost variable. However, links in future projection are all imaginary and the actual duration cannot be given. Therefore, the relationship between flight duration and distance in actual flights in 2005 is employed to
estimate the duration of imaginary links, as shown in Equation (4). Two hours are further added per link connection, assuming connecting costs such as check-in and waiting time. Traffic volume comes from the seat and cargo capacity with the load factor of 70%. Here also, the parameter $\gamma_4$ is the dummy to discriminate the inclusion of China or India.

$$V_{ij} = \sum_{A,B} C_{ABij} \times (P_A P_B)^{\gamma_1} \times (G_A G_B)^{\gamma_2} \times \exp(\gamma_3 D_{AB}) \times \gamma_4$$

(3)

where
- $V_{ij}$: Traffic volume on the link $ij$
- $C_{ABij}$: Probability of traffic between countries A and B pass through link $ij$
- $P_A, P_B$: Population of country A, B
- $G_A, G_B$: GDP of country A, B (USD/capita)
- $D_{AB}$: Distance between countries A and B (km)
- $\gamma_1, \gamma_4$: Parameters to be determined

$\text{Duration (hour)} = 0.0012 \times \text{Distance (km)} + 0.75$

(4)

$t=433.797$  \quad  $t=69.154$  \quad  R squared=.977

2.3 Scenario Analysis of CO$_2$ Emission Projection toward 2050

Results of the future traffic volume estimation are utilized in CO$_2$ emission projection scheme. The total of six scenarios are produced considering variations in fleet composition and link network structure.

2.3.1 Future Fleet Composition

In 2005, the total of 210 passenger and cargo fleet types are globally used. Further, multiple fleet types are utilized simultaneously to a single market or link. In this study, for the sake of excluding outdated fleet types and simpler projection, eight representative fleet types shown in Table 2 are employed for future CO$_2$ emission projection, and one representative fleet type is assigned to each link. Narrowbody denotes the single-aisle aircraft, while widebody denotes the two-aisle aircraft. B747-400F is also categorized as widebody, though it actually has no aisle, since the passenger version of this model has two aisles. These are new and still in production, and vary in capacity and range among others. Even newer types, such as A350 and B787, are under development. They are expected to realize further environmental friendliness, but they are not considered here, since engine data are not in the databases.

Distance is utilized to estimate the fleet size, since distance is an exogenous variable applicable to the future projection. Figure 4 and Equation (5a) depicts the relationship between distance and average fleet size of all country pairs in 2005. The correlation coefficient is .574, indicating reasonably high positive relationship. A closer look at the figure gives us an idea that there may be a minimum fleet size for a given distance, approximated by the Equation (5b). The difference between actual average size (5a) and minimum size (5b) may come from sharing aircrafts with other markets or providing more cabin space for comfort. Here, fleet size minimization assumes the ultimate use of small aircrafts as the result of introducing point-to-point network. Many of the points under the line (5b) in Figure 4 represent the country pairs where cargo flights dominate the traffic. These include links to and from Luxembourg, which has a notably higher share of cargo flights in international market, 20.2%, than the world average of 2.9% in 2005. Airline companies may actually select fleet types other than by distance, such as capacity, performance, business situation and preference of aircraft manufacturers. In this study they are ignored for the simplicity of the calculation and the complex process of fleet selection decision needs further discussion.
For each link, the average fleet size is estimated with Equations (5a) or (5b). The “base” scenario refers to the fleet size estimated with Equation (5a), while the “minimized” scenario utilizes the Equation (5b). The fleet type which (i) is the smallest in terms of seat capacity, and (ii) satisfies the estimated average fleet size, is selected from Table 1 as the representative fleet type for the link. If the average fleet size is estimated to be 280 seats, then B777-200 is assigned to the link. The total volume of passenger traffic demand estimated in the Section 2.2 is divided by 70% of the seat capacity of assigned fleet to provide the number of flights. Subsequently, Equation (1) is utilized to calculate the amount of CO₂ emission. Flight duration is estimated with Equation (4). Thus the fleet type is selected based on passenger market. They can handle cargo traffic to some extent, but in some cases the cargo demand exceeds the capacity. If so, cargo flights using B747-400F is added until the capacity fulfills the demand. An annual efficiency improvement of 1.3% is also considered (Greene, 1992).

### Table 1 Fleet types for future projection

<table>
<thead>
<tr>
<th>Type</th>
<th>Seat capacity</th>
<th>Cargo capacity (tons)</th>
<th>Use</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>A380-800</td>
<td>555</td>
<td>66.4</td>
<td>Passenger</td>
<td>Widebody</td>
</tr>
<tr>
<td>B777-300ER</td>
<td>394</td>
<td>30.4</td>
<td>Passenger</td>
<td>Widebody</td>
</tr>
<tr>
<td>B777-200</td>
<td>305</td>
<td>17.1</td>
<td>Passenger</td>
<td>Widebody</td>
</tr>
<tr>
<td>A330-200</td>
<td>256</td>
<td>19.7</td>
<td>Passenger</td>
<td>Widebody</td>
</tr>
<tr>
<td>B737-700</td>
<td>137</td>
<td>11.1</td>
<td>Passenger</td>
<td>Narrowbody</td>
</tr>
<tr>
<td>ERJ-170</td>
<td>70</td>
<td>7.4</td>
<td>Passenger</td>
<td>Narrowbody</td>
</tr>
<tr>
<td>B747-400F</td>
<td>0</td>
<td>111.0</td>
<td>Cargo</td>
<td>Widebody</td>
</tr>
</tbody>
</table>

![Figure 4 Relationship between distance and fleet size](image)

\[
\text{Fleetsize (seats)} = 0.0211 \times \text{Distance (km)} + 103.19 \\
(t=79.503) (t=90.920) \\
R \text{ squared} = .574
\]  

\[
\text{Fleetsize (seats)} = 0.0211 \times \text{Distance (km)}
\]  

(5a)

(5b)

### 2.3.2 Future Network Structure

Four types of network structure are considered. First, the network comprising links which meets the standards described in 2.2 is referred to as “Base” scenario. “Unchanged” scenario does not assume any network expansion: in other words, the 2005 network lasts to 2050. All country pairs are connected with links in “Full” scenario. This assumes that all air transport is
done by direct flights on direct links, and the traffic need not be distributed onto the network with the Dial’s method. Therefore, the term $\sum_{A, B} C_{ABij}$ is removed from the Equation (3) and subscripts “A” and “B” should also read “i” and “j”, respectively. The “Expanded” scenario assumes more links than the “Base” scenario, but less than the “Full” scenario. This is done by lowering the threshold value of $L_{ij}$ in Equation (2) from the “Base” scenario, and here the value is set to 0.3. “Full” scenario has the most links, followed by “Expanded” and “Base,” and “Unchanged” has the least.

Six scenarios regarding fleet composition and network structure are summarized in Table 2. S-1 is the reference scenario, while S-3B and S-4B assumes the use of smaller aircrafts associated with the point-to-point network. When the fleet size is not considered, S-3A, B S-4A and B are referred together to as S-3 and S-4, respectively. One important thing is that the total worldwide OD traffic volume is same among all scenarios. The difference is how the all OD traffic is distributed to the network and by what type of aircraft it is transported.

<table>
<thead>
<tr>
<th>Network structure</th>
<th>Fleet size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>S-1</td>
</tr>
<tr>
<td>Unchanged</td>
<td>S-2</td>
</tr>
<tr>
<td>Expanded</td>
<td>S-3A, S-3B</td>
</tr>
<tr>
<td>Full</td>
<td>S-4A, S-4B</td>
</tr>
</tbody>
</table>

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Current Air Traffic and CO$_2$ Emission in 2005

Table 3 shows the actual aircraft movement, payload volume and CO$_2$ emission in 2005. Approximately one-tenth of all country pairs, i.e. 219*218=47,742, are directly linked. The total CO$_2$ emission amount of 408.8Tg corresponds to the two-thirds of all CO$_2$ emission from aviation in 2005 including domestic markets (Suzuki et al., 2009). Hereafter, these values are referred to as “current.”

<table>
<thead>
<tr>
<th>Flights per day</th>
<th>21,648</th>
</tr>
</thead>
<tbody>
<tr>
<td>International passenger links</td>
<td>4,684</td>
</tr>
<tr>
<td>International cargo links</td>
<td>4,070</td>
</tr>
<tr>
<td>Passenger-kilometers (billion)</td>
<td>2,246.2</td>
</tr>
<tr>
<td>Cargo ton-kilometers (billion)</td>
<td>175.0</td>
</tr>
<tr>
<td>CO$_2$ emission (Tg)</td>
<td>408.8</td>
</tr>
</tbody>
</table>

#### 3.2 Projected International Air Traffic Demand toward 2050

Figure 5 shows the projected passenger traffic demand, in total passenger-kilometers, toward 2050. The S-1 scenario gives the projected demand of 36.1 trillion passenger kilometers in 2050, which is 16.1 times greater than that in 2005. This corresponds to the annual growth rate of 6.4%, slightly larger than the overall growth rate of 4.8% to 4.9% projected by the Airbus Industrie (2006) and the Boeing Company (2006) for the next 20 years. This may resulted from the fact that the analysis is limited only to the international markets. The Airbus Industrie (2006) estimates that the annual growth rate of the domestic demand in the United States, which has the largest air traffic market, would be approximately 3%, which implies
that the growth rate of the international market may be larger than the whole market. Also, the assumption of the constant economic growth may overestimate the demand.

The largest demand is found in S-2, followed by S-1 and S-3, and the smallest in S-4. Expansion of links enables more passengers to move on the shortest path, while they have to detour around the longer link chain when links are restricted, hence the longer travel per person is expected. The difference between S-2 and S-4 in 2050 is 5.7%, or 2.1 trillion passenger kilometers. For example, a 10,000 km travel in S-4 will be a 10,570 km travel in S-2, corresponding to the additional travel time of 40 minutes.

Figure 6 shows the projected cargo traffic demand, in total ton-kilometers, toward 2050. The demand is expected to be 3.05 trillion ton-kilometers in 2050, which is 17.1 times greater than the actual demand in 2005 or conforms to the annual growth of 6.6%. The value is slightly larger than the annual growth rate of 6.0% to 6.1% estimated by the Airbus Industrie (2006) and the Boeing Company (2006). Here also, S-2 has the largest demand while S-4 has the smallest. The difference between S-2 and S-4 is 7.5%
The projected number of international flights is depicted in Figure 7. Overall, two features can be pointed out from the figure. One is the larger number of flights expected in 2005 when network is fully expanded, and the other is the rapid growth of flights toward 2050 when the fleet size is minimized.

First, the difference of the number of flights in 2005 is compared among scenarios. S-4B and S-4A indicated the largest number of flights, corresponding to 395.4% and 319.0% of that estimated in S-1, respectively. This suggests that further network expansion disperses traffic, hence demands more flights. The number of flights increased also when fleet size is minimized. S-3B and S-4B assumes more flights than S-3A and S-4A, respectively. This is intuitive, since smaller aircrafts transport less passengers at one time, requiring more flights. The projection implies that both network expansion and fleet size minimization may ultimately demand the airport and airway capacity four times larger than the current situation.

The trend of the future growth of flights depends largely on fleet size. S-3B and S-4B indicated relatively rapid growth of flights, reaching 2.0 to 2.1 times more flights than S-1 in 2050. On the other hand, the growth is not prominent in S-3A and S-4A, where the fleet size is not minimized, and the number of flights falls below S-2 in 2050. This phenomenon may be explained by the usage of the fleet size projection model shown in Equations (5a) and (5b). The expanded or full network comprises extremely long links, to which the largest fleet will be assigned. Their capacity far exceeds the current demand, and is large enough to handle the increased demand in the future without additional flights. As the result, the growth of the number of flights is restrained in scenarios without fleet size minimization.

The current and future fleet size composition is summarized in Figure 8. Currently 23.7% of all international flights are actually operated with widebodies. The share goes up to roughly half in S-1, S-2 with some extra growth in 2050, reflecting the future growth of long range traffic demand. Comparing S-3 and S-4, three points can be specified. One is intuitive, that the share of widebodies are less in S-3B and S-4B than in S-3A and S-4A. Second is that the widebody share in S-4A and S-4B are larger than that in S-3A and S-3B, respectively. The last is that the widebody share in 2050 is larger than that in 2005 in S-3, while the trend is opposite in S-4. The latter two can be explained by the network structure and how fleet is assigned. The former is that the ultimate expansion of network (i.e. links to all possible
country pairs) incorporates a handful of extremely long links, demanding the largest aircraft. This led S-4 to be more widebody-dominated. In such case, the fleet is large enough to meet the increased future demand so that no additional flight is necessary. However, shorter markets with smaller fleet easily call for additional flights when the demand is grown, resulting in the growth of narrowbody flights and restraint of widebody share growth in 2050. This can explain the latter phenomenon.

![Projected fleet composition in 2005 and 2050](image)

3.3 Projected CO₂ Emission from International Aviation toward 2050

Figure 9 shows the projected amount of future CO₂ emission. This is the outcome of the mixture of the traffic demand and fleet composition. The S-1 scenario suggests the projected CO₂ emission of 3,946.0Tg in 2050. This is 9.7 times larger in amount than that in the current situation, and corresponds to the annual growth rate of 5.2%. These values are smaller than that of future traffic demand, due possibly to the use of new fleet types and the consideration of efficiency improvement. The S-2 scenario marks the largest amount of projected CO₂ emission in 2050, 4,215.3Tg. S-3A and S-4A follow just below S-1. What made the distinctive difference are scenarios S-3B and S-4B, both indicating 14% to 15% smaller amount of CO₂ emission to that of S-1 in 2050. The difference of the projected amount between S-2, which has the largest, and S-3B, which has the smallest, is 20.5%.

Least amount of CO₂ emission in scenarios S-3B and S-4B indicates that the fleet size minimization has the effect of CO₂ emission reduction. The difference of CO₂ emission among different network structure is less significant. If looked closely, the network expansion also induced the slight reduction of CO₂ emission. However, S-3B has a slightly larger reduction than S-4B, which implies that the excessive expansion of network may retard CO₂ emission reduction effect, due possibly to the dispersion of traffic and extreme growth of the number of flights.
3.4 Model Performance Verification

The prediction performance of above mentioned models is verified by comparing the number of links and flights, volume of traffic and CO$_2$ emissions between the actual values for 2005 calculated in Section 3.1 and the predicted values for 2005 in Sections 3.2 and 3.3. Table 4 shows the prediction results of international links. As high as 98.3% and 98.5% of passenger and cargo links are correctly predicted with the Equation (2). Ignoring the country pairs not linked in actual and predicted networks, 85.2% and 86.4% of predicted links are linked in actual passenger and cargo network, respectively. The upper right hand cell of the table is blank since actual links in 2005 are assumed not to disappear in the future network. Table 5 summarizes the comparison results of actual and predicted traffic and CO$_2$ emission. Except for cargo traffic demand, all values indicated only a slight underestimation with approximately 10% of difference. They also have moderate to high link-by-link correlation coefficient, from 0.631 to 0.852. These support that models utilized in this Chapter demonstrates fairly good prediction performance.

Cargo demand is significantly underestimated. This study assumes the cargo load factor of all flights to be 70%. In reality, the fleet selection and flight operation is made based primarily on passenger travel and it is not necessarily optimized to the cargo demand (Oster et al., 1987), suggesting the variety in load factor. Further, in this study cargo flights are assigned secondarily after passenger flights as described in 2.3.1. Therefore, the “current” cargo demand is not necessarily “actual” and hence the inaccuracy of the projection model. These points should be considered in the subsequent studies to project cargo demand more accurately.

Table 4 Prediction results of international links in 2005

<table>
<thead>
<tr>
<th>Passenger</th>
<th>Prediction: Linked</th>
<th>Prediction: Not Linked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual: Linked</td>
<td>9.8%</td>
<td>-</td>
</tr>
<tr>
<td>Actual: Not Linked</td>
<td>1.7%</td>
<td>88.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cargo</th>
<th>Prediction: Linked</th>
<th>Prediction: Not Linked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual: Linked</td>
<td>8.9%</td>
<td>-</td>
</tr>
<tr>
<td>Actual: Not Linked</td>
<td>1.4%</td>
<td>89.6%</td>
</tr>
</tbody>
</table>
Table 5 Comparison results of actual and predicted traffic and CO₂ emission in 2005

<table>
<thead>
<tr>
<th></th>
<th>Ratio relative to actual value</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Flights</td>
<td>87.2%</td>
<td>0.852</td>
</tr>
<tr>
<td>Passenger Traffic Demand</td>
<td>94.3%</td>
<td>0.631</td>
</tr>
<tr>
<td>Cargo Traffic Demand</td>
<td>51.4%</td>
<td>0.688</td>
</tr>
<tr>
<td>CO₂ Emission</td>
<td>92.2%</td>
<td>0.757</td>
</tr>
</tbody>
</table>

3.5 Geographical Distribution and Projection Results for EASTS Countries

Figure 10 illustrates the geographical distribution of CO₂ emission in 2005 and 2050 under S-1 scenario. While today’s emission concentrates in North America, Europe and some countries in Asia, fast growing economies in Asia and Africa will host a great amount of CO₂ emission in the future. These economies include countries such as Nigeria, India and China.

![Geographical Distribution of CO₂ Emission](image)
Figure 11 compares the amount of CO₂ emission in 2050 between the total of 17 EASTS member countries and non-EASTS countries. All flights are attributed to the country of origin. Overall, with a slight difference among projection scenarios, EASTS countries exceed non-EASTS countries in the future CO₂ emission. EASTS countries currently occupies 28.1% of the world’s total CO₂ emission, while the proportion goes up to 33.6% in 2050 in S-4B.

S-2 indicates the unique trend. The amount of CO₂ emission is greater in S-1 than S-2 in EASTS countries, and in S-2 the emission growth is greater in non-EASTS countries than EASTS countries. A closer look at the data revealed that the passenger and cargo demand to and from EASTS countries are greater in S-1 than S-2 in 2050. Regularly, the network expansion will let passengers travel shorter, hence the less demand in S-1 can be expected. This inverse trend implies that the current international links to and from EASTS countries may be insufficient, thus preventing the demand to grow. Expanding the network, as in S-1, will let the passengers, possibly connecting passengers traveling between countries outside EASTS, stop by an airport in EASTS to take the next flight. The result shown in Figure 10 infers that we are now missing the opportunity to let the international aviation market grow, and linking the EASTS countries to the unconnected countries itself will further generates the international demand.

![Figure 11 Projected CO₂ emission in EASTS and non-EASTS countries in 2050 indexed to current emission](image)

4. CONCLUSION AND FURTHER STUDIES

This study projected the future CO₂ emission from the international aviation market. The network structure and fleet size are considered as the possible future changes of the international aviation services, and six projection scenarios are built to discuss differences. The results first implied that network expansion contributes to restraining international traffic demand by reducing movement distance per unit of passenger or cargo, while at the same time it also demands further provision of flights. The future traffic demand growth indicated little difference among scenarios, while a significant CO₂ emission reduction is observed when fleet size is minimized. The network structure has little effect on CO₂ emission, though CO₂ emission is slightly reduced when the network is expanded. It is also implied that excessive expansion of network will induce less CO₂ emission reduction effect.
As noted above, we can find trade-offs in network structure and fleet size. Expanded network is good for travel distance reduction, but it is not good for efficient aircraft operation. Restricted network is vice versa. Which realizes less amount of CO₂ emission? This research concludes that network expansion and fleet size minimization will be effective for CO₂ emission reduction. In other words, the point-to-point network utilizing smaller planes, such as regional jets, is preferable. However, it is arguable to what extent the network is to be expanded. This point may be affected by the specification of new aircrafts in the future and trend of traffic demand, and needs further discussions.

One of the topics for further studies includes the consideration of the limitation of airport and airway capacity. Analysis of fleet selection behavior will be another, since in this study relatively strong supposition on fleet selection is set. We are now expecting the introduction of A350 and B787 series, which are middle-sized, efficient, and long-range models that are rare in recent aviation industry. In the near future, the long range aircraft will not necessarily be huge. Incorporation of these models into the analysis will provide more up-to-date and more precise CO₂ emission projection.

REFERENCES