CONTINUOUS CONNECTIVITY MODEL FOR THE EVALUATION OF HUB-AND-SPOKE OPERATIONS

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ABSTRACT

The deregulation of the air transport industry in Europe and the United Sates led airlines to reconfigure their networks into hub-and-spoke systems. Recent movements toward Open Skies in the Asian aviation market are also expected to prompt the reformation of airlines' networks in the region. A fine connectivity index is a crucial tool for airlines and airport authorities in the estimation of the degree of hub operations. In this regard, this paper suggests a new index, the Continuous Connectivity Index (CCI), for measuring the coordination of airlines' flight schedules and applies it to the Asian aviation market as well as the European and American markets. The CCI consists of three components: (i) temporal connectivity to readily identify long haul flight connections, which is related to the application of a continuous linear function, the new MCT (Minimum Connect Time) and the MACT (Maximum Acceptable Connect Time), (ii) spatial connectivity to differentiate the attractiveness by applying the de-routing effect with a continuous linear function, and (iii) relative intensity to reflect the effect of direct flight frequency on transfer routes. The CCI is evaluated by examining the casual relationship through regression analyses using two dependent variables: the number of transfer passengers and the transfer rate. Compared with Danesi's index and Doganis' index, the CCI had a higher coefficient of determination, implying a strong causal relationship with the dependent variables.

Keywords: Connectivity, Hub-and-Spoke, Airline Networks, Transfer Passengers

1. INTRODUCTION

The deregulation of the aviation industry in the United States, which started in 1978, has prompted airlines to reconfigure networks and change existing route structures (Reynolds-Feighan, 1998). Airlines have converted their network structures into hub-and-spoke operating systems to generate more profits by minimizing operating expenses. With the three packages of measures in 1987, 1990, 1982, the European aviation industry has also undergone similar changes (Button et al., 1998). Within ten years or so from 1987 when three packages of measures for deregulation were initiated, European airlines had developed distinct route competitiveness and hub networks.

Many Asian countries such as China, India, Japan, and Korea have been forecasted to grow rapidly. This has resulted in a number of important transitions within their aviation industry over the last several years, with the countries considering initiatives similar to those elsewhere around the world. There have been some movements toward deregulation and open skies in Asia. For example, Korea signed a partial open skies agreement with China in 2006 and made an open skies agreement with Japan in 2007. As seen in the U.S. and Europe, Asia is expected to reconfigure its existing networks into hub-and-spoke systems. Amidst this liberalization movement in Asia, airlines are expected to pursue most efficient networks by introducing wave structures that concentrate departure and arrival flights in selected time zones.

Under this environment, the "hub-and-spoke operation" represents an important research topic in the context of Asian markets because the characteristics of airlines' hub-and-spoke operation in Asia are expected to be somewhat different from those in the U.S. or Europe in terms of factors such as geometry, politics, history, economy, and the degree of deregulation, among others. In this regard, this paper establishes the nature of the hub-and-spoke operation in the Asian aviation market. However, the scope of research is not limited to the Asian region. In order to study the characteristics of the hub-and-spoke operation in terms of timetable coordination, we

- Propose the Continuous Connectivity Index (CCI), a new connectivity model that features the temporal connectivity, spatial connectivity, and relative intensity indices;
- Evaluate casual relationships by conducting regression analyses using the CCI as the independent variable and the number of transfer passengers as the dependent variable; and
- Categorize the world's 62 airports into the spoke, hub, and mega hub groups by introducing a framework utilizing the logarithm of the CCI and the transfer rate.

2. INDIRECT CONNECTIVITY

2.1 Connectivity Concept

Following the deregulation of the airline industry, most major airlines quickly adopted the hub-and-spoke operation with a crucial schedule-based product feature (Doganis, 2002). An effective hub operation requires that flights from many spoke airports arrive at the hub airport at approximately the same time (Danesi, 2006). Indirect connectivity is often associated with the concept of hubs. By moving through a hub, passengers from secondary airports can be routed to primary or intercontinental destinations (Malighetti *et al*., 2008). Bootsma (1997) made a clear distinction between the actual temporal configuration of the airline flight schedule and the effects of the airline flight schedule on the number and quality of indirect connections generated by the flight schedule.

The most relevant purpose of any hub wave-system is to maximize its connectivity. Hub connectivity refers to the number and quality of indirect flights available to passengers via an airline hub (Boostma, 1997). The attractiveness of an indirect connection depends on a number of factors such as the waiting time at the hub, routing factors, passengers' perceptions, fares, loyalty programs, and amenities of the hub-airport (Burghouwt & De Wit, 2005; Veldhuis, 1997; Bootsma, 1997). Danesi (2006) mentioned three factors required in the development of a hub-and-spoke network: (i) the spatial concentration of the network structure, (ii) the temporal coordination of flight schedules at hub airports in waves, and (iii) the integration of via-hub sub-services. Large hub airports have a major advantage because connectivity tends to increase in proportion to the square of the number of flight movements. Nevertheless, smaller hubs could compete by offering a higher level of timetable coordination, which does not necessarily depend on the size of hub operations (Rietveld & Brons, 2001).

2.2 Previous Theories

Hub connectivity can be measured through several methods. Generally, it would be desirable to evaluate the total quantity and quality of hub connections. Some previous studies have illustrated several indices indicating the concept of "connectivity." However, measuring the attractiveness that passengers feel for routes is a difficult task because it may reflect many factors.

Veldhuis (1997) defined connectivity between markets and measured the quality and frequency of direct as well as indirect connections. He illustrated this concept by introducing a connectivity matrix. Rietveld and Brons (2001) proposed a measure for the quality of the coordination of timetables by carriers in hub airports. They applied this model to four large European airports, including London Heathrow, Paris Charles de Gaulle, Frankfurt, and Schiphol. A quantitative estimation of hub timetable coordination can be obtained by calculating the ratio between the actual value of connectivity registered at the hub and the value of connectivity that would be observed if flights to/from the hub were scheduled following a fixed reference pattern (Danesi, 2006).

By assuming the need for only a connectivity measure in calculating the so-called connectivity ratio, Doganis and Dennis suggested a model that adopts a less detailed and a more straightforward approach for measuring hub connectivity (Doganis and Dennis, 1989; Dennis, 1994, 2001; Doganis, 2002). With respect to the creation of a viable connection (N_c), they suggested a minimum connect time (MCT) of 45 minutes and a maximum acceptable connect time (MACT) of 90 minutes as the required thresholds in evaluating one arriving flight and one departing flight. The connectivity index by Doganis and Dennis was calculated by summing the number of departure flights of which time is between MCT and MACT from the arrival time of each arrival flight as follows:

$$N_c = \sum_i \sum_j m_{ij} \tag{1}$$

$$\begin{bmatrix} m_{ij} = 0, & \mathrm{MCT} \le t_{d,j} - t_{a,i} \le \mathrm{MACT} \\ m_{ij} = 1, & \text{otherwise} \end{bmatrix}$$

where N_c is the connectivity index defined by Doganis and Dennis, MCT the minimum connect time, MACT the maximum acceptable connect time, $t_{a,i}$ the arrival time of flight *i*, $t_{d,j}$ the departure time of flight *j*, $i = 1,\ldots,n_a$ any flight arriving at the hub, and $j=1,\ldots,n_d$ any flight departing from the hub.

On the other hand, Burghouwt and De Wit (2005) suggested measuring airline hub connectivity by using an approach that combines the methodologies proposed by Veldhuis (1997) and Bootsma (1997). They defined the weighted indirect connection determined by transfer time and in-flight time relative to direct flight option times. They assumed that passengers perceive transfer time to be 2.4 times longer than in-flight time. They applied MACTs differently to connection conditions as follows: the MACT was 180 minutes for connections between two continental flights, 300 minutes for connections between one continental flight and one intercontinental flight, and 720 minutes for two intercontinental flights.

Danesi (2006) suggested a new index to estimate hub connectivity by subdividing time frames more than previous studies; the time frames included the MCT, the MACT, and the intermediate connect time (ICT), among others. He also suggested a temporal connectivity matrix and a spatial connectivity matrix with three-step values of 1, 0.5, and 0 according to time frames. Adopting time frames such as the MCT and MACT of Bootsma (1997), Danesi (2006) suggested an MCT of 45 minutes, an ICT of 90 minutes, and an MACT of 120 minutes for continental-continental flight connections and an MCT of 60 minutes, an ICT of 120 minutes, and an MACT of 180 minutes for continental-intercontinental or intercontinental-intercontinental flight connections.

$$WN_c = \sum_i \sum_j w_{ij} = \sum_i \sum_j \tau_{ij} \delta_{ij} \tag{2}$$

$$\begin{bmatrix} \tau_{ij} = 1.0 & if & MCT_{i,j} \le t_{d,j} - t_{a,i} \le ICT_{i,j} \\ \tau_{ij} = 0.5 & if & ICT_{i,j} \le t_{d,j} - t_{a,i} \le MACT_{i,j} \\ \tau_{ij} = 0 & otherwise & \\ \delta_{ij} = 1.0 & if & DR_{i,j} \le 1.20 \\ \delta_{ij} = 0.5 & if & 1.20 \le DR_{i,j} \le 1.50 \\ \delta_{ij} = 0 & otherwise & \end{bmatrix}$$

where WN_c is the connectivity index defined by Danesi, τ_{ij} the temporal connectivity, δ_{ij} the spatial connectivity, $MCT_{i,j}$ the minimum connect time between *i* and *j*, $ICT_{i,j}$ the intermediate connect time between *i* and *j*, $MACT_{i,j}$ the maximum acceptable connect time between *i* and *j*,

$DR_{i,j}$ the de-routing index($DR_{i,j} = \frac{ID_{i,j}}{DD_{i,j}}$), $DD_{i,j}$ the great circle distance between the point of origin of flights i and the destination of flight j, $ID_{i,j}$ the sum of the great circle distances corresponding to flights i and j, $t_{a,i}$ the arrival time of flight i, $t_{d,j}$ the departure time of flight j, $i = 1,\dots,n_a$ any flight arriving at the hub, and $j=1,\dots,n_d$ any flight departing from the hub.

Malighetti *et al.* (2008) insisted that a hub airport is a provider of projected indirect connectivity which is further enhanced by the airport's dominant airline through the organization of flights in multiple wave systems. They added that non-hub airports can also generate connectivity for transfer passengers. Guimera *et al*. (2005, 2006) proposed that the number of direct connections to an airport is not always a good proxy for its importance as a provider of indirect connections. Reynolds-Feighan and McLay (2006) suggested accessibility indices to analyze the connectivity and attractiveness of European airports. They concluded that interconnections between low-cost carriers or between more than one alliance might be unattractive or unavailable because of additional costs imposed by airline restrictions. Bagler (2004) investigated India's domestic airport network, which comprised air services of all major civil air service providers. He studied the network's topological features and traffic dynamics by considering the intensity of interactions. Malighetti *et al*. (2008) adopted a time-dependent minimum path approach to calculate the minimum travel time between each pair of airports in various networks. That is, if there is a direct link between airport A and airport B, the shortest path length (SPL) between A and B is 1, and if both A and B are connected to a third airport C but are not directly linked, the shortest path length is 2. Park *et al*. (2008) attempted to apply the connectivity concept to cargo transshipments. They investigated the connectivity of airfreight networks as temporal concentrations in Incheon International Airport (ICN).

3. METHODOLOGY

3.1 Continuous Connectivity Model

The model[1] suggested by Doganis and Dennis (1989), which introduced an obvious criterion to find out the actual connection between arrival and departure flights, is considered to be a less detailed and more straightforward approach for measuring hub connectivity. The index of Burghouwt and De Wit (2005) and the index[2] of Danesi (2006) distinguish between the quality and quantity of connections and adopt the de-route effect. In addition, they tried to reflect changes in passengers' perception in their models by applying different MCTs and MACTs to long-haul flight connections.

Previous studies have provided models that have been improved in terms of capturing actual connections and expressing the quality of connections. However, they still lack an accurate embodiment and detailed differentiation. In this regard, we propose the "Continuous Connectivity Index (CCI)," a new index that more accurately identifies the attractivity of transfer routes included in schedules and to more closely reflect passengers' perception. The

[1] This is referred to as "Doganis' Index" for simplicity.
[2] This is referred to as "Danesi's Index" for simplicity.

new model consists of three parts: the Temporal Connectivity Index (TCI), the Spatial Connectivity Index (SCI), and the Relative Intensity Index (RII).

The TCI indicates the possibility of a transfer within a given time window determined by departure flights and arrival flights at the transfer airport. The time window of the TCI implies the actual connect time required between the arrival and departure flights. The TCI has three features: the methodology to establish MCTs and MACTs, the extended MACT for long-haul connections, and a continuous linear function to grade the level of connections.

The current research assumes that a passenger's response would differ according to the in-flight hours of his or her connecting flights. That is, the passenger's perception or tolerance with regard to the MACT would be altered by the flight hours, not by the type of flights (e.g., continental or continental-intercontinental flights). This paper sets MCTs and MACTs differently by using an eight-hour criterion. For flights and connections less than eight hours, the MCT and the MACT are set at 45 and 180 minutes, respectively; otherwise, the MCT and the MACT are set at 60 and 840 minutes, respectively (See Figure 1 and Table 1). The eight flight hours are benchmarked to reflect the approximate flight time to cross Asia, the biggest the continent, and 50% of the maximum flight hours of present commercial planes. The MACT in this paper for connections longer than eight hours (840 minutes) is relatively long in comparison with those in previous studies (e.g., Danesi used 180 minutes). This is to reflect the long hours that many passengers spend waiting for long-haul connections, such as connections from America to Southeast Asia.

This also takes into account the attractivity of schedules. That is, the attractivity decreases as connection time increases. This reflects passengers' efforts to book their transfer flights such that they would depart as quickly as possible after their arrival. In this regard, this paper suggests that the TCI could be expressed by a continuous linear function that applies distributed values from one to zero as the flight connection time varies from the MCT to the MACT (See Figure 2):

$$\begin{bmatrix} \tau_{ij} = \dfrac{-\left(TT_{i,j} - MACT_{i,j}\right)}{MACT_{i,j} - MCT_{i,j}} \quad if \quad MCT_{i,j} \le TT_{i,j} \le MACT_{i,j} \\ \tau_{ij} = 0 \quad if \quad TT_{i,j} > MACT_{i,j}, \quad TT_{i,j} = t_{d,j} - t_{a,i} \end{bmatrix} \tag{4}$$

where τ_{ij} is the temporal connectivity index, $TT_{i,j}$ the actual connect time between the arrival and departure flights, $MCT_{i,j}$ the minimum connect time between i and j, $MACT_{i,j}$ the maximum acceptable connect time between i and j, $t_{a,i}$ the arrival time of flight i, $t_{d,j}$ the departure time of flight j, $i = 1,\ldots,n_a$ any flight arriving at the hub, and $j=1,\ldots,n_d$ any flight departing from the hub.

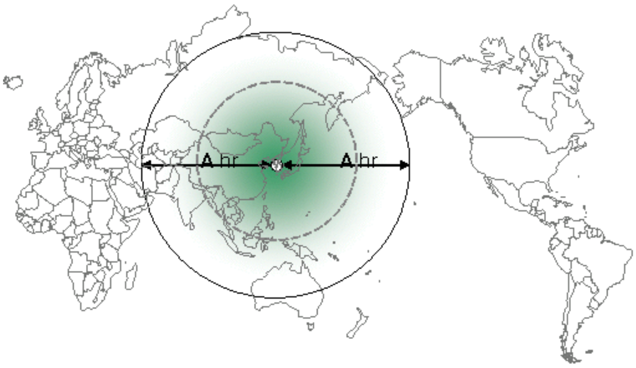
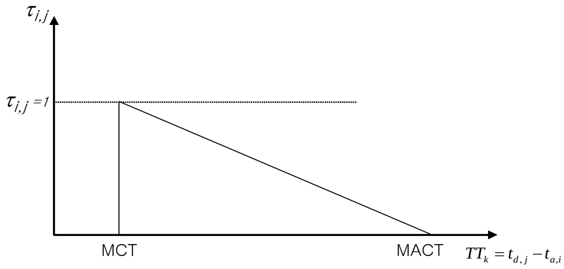
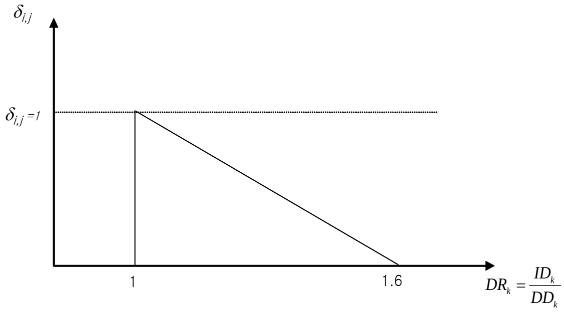


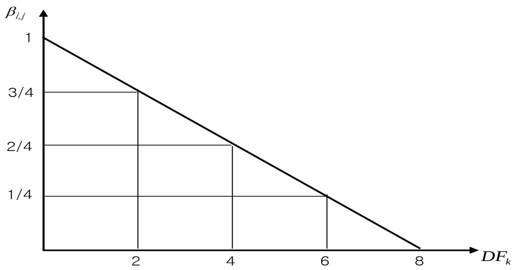
Fig. 1 In-flight hours to cross the Asian continent



The continuous function of the TCI



The continuous function of the SCI



The continuous function of the RII
Fig. 2 Continuous functions of the TCI, the SCI, and the RII

Table 1
The MCT and the MACT by in-flight time (8 hour)

Connect Times (minutes)		$MCT_{i,j}$	$MACT_{i,j}$
Connection	From regions within 8hr in-flight time To regions within 8hr in-flight time	45	180

Type	From regions over 8hr in-flight time To regions within 8hr in-flight time or From regions within 8hr in-flight time To regions over 8hr in-flight time	60	840
	From regions over 8hr in-flight time To regions over 8hr in-flight time	60	840

Spatial connectivity implies the de-routing effect and is expressed by the ratio of the total indirect flight distance (or in-flight time) via a hub to the direct flight distance. Burghouwt and De Wit (2005) suggested that the value of spatial connectivity varies from 1 to 0.6 if the ratio of the total indirect flight distance to the direct flight distance is changed from 1 to 1.4. Danesi (2006) proposed that the value of spatial connectivity is 1 if the de-routing ratio is below 1.2 and that it is 0.5 if the ratio is between 1.2 and 1.5.

In this paper, the SCI has continuous values between 1 and 0 as the de-routing ratio changes from 1 to 1.6 (see Equation 5). The value of the maximum de-routing ratio (1.6) is higher than those used previous studies. This is to capture demands on indirect flights with high de-routing ratios for long-haul flight connections. That is, passengers tend to be more receptive to highly de-routing flights on long-haul flight connections because of fewer direct flight options on long haul routes.

$$\begin{bmatrix} \delta_{i,j} = \dfrac{-\left(DR_{i,j} - 1.6\right)}{0.6} \quad if \quad 1 \le DR_{i,j} \le 1.6 \\ \delta_{i,j} = 0 \quad if \quad DR_{i,j} > 1.6, \quad DR_{i,j} = ID_{i,j} / DD_{i,j} \end{bmatrix} \tag{5}$$

where δ_{ij} is the spatial connectivity index, $DR_{i,j}$ the de-routing index($DR_{i,j} = \frac{ID_{i,j}}{DD_{i,j}}$), $DD_{i,j}$ the great circle distance between the point of origin of flights *i* and the destination of flight *j*, and $ID_{i,j}$ the sum of the great circle distances corresponding to flights *i* and *j*.

This paper introduces the Relative Intensity Index (RII), a new index indicating the relative attractiveness of indirect routes compared with direct routes. If there were many direct flights daily between airport A and airport B in a competitive market, passengers would be less likely to be attracted to indirect flights even if the temporal and spatial connectivity of the indirect route is superlative. Conversely, passengers would be forced to use indirect flights (despite high fares, long transfer hours, and low frequencies) if there were fewer direct flights. The RII uses continuous values that vary between one and zero as the direct flight frequency varies between zero and eight times a day. The current study investigated the effects of the frequency of direct flights on indirect flight. The results indicate that passengers are likely to choose direct flights if the frequency of the direct flights is more than eight times a day. Thus, the attractiveness of indirect flights is assumed to disappear if there are more than eight direct flights a day:

$$\begin{bmatrix} \beta_{i,j} = \dfrac{-DF_{i,j}}{8} + 1 \quad if \quad DF_{i,j} \leq 8\, flights/day \\ \beta_{i,j} = 0 \quad otherwise \end{bmatrix} \tag{6}$$

where β_{ij} is the relative intensity index, and $DF_{i,j}$ the direct flight frequency between origin i and destination j.

Accordingly, the CCI can be expressed as a product of the TCI, the SCI, and the RII:

$$CCI = \sum_i \sum_j w_{ij} = \sum_i \sum_j \tau_{ij} \delta_{ij} \beta_{ij} \tag{7}$$

where CCI is the continuous connectivity index, $\tau_{i,j}$ the temporal connectivity index, $\delta_{i,j}$ the spatial connectivity index, and $\beta_{i,j}$ the relative intensity index.

3.2 Dependent Variables and Geographical Submarkets

In order to evaluate the relations between hub connectivity and the degree of the hub operation, dependent variables should be prudently selected. As Danesi (2006) argued, the hub concept becomes more closely associated with an integrated interchange place where one or more specific airlines concentrate traffic and operate waves of flights. Being a hub means that there are many interchanges and interactions at the airport. Because hub airports have numerous arriving and departing flights, passengers have many choices in terms of connections to their final destination, with their baggage and other goods transported conveniently and efficiently. These interchanges at airports can be linked to other modal systems such as ground and marine transportation and extended to capital, resources, and logistics as well as passengers and baggage. This paper focuses on the passenger hub concept and the related interchange characteristics in terms of the hub connectivity of coordinated schedules. The transfer of passengers, which is an interchange, is the crucial kernel among various types of interchanges at hub airports. Airlines, as a hub operator, endeavor to improve hub connectivity and schedule wave structures to attract more passengers from other markets. Hubbing implies that an airport reflects coordinated schedules of arriving and departing flights and wave structures. Hub airports attract more transfer passengers than non-hub airports because they provide value to customers in terms of flexible schedules, that is, flight frequency, total travel hours, and waiting time at airport. Wei and Hansen (2006) studied various factors such as flight frequency, aircraft sizes, fares, flight distances, and the number of spoke airports, among others, to analyze hub-and-spoke networks. They used the number of transfer passengers as a dependent variable to estimate the effects of fare changes or airport expansion at hub airports. This paper also adopts the number of transfer passengers and transfer rates as dependent variables to evaluate the characteristics of hub connectivity. Furthermore, this study examines how precisely the new index explains hub operations by analyzing the casualty between the index and transfer passenger volumes and transfer rates.

Burghouwt and De Wit (2005) proposed that substantial differences can be observed in the role played by various hubs in each geographical market segment. He analyzed the

competitive strength in eight geographical submarkets of Europe. The current paper investigates 62 airports in Asia, America, and Europe (see Appendix A). Each airport had seven divisions of routes determined by origin (or destination) airports. Consequently, there were 49 total transfer routes for each airport (seven divisions for arrival flights × seven divisions for departure flights). The seven divisions of routes in Asia were Japan, China, Southeast Asia (SEA), America, Europe, Oceania, and Others. The divisions in Europe consisted of Western Europe, Southern Europe, Northern Europe, Eastern Europe, America, Asia, and Others. The divisions in America were Pacific USA, Mountain USA, Central USA, Eastern USA, Other America, Europe, and Others (refer to Appendix B for additional details).
The schedules of the 62 airports were from OAG (Official Airline Guide) data; the schedules were used to compute connectivity indexes. The number of passengers and transfer passengers were from MIDTs (Market Information Data Tapes) of Sabre Holdings. The schedule on Feb. 12, 2006 was used to calculate the connectivity indices. This date was randomly selected to minimize the effect of any specific event on the aviation demand and the schedule. The schedule varied depending on the day from Monday to Sunday, but it was repeated with one set of one week for one season, except dates affected by events such as accidents and unexpected snowfall. As Sunday usually has the busiest traffic, it can be referred as a representative of the schedule of one week and one month in terms of volume. The number of transfer passengers for the month of February 2006 was used as a dependent variable for the regression analysis using the connectivity index as an independent variable. The reason behind the use of the monthly data was that one month was the minimum extraction period for the MIDT. Using monthly data is also advantageous because the effect of specific events not related to the schedule would be distributed throughout the month.

4. HUB CONNECTIVITY

4.1 Empirical Analysis in Transfer Routes

The CCI, Doganis' index, and Danesi's index were calculated for the 49 transfer routes by using the flight schedule of the dominant home carrier of nine representative airports in Asia, Europe, and America. Regression analyses for nine airports' cases were conducted using the connectivity indices and the dependent variables in the 49 transfer routes. Determining the index that shows the strongest casual relationship with the number of transfer passengers would not be difficult because the coefficient of determination by each connectivity index has already been computed under the 95% confidence condition.
The dominant home carriers, which are determined by the volume of passengers, of the nine representative airports in Asia, Europe, and America are shown in Table 2. The carriers in Asia were Air China (CA) at Beijing Capital Airport (PEK), Japan Airlines (JL) at Tokyo Narita Airport (NRT), and Singapore Airlines (SQ) at Singapore Changi Airport (SIN). The carriers in Europe were Air France (AF) at Paris Charles De Gaulle Airport (CDG), Lufthansa (LH) at Munich International Airport (MUC), and KLM Royal Dutch Airlines (KL) at Amsterdam Schiphol Airport (AMS). The carriers in America were Continental Airlines (CO) at Houston George Bush Intercontinental Airport (IAH), America West Airlines (HP) at Phoenix Sky

Harbor International Airport (PHX), and United Airlines (UA) at Washington Dulles International Airport (IAD).

All of the regression analyses by each index satisfied the 95% confidence condition except for the t-ratio of Danesi' index for PHX and the t-ratio of Danesi' index for IAD (Table 2). The CCI showed the highest coefficient of determination for all nine airports, regardless of the location of the airport. Danesi's index was superior to Doganis' index for Asia and Europe, but it was inferior to Doganis' index for America. The CCI was able to capture long-haul connections in Asia because it incorporated the temporal connectivity index, in which the MCT and the MACT were established according to in-flight hours and the MACT reflected the extended time (840 minutes) of long-haul connections. In addition, the CCI showed outstanding characteristics for Europe and America because the TCI, the SCI, and the RII with continuous linear functions graded the level of connections and the CCI incorporated the new concept of relative intensity regarding the frequency of direct flights. Thus, the CCI explained the number of transfer passengers in transfer routes for all nine airports better than the previous indices.

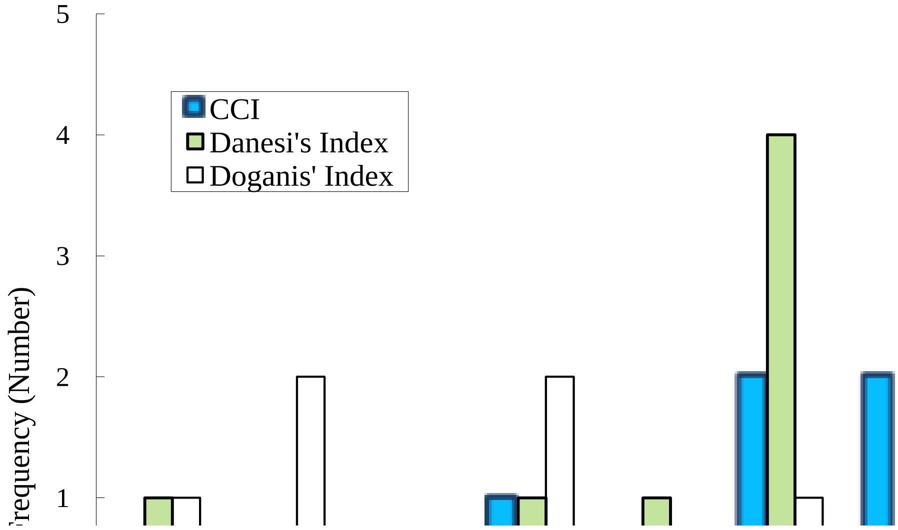


Fig. 3 Distribution of the coefficient of determination by index for nine airports

Table 2
t-ratios, F-statistics and the coefficients of determination calculated by regression analyses with the Indices and the numbers of transfer passengers for the 49 transfer routes of representative airports.

Region	Airport	Dominant Home Carrier	Connectivity	t-ratio (Coefficient)	t-ratio (Independent Variable)	F-Statistics	Coefficient of Determination, R^2
Asia	PEK	CA	CCI	2.60	11.70	137.90	**0.75**
			Danesi's Index	2.60	9.20	85.10	**0.64**
			Doganis' Index	3.20	5.90	34.30	**0.42**
	NRT	JL	CCI	2.80	5.80	33.50	**0.42**
			Danesi's Index	3.90	2.40	5.70	**0.11**
			Doganis' Index	4.04	0.13	0.02	**0.00**
	SIN	SQ	CCI	3.70	9.80	95.60	**0.67**
			Danesi's Index	3.20	7.40	54.80	**0.54**
			Doganis' Index	2.20	6.80	45.90	**0.49**
Europe	CDG	AF	CCI	3.00	13.80	191.60	**0.80**
			Danesi's Index	3.50	9.10	82.80	**0.64**

			Doganis' Index	3.80	3.70	13.50	**0.22**
	MUC	LH	CCI	2.20	23.70	559.70	**0.92**
			Danesi's Index	2.70	14.00	197.00	**0.81**
			Doganis' Index	3.90	8.70	76.20	**0.62**
	AMS	KL	CCI	5.50	10.00	100.20	**0.68**
			Danesi's Index	5.50	8.50	72.20	**0.61**
			Doganis' Index	6.30	3.60	12.60	**0.21**
America	IAH	CO	CCI	2.20	12.80	162.70	**0.78**
			Danesi's Index	2.80	8.80	77.70	**0.62**
			Doganis Index	3.00	11.70	136.20	**0.74**
	PHX	HP	CCI	2.10	49.70	2471.00	**0.98**
			Danesi's Index	1.56	5.79	33.50	**0.42**
			Doganis' Index	0.40	37.50	1404.00	**0.97**
	IAD	UA	CCI	2.00	37.30	1394.00	**0.97**
			Danesi's Index	-0.40	14.70	215.80	**0.82**
			Doganis' Index	3.20	15.70	246.10	**0.84**

Figure 3 shows the frequency line with the coefficient of determination for the nine airports. The CCI had three in the 0.9~1 range and two each in the 0.6~0.7 and 0.5~0.6 ranges. On the other hand, Danesi's Index had four in the 0.6~0.7 range, and Doganis' Index had one each in the 0.9~1, 0.8~0.9, 0.7~0.8, and 0.6~0.7 ranges. The averages of the coefficients of the CCI, Danesi' Index, and Doganis' Index were 0.77, 0.58, and 0.50, respectively.

4.2 The Segmentation of Airports by the CCI

The previous section discussed the characteristics of the CCI, which were evaluated though regression analyses with the connectivity indices and the number of transfer passengers in 49 transfer routes for nine airports' cases. This section discusses the results of the CCI regression analyses using the schedules of dominant home carriers of 62 airports and the number of transfer passengers (or the rate of transfer passengers). The connectivity index and the number of transfer passengers for one airport are considered to be one point of analysis.

Table 3 shows the t-ratios, the F-statistics and the coefficient of determination between the connectivity indices and the number of transfer passengers. The results of all analyses satisfied the 95% confidence condition. The CCI represented the strongest casual relationship with the number of transfer passengers. The coefficient of determination of the CCI was 0.94 (Figure 4), which was close to 1; the coefficients of Danesi's index and Doganis' index were 0.89 and 0.90, respectively. Noteworthy is that the CCI had the strongest casual relationship with the number of transfer passengers and that connectivity was the main factor that determined changes in transfer passengers. That is, this research verifies that connectivity is the most essential factor in hubbing, not factors such as ticket prices, services, and facilities.

Figure 5 shows the relationship between the logarithm of the CCI and the transfer rate of the dominant home carriers of the 62 airports. The coefficient of determination of the CCI was 0.70, whereas those of Danesi's index and Doganis' index were 0.62 and 0.63, respectively (Table 4). These results have two important implications. First, connectivity had a major impact on transfer rates as well as the number of transfer passengers. Previous studies have generally focused on explaining the degree of hub operations by airports (or airlines) through introducing the "connectivity ratio" (i.e., the actual connections divided by viable connections, where the arrival and departure timetables are purely random). However, the results of the current study clearly suggest that the logarithm of connectivity adequately depicts the transfer rate which represents the degree of hub operation. Second, the logarithm of the connectivity index was proportional to the transfer rate. Theoretically, a 10% improvement in connectivity should induce a 10% increase in transfer passengers. However, the results of the current study suggest that a 10% increase in the transfer rate would require a corresponding increase in connectivity by approximately 1.26 times (≒$10^{10\%}$).

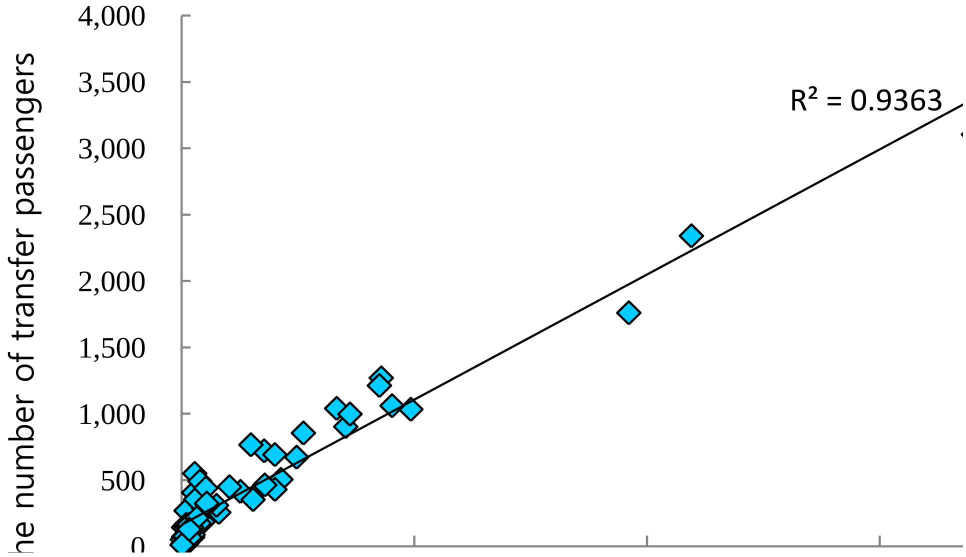


Fig. 4 Relationship between the Continuous Connectivity Index (CCI) and the number of transfer passengers for 62 airports

∗ The CCI is calculated by using the Feb. 12, 2006 schedule of dominant home carriers of the 62 airports worldwide

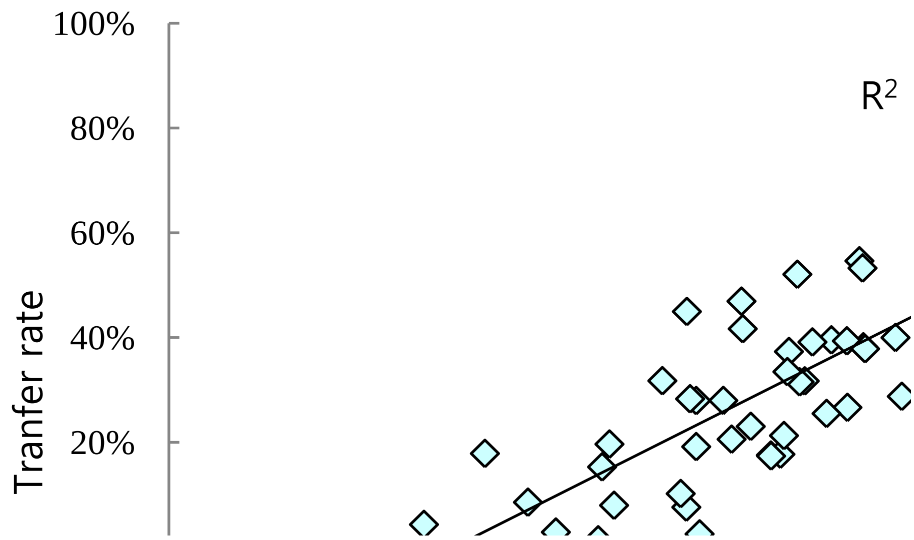


Fig. 5 Relationship between the logarithm of the CCI and the transfer rate for 62 airports

∗ The CCI is calculated by using the Feb. 12, 2006 schedule of dominant home carriers of the 62 airports worldwide

Table 3
t-ratios, F-statistics, and the coefficients of determination calculated by regression analyses with the Indices and the numbers of transfer passengers for 62 airports.

Independent Variable	Dependent Variable	t-ratio (Coefficient)	t-ratio (Independent Variable)	F-Statistics	Coefficient of Determination, R^2
CCI	The number of transfer passengers	7.8	30.7	944.4	0.94
Danesi's Index		7.3	21.9	479.2	0.89
Doganis' Index		5.9	23.6	555.2	0.90

Table 4
t-ratios, F-statistics and the coefficient of determination calculated by regression analyses with the logarithms of Connectivity Indices and the transfer rates for 62 airports.

Independent Variable	Dependent Variable	t-ratio (Coefficient)	t-ratio (Independent Variable)	F-Statistics	Coefficient of Determination, R^2
The logarithm of CCI	Transfer Rate	-5.2	11.9	142.0	0.70
The logarithm of Danesi's Index		-2.1	9.9	97.5	0.62
The logarithm of Doganis' Index		-4.7	10.1	101.7	0.63

Figure 4 shows the 62 airports placed around the regression linear graph (the logarithm of the CCI and the transfer rate). There was a casual relationship between the logarithm of the CCI and the transfer rate. In addition, the airports can be classified into several groups based on the graph. Such classification assumes that the position of airports would change from bottom left to top right along the linear graph if the airports were to grow.

The first group of airports is situated near the bottom left of the graph (the logarithm of the CCI less than 2.5 and the transfer rate less than 30%). The second group is located in the middle of the graph (the logarithm of the CCI between 2.5 and 3.5 and the transfer rate between 30% and 50%). The last group is located near the right top of the graph (the logarithm of the CCI greater than 3.5 and the transfer rate greater than 50%). The segmentation methodology can be expressed as shown in Figure 6 and Table 5.

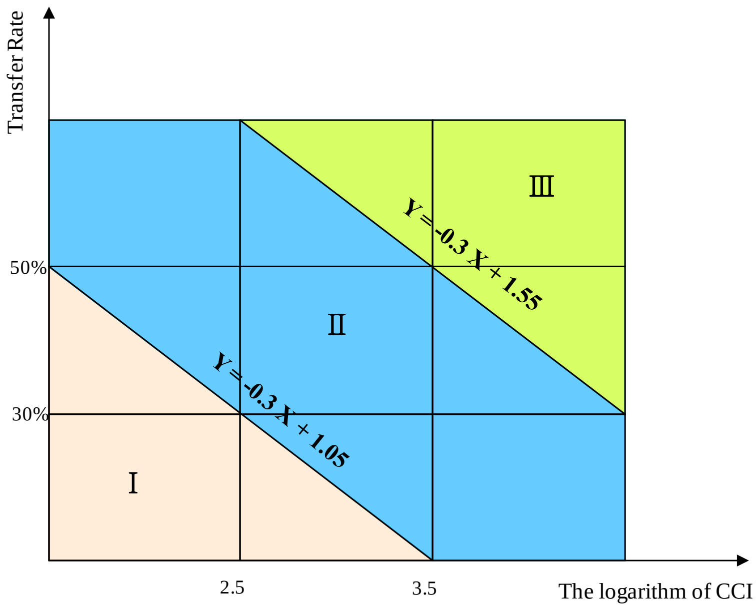


Fig. 6 Framework for airport segmentation

Table 5
The equations for airport segmentation.

Classification	Definition	Equations	Logarithm of CCI	Transfer Rate
Group Ⅰ	**Spoke**	Transfer Rate < -0.3log(CCI)+1.05	Less than 2.5	Less than 30%
Group Ⅱ	**Hub**	-0.3log(CCI)+1.05 ≤ Transfer Rate < -0.3log(CCI)+1.55	2.5~3.5	30~50%
Group Ⅲ	**Mega Hub**	-0.3log(CCI)+1.55 ≤ Transfer Rate	More than 3.5	More than 50%

The first group, the "Spoke Group," comprises 10 airports[3] in Asia, 9 in Europe, and 7 in America, including the Narita (NRT), Incheon (ICN), Beijing (PEK), and Shanghai (PVG) airports in Asia; the London Gatwick (LGW), Paris Orly (ORY), and Stockholm Arlanda (ARN) airports in Europe; and the L.A. (LAX), New York John F. Kennedy (JFK), and Boston Logan (BOS) airports in America (Table 6). The second group, the "Hub Group," comprises 4 airports in Asia, including the Singapore Changi (SIN), Hong Kong (HKG), Guangzhou Baiyun (CAN), and Kuala Lumpur (KUL) airports; 9 airports in Europe, including the London Heathrow (LHR), Madrid Barajas (MAD), and Copenhagen (CPH) airports; and 10 airports in

[3] These analyses were conducted with the Feb. 12, 2006 schedule. It is supposed that the recent positions of several airports such as ICN, PEK, and PVG, which had rapidly grown over the past few years, have changed.

America, including the San Francisco (SFO), Seattle Tacoma (SEA), and Washington Dulles (IAD) airports. The third group, the "Mega Hub Group," comprises 4 airports in Europe, including the Frankfurt (FRA), Paris Charles De Gaulle (CDG), Amsterdam-Schiphol (AMS), and Munich (MUC) airports, and 9 airports in America, including the well-known hub airports such as the Hartsfield-Jackson Atlanta (ATL), Chicago O'Hare (ORD), Detroit Wayne County (DTW), and Houston George Bush (IAH) airports. As explained above, the logarithm of the CCI and the transfer rate represent good tools in the identification of the position of airport in terms of hub operations. The x-axis, the logarithm of the CCI, represents both the quality and quantity of the supply side. The quality indicates the degree of timetable coordination, which is the actual connectivity expressed by the TCI, the SCI, and the RII, whereas the quantity represents the scale such as the number of aircraft movements, which is generally proportional to connectivity. The y-axis, the transfer rate, implies the market power of regions around a transfer airport; this reflects the demand side perspective because the transfer rate is computed as transfer passengers divided by total passengers at a given airport. In general, transfer passengers are customers of origin or destination airports, not transfer airports. A higher transfer rate than 50% would imply that there are more customers from other markets than from the home market. Thus, the transfer rate could represent the market power of the region that a transfer airport belongs to. The segmentation of the 62 airports worldwide is carried out successfully because the framework for the classification contains the characteristics of the both of supply side and demand side.

Table 6

The Spoke (Ⅰ), Hub (Ⅱ) and Mega Hub (Ⅲ) groups.

Group	Region	Airport	Dominant Home Carrier	Group	Region	Airport	Dominant Home Carrier	Group	Region	Airport	Dominant Home Carrier
Ⅰ	Asia	ICN	KE	Ⅰ	Europe	ARN	SK	Ⅱ	Europe	FCO	AZ
Ⅰ	Asia	NRT	JL	Ⅰ	Europe	BRU	SN	Ⅱ	Europe	MXP	AZ
Ⅰ	Asia	FUK	NH	Ⅰ	Europe	DUS	LH	Ⅱ	Europe	CPH	SK
Ⅰ	Asia	KIX	NH	Ⅰ	Europe	ATH	OA	Ⅱ	Europe	ZRH	LX
Ⅰ	Asia	NGO	NH	Ⅰ	Europe	HAM	LH	Ⅱ	Europe	LIS	TP
Ⅰ	Asia	PEK	CA	Ⅱ	Asia	HKG	CX	Ⅱ	Europe	HEL	AY
Ⅰ	Asia	PVG	MU	Ⅱ	Asia	CAN	CZ	Ⅱ	Europe	PRG	OK
Ⅰ	Asia	CGK	GA	Ⅱ	Asia	SIN	SQ	Ⅲ	America	ATL	DL
Ⅰ	Asia	TPE	CI	Ⅱ	Asia	KUL	MH	Ⅲ	America	ORD	AA
Ⅰ	Asia	MNL	PR	Ⅱ	America	LAS	WN	Ⅲ	America	DFW	AA
Ⅰ	America	LAX	UA	Ⅱ	America	EWR	CO	Ⅲ	America	DEN	UA
Ⅰ	America	JFK	B6	Ⅱ	America	SFO	UA	Ⅲ	America	IAH	CO
Ⅰ	America	MCO	DL	Ⅱ	America	MIA	AA	Ⅲ	America	PHX	HP

Ⅰ	America	BOS	US	Ⅱ	America	YYZ	AC	Ⅲ	America	DTW	NW
Ⅰ	America	FLL	CO	Ⅱ	America	SEA	AS	Ⅲ	America	MSP	NW
Ⅰ	America	YUL	AC	Ⅱ	America	MEX	MX	Ⅲ	America	CLT	US
Ⅰ	America	YYC	AC	Ⅱ	America	IAD	UA	Ⅲ	Europe	CDG	AF
Ⅰ	Europe	LGW	BA	Ⅱ	America	YVR	AC	Ⅲ	Europe	FRA	LH
Ⅰ	Europe	BCN	IB	Ⅱ	America	SJU	AA	Ⅲ	Europe	AMS	KL
Ⅰ	Europe	ORY	AF	Ⅱ	Europe	LHR	BA	Ⅲ	Europe	MUC	LH
Ⅰ	Europe	DUB	EI	Ⅱ	Europe	MAD	IB				

5. CONCLUSIONS

An appropriate definition of schedule coordination would be important in the identification of the degree of hub operations by airlines. The hub operation can be expressed as the convenience of transfers in terms of schedule coordination, which is generally proportional to the size of airline networks. However, relatively dense connectivity can be achieved through fine schedule coordination, even though not many aircrafts are employed. Doganis and Dennis (1989) measured the number of viable connections as an indicator of connectivity and defined the connectivity ratio as actual connections divided by expected viable connections in purely random arrival and departure timetable situations). Burghouwt and De Wit (2005) proposed the weighted indirect connection, in which the quality is related to the hub transfer time and the indirect in-flight time. Danesi (2006) defined weighted connectivity by including the temporal and spatial matrices to improve the concept of connectivity.

This paper proposes a new index, the Continuous Connectivity Index (CCI), to improve the indices of previous studies and to incorporate a better the concept of connectivity. This index is expected to identify the degree of timetable coordination to the highest degree. The CCI is composed of three parts: the Temporal Connectivity Index (TCI), the Spatial Connectivity Index (SCI), and the Relative Intensity Index (RII). The TCI is calculated by applying a continuous linear function from one to zero as the range of connection time between the MCT and the MACT. The TCI has three features: eight in-flight hours as a criterion in the determination of the MCT and the MACT, the extended MACT for long-haul connections, and a continuous linear function in the TCI. The SCI implies the de-routing effect, which is expressed by the ratio of the total indirect flight distance (or in-flight time) via a hub to the direct flight distance. The continuous linear function of the SCI varies from one to zero as the de-routing ratio changes from 1 to 1.6. The RII is a new index that indicates the relative attractiveness of the indirect route compared with the direct route. The RII has continuous values from one to zero as direct flight frequency varies from zero to eight times a day.

This paper investigates casual relationships between the CCI and the number of transfer passengers in 49 transfer routes at nine airports. The results showed that the CCI had much higher coefficients of determination than Doganis' Index and Danesi's Index under the 95% confidence condition; that is, the CCI identified the degree of hub operations by airlines better than the indices proposed by previous studies. Furthermore, the regression analysis of 62 airports showed that the CCI had the strongest casual relationship with the number of transfer passengers. The coefficient of determination of the CCI was 0.94, suggesting that connectivity is a major factor determining changes in transfer passengers. In addition, the logarithm of the CCI was proportional to the transfer rate. The coefficient of determination by the regression analysis with the CCI and the transfer rate was 0.70. The results verify that connectivity has a large effect on transfer rates, as well as on the number of transfer passengers, and that the logarithm of the connectivity index is proportional to the transfer rate. Assuming that airport positions would change from bottom left to top right along the linear graph (with the logarithm of CCI and transfer rate) if airports were to grow, 62 airports were segmented into the Spoke, Hub, and Mega Hub groups. The classification framework consisted of the logarithm of the CCI (implying both the quality and quantity of the supply side) and the transfer rate (representing the market power of the demand side). The 62 airports were successfully segmented, which should be helpful in achieving a deeper understanding of the structure of airport development.

Appendix A. Airports and Dominant Home Carriers

No.	AIRPORT	CODE	DOMINANT HOME CARRIER	CODE	CITY/COUNTRY	REGION
1	INCHEON	ICN	Korean Air	KE	SEOUL, KR	Asia
2	NARITA	NRT	Japan Airlines	JL	TOKYO, JP	Asia
3	FUKUOKA	FUK	All Nippon Airways	NH	FUKUOKA, JP	Asia
4	KANSAI	KIX	All Nippon Airways	NH	OSAKA, JP	Asia
5	NAGOYA	NGO	All Nippon Airways	NH	NAGOYA, JP	Asia
6	BEIGING	PEK	Air China	CA	BEIJING, CN	Asia
7	HONG KONG	HKG	Cathay Pacific	CX	HONG KONG, CN	Asia
8	GUANGZHOU	CAN	China Southern Airlines	CZ	GUANGZHOU, CN	Asia
9	SHANGHAI PUDONG	PVG	China Eastern Airlines	MU	SHANGHAI, CN	Asia
10	SINGAPORE CHANGI	SIN	Singapore Airlines	SQ	SINGAPORE, SG	Asia
11	JAKARTA	CGK	Garuda Indonesia	GA	JAKARTA, ID	Asia
12	KUALA LUMPUR	KUL	Malaysia Airlines	MH	KUALA LUMPUR, MY	Asia
13	TAIPEI	TPE	China Airlines	CI	TAIPEI, TW	Asia
14	MANILA	MNL	Philippine Airlines	PR	MANILA, PH	Asia
15	ATLANTA HARTSFIELD	ATL	Delta Air Lines	DL	ATLANTA, GA	America
16	CHICAGO O'HARE	ORD	American Airlines	AA	CHICAGO, IL	America
17	LOS ANGELES	LAX	United Airlines	UA	LOS ANGELES, CA	America
18	Dallas/Fort Worth	DFW	American Airlines	AA	DALLAS/FT WORTH, TX	America
19	DENVER	DEN	United Airlines	UA	DENVER, CO	America

20	JOHN F KENNEDY	JFK	JetBlue Airways	B6	NEW YORK, NY	America
21	LAS VEGAS	LAS	Southwest Airlines	WN	LAS VEGAS, NV	America
22	HOUSTON	IAH	Continental Airlines	CO	HOUSTON, TX	America
23	PHOENIX	PHX	America West Airlines	HP	PHOENIX, AZ	America
24	ORLANDO	MCO	Delta Air Lines	DL	ORLANDO, FL	America
25	NEWYORK	EWR	Continental Airlines	CO	NEWARK, NJ	America
26	DETROIT METROPOLITAN	DTW	Northwest Airlines	NW	DETROIT, MI	America
27	SAN FRANSCISCO	SFO	United Airlines	UA	SAN FRANCISCO, CA	America
28	MINNEAPOLIS	MSP	Northwest Airlines	NW	MINNEAPOLIS/ST PAUL, MN	America
29	MIAMI INT'L	MIA	American Airlines	AA	MIAMI, FL	America
30	CHARLOTTE	CLT	US Airways	US	CHARLOTTE, NC	America
31	TORONTO	YYZ	Air Canada	AC	TORONTO, ON, CA	America
32	SEATTLE	SEA	Alaska Airlines, Inc.	AS	SEATTLE/TACOMA, WA	America
33	BOSTON LOGAN	BOS	US Airways	US	BOSTON, MA	America
34	MEXICO JUAREZ	MEX	Mexicana de Aviación	MX	MEXICO CITY, MX	America
35	WASHINGTON DULLES	IAD	United Airlines	UA	WASHINGTON, DC	America
36	FORT LAUDERDALE	FLL	Continental Airlines	CO	FORT LAUDERDALE, FL	America
37	VANCOUVER	YVR	Air Canada	AC	VANCOUVER, BC, CA	America
38	MONTREAL	YUL	Air Canada	AC	MONTREAL, QC, CA	America
39	CALGARY	YYC	Air Canada	AC	CALGARY, AB, CA	America
40	SAN JUAN	SJU	American Airlines	AA	SAN JUAN, PR	America
41	LONDON HEATHROW	LHR	British Airways	BA	LONDON, GB	Europe

Appendix A. (Continued)

No.	AIRPORT	CODE	DOMINANT HOME CARRIER	CODE	CITY/COUNTRY	REGION
42	CHARLES DE GAULLE	CDG	Air France	AF	PARIS, FR	Europe
43	FRANKFURT	FRA	Lufthansa	LH	FRANKFURT, DE	Europe
44	MADRID	MAD	Iberia Airlines	IB	MADRID, ES	Europe
45	AMSTERDAM SCHIPHOL	AMS	KLM Royal Dutch Airlines	KL	AMSTERDAM, NL	Europe
46	LONDON GATWICK	LGW	British Airways	BA	LONDON, GB	Europe
47	MUNCHEN	MUC	Lufthansa	LH	MUNICH, DE	Europe
48	ROME	FCO	Alitalia	AZ	ROME, IT	Europe
49	BARCELONA	BCN	Iberia Airlines	IB	BARCELONA, ES	Europe
50	PARIS ORLY	ORY	Air France	AF	PARIS, FR	Europe
51	MILAN MALPENSA	MXP	Alitalia	AZ	MILAN, IT	Europe
52	DUBLIN	DUB	Aer Lingus	EI	DUBLIN, IE	Europe
53	COPENHAGEN	CPH	Scandinavian Airlines	SK	COPENHAGEN, DK	Europe
54	ZURICH	ZRH	Swiss International Air Lines	LX	ZURICH, CH	Europe
55	STOCKHOLM ARLANDA	ARN	Scandinavian Airlines	SK	STOCKHOLM, SE	Europe
56	BRUSSELS NATIONAL	BRU	Brussels Airlines	SN	BRUSSELS, BE	Europe
57	DUSELDORFT	DUS	Lufthansa	LH	DUSSELDORF, DE	Europe
58	ATHENS HELLINIKON	ATH	Olympic Airlines	OA	ATHENS, GR	Europe
59	LISBON	LIS	TAP Portugal	TP	LISBON, PT	Europe

60	HELSINKI	HEL	Finnair	AY	HELSINKI, FI	Europe
61	HAMBURG	HAM	Lufthansa	LH	HAMBURG, DE	Europe
62	PRAGUE	PRG	Czech Airlines	OK	PRAGUE, CZ	Europe

Appendix B. Divisions of Routes by Continent

Number	Asia	Europe	America
1	Japan	Western Europe	Pacific USA
2	China	Eastern Europe	Mountain USA
3	Southeast Asia	Southern Europe	Central USA
4	America	Northern Europe	Eastern USA
5	Europe	America	Other America
6	Oceania	Asia	Europe
7	Others	Others	Others

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