Rethinking Airport Improvement: Analysis of Domestic Airline Service to U.S. Metroplex Airports

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Abstract

The airline transportation system is a significant component of the U.S. economy providing rapid, safe, cost-effective transportation services. Regional airport authorities play a significant role in shaping the airline transportation system. Operating as "public utilities," airport authorities seek to serve the interests of the businesses and residents of their region by working to ensure cost-effective connectivity in support of the region's economy.

This paper presents the results of an analysis of the degree to which regional authorities have ensured maximization of airline service for their regional economies. A Data Envelopment Analysis benchmark was used to determine "best-in-class" in terms of frequency and connectivity based on the size of the regional economy and population. The results indicate that 20 of the top 29 metropolitan areas have high levels of service. The analysis identified nine regions that exhibit gaps in their level of service relative to the size of their population and regional economy. In two of the nine regions there is adequate connectivity, but insufficient frequency. In two of the nine regions there is insufficient connectivity. In five of the nine regions there is both insufficient connectivity and frequency of service. The implications of these results for the purpose of strategic planning on a national scale, airport improvement funding, and regional planning are discussed.

1 Introduction

The U.S. airline transportation system is a significant component of the U.S. economy. This system provides rapid, safe, cost-effective transportation of passengers and light-weight cargo that cannot be substituted by other modes of transportation over the large geographic region of the United States.

Major airports in the United States, operating under profit-neutral financial regulations (Carney & Mew 2003) (p. 230), as "public utilities," play a significant role in shaping the national airline transportation system. In service to multiple regional stakeholders (Schaar & Sherry 2010), airport authorities incentivize the type and quantity of airline transportation service provided (Belobaba et al. 2009) (pp. 168-175), (Graham 2003) (p. 189).

This paper presents the results of an analysis of the degree to which regional authorities have ensured maximization of airline service for their regional economies. A Data Envelopment Analysis (DEA) benchmark was used to determine “best-in-class” in terms of frequency and connectivity based on the size of the regional economy and population.

The results are summarized as follows:

- 20 of the top 29 metropolitan areas have high levels of service
- The analysis identified nine regions that exhibit gaps in their level of service relative to the size of their population and regional economy
- Two of the nine regions have adequate connectivity, but insufficient frequency
- Two of the nine regions have insufficient connectivity
- Five of the nine regions have both insufficient connectivity and frequency of service.

These results have significant implications for strategic planning on a national scale, airport improvement funding, and regional planning. Whereas flight delays are indicative of insufficient capacity, the more important question is if the existing airport resources are being used most efficiently.

This paper is organized as follows: Section 2 reviews the airport stakeholders and some of their goals. Section 3 discusses the study methodology, including the means for selecting performance parameters and the benchmarking model used. Section 4 reviews the study results. Section 5 presents the conclusions and future work.

2 The Airport’s Stakeholders and Their Goals

With major airports in the United States operating under profit-neutral financial regulations (Carney & Mew 2003) (p. 230), they are not subject to goals of maximizing profits but instead must meet the goals of its multiple stakeholders.

An analysis of the airport’s stakeholders (Schaar & Sherry 2010) described the stakeholders and their interrelationships by the diagram shown in Figure 1, and assessed their goals for the airport.

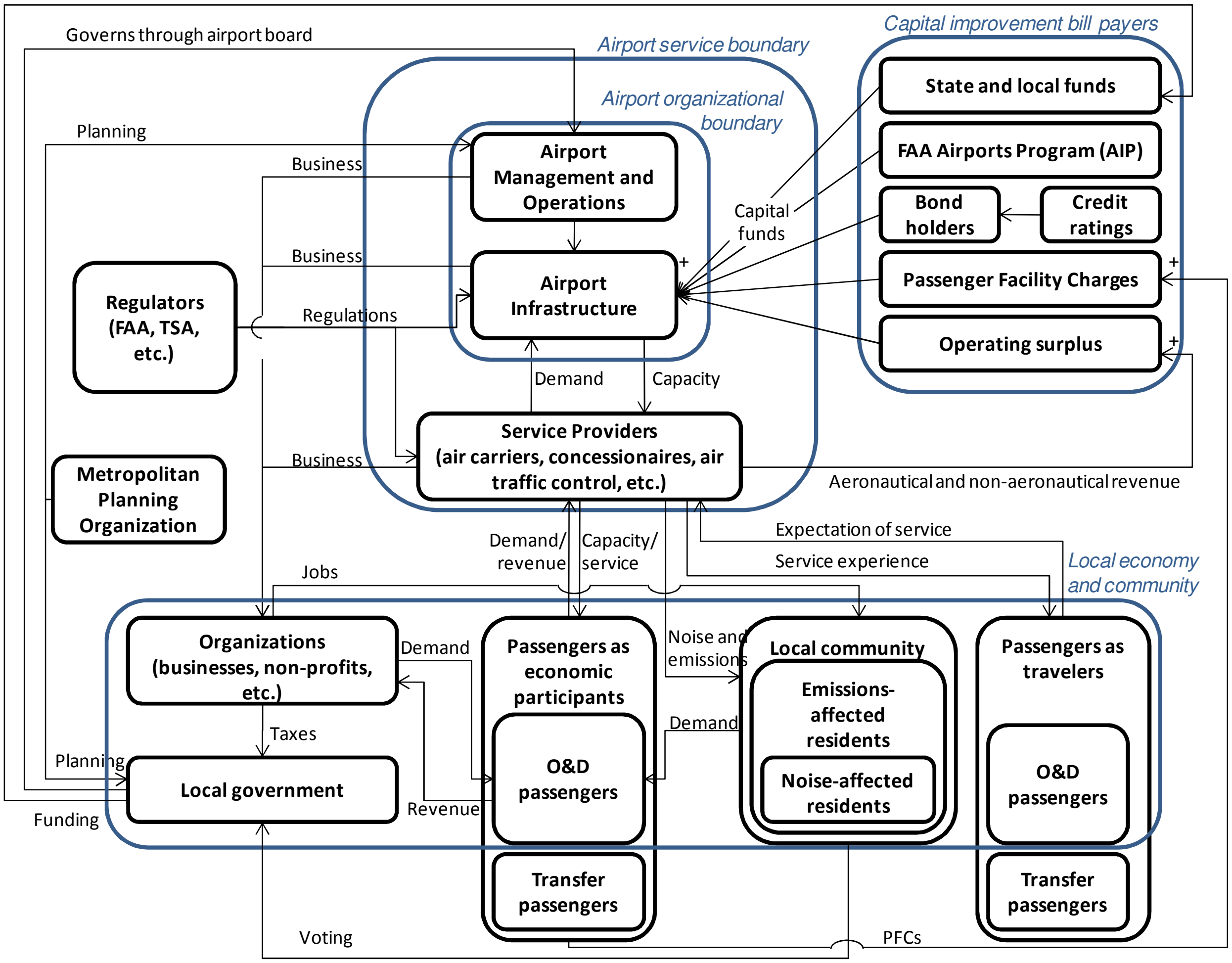

Figure 1 – The financial, customer, and other relationships between airport stakeholders (Schaar & Sherry 2010)

The analysis found that the stakeholders' goals for the airport were based in part on factors wholly within the control of airport management (the "airport organizational boundary" in the figure), but also on factors that were only partly within the control of management, or entirely outside management's control.

The goal of "maximizing the number of destinations served and frequency of those services" emerged from the analysis as common to stakeholder groups such as local businesses, residents, the local government, and the airport organization itself. It is an example of a goal that is not fully within the control of airport management since airlines determine where to add or reduce service.

The goal reflects a "symbiotic" relationship between a region's economy and the local air service, where air service stimulates economic growth (Button & Stough 2000) and growth in a region's economy drives increased demand for air travel.

The stakeholders who are concerned with this goal have a need for evaluating the degree to which it is being achieved in US metropolitan areas. Local governments and airport authorities must understand if their region is currently well served by airlines or if added effort is necessary to attract additional air service. If a shortfall exists in the degree to which the goal is being met, they must gain insight about what is causing the performance gap. Conversely, a region's residents and business community must understand if their needs are being met by the airport(s) in their region, or if they should demand more from their local government and airport authority in terms of attracting new air service to their community.

A comparative benchmark is a means to evaluate this goal. The benchmark allows for a normalized comparison across major US metropolitan areas and gives stakeholders an understanding of which areas are not currently well served and can also provide insight into the causes of any performance gaps.

3 Methodology

This section discusses the study methodology. It provides the motivation for the selection of performance parameters and discusses the choice of model for benchmarking. It also describes the data sources and pre-processing as well as the method used for computing benchmark scores. Finally, it presents the method for sensitivity analysis of the results.

3.1 Scope of Analysis

The study reviews the levels of air service in metropolitan areas. Some metropolitan areas include multiple airports (e.g. the Boston metropolitan area, with Boston-Logan, Providence, and Manchester airports) and other areas are served by a single airport (e.g. Atlanta). Table 1 shows the airports included in the study, organized by metropolitan area. A full description of the methodology for determining metropolitan areas and mapping airports to those areas is provided in section 3.4.

Metropolitan Area	Airport Name	Airport Code
Atlanta	Hartsfield - Jackson Atlanta International	ATL
Boston	General Edward Lawrence Logan International	BOS
	Manchester	MHT
	Theodore Francis Green State	PVD
Charlotte	Charlotte/Douglas International	CLT
Chicago	Chicago Midway International	MDW
	Chicago O'Hare International	ORD
Cincinnati	Cincinnati/Northern Kentucky International	CVG
	James M Cox Dayton International	DAY
Cleveland	Cleveland-Hopkins International	CLE
Dallas	Dallas Love Field	DAL
	Dallas/Fort Worth International	DFW
Denver	Denver International	DEN
Detroit	Detroit Metropolitan Wayne County	DTW
Honolulu	Honolulu International	HNL
Houston	William P Hobby	HOU
	George Bush Intercontinental/Houston	IAH
Las Vegas	McCarran International	LAS

Metropolitan Area	Airport Name	Airport Code
Los Angeles	Los Angeles International	LAX
	Ontario International	ONT
	Bob Hope	BUR
	John Wayne Airport-Orange County	SNA
	Long Beach /Daugherty Field/	LGB
Memphis	Memphis International	MEM
Miami	Fort Lauderdale/Hollywood International	FLL
	Miami International	MIA
	Palm Beach International	PBI
Minneapolis	Minneapolis-St Paul International/Wold-Chamberlain	MSP
New York	John F Kennedy International	JFK
	La Guardia	LGA
	Newark Liberty International	EWR
	Long Island MacArthur	ISP
Orlando	Orlando International	MCO
Philadelphia	Philadelphia International	PHL
Phoenix	Phoenix Sky Harbor International	PHX
Pittsburgh	Pittsburgh International	PIT
Portland	Portland International	PDX
Salt Lake City	Salt Lake City International	SLC
San Diego	San Diego International	SAN
San Francisco	San Francisco International	SFO
	Norman Y. Mineta San Jose International	SJC
	Metropolitan Oakland International	OAK
Seattle	Seattle-Tacoma International	SEA
St. Louis	Lambert-St Louis International	STL
Tampa	Tampa International	TPA
Washington-Baltimore	Ronald Reagan Washington National	DCA
	Washington Dulles International	IAD
	Baltimore/Washington International Thurgood Marshall	BWI

Table 1 - Airports included in study

3.2 Selection of Model Parameters

Section 2 described one of the airport's goals as being to "maximize the number of destinations served and frequency of those services". To conduct a benchmark of the level to which this goal is achieved in each metropolitan area, the goal is translated into performance parameters that can be measured.

3.2.1 Measuring the Level of Air Service

The goal includes maximizing both the number of destinations served, as well as the frequency of those services. Two performance metrics are proposed in order to gauge the level to which this goal is achieved:

The first measure is the number of non-hub destinations served nonstop from any airport in the metropolitan area. This measure maps directly to the goal. Destinations which were served only on an occasional basis should not be considered and a lower bound of service at least once per week is imposed.

The second measure is the average daily frequency of service to the top domestic hubs (the definition of top domestic hubs is treated in section 3.4). This measure addresses the goal in two ways:

- It gives an indication of the level of frequency of service across a set of key routes
- It is a measure of the level of ease with which a large number of destinations can be reached through a single connection

These two measures reflect the two factors that impact total trip time, as discussed by (Belobaba et al. 2009) (pp. 58-59). Total trip time involves both the time on board the aircraft as well as "schedule displacement," with the latter being the amount of time that passes between a passenger's desired departure time and the time when a flight is available. The number of destinations served nonstop will contribute toward minimizing the time on board the aircraft, and a high frequency of flights will minimize the schedule displacement.

3.2.2 Normalizing the Level of Air Service

Demand for air services from a region's individual residents and businesses. Although some airports' passenger traffic is made up more heavily of connecting traffic and other airports' traffic to a greater degree consists of origin and destination (O&D) passengers, the number of individuals that reside in the region and the level of business activity are key drivers of the level of demand for air service, as shown in Figure 2 and Figure 3.

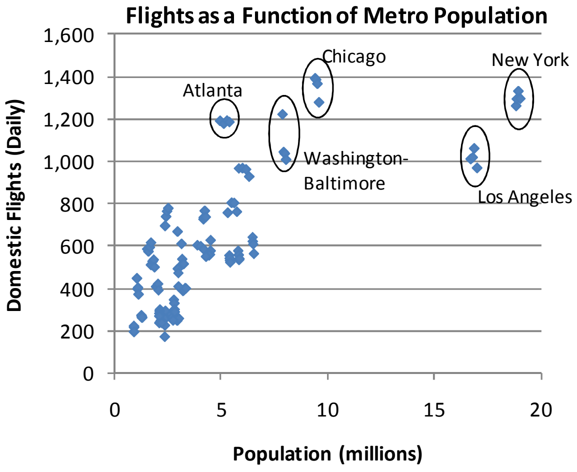

Figure 2 - Relationship between metropolitan area population and the number of domestic flights for the metro areas in Table 1, 2005-2008

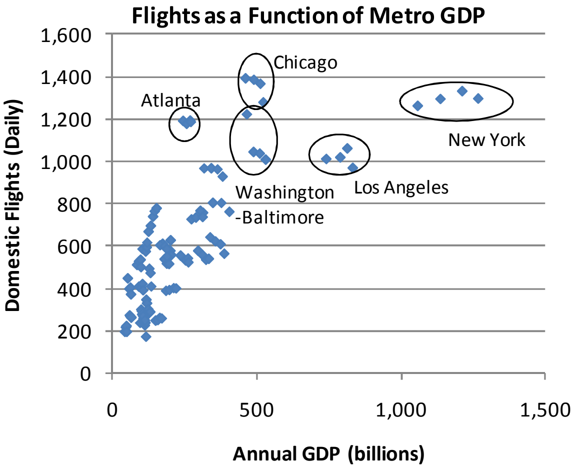

Figure 3 – Relationship between metropolitan area GDP and the number of domestic flights for the metro areas in Table 1, 2005-2008

The relationship between the population and the regional GDP was tested and showed a very high degree of correlation, with a Pearson coefficient of 0.979. This correlation indicates that as the population goes up, so does the regional GDP, and vice versa. The relationship between the two parameters can be expressed as the GDP per capita, where the regional GDP is divided by the population. In spite of the high degree of correlation between the two parameters, a range of values for the GDP per capita exist between different metropolitan areas, as shown in Figure 4.

To account for the impact of both population and GDP on the level of flights in metropolitan areas, and to address the goals of both the region's population as well as its businesses, the benchmark data for the levels of air service should be normalized to account for the region's population and its regional GDP.

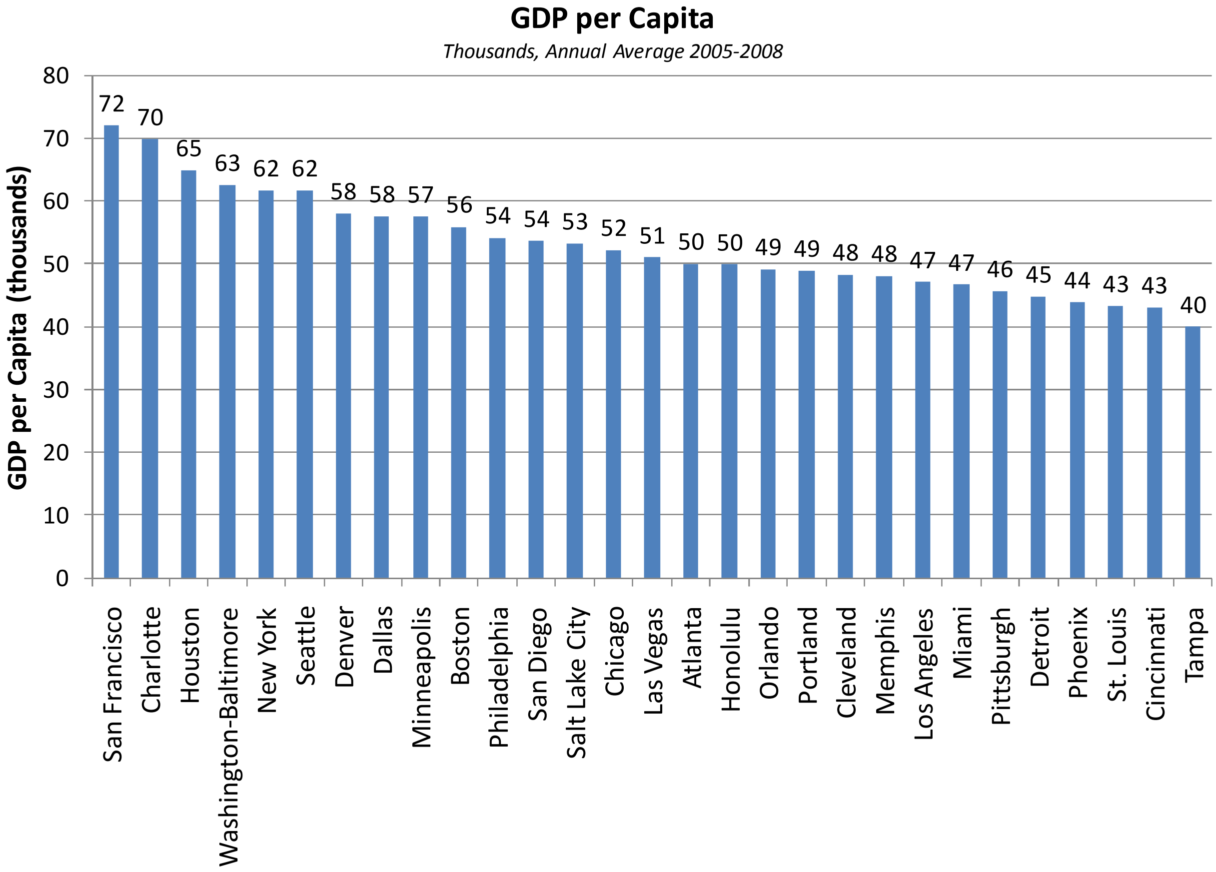

Figure 4 – Annual GDP per capita (thousands of US$), 2005-2008

3.2.3 Summary of Model Parameters

The measures of the level of air service and the parameters used to normalize them are combined in this conceptual ratio:

(destinations served nonstop, frequency of service to hubs) : (population, GDP)

The metropolitan areas with the highest number of destinations served and the highest frequency in relation to their population and GDP will be considered to have the highest relative level of air service.

3.3 Choice of Benchmark Model

The parameters for the model are the number of nonstop non-hub destinations served and the average daily frequency of service to the top domestic hubs, normalized by regional population and GDP. This model can conceptually be expressed as the ratio (destinations served, frequency) : (population, GDP). The units of measure for these metrics are airports, daily flights, people, and US$, respectively. Combining these metrics into a comparative benchmark is a case where the analysis combines multiple parameters of different units, and where the production or utility function is unknown. In this scenario, Data Envelopment Analysis (DEA) is an appropriate method for calculating the composite benchmark scores (Schaar et al. 2010).

DEA is a non-parametric technique which allows for comparison of the efficiency with which Decision-Making Units (DMUs) convert inputs (resources) into desirable outputs. As it is a non-parametric technique, the production function for the domain being modeled does not have to be known. In the present study, the inputs are the population and GDP and the desirable outputs to be maximized are the number of destinations served and the frequency of service to the top domestic hubs.

DEA was introduced by Cooper, Charnes, and Rhodes in 1978 (Charnes et al. 1978). The algorithm looks to identify the DMU(s) with the best inherent efficiency in converting inputs $x_1, x_2, \ldots, x_n$ into outputs $y_1, y_2, \ldots, y_m$. All other DMUs are then ranked relative to the most efficient DMU(s).

Model for DMU a:

$$\max h_a = \frac{\sum_r u_r y_{ra}}{\sum_i v_i x_{ia}}$$

Where u_r and v_i are weights applied to outputs y_{rj} and inputs x_{ij}

Subject to

$$\frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \leq 1 \quad \text{for each unit } j$$

$$u_r, v_i \geq 0$$

The problem is converted to a linear problem by setting the denominator in the objective function and the constraints = 1 in a new, separate constraint. The problem is then translated to its dual for improved solution efficiency:

$$\min(\theta_a, \lambda) = \theta_a$$

where λ is a vector $\lambda_1 \ldots \lambda_n$ and θ_a is a scalar.

Subject to

$$\theta_a x_a - X\lambda \geq 0$$
$$Y\lambda \geq y_a$$
$$\lambda \geq 0$$

The problem is solved once for each DMU to obtain the weights that maximize its efficiency score. Computing optimal weights for each DMU reflects the underlying assumption that the management of the DMU can make tradeoff choices about which parameters to focus on at the expense of other parameters. The parameters on which focus has been placed in order to achieve stronger performance can then receive a proportionally higher weight than other parameters.

The DEA model computes an overall score for each DMU, representing the efficiency with which that DMU performs relative to the other DMUs in the analysis. Figure 5 shows an example of results from an output-oriented DEA analysis with two outputs and a single input (in this simplified example, it is assumed that all DMUs have the same value for the input). In this example, DMUs B, C, D, E, and F are all located on the frontier which means they are at full efficiency. DMU A is located inside the frontier, meaning that it is inefficient. DMU A's efficiency score is computed as:

$$\frac{OA_p}{OA}$$

where A_p represents the target on the frontier for A. In the output-oriented analysis, all inefficient DMUs will have scores greater than 1.

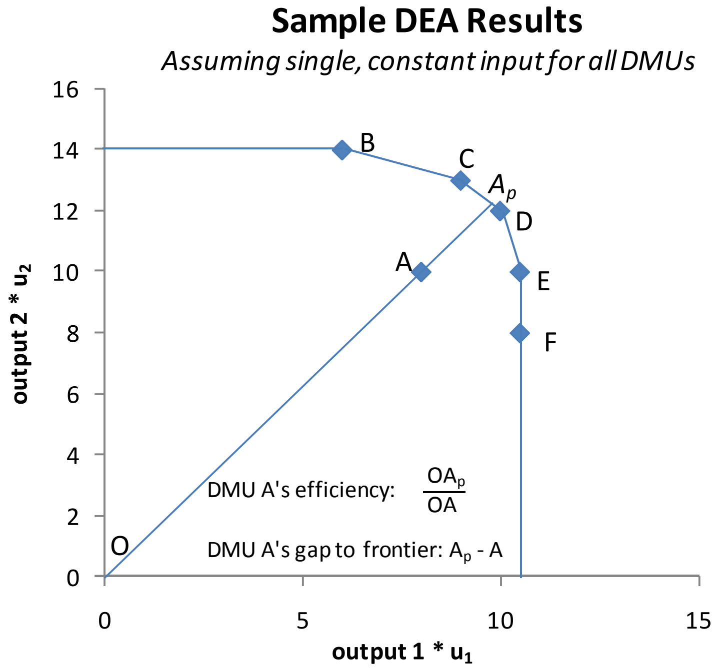

Figure 5 - Sample results of output-oriented DEA analysis. All DMUs on the frontier are fully efficient, while DMU A is inefficient.

The model outputs also include the shortest distance from the efficiency frontier for an inefficient DMU, which represents the gap that must be closed for that DMU to achieve full efficiency. In Figure 5, this gap is represented by $A_p - A$.

A variety of different versions of DEA have been developed and past studies of airport performance have applied different models with limited motivation for why the model was selected and to address this deficiency, a framework and heuristics for selection of a DEA model for airport benchmarking have been developed (Schaar et al. 2010). The framework is presented in Figure 6 and the associated heuristics are summarized in Figure 7.

	Scalarizing function			Technology			
	Aggregation	**Weights**	**Orientation**	**Returns to scale**	**FDH**	**Integrality**	**Timespan**
Possible choices	• ε-maximin • Maximin • Additive	• Simple • Range-adjusted • Specific	• Yes • No	• Constant • Variable • Non-increasing • Non-decreasing • Individual-bounded	• Yes • No	• Full • Partial • None	• Single time period • Multiple time periods with Malmquist • Multiple time periods without Malmquist

Note that not all combinations are relevant (e.g. CRS models always have no orientation)

Figure 6 - Structure of a DEA model framework for airport benchmarking (Schaar et al. 2010)

Scalarizing function			Technology			
Aggregation	**Weights**	**Orientation**	**Returns to scale**	**FDH**	**Integrality**	**Timespan**
Use either ε-maximin or additive. If a motivation for why the proportional mix of inputs or outputs is irrelevant, then use additive. Otherwise, use ε-maximin.	Use specific weights unless evidence exists that range-adjusted weights are more appropriate.	If the model requires orientation, then choose orientation to reflect which parameters are controllable by management.	If modeling some version of labor and capital resources as inputs and passengers and aircraft movements as outputs, then use VRS. Otherwise, study the parameters to determine if VRS or CRS exist.	Unless compelling evidence that study results will be better accepted if only observed values are used for peer comparisons, do not use FDH.	Use integrality constraints for inputs and outputs with low magnitudes, such as runways.	If modeling some version of labor and capital resources as inputs and passengers and aircraft movements as outputs over multiple time periods, then use a Malmquist index. For other domains, review if technology changes over time have occurred.

Figure 7 - Airport DEA framework and heuristics (Schaar et al. 2010)

The results of the application of the framework and heuristics to determine a model for this analysis are now presented.

- **Aggregation**: The heuristics specify that either an ε-maximin function or an additive function should be used. The additive function should be used only if a motivation exists for why the current proportional mix of inputs or outputs (depending on the orientation chosen) is irrelevant and can be changed. Otherwise, the ε-maximin function should be chosen. In this study, no evidence that the proportional mix of input or outputs can be changed between different metropolitan areas. As a result, the ε-maximin function is chosen.
- **Weights**: Since tradeoffs between the two outputs will be different between metropolitan areas, specific weights should be used according to the heuristics.
- **Orientation**: The heuristics state that the model orientation should be determined based on which factors are considered the most controllable by management. In this analysis, the population and GDP inputs cannot be controlled by airport management, but although they are not directly controllable, the output measures of destinations served and frequency can be influenced by airport management and local governments. This influence can come through providing air carriers with market research data as well as with financial incentives and marketing support for providing service to the airport (Graham 2003) (p. 189). This determines this analysis as output-oriented.
- **Returns to scale**: The framework specifies a choice between constant returns to scale (CRS) and variable returns to scale (VRS). The outputs in this model can both be assumed to reflect VRS: First, the number of new destinations which are feasible to serve decreases as the number of already served destinations increases, since only a finite number of metropolitan areas exist where the local market provides sufficient demand to warrant nonstop service. Second, the potential for increased frequency of nonstop service to hubs declines as the level of existing frequency and airport congestion increases; in a hypothetical case, rather than providing service on a market every 5 minutes with a 50-seat aircraft, providing service every 10 minutes with a 100-seat aircraft would become necessary as airport capacity runs out (as utilization of airport capacity approaches its physical limit, policy/regulation changes may be necessary to incent airlines to fly larger aircraft (Donohue et al. 2008) (pp. 115-116)).
- **FDH**: The Free Disposal Hull should be applied only if some reason exists why comparison only to observed combinations of inputs and outputs should be made, but no such reason exists in this analysis.
- **Integrality**: Integrality constraints should be applied in cases where input or outputs are indivisible into fractions and of low magnitude, and if significant errors in the results would be introduced if these inputs or outputs were assumed to have decimal values. The parameter with integrality constraints and the lowest magnitude in this study is the number of non-hub destinations served nonstop, but with a median value of 88 for the years studied, this parameter’s magnitude remains sufficiently high that no integrality constraints are necessary in the model.

- **Timespan**: If any key technology changes have occurred during the timespan being studied that would impact the ability of DMUs to achieve strong performance, then a Malmquist index method should be used. If not, the performance for each year can simply be analyzed independently. In the present analysis, technology changes would involve the introduction of something which made it feasible for air carriers to serve more destinations than before, or something which allowed for increased frequency of service. From a technology point of view, this would involve the introduction of new aircraft types with significantly different performance characteristics in terms of for instance fuel consumption, crew requirements, or number of seats. No new aircraft models for domestic use entered into service during the 2005-2008 period from Boeing (The Boeing Company 2010), Airbus[1] (Airbus S.A.S. 2010), Bombardier (Bombardier 2010), or Embraer (Embraer 2010). As a result of no major changes occurring in this time period, no Malmquist Index calculation is necessary.

Figure 8 summarizes the modeling assumptions for this analysis.

Scalarizing function			**Technology**			
Aggregation	**Weights**	**Orientation**	**Returns to scale**	**FDH**	**Integrality**	**Timespan**
ε-maximin	Specific weights	Output oriented	VRS	Not use of FDH	No integrality constraints	No use of Malmquist index; simply one analysis per year

Figure 8 - DEA model parameter choices

These modeling assumptions are represented in the output-oriented BCC (Banker et al. 1984) algorithm with minimum weight constraints, which was used in this analysis. This model has the following dual problem formulation:

$$\max(\phi_a,\lambda) = \phi_a + \varepsilon(s^+ + s^-)$$

Subject to

$$\begin{aligned} &\phi_a y_a - Y\lambda + s^+ = 0 \\ &X\lambda + s^- = x_a \\ &e\lambda = 1 \\ &\lambda \geq 0, s^+ \geq 0, s^- \geq 0 \end{aligned}$$

The DEA scores were computed by implementing the BCC algorithm in Matlab, using an interface to the CPLEX optimization engine as the solver for the linear program. For the implementation, the infinitesimal constant ε was set to 1.0 * E-6. A further discussion of the choice of this value is available in section 4.5.1.

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[1] The Airbus A380 was in fact first delivered in 2007, but this aircraft is not used for US domestic service

3.4 Data Collection and Pre-Processing

This section describes the means of obtaining and preparing the benchmark data for the analysis.

3.4.1 Determination of Metro Areas

The scope of the analysis was to include the metropolitan areas which have at least one of the OEP-35 airports listed in Table 2, and expand the study to include any other commercial airports that also service those metropolitan areas from within a given distance. In a second step, if any of the non-OEP-35 airports were located in a different nearby, second metropolitan area, then that second metropolitan area was merged with the first in order to capture the region's full population and GDP.

The definitions of "metropolitan areas" follow those of the US government's Office of Management and Budget (OMB). The OMB defines "Metropolitan Statistical Areas" (MSAs) based on data from the Census Bureau (Office of Management and Budget 2010).

Airport Name	Airport Code
Hartsfield - Jackson Atlanta International	ATL
General Edward Lawrence Logan International	BOS
Baltimore/Washington International Thurgood Marshall	BWI
Cleveland-Hopkins International	CLE
Charlotte/Douglas International	CLT
Cincinnati/Northern Kentucky International	CVG
Ronald Reagan Washington National	DCA
Denver International	DEN
Dallas/Fort Worth International	DFW
Detroit Metropolitan Wayne County	DTW
Newark Liberty International	EWR
Fort Lauderdale/Hollywood International	FLL
Honolulu International	HNL
Washington Dulles International	IAD
George Bush Intercontinental/Houston	IAH
John F Kennedy International	JFK
McCarran International	LAS
Los Angeles International	LAX
La Guardia	LGA
Orlando International	MCO
Chicago Midway International	MDW
Memphis International	MEM
Miami International	MIA
Minneapolis-St Paul International/Wold-Chamberlain	MSP
Chicago O'Hare International	ORD
Portland International	PDX
Philadelphia International	PHL
Phoenix Sky Harbor International	PHX
Pittsburgh International	PIT
San Diego International	SAN
Seattle-Tacoma International	SEA
San Francisco International	SFO
Salt Lake City International	SLC
Lambert-St Louis International	STL
Tampa International	TPA

Table 2 - OEP-35 airports (FAA 2009)

In their discussion of Multi-Airport Systems, (Neufville & Odoni 2003) (p. 133) propose that studies only include airports that serve at least 1 million passengers per year. That limit is used in this analysis and only the 55 non-OEP-35 airports which met that criterion for at least one year between 2005 and 2008 were included for consideration.

A distance limit of 70 road miles from the city center of the main metropolitan area was used to determine which among the non-OEP-35 airports to include in the study, resulting in a final list of 13 additional airports, as shown in Table 3.

Airport Name	Airport Code
Bob Hope	BUR
Dallas Love Field	DAL
James M Cox Dayton International	DAY
William P Hobby	HOU
Long Island MacArthur	ISP
Long Beach /Daugherty Field/	LGB
Manchester	MHT
Metropolitan Oakland International	OAK
Ontario International	ONT
Palm Beach International	PBI
Theodore Francis Green State	PVD
Norman Y. Mineta San Jose International	SJC
John Wayne Airport-Orange County	SNA

Table 3 - Non-OEP-35 airports added to the study

With the addition of the 13 airports to the metropolitan areas, the locations of those airports which were situated in another, nearby metropolitan area were merged with the original metropolitan areas to accurately reflect the area's total population and GDP. Those areas were:

- The Manchester-Nashua, NH, MSA and the Providence-New Bedford-Fall River, RI-MA, MSA which were added to the Boston metropolitan area.
- The Dayton, OH, MSA which was added to the Cincinnati metropolitan area.
- The Riverside-San Bernardino-Ontario, CA, MSA which was added to the Los Angeles metropolitan area.
- The San Jose-Sunnyvale-Santa Clara, CA, MSA which was added to the San Francisco metropolitan area.

Finally, the Washington, DC, and Baltimore, MD, metropolitan areas were merged into one single area since the two three airports serving the two cities are all located within 61 miles of the two city centers.

3.4.2 Data Sources

Three data sources were used for the analysis:

- **GDP data**: Data on GDP by MSA was obtained from the US government's Bureau of Economic Analysis (BEA) (Bureau of Economic Analysis, U.S. Department of Commerce 2010). The BEA produces annual estimates of the GDP of each of the 366 US MSAs by computing the sum of the GDP originating in all industries in each MSA.

- **Population data**: Data on the population of each MSA was gathered from the US Census Bureau (U.S. Census Bureau 2010b). The annual MSA population is estimated by the Census Bureau based on the Census 2000 combined with a number of more recent data sources. The Census Bureau points out that because there is a lag in some of the data sources that complement the Census 2000 data, estimates for older vintages tend to be more accurate than those for more recent vintages (U.S. Census Bureau 2008).
- **Data on destinations and frequencies**: This data was prepared using the T100 database which is compiled from data collected by Office of Airline Information (OAI) at the Bureau of Transportation Statistics (BTS) (Bureau of Transportation Statistics 2010b). The T100 database is a complete census of flights by US and foreign carriers and provides data on the number of operations and passengers carried between each city pair.

3.4.3 Defining Hubs

The definition of all-points domestic hubs in the analysis was based on an initial analysis of the T100 database. The objective was to identify those airports that provide connections to the largest number of other airports. For the 2005-2008 time period, the analysis found the number of domestic airports served nonstop[2] presented in Table 4, and identified the average number of other OEP-35 airports served nonstop listed in Table 5.

Airport	Average number of domestic airports served nonstop	Rank
ATL	171	1
ORD	141	2
DFW	138	3
MSP	137	4
DEN	134	5
DTW	128	6
IAH	121	7
LAS	119	8
CVG	119	9
CLT	102	10
SLC	101	11

Table 4 - Average number of domestic airports served nonstop at least 52 times annually (source: T100 database)

Airport	Average number of OEP-35 airports served nonstop	Rank
ATL	34	1
DEN	34	1
DFW	34	1
MSP	34	1
CVG	33	5
DTW	33	5
IAH	33	5
LAS	33	5
LAX	33	5
ORD	33	5
PHX	33	5

Table 5 - Average number of OEP-35 airports served nonstop at least 52 times annually (source: T100 database)

The first four airports in Table 5 were connected to all other OEP-35 airports in each of the years from 2005 to 2008. In addition, these airports all rank among the top five airports in terms of the overall number of domestic destinations served, as shown in Table 4. The remaining top-five airport from Table 4 is ORD which, although it lacks service to one of the OEP-35 airports, ranks as the second most connected airport to other domestic airports. Based on this data, the list of hubs for this analysis is: ATL, ORD, DFW, MSP, and DEN. The impact of this definition is tested as part of the sensitivity analysis discussed in section 3.6.

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[2] Only destinations that were served at least 52 times per year were considered, to ensure that at least weekly service existed.

3.4.4 Preparing Benchmark Data

Each of the data sources required some pre-processing for use in the benchmark analysis. This section describes that pre-processing.

Both the GDP and the population data was reported separately for each MSA. Because of the merging of some areas as described in section 3.4.1, their GDP and population data were summed to provide totals for the entire metropolitan areas.

The data on the number of non-hub destinations served nonstop was computed from data using these conditions and assumptions:

- Departures were considered from the metro area as a whole rather than from individual airports. For instance, if both EWR and LGA airports in the New York region had nonstop service to MSP, this would only be counted as one nonstop destination for the New York metropolitan area.
- At least 52 flights during the year were required in order for an O&D pair to be considered to have nonstop service.

The data on the daily frequency of service to hubs was prepared using these conditions and assumptions:

- Just as for the number of non-hub destinations served, departures were considered from the metro area as a whole rather than from individual airports. However, in the example with EWR and LGA above, if each airport had service four times daily, the New York region would be counted as having a frequency of eight.
- For those airports that were hubs, only service to the four other hubs could be counted while for non-hub airports, service to the five hubs was counted. To adjust for this, the hub airports' totals were increased by the average of their service to each of the other four hub airports; in practice this amounted to a multiplication of each hub airport's total by a factor of 1.25.

3.5 Summary of Input and Output Parameters

This section provides four-year average values for each of the four input and output parameters used in the DEA analysis. Although the analysis was done separately for each of the four years, this overview provides averages for the whole period 2005-2008.

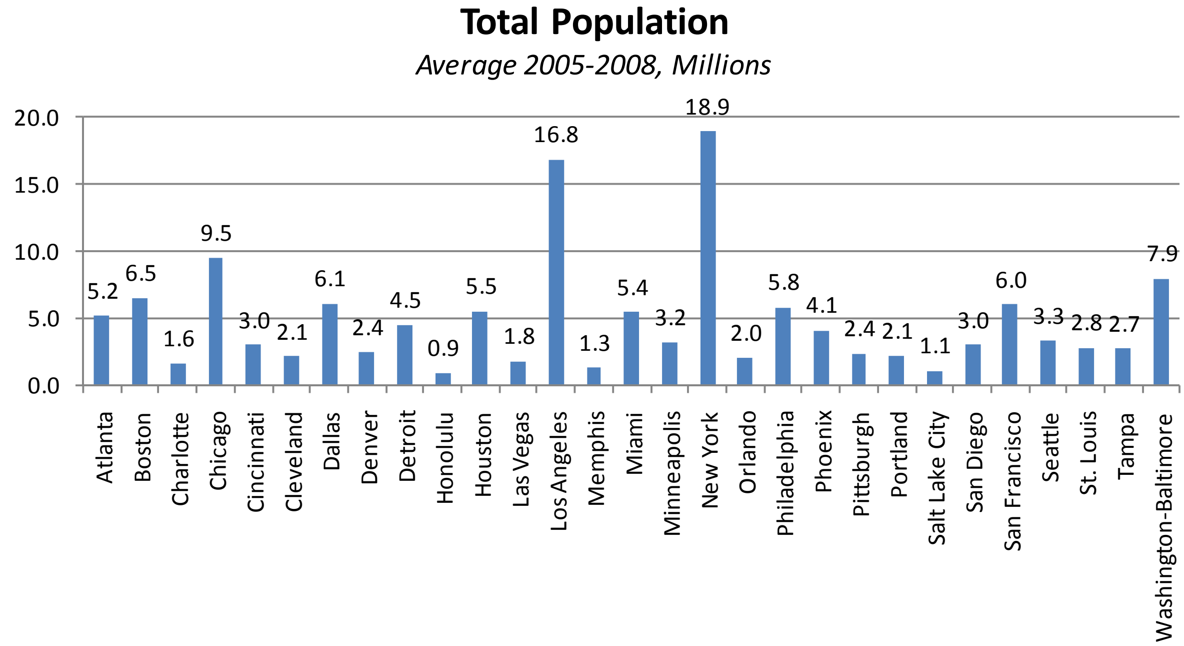

Figure 9 - Total population of metropolitan areas in millions, average 2005-2008

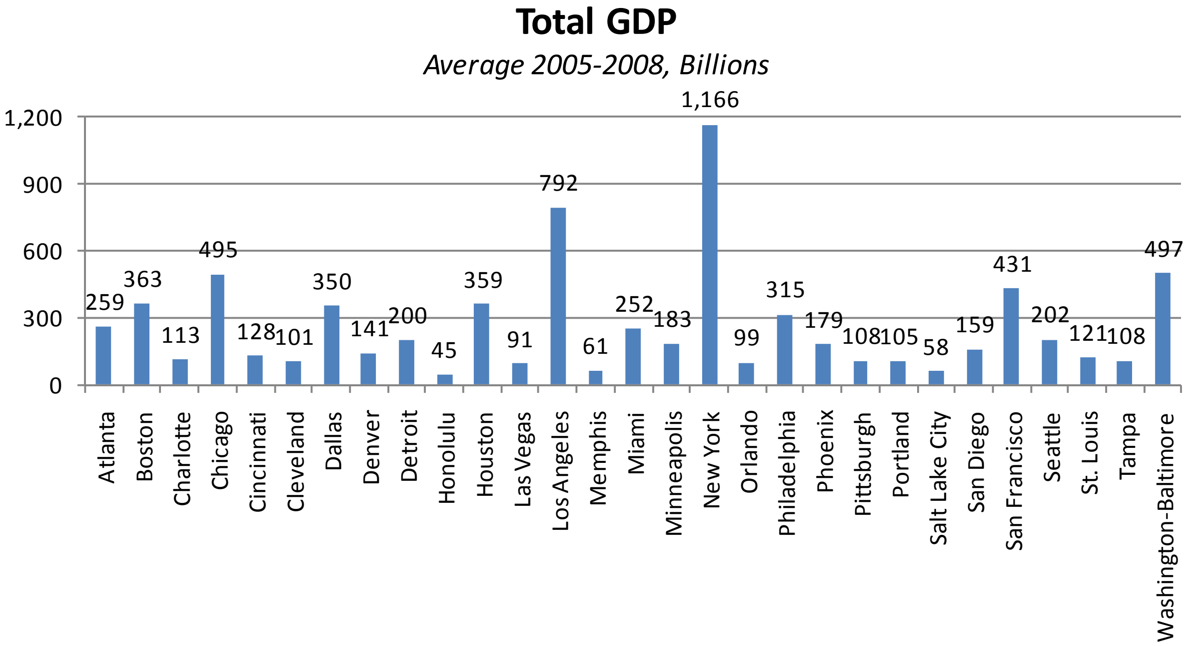

Figure 10 - GDP by metropolitan area in billions of US$, average 2005-2008

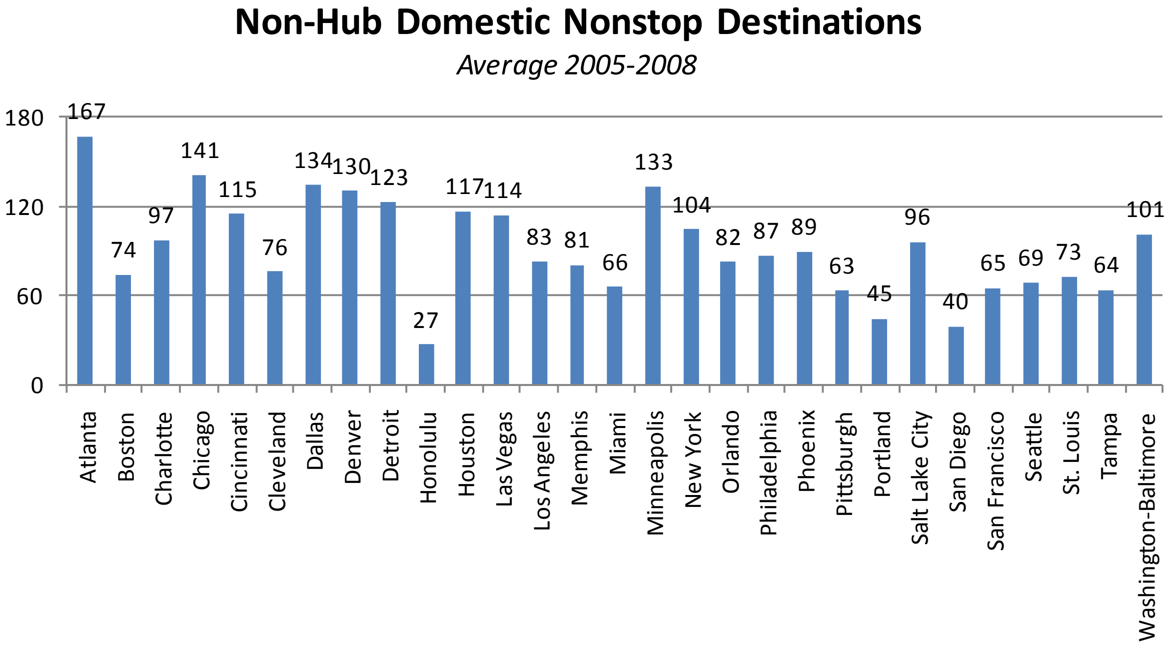

Figure 11 –Number of non-hub domestic destinations served nonstop, average 2005-2008

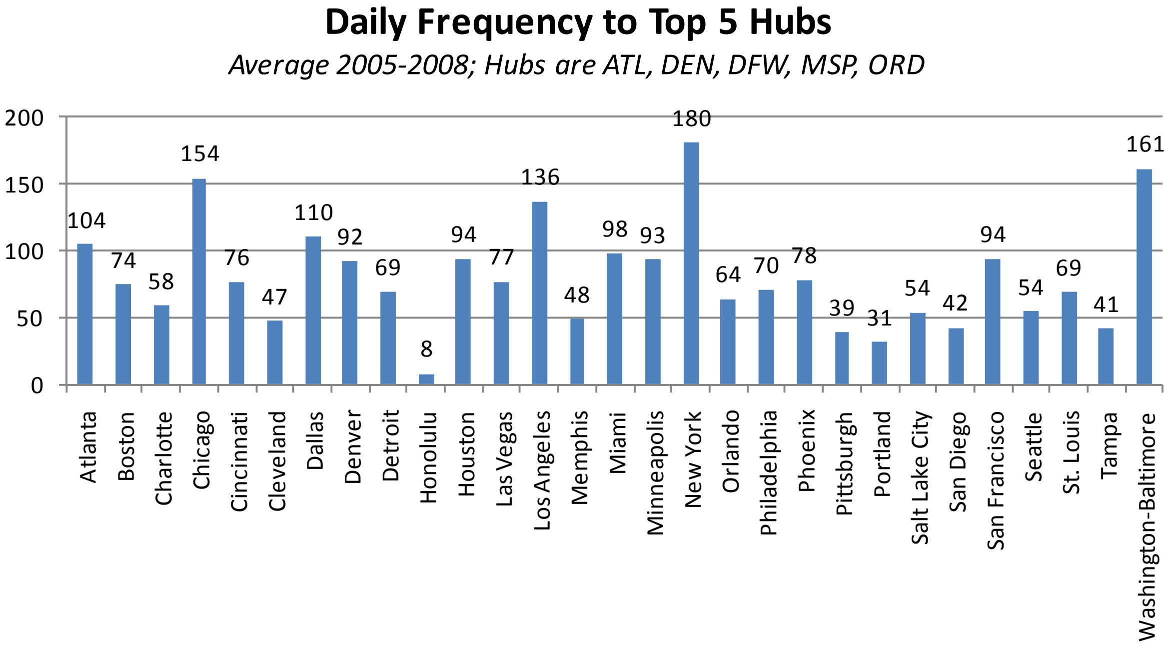

Figure 12 - Daily service frequency to top 5 hubs, average 2005-2008

The input data covered those metropolitan areas that have at least one OEP-35 airport. This represents each of the 30 largest metropolitan areas in terms of GDP, with the exception of Kansas City, MO, which had on average the country's 28th largest GDP from 2005 to 2008 (Bureau of Economic Analysis, U.S.

Department of Commerce 2010) but is not served by an OEP-35 airport. Similarly, this represents each of the 30 largest metropolitan areas in terms of population, with the exception of Sacramento, CA, Kansas City, MO, and San Antonio, TX, which had the 26th, 28th, and 29th largest populations on the average from 2005-2008 (U.S. Census Bureau 2010b).

3.6 Sensitivity Analysis

The purpose of the sensitivity analysis is to understand the degree to which the findings stand up to any potential changes in the input and output data or the underlying model assumptions of the study.

The choice of DEA model has been shown to have a potentially radical impact on the results of airport performance studies (Schaar & Sherry 2008). Some studies have attempted to address that by using a variety of different models (Sarkis 2000), but this can lead to contradictory and inconclusive results. This paper instead used a framework (Schaar et al. 2010) to guide model selection. Any variations of the results based on using another DEA model would not be relevant since such a model would be selected without a rationale for its applicability. As a result, no sensitivity analysis using a different DEA model was conducted.

However, in the study of DEA models which use minimum weights, a significant body of work exists (e.g. (Mehrabian et al. 2000) and (Allen et al. 1997)) but no conclusive determination of a standard approach to the choice of minimum weights exists. To address this lack of standardization, the sensitivity analysis in this study includes tests of varying these minimum weights.

Regarding the input data on GDP and regional population, no assumptions had to be made; rather, both of these categories of data were based on government standard definitions. No sensitivity analysis of variations in GDP and population data was conducted.

The data on output parameters regarding the number of non-hub destinations served nonstop and the frequency of service to the top 5 hubs was based not on sampling data but rather on full census data. This means that no sensitivity analysis is necessary to test the impact of sampling errors. However, the data on both of these performance parameters is dependent on the definition of hubs. To test the robustness of the findings with respect to the definition of hubs, the sensitivity analysis included tests of using the top 3, 4, 6, and 7 hubs based on the total number of domestic destinations served nonstop (the list of these airports can be found in Table 4).

The results of the sensitivity analysis tests are presented in section 4.5.

4 Results

This section presents the resulting scores for the level of air service and discusses the implication of these results. It presents the findings from the sensitivity analysis and discusses some limitations of the results. The section also includes a study of the impact of the level of air service on airline yields.

4.1 Level of Air Service

The average of the results of the analysis for 2005-2008 is presented in Figure 13, where lower scores indicate better levels of service. The results are also plotted on a map of the United States in Figure 14.

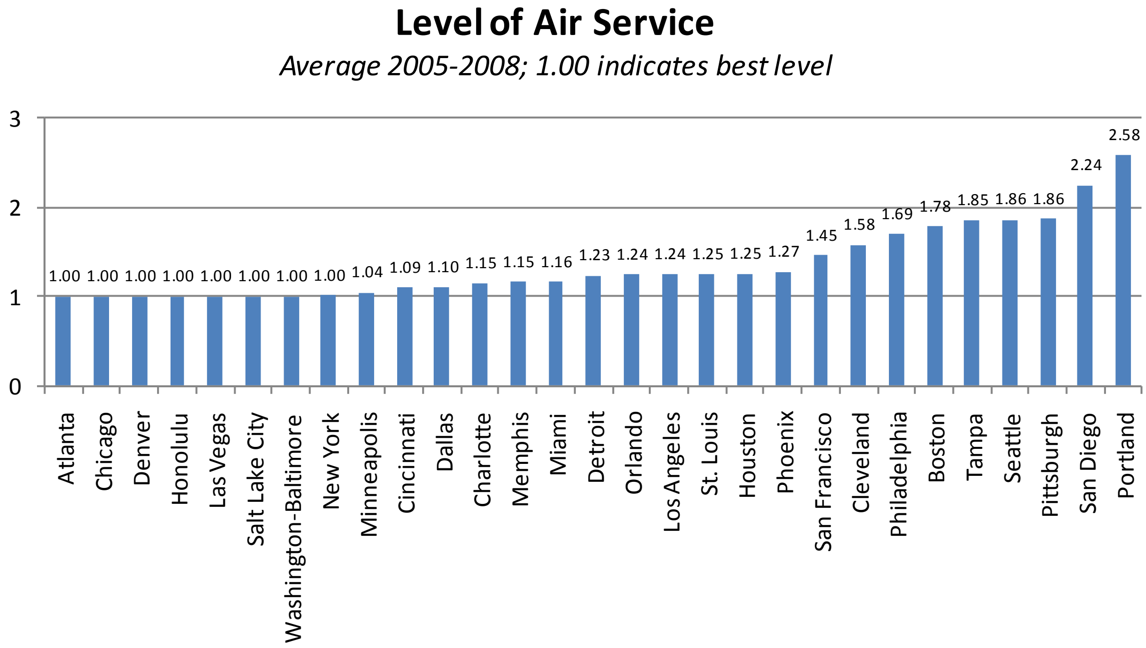

Figure 13 – Average levels of Air Service 2005-2008. 1.00 indicates the best level, and high values indicate poor service

The results show the highest levels of service for Atlanta, Chicago, Denver, Honolulu, Las Vegas, Salt Lake City, and Washington-Baltimore[3]. In contrast, the lowest levels of service exist for Portland, San Diego, Pittsburgh, Seattle, and Tampa, with the first two standing out as having lower levels of service.

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[3] Note that although New York is listed as 1.00, it is in fact not fully efficient in 2005 but due to rounding error its average appears efficient.

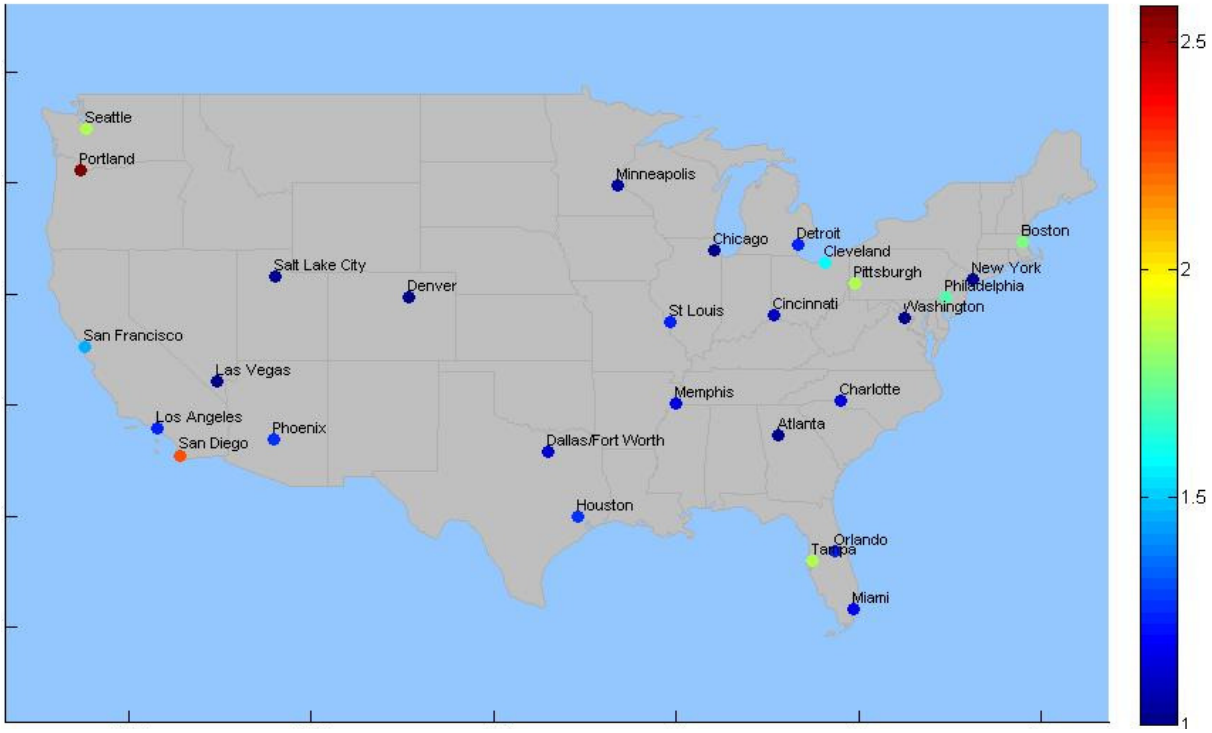

Figure 14 - Visualization of levels of air service (Honolulu omitted), 2005-2008 average. 1.00 (dark blue) indicates the best level of air service and high values indicate poor levels of service

4.2 Gaps for Underserved Metropolitan Areas

The underserved metropolitan areas are defined as those with service levels greater than 1.00, and are considered inefficient in the DEA analysis. The DEA algorithm provides targets which DMUs should hit in order to move from inefficiency to efficiency. The targets are computed by multiplying each output by the DMU's efficiency score from the DEA analysis. These points are the closest projections on the convex hull represented by the efficient frontier.

These projections can provide improvement goals for managers at inefficient airports. When the original parameter values are subtracted from these targets, the gap that must be closed is obtained. Those gaps are presented in Table 6. The metropolitan areas in Table 6 that have blank values for the gaps for both the number of non-hub nonstops and the number of departures to top hubs are fully efficient in that year.

The inefficient DMUs which have a nonzero slack on one of the output parameters have the shortest distance to the efficient frontier by maximizing output only on the other parameters with a zero slack, irrespective of what is done for the parameter with slack. As a result, the gap for those DMUs to the goal on the frontier is described Table 6 only in terms of the parameter with a zero slack, with the other parameter being left blank.

	Distance to Frontier							
	2005		2006		2007		2008	
	Non-hub nonstops	Departures to top hubs	Non-hub nonstops	Departures to top hubs	Non-hub nonstops	Departures to top hubs	Non-hub nonstops	Departures to top hubs
Atlanta								
Boston	56	62	56	60	56	55	61	55
Charlotte	6	4	17	10	22	13	11	6
Chicago								
Cincinnati			11	7	17	12	13	9
Cleveland	37	26	46	30	53	33	37	19
Dallas	12	10	14	12	16	13	12	9
Denver								
Detroit	23	12	32	19	33	19	26	15
Honolulu								
Houston	28	23	30	24	28	23	29	23
Las Vegas								
Los Angeles	22	40	23	38	17	27	19	29
Memphis	8	5	14	9	12	8	15	9
Miami	14	21	13	20	8	12	6	8
Minneapolis			4	3	11	7	8	5
New York	2	3						
Orlando	21	16	28	21	18	14	12	10
Philadelphia	58	50	63	51	63	50	57	44
Phoenix	31	26	20	19	22	19	23	20
Pittsburgh	38	22	51	29	64	38	51	42
Portland	63	48	68	52	78	52	72	46
Salt Lake City								
San Diego	45	56	43	55	55	53	51	47
San Francisco	33	52	29	43	24	35	32	41
Seattle	66	51	59	47	59	46	53	41
St. Louis	19	17	23	21	17	17	12	13
Tampa	47	29	58	37	57	40	53	34
Washington-Baltimore								

Table 6 – Distance to the air service frontier. These are gaps in the level of service to be closed for achieving air service level of 1.00. The gaps are the shortest distance to the frontier.

4.3 Discussion of Results

The results initially show a relatively tight distribution of the levels of service for many airports ranging from 1.00 up to Phoenix at 1.27, where a more drastic deterioration occurs, beginning with San Francisco. San Diego and Portland stand out as having significantly worse service than any other metropolitan area. Some factors impacting these results, such as geography, are not controllable, while other factors may be within the scope of influence of airport management and local government.

This section discusses these factors which impact the outcomes of the benchmark. The average levels of air service, GDP per capita, and average gaps are summarized in Table 7 along with a brief discussion about the performance of individual metropolitan areas. The remainder of the section discusses the possible causes for high and low levels of air service.

Metro Area	GDP/ Capita (Average)	Level of Air Service (Average)	Distance to Frontier		Comments
			Gap for Destinations (Average)	Gap for Frequency (Average)	
San Francisco	$72,013	1.45	30	43	Somewhat poor air service.
Charlotte	$69,806	1.15	14	8	
Houston	$64,873	1.25	29	23	
Washington-Baltimore	$62,526	1.00	0	0	Full air service
New York	$61,692	1.00	0	1	Nearly full air service (rounding error)
Seattle	$61,652	1.86	59	46	Poor air service. Located in the far Northwest where no metropolitan area has high levels of air service.
Denver	$58,004	1.00	0	0	Full air service
Dallas	$57,555	1.10	13	11	
Minneapolis	$57,473	1.04	6	4	
Boston	$55,893	1.78	57	58	Poor air service in spite of including BOS, PVD, and MHT in this metropolitan area. One factor is that PVD is heavily dominated by Southwest Airlines (American University School of Communication 2010) which results in limited service to the top hubs.
Philadelphia	$54,163	1.69	60	49	Poor air service.
San Diego	$53,630	2.24	49	53	Poor air service.
Salt Lake City	$53,216	1.00	0	0	Full air service
Chicago	$52,196	1.00	0	0	Full air service
Las Vegas	$50,998	1.00	0	0	Full air service
Atlanta	$50,016	1.00	0	0	Full air service
Honolulu	$49,869	1.00	0	0	Full air service
Orlando	$49,146	1.24	20	15	In spite of extensive holiday traffic, Orlando is not at full air service.
Portland	$48,888	2.58	70	49	Poor air service. Low yields may contribute (see Figure 19).
Cleveland	$48,269	1.58	43	27	Somewhat poor air service. Reduction of hubbing by Continental may contribute (Rollenhagen 2003).
Memphis	$48,056	1.15	12	7	
Los Angeles	$47,074	1.24	20	33	
Miami	$46,632	1.16	10	15	
Pittsburgh	$45,638	1.86	51	33	Poor air service, in large part due to US Airways hub elimination (Grossman 2007). Service deteriorated significantly each year from 2005 to 2008.
Detroit	$44,756	1.23	29	16	
Phoenix	$43,828	1.27	24	21	
St. Louis	$43,217	1.25	18	17	
Cincinnati	$43,040	1.09	10	7	

Metro Area	GDP/ Capita (Average)	Level of Air Service (Average)	Distance to Frontier Gap for Destinations (Average)	 Gap for Frequency (Average)	Comments
Tampa	$39,932	1.85	54	35	Poor air service. The city's relative proximity to Orlando could contribute, but that impact should be limited since Tampa city center is 86 miles from MCO.

Table 7 - Summary of study results, 2005-2008, in order of GDP per capita. Areas with air service performance above 1.3 are highlighted as those areas have poor levels of air service.

4.3.1 Impact of Geography

Although many of the less well served metropolitan areas are located in one of the four “corners” of the continental United States as shown in Figure 14, many of these less well served metropolitan areas exist in the vicinity of other metropolitan areas with high levels of service. This suggests that some areas’ lower levels of service may stem less from their geographic distance from the center of the country and more from their proximity to another well-served metropolitan area.

For example, Tampa exhibits low levels of air service and is located in the southeast corner of the United States, but neighboring Orlando exhibits high levels of air service. This suggests that Tampa’s low level of air service may be traced more to its proximity to Orlando than to its southeasterly location.

Seattle and Portland are exceptions to this, since they both exhibit low levels of service and are not in the proximity of a well-served area.

4.3.2 Impact of Capacity Limitations

A lack of infrastructure capacity in the form of runways, terminals, or other facilities at an airport may limit the ability of airlines to add service even though demand exists.

A proxy for capacity limits is the level of delays at an airport; heavy delays suggest that the airport infrastructure has difficulty accommodating the level of demand at the airport. Figure 15 and Figure 16 show the percentage of on-time departures and arrivals at major US airports.

This data suggests that a contributing cause of the low levels of air service in areas such as Philadelphia, which has the third-worst departure delays and fifth-worst arrival delays, may be capacity limitations. Other areas such as New York and Chicago are currently well-served in terms of the level of air service, but because of capacity limitations, they may find that the future level of air service cannot grow at the same level as their population and regional economies, resulting in a proportionately reduced level of air service.

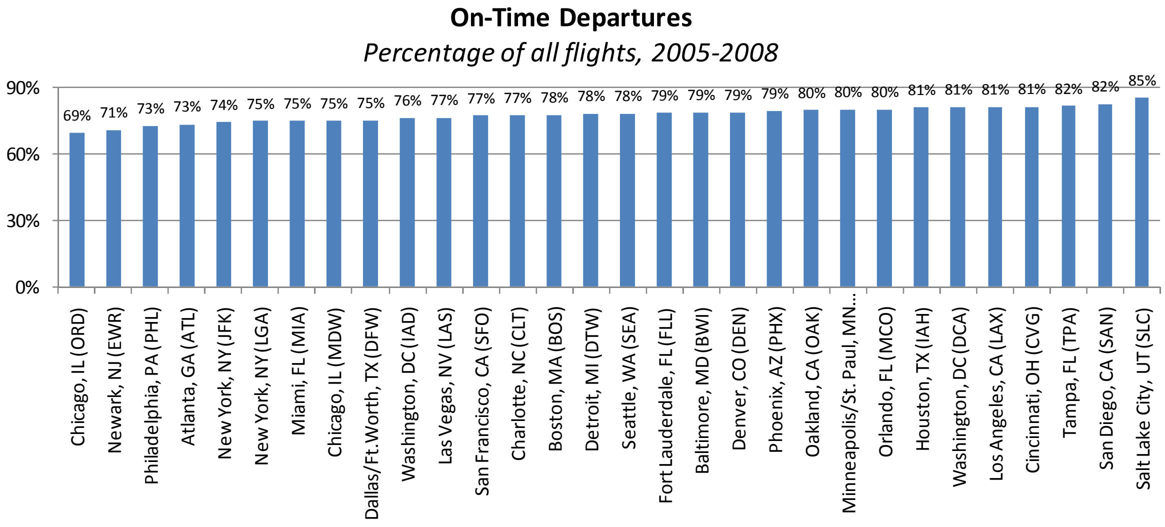

Figure 15 - Percentage of airline on-time departures at major US airports, average for 2005-2008 (Bureau of Transportation Statistics 2010a).

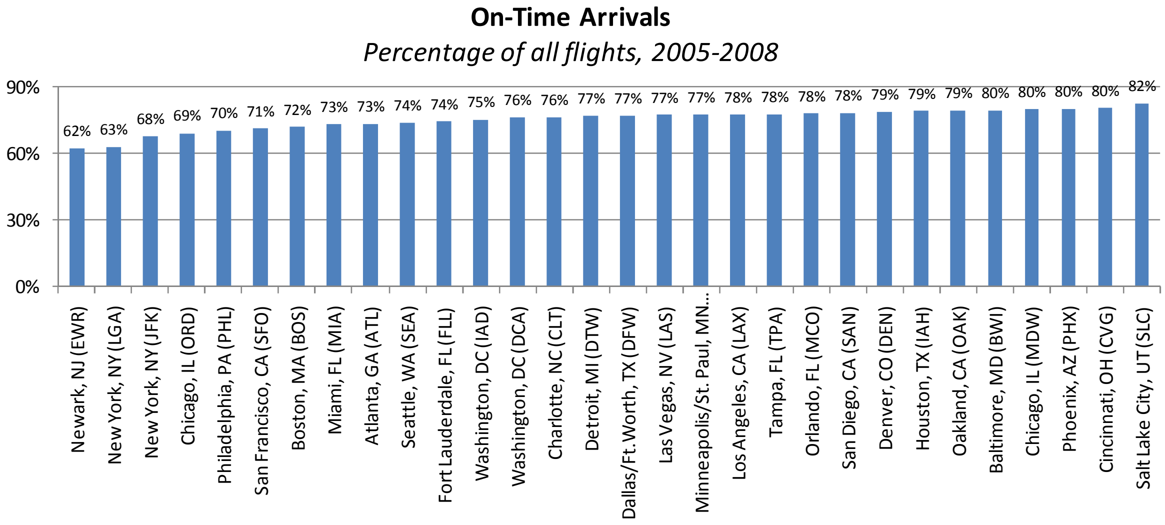

Figure 16 - Percentage of airline on-time arrivals at major US airports, average for 2005-2008 (Bureau of Transportation Statistics 2010a).

To address capacity limitations, airports and the FAA can undertake projects to improve the capacity. These capacity improvements are summarized in (Federal Aviation Administration 2007) (p. 27, Appendix C) and Table 8 shows the improvements which will be applied prior to 2015 and 2025, respectively. Note that the table omits three improvements[4] which will be made to all OEP-35 airports, as those improvements do not provide any distinguishing approaches to each airport.

Metro Area	Airport	New/extended runways (2006 or later)	Independent parallel approaches (IMC) -- spacing 2500-4299 ft	Triple indep. parallel approaches (IMC)	Mixed triple independent/dependent parallel approaches (IMC)	Paired approaches, e.g. SOIA -- MMC (spacing 700-2499 ft)	-- IMC (spacing 1200-2499 ft)	Dependent Approaches -- MMC/IMC (700-2500 ft spacing) -- 1.5 NM diagonal behind Small, Large -- wake vortex sep behind B757/Heavy	LAHSO (all weather) if >7000 ft to intersection	Simultaneous Converging Approaches (IMC)	Standard Departure/Departure separations (no departure constraints)	Independent parallel departures (IMC) -- no wake vortex separation behind Small/Large (700-2500 ft spacing)
Atlanta	**ATL**					< 2025						
Boston	**BOS**	< 2015				< 2015	< 2025				< 2025	
	MHT											
	PVD											
Charlotte	**CLT**	< 2025			< 2025							
Chicago	**MDW**											
	ORD	< 2015		< 2015								
Cincinnati	**CVG**											
	DAY											
Cleveland	**CLE**											
Dallas	**DAL**											
	DFW	< 2025										
Denver	**DEN**	< 2025										
Detroit	**DTW**			< 2025								
Honolulu	**HNL**								< 2025			
Houston	**HOU**	< 2025										
	IAH	< 2025										
Las Vegas	**LAS**					< 2025			< 2025	< 2025	< 2025	< 2025
Los Angeles	**LAX**					< 2025		< 2025				
	ONT											
	BUR											
	SNA											
	LGB											
Memphis	**MEM**											
Miami	**FLL**	< 2015	< 2025								< 2025	
	MIA					< 2025		< 2025	< 2025			< 2025
	PBI	< 2015										
Minneapolis	**MSP**									< 2025		
New York	**JFK**										< 2015	
	LGA											
	EWR					< 2015		< 2025				< 2025
	ISP											
Orlando	**MCO**			< 2015				< 2025				< 2025

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[4] These three improvements are: 1) Reduced Separation Standards (use visual separation in MMC and use 2/3/4/5 NM in IMC); 2) Improved threshold delivery accuracy; 3) 1.5 NM Departure/Arrival separation (IMC) (spacing < 2500 ft or same runway)

Metro Area	Airport	New/extended runways (2006 or later)	Independent parallel approaches (IMC) -- spacing 2500-4299 ft	Triple indep. parallel approaches (IMC)	Mixed triple independent/dependent parallel approaches (IMC)	Paired approaches, e.g. SOIA -- MMC (spacing 700-2499 ft)	-- IMC (spacing 1200-2499 ft)	Dependent Approaches -- MMC/IMC (700-2500 ft spacing) -- 1.5 NM diagonal behind Small, Large -- wake vortex sep behind B757/Heavy	LAHSO (all weather) if >7000 ft to intersection	Simultaneous Converging Approaches (IMC)	Standard Departure/Departure separations (no departure constraints)	Independent parallel departures (IMC) -- no wake vortex separation behind Small/Large (700-2500 ft spacing)
Philadelphia	**PHL**	< 2015										
Phoenix	**PHX**		< 2025									
Pittsburgh	**PIT**											
Portland	**PDX**		< 2025			< 2015					< 2025	
Salt Lake City	**SLC**			< 2025							< 2025	
San Diego	**SAN**										< 2025	
San Francisco	**SFO**							< 2025			< 2025	< 2025
	SJC											
	OAK					< 2025		< 2025		< 2025		< 2025
Seattle	**SEA**	< 2015	< 2025			< 2015						
St. Louis	**STL**							< 2015				< 2015
Tampa	**TPA**	< 2025						< 2025				< 2025
Washington-Baltimore	**DCA**											
	IAD	< 2015 < 2025		< 2015								
	BWI	< 2025										

Table 8 - Planned airport capacity improvements (Federal Aviation Administration 2007). For greyed-out airports no data was available. Capacity improvements that apply to all OEP-35 airports have been omitted.

The table shows improved capacity planned at PHL in the form of new/extended runways but no new/extended runways at any of the airports in Los Angeles, New York or San Francisco. It also shows no planned improvements at LGA

4.3.3 Impact of a Lack of Hub Service

An airport's status as a hub for a carrier brings connecting passenger traffic, allowing the air carrier to provide higher frequency service and to serve more destinations than would have been possible if the airport had only been an O&D market (Belobaba et al. 2009) (p. 163).

Pittsburgh's low level of air service is in part the result of its lack of hub status for any airline since US Airways consolidated its hubs to Philadelphia and Charlotte (Grossman 2007). Similar conditions may exist in Cleveland (Rollenhagen 2003) which also reports a relatively low level or air service.

4.3.4 Impact of Local Industry Base

The needs for air transportation may vary by industry. For instance, in a comparison of two areas with the same GDP and population, it may that one has better conditions for higher levels of air service than the other as a result of differences in industry makeup.

In a 2000 study, it was found that regions with a stronger focus on high-tech industries were more likely to have airline hub service (Button & Stough 2000) (pp. 231-264). The definition of high-tech industries used in that study was derived from a 1986 characterization of high-tech industries (Rees 1986) (pp. 76-92), which determined that the high-tech industry was made up of 88 categories of economic activity from the Standard Industrial Classification (SIC) system. The SIC system was replaced in 1997 by the North American Industry Classification System (NAICS) (U.S. Census Bureau 2010a), and data is not publicly available at the detailed level of the 88 original categories for the 2005-2008 time period.

To provide a high level assessment of the high-tech industries' role in the level of air service of metropolitan areas, the original 88 categories were consolidated into five high-level categories from the NAICS: Mining, utilities, manufacturing, information, and professional and technical services. Figure 17 presents the data retrieved using this definition, and Figure 18 shows a scatter plot of the level of air service as a function of the high-tech industry contribution as a portion of the total regional economy.

This data does not indicate that the under-served areas have a low portion of high-tech industry. In contrast, the areas with poor levels of air service often exhibit high portions of high-tech industry; Seattle and Portland are such examples. Further analysis of more detailed GDP breakout data is necessary to find if other industries have an impact on the level of air service.

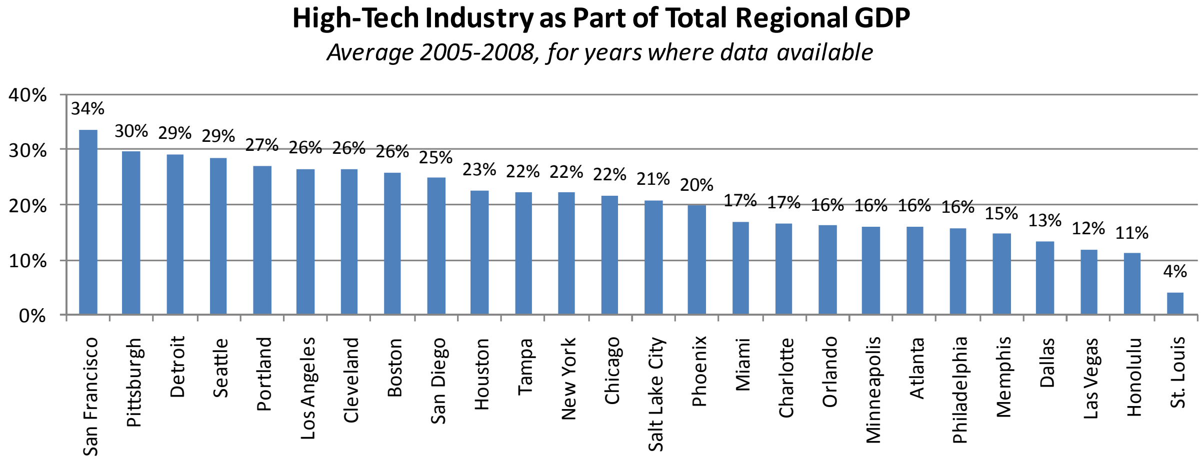

Figure 17 – High-tech industry as a percentage of total regional GDP. Cincinnati, Denver, and Washington-Baltimore omitted due to lack of data. High-tech industry defined as NAICS categories of mining, utilities, manufacturing, information, and professional and technical services. Average based only on those years where data in the largest number of categories was available for each city; some categories are marked in the data source as "not shown in order to avoid the disclosure of confidential information". (Bureau of Economic Analysis, U.S. Department of Commerce 2010)

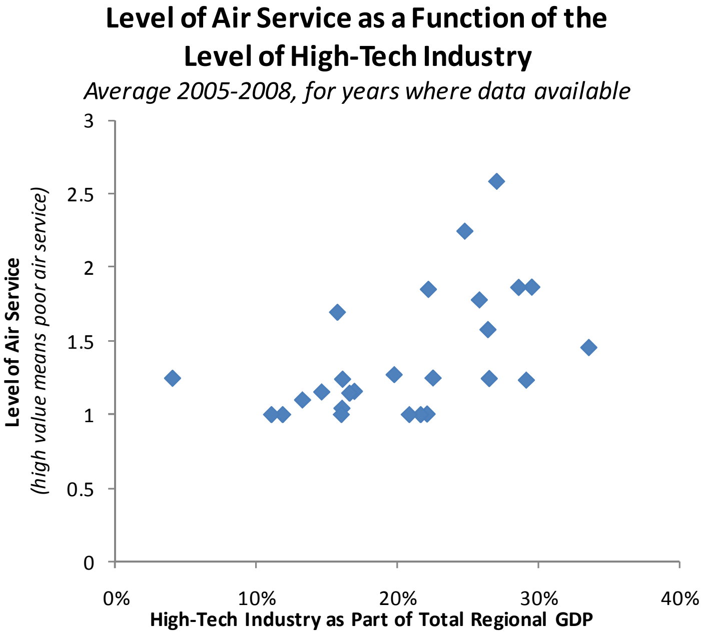

Figure 18 - Level of air service as a function of high-tech industry as a percentage of total regional GDP (methodology description in caption for Figure 17)

4.3.5 Impact of Airline Yield

Airlines are private enterprises which seek to make a profit by supplying services to meet demand. Where profits are high, the incentive exists for air carriers to add more service, while locations where profits are low provide less incentive for increased levels of service. The level of air service in a metropolitan area may be dependent on the level of airline yields for services to and from that area.

The average yields were computed for the 2005-2008 period for each airport in the analysis. Data on revenues and passenger volumes were derived from the Airline Origin and Destination Survey (DB1B) database (Bureau of Transportation Statistics 2010c). Annual yields, expressed in US$ per Revenue Passenger Mile (RPM) for each O&D pair is computed as follows (Belobaba et al. 2009) (p. 48):

$$Yield_{O,D} = \frac{Revenue_{O,D}}{Distance_{O,D} * Passengers_{O,D}}$$

The yields for each metropolitan area was determined by computed a passenger-weighted yield from the data from each airport in the area. The resulting data is displayed in Figure 19.

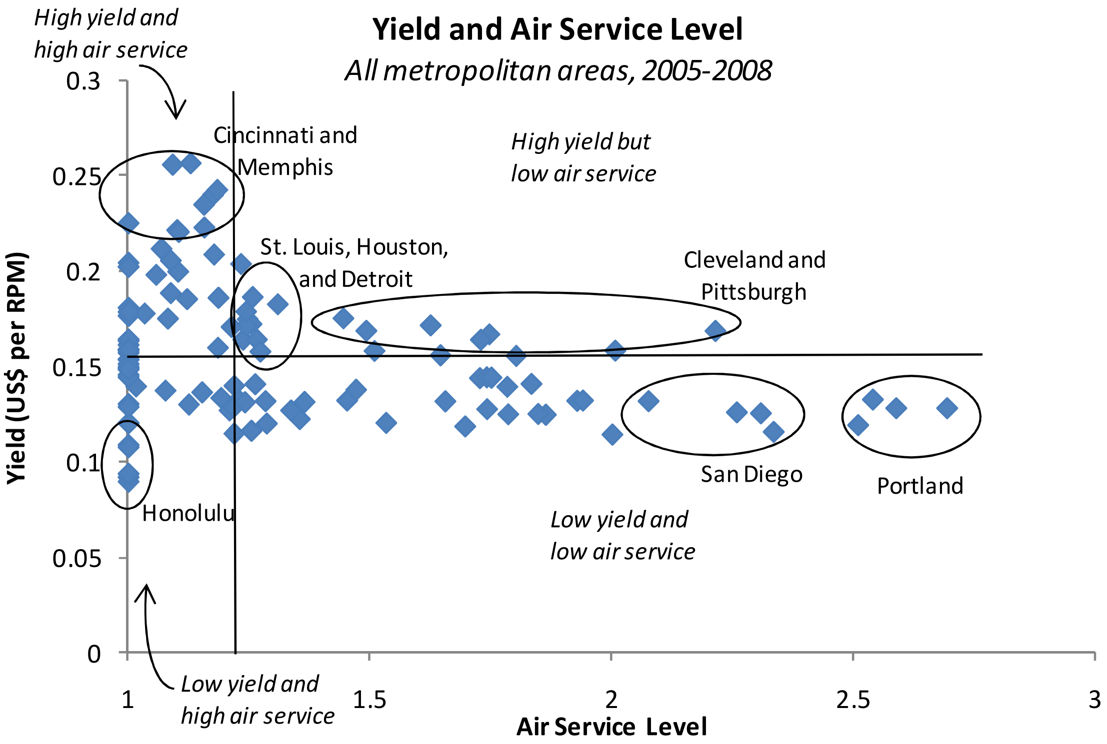

Figure 19 – Yield by metropolitan area in relation to air service level. The best air service level is at 1.00 and the worst service level is at 3.00. The horizontal and vertical lines in the figure represent the median yield and air service levels, respectively.

The data in Figure 19 suggests that low yields may be contributing to low levels of air service in areas such as Portland and San Diego, located in the lower right-hand quadrant in the figure. Low demand or high degrees of competition in these areas contribute toward the low yield, making them less attractive to airlines for adding further services.

The data also suggests that some areas exist where the level of air service is high in conjunction with high yields. This is the top-left quadrant of the figure and includes areas such as Cincinnati and Memphis. The focus for the airport authority and local government in these areas should not be to improve air service but rather to create a more competitive environment where yields are reduced as a result of lower fares for travelers.

Lastly, the areas located in the upper right-hand quadrant of the figure are under-served in terms of air service but report above-median yields. These appear to represent opportunities for air carriers in that there is room for adding new, profitable service. The airport authority and local government in these areas should focus on both adding increased service and creating more competition in order to reduce travel costs for its residents. These cities include St. Louis, Houston, Detroit, Cleveland, and Pittsburgh.

4.4 Limitations of Results

Although the extent of their impact is unknown, several factors which may have affected the outcome of the analysis exist:

- The calculation of the level of air service does not factor in the geographic location of the metropolitan area. It is possible that areas located near the center of the continental United States have an inherently greater possibility of achieving high levels of air service.
- The calculation does not take into account the effects of economic geography. It is for instance possible that the industrial base of one metropolitan area is more prone to using air service than that of other areas.
- The calculation does not account for the impact of capacity limitations on gates, runway capacity, etc. It appears that this limits the score for cities like San Diego.
- The calculation does not consider the relatively close proximity of some metropolitan areas to other areas. It is possible that the proximity to another area impacts a region's level of air service.
- International traffic was excluded from the study since 14 airports among the OEP-35 airports represented 70% of all international passenger enplanements in 2006 (FAA 2008) (pp. 23-24). A study that included international traffic would show different results.

4.5 Results of Sensitivity Analysis

This section presents the results of the sensitivity analyses described in section 3.6.

4.5.1 Sensitivity to Weights

In the original analysis, the standard weight boundaries ε from the BCC model were used. These are the boundaries on the minimum values on the weights applied to each output in the DEA calculation. In the BCC model these are simply specified as infinitesimal and in the model implementation, they were set at 1.0 * E-6.

In the sensitivity analysis, the weights were varied between the minimum value of 1.0 * E-6 up to the maximum feasible output weight values. The maximum feasible values are the maximum observed values multiplied by 0.5 (as a result of there being two output parameters). The maximum feasible values are those which result in the constraints being binding for one or more DMUs.

The input parameter weights are not varied since any minimum values unfairly penalize the performance of the larger metropolitan areas due to the differences in magnitude of the different areas' values.

In the case where the analysis uses the maximum feasible weights, the DMU(s) with the highest magnitude of outputs are forced to apply exactly those weights, effectively removing the DMU's ability to select its own optimal weights. The higher the boundary on weights, the lower the flexibility for DMU's to determine their own optimal weights.

For the output weights, seven variations on the weight boundaries were tested for each year; the first test $i=1$ used the standard 1.0 E-6 weights, and in each subsequent test $i=2..7$ the boundary was proportionally increased such that the test i=7 had the maximum feasible boundaries (for tests $i=2..7$ the weight boundaries were determined as $\text{boundary}_\text{i} = \text{max(weight)} / 2 * (i - 1) / 6$).

The average scores computed in the sensitivity analysis are presented in Figure 20. A comparison of the rankings of each metro area's scores between Test 1, Test 2, and Test 7 is presented in Table 9.

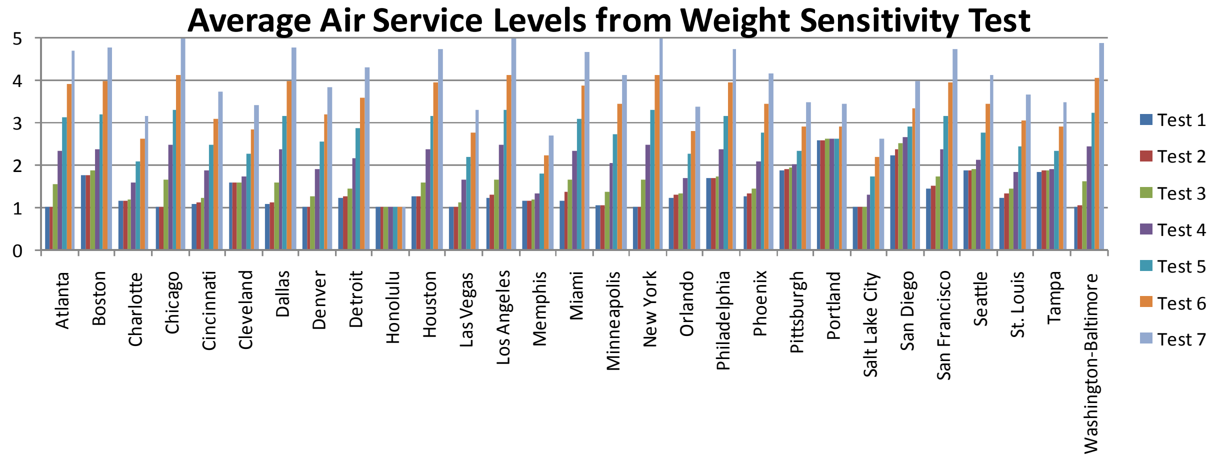

Figure 20 - Results from weight boundary sensitivity tests. Test 1 has the least restrictive weight boundaries, and Test 7 has the most restrictive boundaries

	Ranking in Sensitivity Test			
	Test 1	**Test 2**	**…**	**Test 7**
Atlanta	1	1		20
Boston	24	24		25
Charlotte	12	12		4
Chicago	1	1		27
Cincinnati	10	11		12
Cleveland	22	22		7
Dallas	11	10		24
Denver	1	1		13
Detroit	15	15		18
Honolulu	1	1		1
Houston	19	14		21
Las Vegas	1	1		5
Los Angeles	17	17		27
Memphis	13	13		3
Miami	14	20		19
Minneapolis	9	8		15
New York	8	7		27
Orlando	16	16		6
Philadelphia	23	23		22
Phoenix	20	18		17
Pittsburgh	27	27		10
Portland	29	29		8

	Ranking in Sensitivity Test			
	Test 1	Test 2	…	Test 7
Salt Lake City	1	1		2
San Diego	28	28		14
San Francisco	21	21		23
Seattle	26	26		16
St. Louis	18	19		11
Tampa	25	25		9
Washington-Baltimore	1	9		26

Table 9 - Rankings from selected sensitivity tests. Test 1 has the least restrictive weight boundaries and Test 7 has the most restrictive boundaries.

The results show that the rankings in Test 1 and Test 2, which have the lowest boundaries, remain largely the same. Between the two tests, 20 metropolitan areas retain the same ranking, 6 areas shift one or two rankings, and 3 areas shift more than 2 rankings. However, with Test 3, rankings begin to shift more significantly, and by Test 7 only one airport, Honolulu, maintains its original ranking.

This shows that the selection of weight boundaries do matter to the results if they go well above the infinitesimal. However, the BCC model specifies that infinitesimal weight boundaries be used, and the similarity between the results of Test 1 and Test 2 shows that the exact choice of infinitesimal weight boundaries in the model implementation has little impact; the boundaries in Test 2 already far exceed what could be considered reasonable infinitesimal weight boundaries in the model. This indicates that the boundaries of 1.0 * E-6 used in the analysis are acceptable.

4.5.2 Sensitivity to Hub Definition

In the sensitivity test where the definition of hubs was changed as described in section 3.6, tests were run for 3, 4, 5, 6, and 7 hubs. The results were then averaged across all cases, and standard deviations for the level of air service were computed. The results of this analysis are shown in Figure 21.

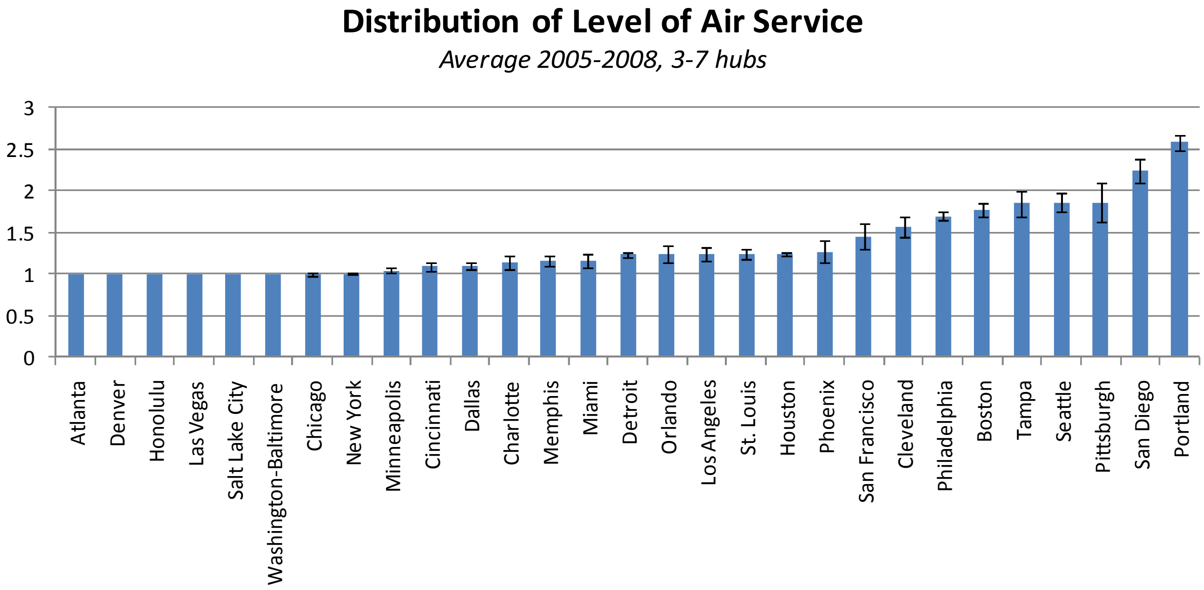

Figure 21 - Results from hub definition sensitivity test. The bars show the average score, and the error bars show +- the standard deviation.

The results show a very small standard deviation for the fully efficient metropolitan areas and limited standard deviations elsewhere, indicating a very limited impact on the results from changes in the definition of how hubs are determined.

5 Conclusions and Future Work

The analysis defined the level of service in US metropolitan areas as the number of non-hub destinations served and the frequency of service to hubs, and found that the least well-served areas are Portland, OR, San Diego, CA, Pittsburg, PA, and Seattle, WA. The analysis presented the gaps that, if closed, would have resulted in matching the level of air service at the best-served areas.

The results suggest that some areas have a lower opportunity for high levels of air service as a result of their geographic proximity to other areas with high degrees of air service or as a result of their regional industry base generating a low level of demand for air travel. These are factors that are generally uncontrollable by local airport authorities or local and federal government bodies.

In contrast, the results suggest that some areas have a low level of air service as a result of factors which may be controlled or influenced.

Areas such as Philadelphia appear to be underserved as a result of limited infrastructure capacity. This suggests that allocating funding for adding new capacity through for instance a new runway should result in improved service for the local population and economy.

Other areas, such as Pittsburgh and Cleveland report low levels of air service but also record above-median yield levels. This suggests that these areas represent opportunities for added service by air carriers, and that the local airport authorities and government should focus efforts on recruiting new air service in order for the region's population and businesses to be better served.

Future work should include investigating other factors which may impact the level of air service, and conversely, factors which may be impacted by the level of air service. These include factors such as the more detailed composition of regional GDP by different industry types to investigate the impact of categories other than high-tech, as well as measures of distance from the geographic center of the United States and proximity to other metropolitan areas.

Future work should also address forward-looking benchmarking of the level of air service by using forecasts of economic and population growth to identify metropolitan areas that may see their level of air service suffer unless investments are made in increased capacity or increased efforts are undertaken to attract improved levels of air service.

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