NASA/CR–2010-216853

Analysis of Dependencies and Impacts of Metroplex Operations

Daniel A. DeLaurentis and Sricharan Ayyalasomayajula
Purdue University, West Lafayette, Indiana

October 2010

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Cooperative Agreement NNX07AT23A

October 2010

Available from:

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1 Introduction

This report documents research performed by Purdue University under sub-contract to the George Mason University (GMU) for the Metroplex Operations effort (under NASA contract number NNX07AT23A) sponsored by NASA's Airportal Project (Subtopic 20 in the NASA Research Announcement NNH06ZEA001N). Purdue University conducted two tasks in support of the larger efforts led by GMU: a) a literature review on metroplex operations followed by identification and analysis of metroplex dependencies, and b) the analysis of impacts of metroplex operations on the larger U.S. domestic airline service network. The tasks are linked in that the ultimate goal is an understanding of the role of dependencies among airports in a metroplex in causing delays both locally and network-wide. Put simply by the FAA*: "Congestion, airports in close geographical proximity, and other limiting factors reduce efficiency in busy Metroplex airspace." As such, the Purdue team has *formulated a system-of-systems framework to analyze metroplex dependencies (including simple metrics to quantify them) and develop compact models to predict delays based on network structure*. These metrics and models were developed to provide insights for planners to formulate tailored policies and operational strategies that streamline metroplex operations and mitigate delays and congestion.

Metroplex airports share major portions of both airspace resources and local population from which demand emanates. Coordination among and competition for the limited number of operations into and out of a metroplex occur in the presence of dependencies between these airports. When demand outstrips available resources under a given operational strategy, delays result. Further, delays occurring at a metroplex's airports propagate across the National Airspace System (NAS) via airline service networks. The graphic in Fig. 1 is a schematic of the New York/New Jersey metroplex (NYNJ) that illustrates how airports interact with one another (via dependencies) as well as with the other airports in the NAS (via airline service networks). The dashed-oval depicts the metroplex's airspace with the arrows notionally representing the dependencies between EWR, JFK and LGA (denoted by squares). These dependencies arise from numerous categories such as the arrival and departure fixes in use, policy/regulatory issues such as capacity limits on the airports, and economic issues such as landing fees. At the same time, NYNJ airports interact with the other airports (circles) in the NAS via schedules airline service (denoted by solid lines). These flights are allocated and managed by different airlines that are competing with each other for the same market share, thus adding another dimension to the complex couplings between a metroplex's airports. Therefore, it is imperative to also understand the topological properties of the different airline networks serving a metroplex and the dynamics of their interactions to gain a holistic view of what causes a metroplex to have congestion and flight delays. As documented later in this report, statistical properties of service networks of different airlines were studied, leading to a regression-based model developed to estimate the number of flights delayed at a metroplex. The model attempts to correlate the topological properties of airline service networks with the number of delayed flights at an airport in a year. The model has been further refined to also estimate the number of monthly delays at an airport. Work is underway to correlate the fluctuation in delays with seasonal variations in weather and traffic volume. The details of the framework, dependency metrics, studies of airline networks, and the delay estimation models are provided in the following sections.

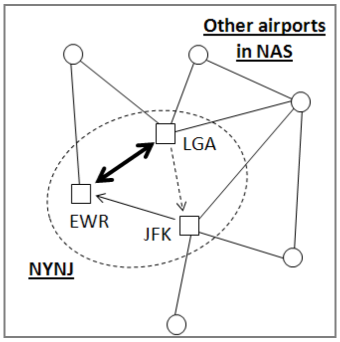

Fig. 1. Notional representation of service between NYNJ and other airports in NAS

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* "FAA Response to the Recommendations of the RTCA NEXTGEN Midterm Implementation Task Force," http://www.faa.gov/about/initiatives/nextgen/media/FAA_TASKFORCE_RESPONSE_1-31-2010.pdf

2 Technical Approach

2.1 Foundation for network and dependency analysis: A System-of-Systems framework

A system-of-systems (SoS) is a collection of independent, often heterogeneous, components that collaborate via interacting networks to produce some unique capability (ref. 1). Since each entity has both independent and collaborative operations scenarios, conflict in their objectives may arise. Applicability of the system-of-systems approach to study the air transportation system was demonstrated in (ref. 2). Therefore, this approach was adopted to analyze metroplex operations in the current project. The decomposition in Table 1 is a result of this effort and is essential to 1) identify the hierarchy amongst the various networks in the NAS (rows in the chart), and 2) understand how the interactions within each of these networks across the different dimensions (columns), in combination with different stakeholder interests, affect a metroplex's operations. Additional descriptions of the dimensions and the significance of the vertical decomposition are available in (ref. 3 and 4).

A graphical depiction of hierarchical SoS relationships in air transportation with focus on metroplex is displayed in Fig. 2. Interactive relationships between components are readily apparent. For example, airlines serving metroplex airports interact with one another to enhance their business and increase their net earnings (β- and γ-levels in Fig. 2); airports are nodes and the flights between them are links in this network. On the other hand, studying a composite flight network combining the service networks of all airlines provides insights into NAS-wide traffic between the various airports (δ-level in Fig. 2). Another level of abstraction of this network leads to a scenario wherein metroplex airports are replaced with 'modules' that are connected to the other NAS-wide metroplex modules and airports (the γ-level in Fig. 2). Airports within each module are dependent on each other via dependencies, where as they are connected to the remainder of NAS by means of airline service networks. Recalling Fig. 1, the 'external' interactions occurring between other airports and metroplex modules in NAS are different from those 'internal' to the metroplex module.

Table 1. A System-of-systems Definition Matrix with Focus on Metroplex

		System-of-systems Dimensions			
		Resources	*Operations*	*Policy*	*Economics*
Layers of Networks	ε	Global Air Transportation	Global airline operations	Bilateral agreements, ICAO regulations etc.	WTO; Global Marketplace
	δ	National Air Transportation System	All airlines at all airports in the US	National Air Transportation System policies	Forecasts of National Air Transportation
	γ	Metroplex and non-Metroplex airports	One airline's operations at all airports	Policies concerning slots, code-sharing etc. in a metroplex	Economics of an airline and metroplex
	β	Airports	One airline's operations at an airport	Policies concerning aircraft operations, noise regulations, use of airport resources etc.	Economics of building, operating, leasing etc. of airports and airport resources
	α	Aircraft, runway, ATC etc.	Aircraft movements on runways	Policies concerning airport runway and surface operations	Economics of building, operating, leasing etc. of runways and aircraft

In order to understand 'internal' interactions, metrics to quantify the dependencies between metroplex airports were developed. In order to understand 'external' issues, the topology of the network of flight operations between a metroplex and the other airports was analyzed. A composite network model was constructed by combining the service networks of various airlines serving a metroplex, and their statistical properties were studied. The results were used to assess impact of different operational and regulatory scenarios in airline operations (with airline profitability coming from GMU analysis) on the overall performance of NAS. The graphic in Fig. 3 is a framework being developed for evaluating the impact of various metroplex operational strategies. It is based on the hypothesis that an understanding of the dependencies in a metroplex and the interactions between the overall service network and the metroplex's operations is essential to developing appropriate congestion mitigation strategies for the metroplex. As part of this, the impact of these strategies on the various stakeholders is also studied. The notional Pareto chart in the lower right corner of Fig. 3 compares the effects of congestion mitigation solutions, such as slot controls, new runways, etc., on the overall service network and airlines. Candidate measures for evaluating the performance of the overall service network are the number of delayed flights, passenger throughput etc., while they are profitability, number of markets served, etc. for airlines. The remainder of this section describes the process adopted to characterize and analyze metroplex dependencies, and an analysis of the interactions between the overall service network and metroplex operations.

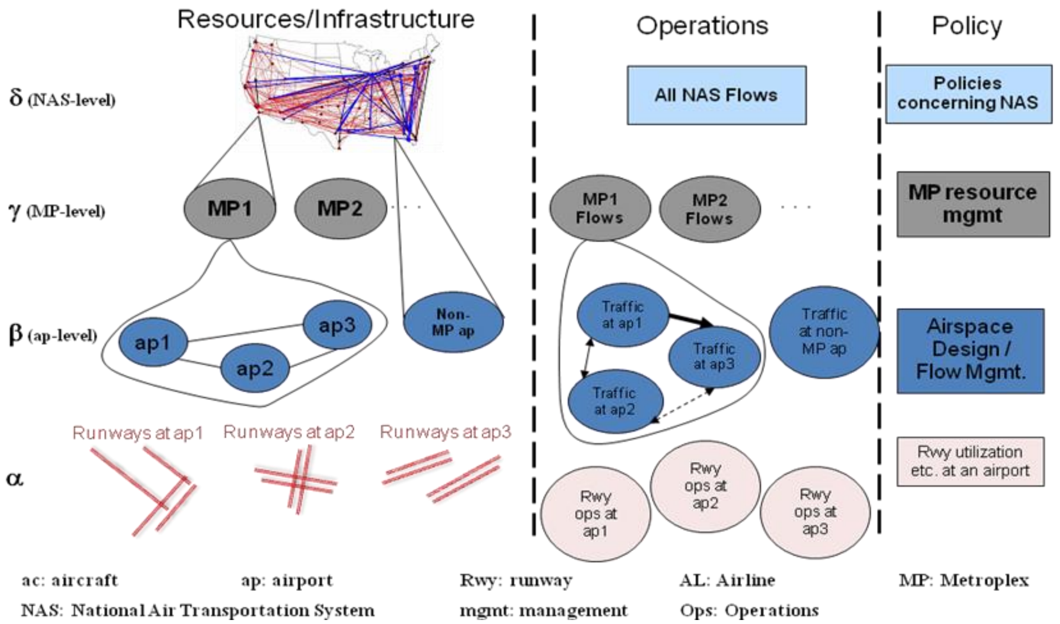


Fig. 2. System-of-Systems Depiction of Hierarchical Interactions in NAS

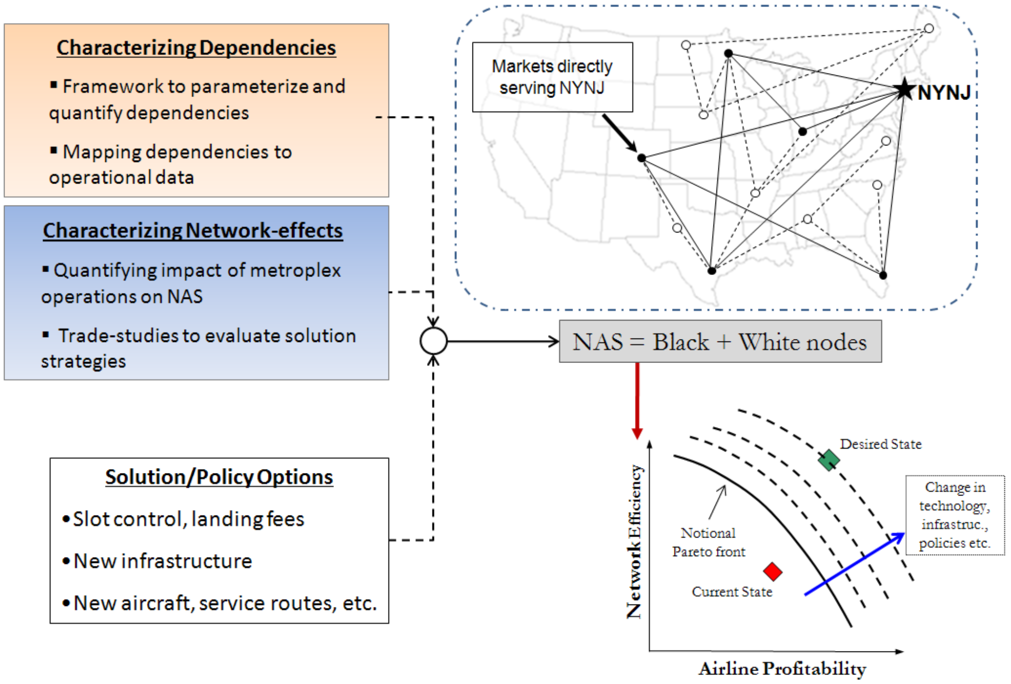


Fig. 3. Framework for integrated analysis of metroplex operational strategies

2.2 Characterization of Metroplex Dependencies

Metroplex dependencies occur across different dimensions between the constituent airports (Table 2). For example, passengers flying into LGA for their transatlantic flight from JFK require a means of transferring between these airports, possibly via a ground-link. In this case, JFK and LGA have an operational dependency to meet passenger needs. On the other hand, the NYNJ airports are owned and managed by the Port Authority of New York and New Jersey (PANYNJ) (ref. 5) As a result, these airports can now be considered as a collective entity that is trying to sustain itself economically while fulfilling its primary purpose of providing safe and reliable air transportation. That is, the NYNJ airports have economic and regulatory dependencies stemming from a single owner (PANYNJ). Other metroplexes will have different economic dependencies as their ownership and management structures vary. In either case, the controlling agencies enact regulations and policies that can affect all airports in a metroplex, and there can be strong cross-effects between the various dimensions of dependencies in the metroplex. For example, imposing slot-controls at one airport can alter the nature and form of operational and economic dependencies between the airports (different arrow-heads and solid and dashed-lines between NYNJ airports in Fig. 1).

Table 2. Dimensions of metroplex dependencies

Dimension	Example Attributes
Resource	Airport proximities, runway configurations, airspace geometry
Operational	Airport operations, airlines, capacities, passenger ground-link
Policy/Regulatory	Slot-controls, congestion-pricing, noise regulations, carbon credits
Economic	Ownership of airports, landing fees, lease of terminals

Airline operations contribute toward operational dependencies. Though these airports serve the same metropolitan area, airlines often consider them as separate markets. Consequently, airline competition drives operational redundancies by serving the same set of markets from multiple metroplex airports. Data was collected to identify markets with at least 200 annual flights to any of the three major NYNJ from 2000 to 2006.The chart in Fig. 4 shows the fraction of these markets that have service to all three NYNJ airports). Across the seven year span presented, this fraction was typically about 30% (though it has steadily risen since 2001). Appendix C examines another form of operational dependency at the individual airline level in NYNJ.

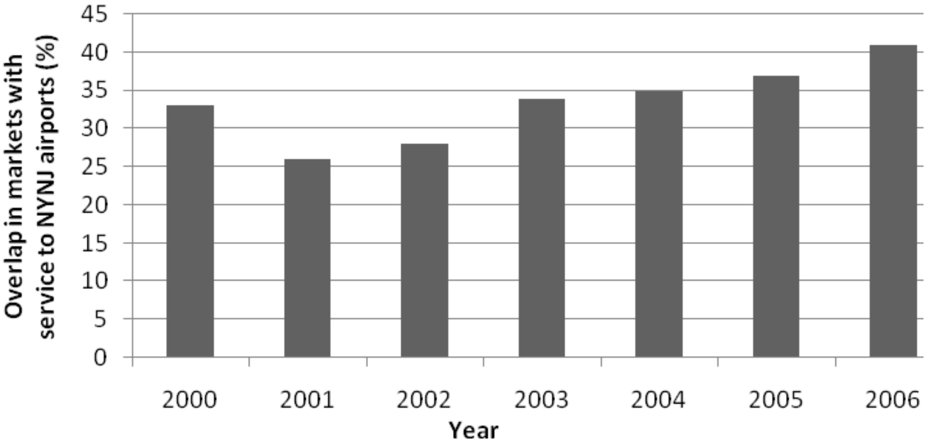


Fig. 4. Fraction of markets common to EWR, JFK and LGA in NYNJ (%)

2.2.2 Dependency metrics

Formulation of dependency metrics focused first on the resource and operational dimensions. Two types of dependency analyses were conducted to form metrics: constructive and observational/interpretive. Constructive analysis deals with the physical resources of a metroplex airport (e.g., runway configurations) and their influence on operations at the metroplex. Observational/Interpretive analysis uses operational data to determine the impact of dependencies (and their interaction) on metroplex operations.

2.2.2.1 Constructive Analysis: Coarse-grain dependency metrics

While it is clear that complicated dependencies may exist in the metroplex airspace, the airspace utilization is driven by the number of runways, their orientation, and airport proximity. Thus, a “course-grain” metric was developed to analyze how runways influence traffic patterns, congestion and delays, and also to serve as a qualitative study of how airport infrastructure influences its operations. Metroplex runway configuration, usage, and proximity were considered to develop these metrics.

A reference runway was defined within the metrics to capture the runway dependencies. The runway with the most traffic in a year was chosen as the reference runway; other runways are compared to develop the intermediate components of the dependency metrics (Table 3). Data for traffic on each runway was estimated from the FAA’s Aviation System Performance Metrics (ASPM) (ref. 6).

Table 3. Coarse-grain dependency metrics for runways at an airport, an airport, and a metroplex

Metric	Property	Definition
Runway length dependency ($d_{l(i)}$)	• Estimate of how runway length affects runway flight traffic volume	$d_{l(i)} =$ 1.0; when $l_i / l_{RR} < 0.6$ 0.9; when $0.6 \leq l_i / l_{RR} < 0.8$ 0.6; when $0.8 \leq l_i / l_{RR} < 0.9$ 0.3; when $0.9 \leq l_i / l_{RR}$
Runway orientation dependency ($d_{o(i)}$)	• Estimate of how runway orientation affects runway traffic volumes • Parallel runways have least interference and least dependency	$d_{o(i)} =$ 0.1; rwy$_i$ parallel to *RR* 1.0; rwy$_i$ perpendicular to *RR* 0.5; rwy$_i$ approx. 45° to *RR*
Runway proximity dependency ($d_{p(i)}$)	• Estimate of how runway proximity affects runway traffic volumes	$d_{p(i)}$ = (Distance to *RR*) / (max. runway to runway distance in airport) $= d_{i,RR} / \max.(d_{i,j})$
Runway Dependency Metric of runway *i* (RDM$_i$)	• Composite dependency metric for runway *i*	$\text{RDM}_i = d_{l(i)} * d_{o(i)} * d_{p(i)}$
Runway Dependency Metric of an airport (RDM-A)	• Composite of all runway dependencies at an airport • Traffic on each runway used as weights to capture the runway’s ‘contribution’	RDM-A = Σ (Rwy_ops_i * RDM$_i$) / (Total airport operations) where Rwy_ops_i depicts the number of flights operated from runway *i*
Runway Dependency Metric of a metroplex (RDM-M)	• Similar to RDM-A, but extended to a metroplex	RDM-M = Σ (Rwy_ops_i * RDM$_i$) / (Total metroplex operations)

RR – Reference Runway; rwy$_i$ – runway *i*; l_i – length of rwy$_i$; $d_{i,j}$ – distance between rwy$_i$ and rwy$_j$;
$d_{i,RR}$ – distance between centers of rwy$_i$ and Reference Runway (*RR*); $d_{l(i)}$ – length dependency of rwy$_i$;
$d_{o(i)}$ – orientation dependency of rwy$_i$; $d_{p(i)}$ – proximity dependency of rwy$_i$;
Rwy_ops_i – number of flights operated from rwy$_i$

The dependency metric of a runway was defined as the product of the individual metrics and was combined with the traffic on each runway to compute an airport's dependency based on the dependencies between its runways; hence the terms 'Runway Dependency Metric of a runway' and 'Runway Dependency Metric of an airport.' The airport metric was extended to a metroplex by treating a metroplex as a very large airport with its runways widely separated from one another. The reference runway in this case was the runway with the most traffic in the metroplex. A high value of the metric indicates larger degree of dependency.

2.2.2.2 Observational Dependency Analysis: Capacitated metroplex operations

In principle, by observing the recorded data on operations at metroplex airports, one could conceive of a capacity diagram for a metroplex similar to those constructed for airports. Airport capacity diagrams display departure operations vs. arrival operations and each data point in the diagram plots the number or arrivals and departures in a given hour period. The particulars of an airport are also used to generate boundary lines on the diagram above which operations are not deemed safe at that airport. Construction of a capacity diagram for a metroplex is conceivable but was beyond the scope of this study. However, an initial step in this direction was conducted via identification of the "boundary violations" for NYNJ by finding one hour periods when all three major airports were at, or over, their capacity boundaries. By examining these instances, the nature of operational dependencies between airports can be investigated more clearly in the future. The method and the NYNJ example are presented next.

The aforementioned ASPM database was queried to find "what was happening" at JFK during one hour periods when both LGA and EWR were at or over capacity in 2007 and 2008. There were four instances (out of 8760 possible one hour periods per year) in 2007 and two in 2008 when EWR and LGA were at or beyond their predetermined capacity limits while JFK was well below its capacity. The fact of very few occurrences is due to operations caps put in place at LGA in 2007; with operations caps, LGA is rarely in violation of its capacity limits.

The values in Table 4 depict the number of one hour periods in 2007 and 2008 when operations at LGA were below capacity, at the same time that EWR and JFK were at or beyond their nominal hourly capacities. The capacity curves for each of the three airports are shown in Fig. 5 (for 2007) and Fig. 6 (for 2008) along with the data for the instances mentioned in Table 4 (each instance is represented as a red circle). In 2007, there were 248 occurrences and 19 in particular that seemed to have reduced performance (actual ops less than scheduled), indicating an implication of operational dependency. When the other two major airports are capacitated, the operations-capped LGA still was prone to feeling the effects. In 2008, operations caps were also imposed at EWR and JFK; thus, you see only one occurrence in the entire year. This does not mean that dependencies are eliminated; just that the caps are working in terms of prohibiting airports from operating at levels beyond what is attainable. Capacity diagrams for a metroplex, similar to those used for every airport, can be very valuable for decision makers to develop effective policies to better manage the metroplex's resources. Details of the attempts to compute metroplex capacities and develop metroplex capacity diagrams are provided in the results section.

Table 4. Number of below-capacity hours at LGA while EWR and JFK were at or beyond their capacity

Year	**No. of total occurrences**	**Actual flights (arr/dep) were fewer than scheduled by at least 8**	
		No. of occurrences	*Time of occurrence*
2007	248	19	3PM and 4PM; Mostly Jul. and Aug.
2008	1	0	--

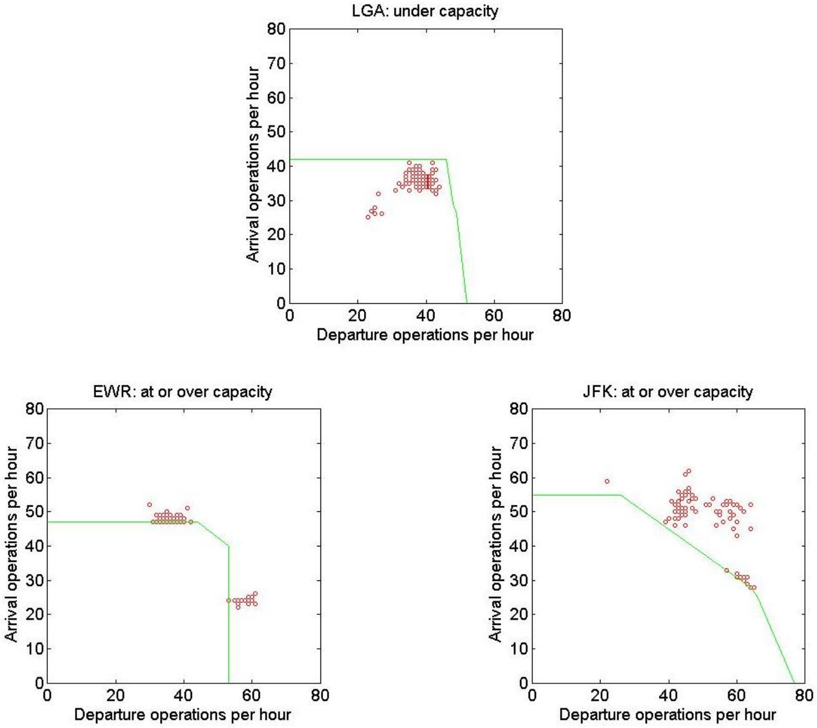


Fig. 5. Instances in 2007 when LGA was operating below its normal hourly capacity while EWR and JFK were at or beyond their normal capacities. Numerical values not shown for clarity.

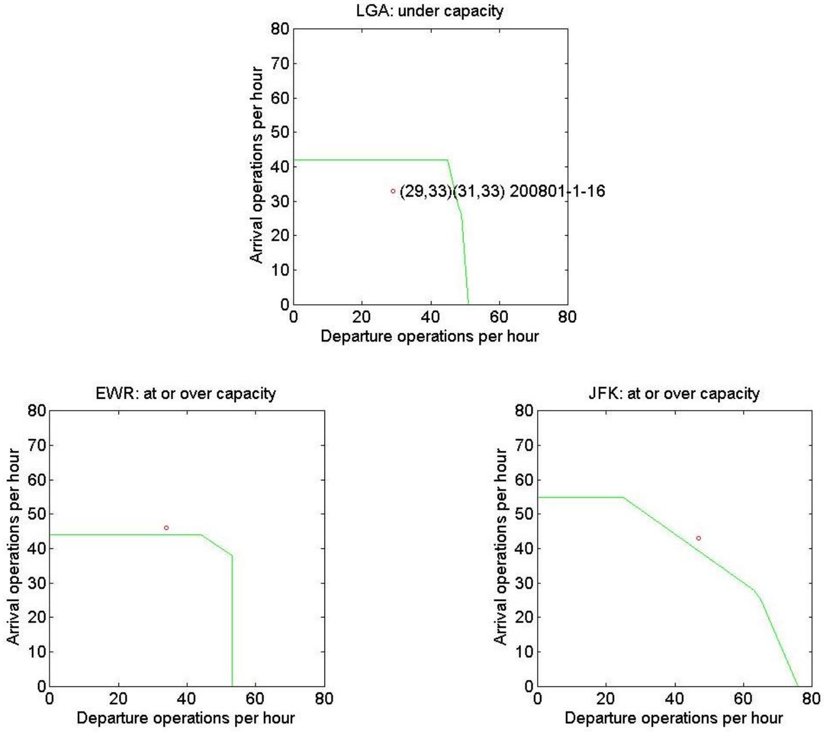


Fig. 6. In 2008, there was only one instance when EWR and JFK were at or beyond their normal capacities (LGA was below capacity at this instance). Numerical values in LGA data point are: (Actual Arrivals, Actual Departures)(Scheduled Arrivals, Scheduled Departures) YearMonth-Day-Hour of the day

2.3 Characterization of Network-effects: Delay prediction model

As illustrated notionally in Fig.1, the external interactions associated with a metroplex are primarily via the markets served by the airlines. Changes to the flights departing and arriving from a metroplex have consequences in the NAS network. GMU teammates investigated the operations of a conceptual benevolent monopolist airline operating at one of the three major NYNJ airports. Such an airline has a monopoly at this airport but is ‘non-selfish’ in the sense that it optimizes its schedules to increase its profits while satisfying as much of the demand as possible. Optimized schedules were developed by GMU for this Benevolent Monopolist Airline (BMA) under different scenarios of fuel price and capacity limits at the metroplex airport. The desire to know the network-wide implications of such a new schedule necessitates the need for a compact model of network performance.

The profit from these optimized schedules comprises airline profitability in the Pareto chart of Fig. 3. In order to understand the interaction of these schedules with the composite flight network (described above), and to study the impact of BMA’s decisions on the performance of the NAS, a regression-based delay prediction model was developed (ref. 9). The model estimates the number of flights delayed at an airport based on its ‘role’ in the composite flight network—a delayed flight is an arrival or departure that was delayed by more than 15 min. Statistical properties of the composite network were measured via tools from network theory (ref. 7, 8 and 9). The model was based on parameters describing the different properties of the service network’s topology: the criticality of an airport (a node) in preventing or causing cascading delays, the importance of the connectivity between two airports (a link) and how well-connected an airport is (a regional airport, hub or a super-hub). The population served by an airport was also included as a variable in the model to understand its role in transforming an airport from a regional airport status to a hub and/or a super-hub. A glossary of the network parameters used in the model is given in Appendix E.

Equation (1) describes the general structure of the delay-prediction model. The variables in bold-type font are various parameters representing an airport’s network statistics and other characteristics. All variables were normalized to reduce difficulties caused by differences in scale with the statistics of the airport with the highest number of delays. For example, Chicago O’Hare International (ORD) had the highest number of delays in 2007 (ref. 6). Therefore, to develop a model for estimating the number of delayed flights at an airport in 2007 all variables were normalized with respect to ORD’s network statistics (Eq. (2)).

$$\begin{aligned} \mathit{Delayed\ Ops} = {} & (\mathbf{constant} + c_{dom} * \mathbf{dom\_traffic} + c_{cc} * \mathbf{clus\_coeff} + c_{evc} * \mathbf{eig\_vec\_centrality} \\ & + c_{pop} * \mathbf{population} + c_{intl} * \mathbf{international})^2 * n_{ref} \end{aligned} \tag{1}$$

$$\begin{aligned} \mathit{Delayed\ Ops} = {} & (0.05075 + 0.83866 * \mathbf{dom\_traffic} - 0.00474 * \mathbf{clus\_coeff} + 0.13504 * \mathbf{eig\_vec\_centrality} \\ & + 0.10148 * \mathbf{population} + 0.03273 * \mathbf{international})^2 * 219121 \end{aligned} \tag{2}$$

2.3.1 Data collection, assumptions and model validation

To develop the model in Eq. 2, data was collected from the Bureau of Transportation Statistics (BTS) database for all domestic airports in 2007 (ref. 10). Examples of data collected include: the number of arrivals and departures between any two airports, the number of arrival and departure delays at an airport, and the number of destinations directly connected to an airport. The service network thus generated was a composite of the service networks of all airlines; the focus of this model was on the overall connectivity between airports rather than on airline competition for the market share at these airports. The population data was obtained from the U.S. 2000 Census Survey (ref. 11); the population within a sixty mile radius of an airport was considered to be ‘served’ by the airport.

There are over 1,200 airports in the U.S. and the computational challenge to analyze the interactions between all these airports was found to be formidable. Further, only about 25% of these airports account for the entire domestic flight traffic. Consequently, a set of 268 airports was chosen to conduct all analyses. The set was compiled by analyzing the U.S.-carriers-only T-100 domestic segment data from BTS for the years 2002 to 2007 (ref. 10). An individual list of airports contributing to 94% of total annual domestic commercial flights was compiled for each of the years from 2002 to 2007. Those airports that appeared in at least four out of these six years were chosen to form the set of 268 airports. This final set presented a much smaller network to analyze while contributing to at least 94% of domestic commercial traffic. This has strong implications on all analyses in that this set can be considered as a ‘surrogate’ to the NAS for studying the various policy and operational scenarios—only a few airports ‘making’ or ‘breaking’ a regulation or operational change with nation-wide impacts affords policy makers the freedom to focus on only this small set rather than the entire NAS. Such a set also loosely follows the logic behind more well-known datasets such as OEP 35, OPSNET 45, and LMINET 102 in that all of them present a smaller set of variables in order to focus on broad, sweeping impacts.

The model in Eq. (2) can be employed to estimate the number of delayed flights at an airport in a year, as long as a new composite service network is ‘similar’ in its topological structure to the base network used to generate the model. For example, the new network can be a variation of the base network in terms of small changes to the number of markets served and traffic on each route, the population using an airport, the fleet mix on a route, and so on. These new networks can be candidate solutions “designed” to achieve improved passenger/flight throughput, higher revenue/profits for airlines and airports, reduced delays at selected airports, etc., and Eq. (2) can be employed to predict the number of delayed operations at each of the airports within the new networks.

The graph in Fig. 7 is a comparison between actual data and the values predicted by the delay-prediction model for the number of flight delays at the set of 268 airports for 2007. The small circles denote airports, with some of them identified individually as belonging to NYNJ (triangle), NorCal (bigger circle) and SoCal (diamond) metroplexes. A ±5% error band is also shown in the graphic to enhance the comprehension of the model’s behavior. On the whole, the model presents a tool with satisfactory error levels to estimate the number of delayed flights at the major airports. This is a very important result in that the model can be employed to evaluate the various candidate networks from the perspective of various stakeholders—higher passenger and flight throughput, reduced congestion and delays, smaller turn-around times for flights etc. for airports; operations and schedules yielding increased profits, higher load-factors, bigger market-share etc. for airlines, and so on.

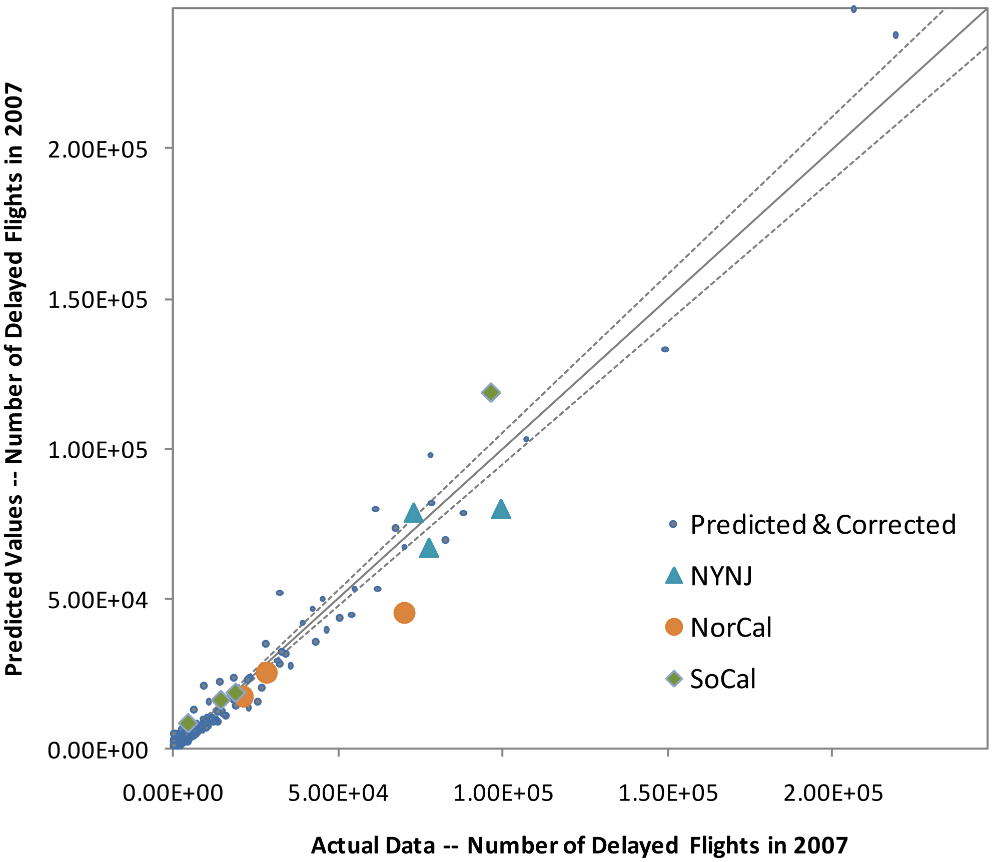


Fig. 7. Validation of annual airport delay-prediction model for 2007 against actual data

3 Results

3.1 Characterization of dependencies

3.1.1 Study of analogous metroplexes

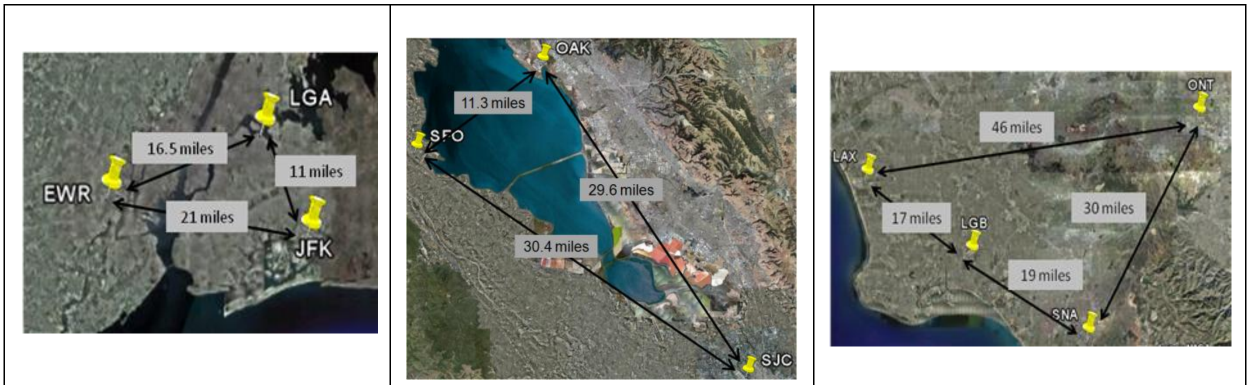
In addition to NYNJ, several other metroplexes were analyzed to understand how dependencies differ from one metroplex to another and as a precursor to study of how generic solutions to minimize congestion and delays perform for different metroplexes. These other metroplexes included: Northern California (SFO/SJC/OAK), Southern California (LAX/LGB/ONT/SNA), Chicago (ORD/MDW/MKE), Miami (MIA/FLL/PBI), and Washington, DC (DCA/IAD/BWI).

Data were collected to compare these metroplexes across the different dimensions of dependencies (a subset of information gathered is shown in Table 5), including: 1) operational issues—proximity of metroplex airports, runway configurations (length and direction), operational capacity (number of flights, passenger throughput, gates, etc.); 2) economic issues—ownership of the airports (single/multiple, public/private); 3) regulatory/policy issues—the TRACON they belong to, airport capacity limits, etc.; and 4) type of airlines operating at the metroplex (domestic/international, legacy/regional etc.).

Table 5. Data fields employed in comparing different metroplexes

Data fields	NYNJ	NorCal	Chicago
1. Ownership of airports	Port Authority of New York and New Jersey	SFO—City & County of San Francisco; OAK—Port of Oakland; SJC—City of San Jose	ORD & MDW—City of Chicago; MKE—Milwaukee County
2. TRACON	Ronkonkoma, NY (ZNY)	Sacramento, CA (NCT)	ORD & MDW—Elgin, IL (C90); MKE—Milwaukee, WI
3. Airport proximities (mi.)	JFK-EWR (21); JFK-LGA (11); EWR-LGA (16.5)	SFO-OAK (11.3); SFO-SJC (30.4); OAK-SJC (29.6)	ORD-MDW (15.5); ORD-MKE (67); MDW-MKE (80.8)
4. No. of gates	JFK (106), EWR (103), LGA (74)	SFO (94), OAK (30), SJC (32)	ORD (178), MDW (43), MKE (45)
5. No. of flights (domestic and intl. flights of US carriers only in 2007)	JFK (326,973); EWR (365,2); LGA (335,89)	SFO (282,143); OAK (164,819) SJC (118,504);	ORD (799,204); MDW (194,284); MKE (145,722)

After preliminary analysis, Northern California (NorCal) and Southern California (SoCal) metroplexes were chosen for further study. An initial analysis showed that while both NorCal and SoCal differed from NYNJ in having multiple entities with ownership of the airports, NorCal was similar to NYNJ in the geographical layout of an approximate triangle (Fig. 8).



a. New York/New Jersey metroplex

b. Northern California metroplex

c. Southern California metroplex

Fig. 8. Schematic of three metroplexes comparing positioning of their constituent airports

The network of airports connected to NorCal and SoCal was analyzed and compared to NYNJ (Table 6). For this purpose, composites of service networks of all airlines servicing the metroplexes were generated. Only those airports that had at least 10 flights to and from these metroplexes from June to August 2007 were included (first column in Table 6). NYNJ airports had about 34% of overlap in the markets served (Fig. 4), as did NorCal, but the overlap was only 8% for SoCal for the same period. This time period was chosen to study the operations at other metroplexes when NYNJ airports were experiencing the worst delays and congestion in recent years (ref. 12). The results of this comparative study showed that NorCal was more similar to NYNJ in terms of network cohesiveness (average clustering coefficient of metroplex airports—third column in Table 6) while SoCal was more similar in terms of network size (113 airports inclusive of metroplex airports) for NYNJ compared to 103 for SoCal. NorCal was chosen as the analogue metroplex due to the similarity in relative position of its airports to NYNJ and also owing to the extent of market overlap amongst its airports. For more details about the different network parameters in Table 6, refer to Appendix E.

Table 6. Network analysis of different metroplexes – June–August, 2007

	No. of airports in the network	Avg. degree	Avg. Clust. Coeff. (CC)	Avg. deg. of metroplex airports	Avg. CC of metroplex airports
NYNJ	113	30	0.74	61	0.48
NorCal	85	21	0.64	38	0.44
SoCal.	103	26	0.61	49	0.59

3.1.2 Coarse-grain dependency metrics: runway-dependency metrics

Results from computing coarse-grain dependency metrics via the two formulas in Sec. 2.2.2 are shown in Table 7 and Table 8. The metrics were computed for a six year period from 2002 to 2007. In addition to the NYNJ and NorCal metroplexes, the team also chose Hartsfield-Jackson Atlanta International (ATL) and Denver International (DEN) airports as part of the study to understand how the metric reflects reality at an airport that dominates the local TRACON airspace. ATL and DEN each have operations comparable in volume to JFK and SFO (NYNJ and NorCal metroplexes, respectively), each have multiple airlines operating out of them, and each (especially ATL) face problems of delays and congestion.

Table 7. Runway dependency metrics for NYNJ and NorCal

Year	**Metroplex traffic in 2007**		**Reference Runway**		**RDM-M (d_l*d_o*d_p)**	
	NYNJ	NorCal	NYNJ	NorCal	NYNJ	NorCal
2007	1,233,473	697,489	JFK 31L	SFO 28R	0.359	0.08
2006	1,184,445	678,501	EWR 22R	SFO 28L	0.191	0.085
2005	1,141,250	666,660	EWR 22L	SFO 28R	0.177	0.08
2004	1,113,671	673,929	EWR 22R	SFO 28R	0.199	0.08
2003	1,016,652	619,400	EWR 22L	SFO 28R	0.197	0.062
2002	913,420	620,531	EWR 22L	SFO 28R	0.206	N/A

Table 8. Runway dependency metrics for ATL and DEN

Year	**Airport traffic in 2007**		**Reference Runway**		**RDM-A (d_l*d_o*d_p)**	
	ATL	DEN	ATL	DEN	ATL	DEN
2007	962,390	594,001	ATL 27R	DEN 17R	0.024	0.051
2006	945,018	570,757	ATL 27R	DEN 8	0.024	0.103
2005	945,946	535,267	ATL 27R	DEN 8	0.049	0.088
2004	936,677	534,661	ATL 27R	DEN 17R	0.049	0.066
2003	874,647	474,688	ATL 27R	DEN 17R	0.049	0.061
2002	836,262	397,938	ATL 27R	DEN 17R	0.049	0.058

3.1.2.1 Comparison of dependencies in NYNJ and NorCal via dependency metrics

From Table 7 it can be observed that dependencies at NYNJ are larger than those at NorCal, driven by greater traffic and fewer parallel runways than NorCal. Further, there are two major domestic and international hub airports in NYNJ (EWR and JFK) compared to only one in NorCal (SFO), resulting in more dependency interactions between the constituent airports. Metric values also varied with the choice of reference runway (RR). For NYNJ, from 2002 to 2006, the RR was located at EWR, shifting to JFK in 2007. This was due to a significant increase in JFK traffic in 2007. As a result, the runway proximity dependency became a major factor in affecting this change (Table 3). Further analysis needs to be conducted to understand if this mechanism influenced dependencies at NYNJ in 2008 and 2009 as well. For NorCal, ASPM data was not available to estimate operations per runway for OAK and SJC in 2002, and as a result, the corresponding dependency metrics for NorCal were significantly different from other years in the period of study. Consequently, the analysis period for NorCal starts from 2003.

In the case of non-metroplex airports, the dependency metrics (though very small in magnitude compared to NYNJ) decreased for ATL from 2005 to 2006 (Table 8). This decrease was due to the addition of runways 10/28 at ATL in 2006, and indicates that runways were less dependent on each other starting from 2006, or, operations at ATL were more 'decoupled' from 2006. On the other hand, there was some variation in the dependencies at DEN from 2005 to 2007, peaking in 2006. A likely reason is that a new runway was added to DEN in 2004, prompting a realignment of traffic across the various runways—runway 8 was the RR for 2005 and 2006 compared to runway 17R for the remaining period of this analysis. Analysis of 2008 data has to be completed to verify if this stable trend continued. An interesting observation was the apparent similarity between NorCal and DEN (Table 7 and Table 8). This is most likely due to the fact that SFO is the most dominant airport in terms of volume of operations in NorCal (as opposed to NYNJ where both EWR and JFK have similar number of operations), causing NorCal to be influenced by SFO and thereby resembling a hub-airport. Further, SFO's runway configurations are more similar to DEN than ATL (where all runways are parallel to one another), and has resulted in NorCal being more similar to DEN than ATL.

These results illustrate the RDM-M metric appears to reflect operational changes that affect dependencies; however, much work remains in understanding dependencies both at an airport and at a metroplex level. Alternative ways to quantify dependencies are currently being explored, such as redefining the metrics without the use of a reference runway, or using a different definition for a reference runway.

3.1.3 Observational dependency analysis

3.1.3.1 Computing metroplex capacity

To compute metroplex capacity, FAA Circular AC: 150/5060-5 was used (ref. 13). The Circular was issued to compute airport capacities and delays for different runway configurations for planning purposes. But this document dates back to 1983, and its applicability had to be validated for present-day airport operations. LGA was chosen as the airport for validating this document by comparing traffic data obtained from the BTS database for 2002 to 2007 (Table 9) (ref. 10). The annual traffic projections for LGA using the Circular were widely different from historic data. While there were no details provided in the Circular as to how the empirical relations between runway configurations and airport traffic were developed, it is assumed that they were based on operational and safety standards in place in 1983 (date of the Circular). Refer to Appendix A for more details on how the document was employed in Table 9.

Table 9. Validation of FAA Circular for LGA from 2002–2007

Year	**LGA Traffic (T-100)**	**ASV projections from Circular**
2007	377,077	225,000
2006	385,542	225,000
2005	384,906	225,000
2004	385,122	225,000
2003	358,248	225,000
2002	280,575	225,000

The team attempted to compute metroplex-wide annual capacity using the Circular by treating a metroplex as a very large airport with widely separated runways—NYNJ was chosen as the test case. The sum total of the traffic at its major airports was compared with the Circular's projections, but poor results similar to the LGA case were obtained. This implies that though the Circular offers a simple methodology to determine an airport's annual capacity, it cannot be directly applied to a metroplex as demonstrated. This is in addition to the earlier stated fact that the Circular is based on operational standards and assumptions that are not applicable to current day operations. That is, the factors driving a metroplex's operations are much more complicated than those at an airport. This underscores the earlier hypothesis that dependencies play a very important role and it is imperative to gain a good understanding of them to develop strategies for enhancing the metroplex's operational performance. Therefore, any methodology to determine a performance metric such as a metroplex's capacity should incorporate its dependencies. Further, the implications of such a methodology are far and many: metroplex planners would have better decision-support in attempting to increase capacity, reduce congestion, reduce operational costs and expenditure (new operational procedures, installing new equipment, etc.), and so on. Refer to Appendix B for more details on how the Circular was used to compute the annual capacity values for LGA and NYNJ.

3.1.3.2 Correlation between dependency metrics and metroplex traffic data

The graphic in Fig. 9 shows how the runway dependency metrics for NYNJ varied with traffic from 2002 to 2007. Traffic data for the three major NYNJ airports were used here and were obtained from the BTS online database. The traffic data were normalized relative to the 2002 values. The same results for NorCal are shown in Fig. 10.

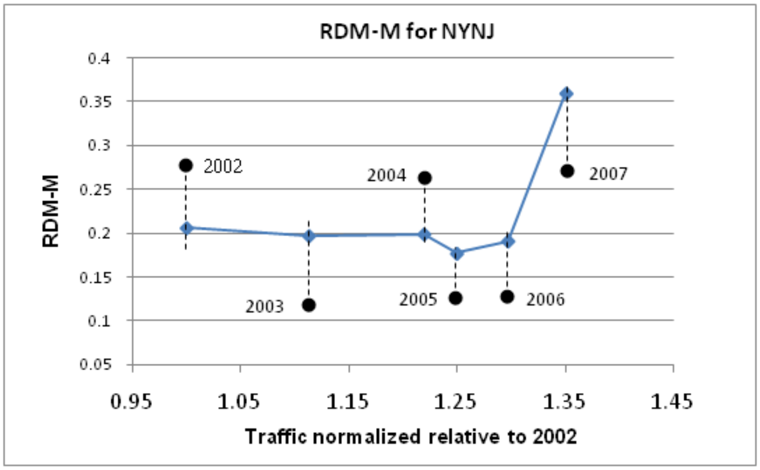


Fig. 9. Correlation between runway dependency metric for NYNJ and traffic data

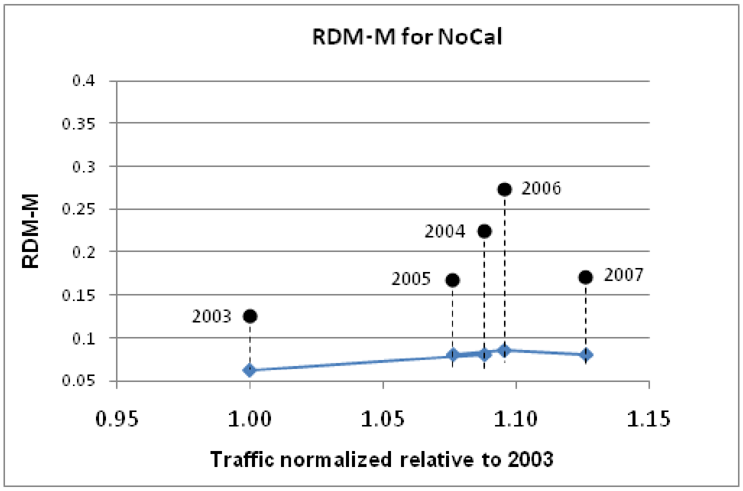


Fig. 10. Correlation between runway dependency metric for NorCal and traffic data

The purpose of this correlation analysis was to determine if one could use the dependency metrics to measure changes in dependencies caused by changes in metroplex operations. From Fig. 9 it can be observed that while the traffic increased by about 20% from 2002 to 2004, the metric did not change significantly. Also, for a 10% increase in traffic from 2004 to 2006 (relative to 2002) the change in the metric was largely insignificant (except for a slight decrease in 2005). But from 2006 to 2007, for a 5% increase in traffic, the change in the metric was very significant. The shift in reference runway from EWR to JFK caused this change, as observed in Table 7. For NorCal, the data for 2002 was excluded due to difficulties in estimating the traffic per runway (Sec. 3.1.2). There was a slight decrease in traffic from 2004 to 2005 (Table 7). The correlation studies for NorCal did not elicit any discernible pattern. Again, this could be a result of the definitions of the dependency metrics, or other factors not accounted for. Similar results were observed in the case of ATL and DEN. Overall, it appears that the metric does have correlative value when there is a shift in the reference runway, but less so for simple (and modest) growth in traffic.

3.2 Characterization of Network-effects

3.2.1 Trade-studies: Optimized operations of Benevolent Monopolistic Airline

The impact of altering airline service networks connecting a metroplex to other airports in the NAS was analyzed to determine the impact on the overall performance of the NAS. Trade-studies were conducted to determine how changes in an airline's network properties affect its profitability on one hand, and system delays on the other (depicted by the notional Pareto chart in the lower right hand corner of Fig. 3). The delay-predictor model described in Sec. 2.3 was used to compute the number of delayed operations. Profits from the optimized schedules of the Benevolent Monopolist Airline (BMA) developed by the GMU team were used to represent airline profitability. The optimized schedules of BMA when operating at JFK are shown in Table 10. Optimized schedules were developed for three scenarios of 15 minute airport capacities for arrivals and departures at a fixed value of fuel price for the third quarter of 2007, 2008 and 2009. Similar schedules for EWR and LGA are shown in tables Table 11 and Table 12, respectively.

Table 10. Summary of optimized schedules for BMA for 3rd quarter in 2007, 2008 and 2009 at JFK

YearQuarter	**2007Q3**			**2008Q3**			**2009Q3**		
Fuel Price ($/gal.)	2.06			3.53			1.92		
Operations per 15 min	18	20	24	18	20	24	18	20	24
Markets	46	46	46	47	45	46	53	53	53
No. of daily ops at JFK	560	614	622	530	530	560	606	666	686
Profit ($M/Day)	3.825	4.748	4.870	4.030	4.089	4.137	4.153	4.667	4.766

Table 11. Summary of optimized schedules for BMA for 3rd quarter in 2007, 2008 and 2009 at EWR

YearQuarter	**2007Q3**			**2008Q3**			**2009Q3**		
Fuel Price ($/gal.)	2.06			3.53			1.92		
Operations per 15 min	18	20	24	18	20	24	18	20	24
Markets	74	73	76	61	63	63	71	73	73
No. of daily ops at EWR	706	740	794	610	646	664	668	716	738
Profit ($M/Day)	5.774	5.884	5.991	5.123	5.347	5.410	4.514	4.783	4.842

Table 12. Summary of optimized schedules for BMA for 3rd quarter in 2007, 2008 and 2009 at LGA

YearQuarter	**2007Q3**			**2008Q3**			**2009Q3**		
Fuel Price ($/gal.)	2.06			3.53			1.92		
Operations per 15 min	16	18	20	16	18	20	16	18	20
Markets	59	59	61	58	59	59	60	60	60
No. of daily ops at LGA	784	834	862	700	718	726	764	810	832
Profit ($M/Day)	3.981	4.087	4.119	3.178	3.205	3.219	3.860	3.938	3.968

The optimized schedules in Table 10 through Table 12 are for a quarter of a year, whereas the delay-predictor model in Eq. (1) was developed to compute annual delayed operations. As such, the model was modified to compute the number of quarterly delays. The model for 2007Q3 has an R^2 value of 0.96, 2008Q3 has an R^2 value of 0.95 and 2009Q3 has an R^2 value of 0.94 (equations (3), (4) and (5), respectively).

$$\begin{aligned} \textit{Delayed Ops} = (&0.05131 + 0.75656 * \mathbf{dom\_traffic} - 0.00570 * \mathbf{clus\_coeff} + 0.14713 * \mathbf{eig\_vec\_centrality} \\ &+ 0.09324 * \mathbf{population} + 0.01957 * \mathbf{international})^2 * 62474 \end{aligned} \tag{3}$$

$$\mathit{Delayed\ Ops} = (0.02037 + 0.71607 * \mathbf{dom\_traffic} + 0.03140 * \mathbf{clus\_coeff} + 0.17373 * \mathbf{eig\_vec\_centrality} + 0.11231 * \mathbf{population} + 0.09207 * \mathbf{international})^2 * 44948 \tag{4}$$

$$\mathit{Delayed\ Ops} = (0.03147 + 0.71625 * \mathbf{dom\_traffic} + 0.01757 * \mathbf{clus\_coeff} + 0.15094 * \mathbf{eig\_vec\_centrality} + 0.05554 * \mathbf{population} + 0.04405 * \mathbf{international})^2 * 53295 \tag{5}$$

Results of the trade-studies between NAS-wide delays and BMA's profitability when operating from JFK are shown in Fig. 11. The number of delayed operations for the different optimized schedules did not differ significantly between each 15-minute capacity scenario for the third quarters of 2007 and 2009. This indicates that changes in BMA's schedules and the resulting changes to the composite service network were not of significant magnitude to have a marked impact on NAS-wide operations. This could also be a result of the structure of the delay-predictor model. As described earlier, the model was most sensitive to changes in flight frequency between airports, and predicts a greater number of delayed flights when there is an increase in an airport's flight traffic (equations (3) to (5)). Consequently, due to the increase in BMA's schedules at JFK (Table 10), the model predicted a corresponding increase in the number of delayed flights. Since BMA's monopoly was restricted to only one airport (JFK here) operations at other airports in the NAS were not so affected as to result in a substantial NAS-wide increase in delays. This is more evident in Fig. 12, which compares the number of delayed flights at JFK against BMA's profitability; an increase in BMA's schedules at JFK resulted in a greater number of delayed flights. There was a small reduction in the number of delayed flights when capacity was increased from 18 to 20 flights per 15 minutes at JFK in 2008 due to the fact that the number of BMA's operations at JFK stayed the same for these two scenarios. The apparent reduction can be attributed to 1) the change in schedules to some of the markets served by BMA, which slightly affected the composite service network properties, leading to a reduction in delays, or 2) the uncertainty in the delay-prediction model. Further study will illuminate the relative contribution of these two factors.

Results from similar trade-studies for EWR and LGA for the third quarters of 2007, 2008 and 2009 are shown in Fig. 13 and Fig. 14. The steeper slopes for EWR and LGA indicate a more pronounced (negative) correlation between airline profitability and delayed operations at those airports. To explore further, BMA's schedules were also analyzed to compute the change in airline profit vs. the change in the number of delays (Fig. 15). The purpose of this study was to understand the 'cost' of BMA's profitability. The change in delays and profit were computed with respect to the smallest per hour (or per 15 minute) airport capacity scenario at each airport—72 for JFK and EWR and 64 for LGA. It can be observed from Fig. 15 that in 2007, BMA's operations at LGA incurred the highest number of delays for every $1 million profit. And overall, EWR had the highest number of delayed flights for every $1 million profit of BMA, suggesting that the same kind of operational decisions by an airline can lead to different results for the stakeholders (airline and airport here). That is, certain policies or actions can be more effective at particular airports, and these same policies or actions can be detrimental at others. For the results in Fig. 15, JFK is the most favorable candidate in terms of the airline being profitable while causing fewer delayed flights compared to the other two airports—within the same metroplex, there is an asymmetry between the airports with respect to the outcome from implementing similar strategies.

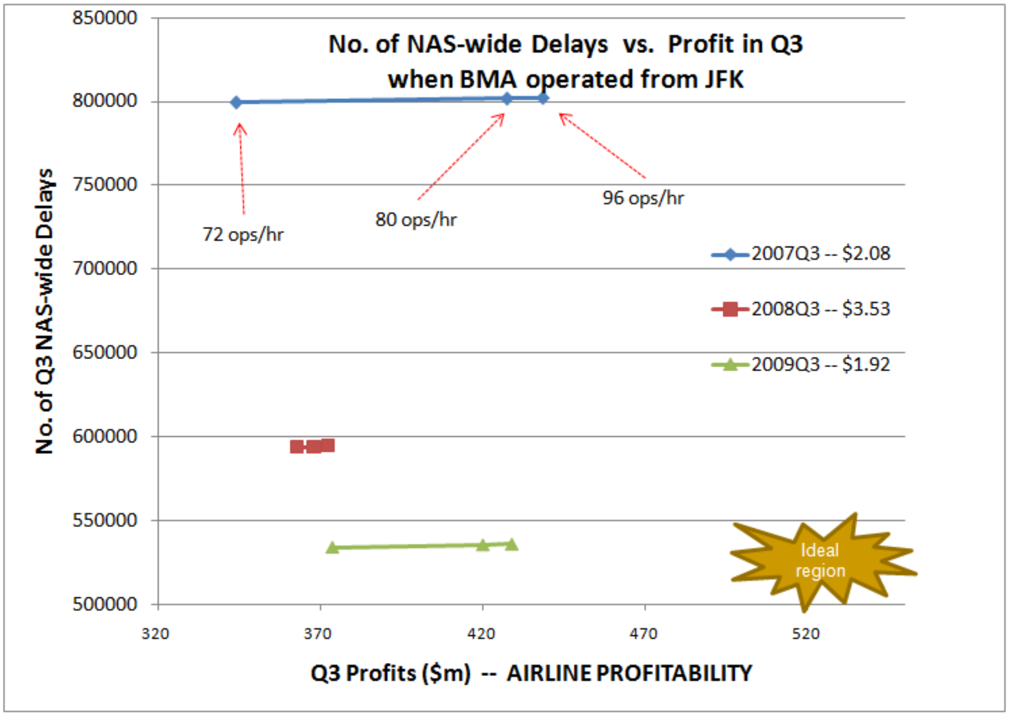


Fig. 11. Trade-studies to analyze impact of BMA's service on its profitability and NAS-wide delays when operating from JFK

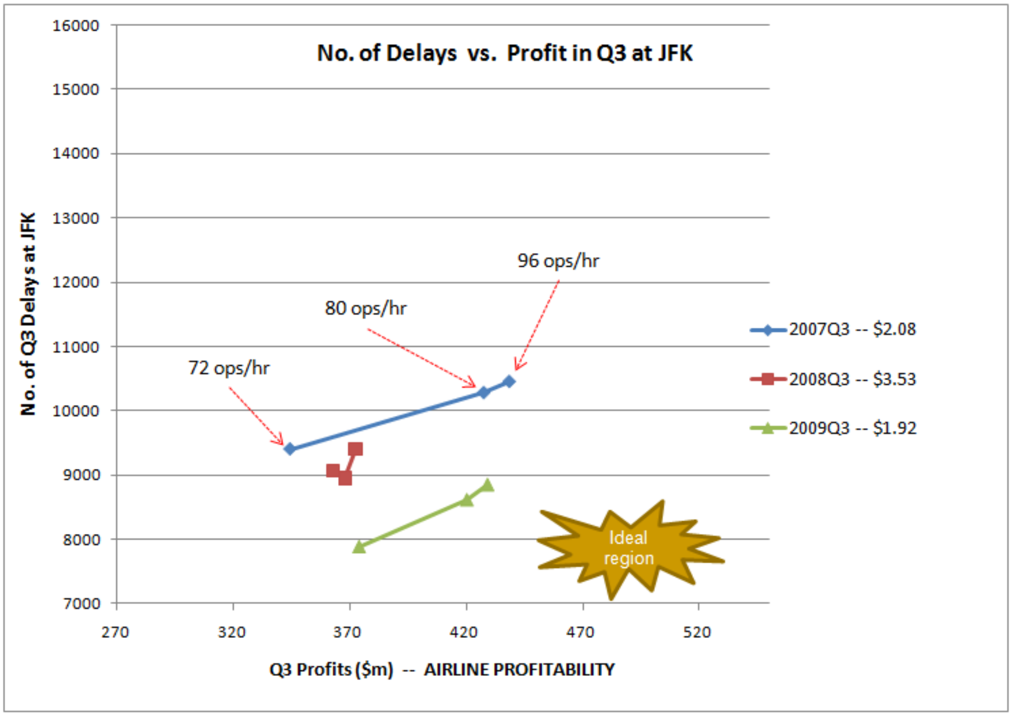


Fig. 12. Trade-studies to analyze impact of BMA's service on its profitability and JFK delays when operating from JFK

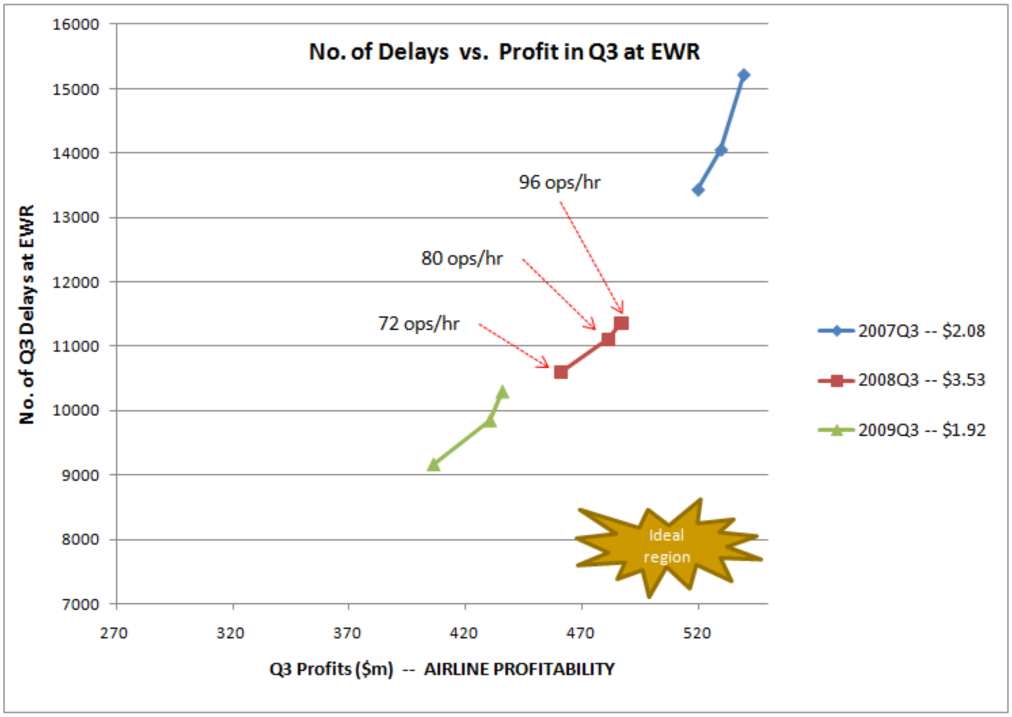


Fig. 13. Trade-studies to analyze impact of BMA's service on its profitability and EWR delays when operating from EWR

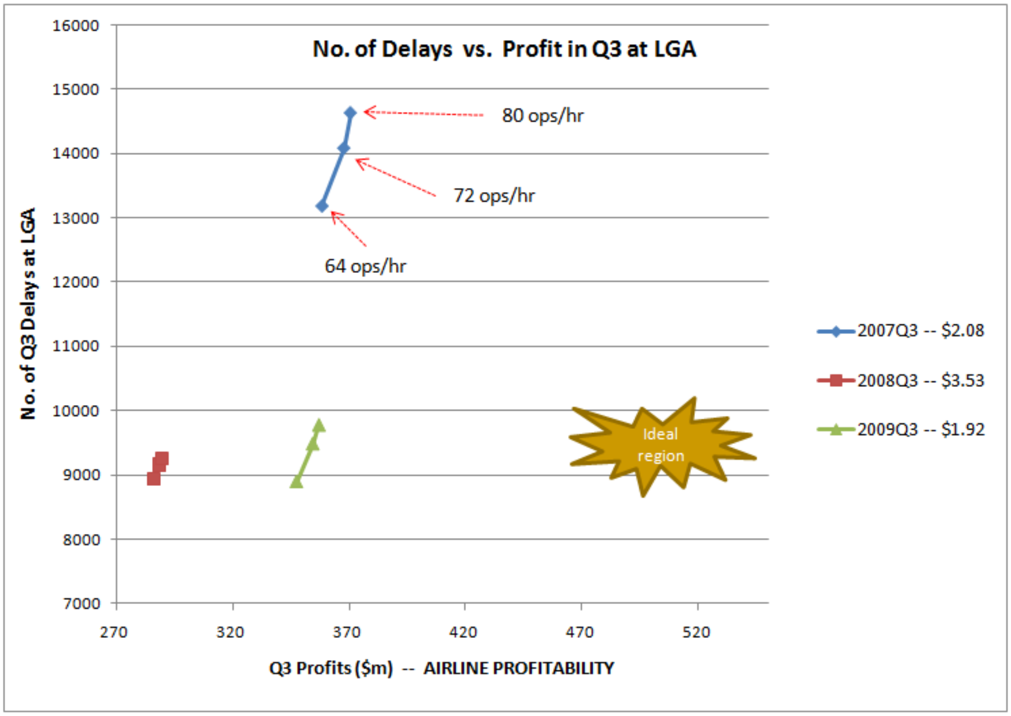
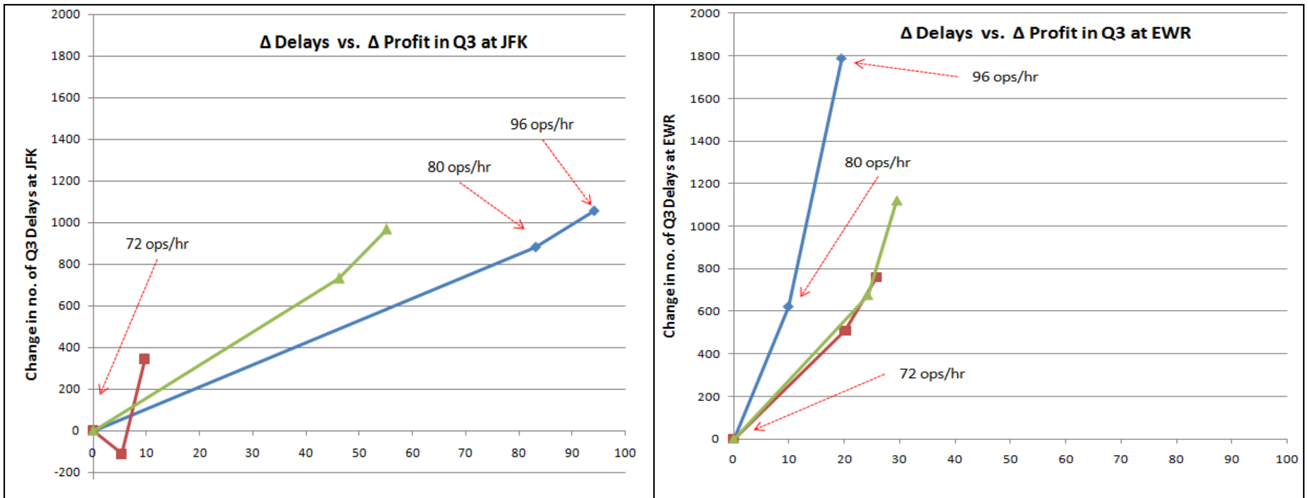
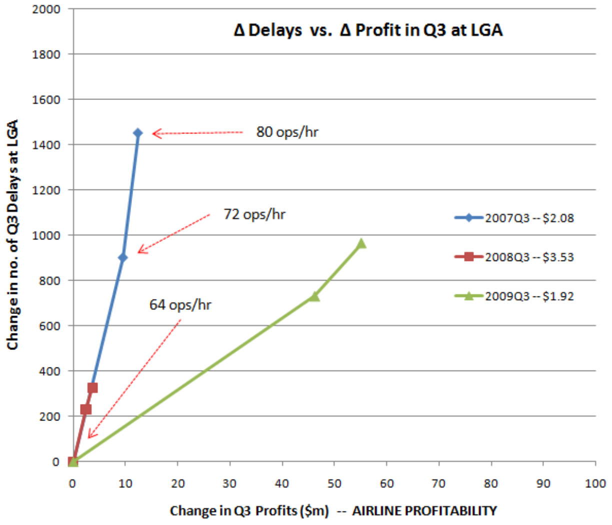


Fig. 14. Trade-studies to analyze impact of BMA's service on its profitability and LGA delays when operating from LGA



a. BMA operating from JFK

b. BMA operating from EWR



c. BMA operating from LGA

Fig. 15. Trade-studies to analyze change in number of delayed flights with change in BMA's profitability

4 Further Work

4.1 Improved delay-prediction models

The delay models described earlier suffered from certain disadvantages. For example, the models did not include aircraft size as a predictor variable. The size of an aircraft affects separation requirements, which in turn affect the arrival and departure rates at an airport. Further, each aircraft size comes with advantages and disadvantages. Smaller aircraft feature shorter gate turn-around times and carry lower overhead costs, but are severely hampered in terms of the passenger volume they can transport. This can be mitigated only by using a large number of these aircraft, which in turn can saturate the airspace, leading to congestion and delays. On the other hand, larger aircraft can transport large volume of passengers but require wider separation distances, thereby reducing an airport's arrival and departure rates. Also, not all airports can handle large aircraft (heavy or super-heavy class). In addition to aircraft size, the models also exclude factors such as load factor, airport dependencies (either in terms of the metrics used to compute them as described earlier or in some other form), local weather, and so on. This section describes efforts currently underway to incorporate some of these factors and thereby improve the fidelity of the models.

4.1.1 Estimation of monthly delays and effects of weather

The delay-prediction models described earlier were developed to estimate the number of annual and quarterly delays at an airport. Therefore, as a first step, the models are being modified to estimate the number of monthly airport delays, the premise being that an airport's traffic is not uniform throughout the year or a quarter—the busiest times of travel are the summer months of June through August and the holiday season from October to January, excluding occasional pockets of increased travel such as the Super Bowl, the Olympics etc. As such, policies and regulations enacted to mitigate congestion and delays should be sufficiently versatile to not only deal with these busy periods, but also to not impose additional constraints on airports and airlines during the off-peak periods. For example, imposing limits on airport capacity reduces delays and congestion, but can lead to under-utilization of capacity that could otherwise have been used to accommodate more flights, creating additional revenue to both airports and airlines. Another way to improve the fidelity of the models is to capture the effects of weather on air traffic by investigating if weather can be included as a predictor variable in the models or if it can be treated only as uncertainty.

The graph in Fig. 16 depicts the number of monthly delayed flights at the OEP 35 set of airports as a percentage of the number of annual delayed flights at each of these airports in 2007; the black dashed-line represents the mean monthly values for OEP 35. The model under development attempts to estimate monthly variations in delays and use these estimates to predict delays in the following year. The flow chart in Fig. 17 describes the logic in developing this model. It consists of a longitudinal analysis of an airport, or a set of airports (such as OEP 35), to identify any discernible patterns in the number of monthly delayed flights. In Fig. 17, all months from 2002 to 2007 are shown as an example period of analysis for developing a model that estimates the number of delayed flights in January, 2008.

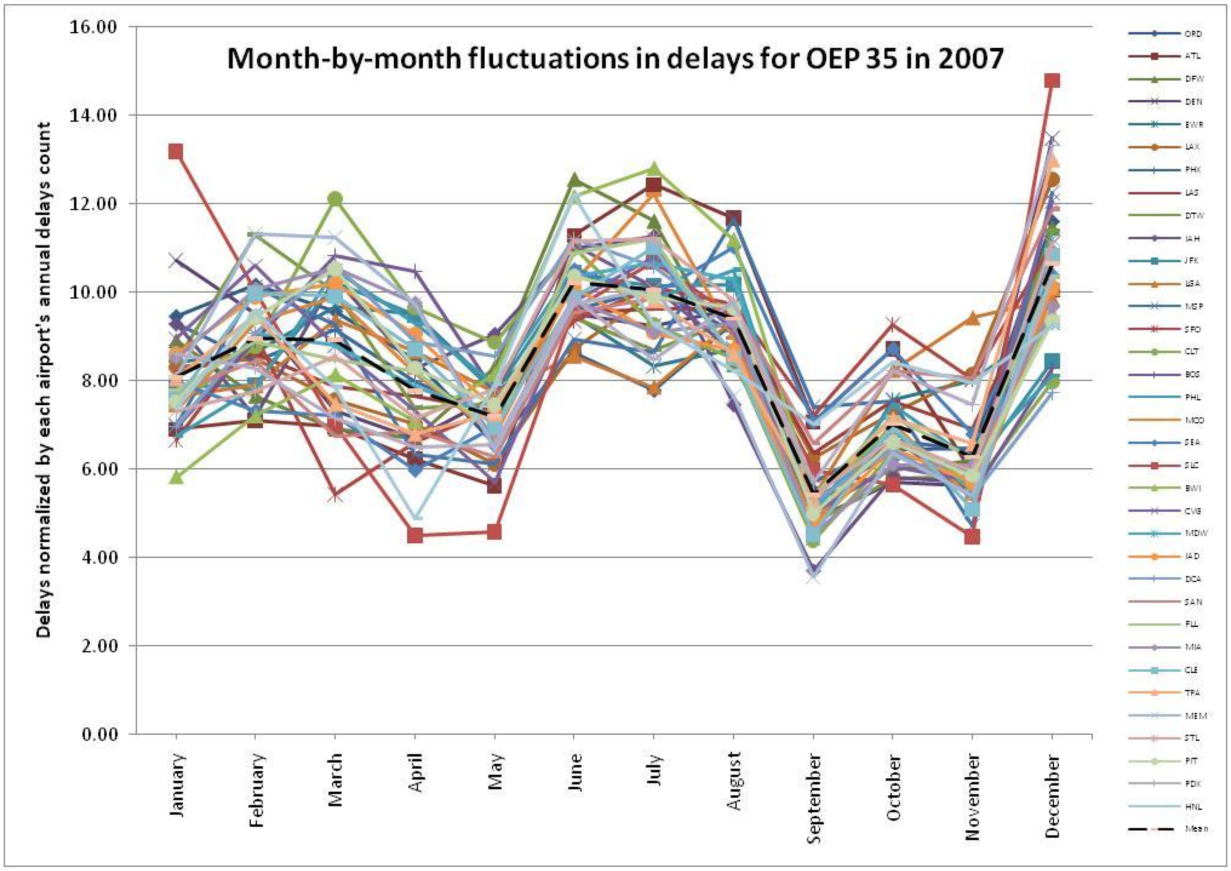


Fig. 16. Changes in airport delays within a year

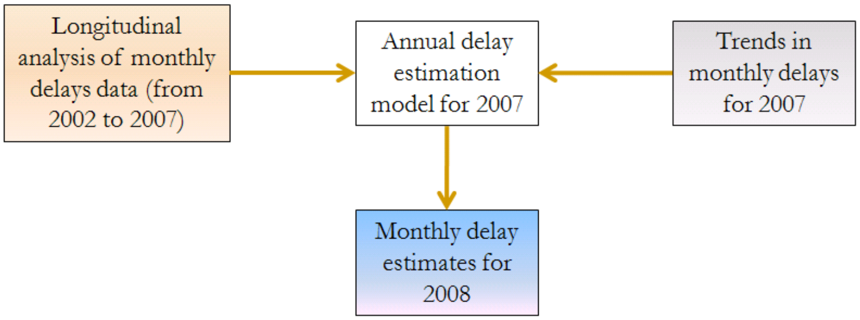


Fig. 17. Logic to estimate monthly delays for OEP 35 airports for the following year by using current year's data

The curve in Fig. 18 is a fitted trend-line for the number of domestic delayed flights at Chicago O'Hare International Airport (ORD) in the month of January for the years 2002 to 2007. The curve followed a Fourier series:

$$coeff_{ORD\_Jan} = a_0 + a_1 \cos(\omega x) + b_1 \sin(\omega x)$$

$$\text{where } a_0 = 10.26,\ a_1 = 2.902,\ b_1 = -1.761,\ \omega = 1.694$$

$$x = 1 \text{ for 2002, 2 for 2003… and 6 for 2007}$$

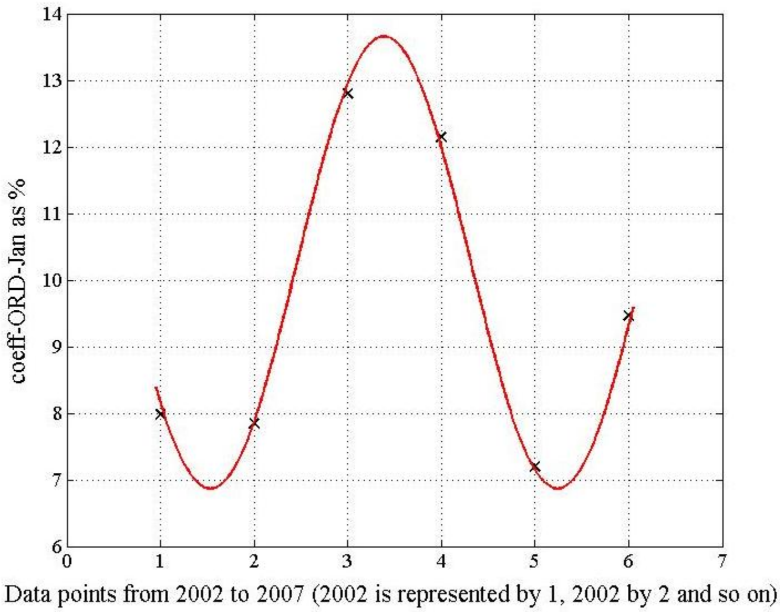


Fig. 18. Trend in the number of delayed flights at Chicago O'Hare (ORD) in January from 2002 to 2007

The Fourier series shown in Fig. 18 depicts how the number of delayed flights in January at ORD varied from 2002 to 2007 as a percentage of the total flights at ORD in the corresponding year. The new delay-prediction model under development makes use of such patterns for delays in particular months (e.g., January) and across all months (data shown in Fig. 16) at an airport (e.g., ORD) to predict the number of delayed flights at that airport at a future period (January 2008). This model is being developed as part of a framework for predicting monthly delays at a set of airports, instead of just at one airport. The focus is currently on OEP 35 airports to demonstrate the viability of this approach and to build confidence in the approach as well as the models. This framework, in tandem with the framework for conducting dependency analyses, is envisaged to provide a means to evaluate how future regulations affect operations at a metroplex and how one metroplex compares to another in terms of operational volumes and delays.

4.1.2 Influence of aircraft size on delays

Work is underway to analyze the effects of aircraft size on airport delays and determine how to incorporate them into the delay-prediction model. Specifically, the analysis will focus on understanding how traffic fleet-mix at an airport influences delays. This effort is in the initial stages of research and development to present any significant findings in this report.

4.2 Other studies

In addition to understanding the effects of metroplex dependencies and interactions between airline service networks on delays and congestion, the following studies are also being conducted.

4.2.1 Measures of network efficiency

The trade-studies described earlier employ the number of delayed flights at an airport and/or across NAS as a measure of network efficiency/performance. While this serves the purpose of evaluating network performance under alternative regimes of airline behavior (as depicted by response of Benevolent Monopolist Airline to variations in market conditions), it does not offer deeper insights to answer questions such as:

a. Is the network robust enough to buffet the spread of delays from one airport to another?
b. Is the network flexible enough to maintain a minimum level of connectivity (in terms of flights and passenger throughput) in the event of a critical failure?
c. Which is the more suitable airport in a metroplex to implement a certain regulation or policy?
d. Where should efforts be concentrated to foster the development of the next metroplex such that the current problems of delays and congestion are significantly mitigated while enhancing the passenger and flight throughput?
e. What is the role of airline competition in influencing answers or solutions to the above questions?

Efforts are underway to identify/define a suitable metric that can not only answer these but is also simple for easy computation and analysis.

4.2.2 Impact of adding capacity

The values in Table 13 depict change in the number of delayed flights (computed using the annual delay-prediction model for 2007) when traffic to a metroplex is increased. The results show that an increase in traffic within NYNJ led to a larger increase in NAS-wide delays than the same increase at either NorCal or SoCal. On the other hand, the increase in delays within each of these metroplexes was almost the same. The changes were computed with respect to the delays predicted by the model before any change in traffic in 2007. These results were computed assuming no change in airport and metroplex capacity.

Table 13. Impact of change in traffic on delays at a metroplex and across NAS

Metroplex	NAS-wide delays*		Change in NAS-wide delays (%)		Change in metroplex delays (%)	
	10% increase in traffic	20% increase in traffic	10% increase in traffic	20% increase in traffic	10% increase in traffic	20% increase in traffic
NYNJ	3,341,504	3,368,661	0.79	1.61	10.08	23.01
NorCal	3,322,755	3,330,218	0.22	0.45	11.20	23.00
SoCal	3,322,528	3,329,757	0.22	0.44	10.55	24.30

**Predicted number of NAS-wide delayed flights before change in metroplex traffic = 3,315,321*

This case-study was conducted to answer the following questions:

a. How does an increase in capacity impact delays at a metroplex and across NAS?

b. Which metroplex is the most appropriate candidate for adding capacity to achieve maximum reduction in delays both at the metroplex and across NAS?

To answer these questions, the efficacy of different mechanisms to increase capacity will be investigated. These include options such as changing the composition of traffic to a metroplex (fleet-mix) and increasing airport capacity. This complements the efforts described earlier to improve the delay models by incorporating factors such as aircraft size and fleet mix into them.

4.2.3 Bayesian-based model

A model using a Bayesian-approach is being developed in parallel with the regression-based model to predict the number of delayed flights, to provide an alternate description to what causes delays and how they propagate across the NAS. The Bayesian approach offers certain advantages over the regression approach, such as the ability to account for uncertainties and noise in the data, and the flexibility to be altered quickly if the set of variables are found to be incomplete or inaccurate. The chart in Fig. 19 compares the regression and Bayesian models against data for the OEP 35 airports in 2007. Note that the y-axis depicts the number of delayed operations at an airport as a percentage of its total annual operations. These initial results showed that as yet there was no clear indication as to which approach is more successful at predicting the number of delayed flights. Research is currently underway to both improve the Bayesian model and to determine if its advantages clearly out-perform the regression approach.

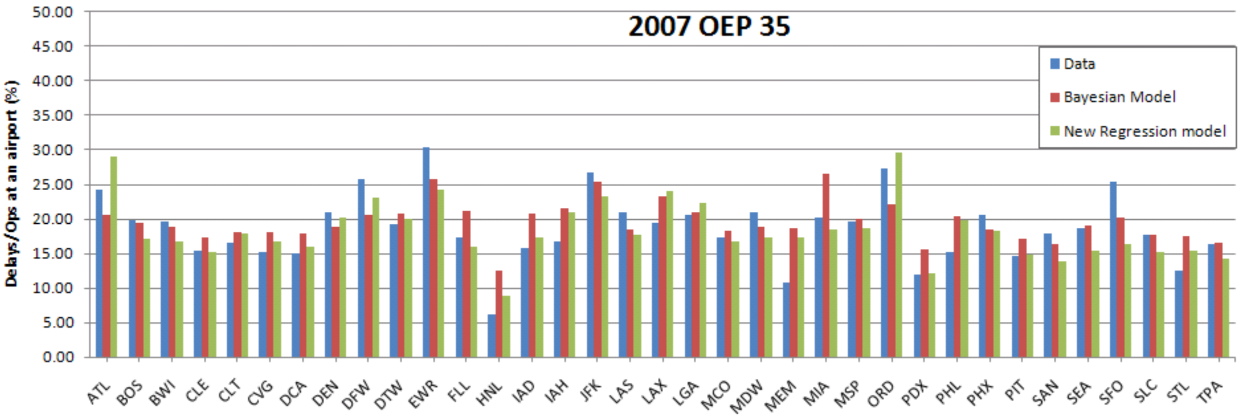


Fig. 19. Comparison between the regression-based model and the Bayesian-based model

Appendix A

Introduction to FAA Circular AC: 150/5060-5

The Circular provides empirical relationships to compute the annual service volumes at an airport for planning purposes. As the name suggests, it is only an advisory document providing guidelines to airport planners. The circular was released in 1983 using then-existing standards for aircraft separation, air traffic controller workload criteria etc. Consequently, the team wanted to validate its applicability to current airport operations. The circular provides projections of airport annual service volume (ASV) by means of two parameters – aircraft mix index and the runway configuration to be used most.

A.1 Aircraft mix-index

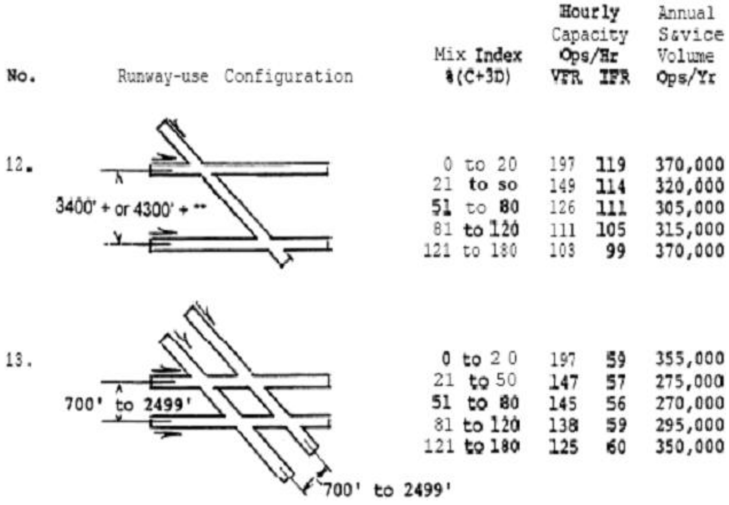
This parameter is indicative of the type of aircraft that fly into and out of an airport. The FAA identifies four classes of aircraft as shown in Table 14. The aircraft mix index is defined as in Eq. (B1), where C and D represent the percentage of aircraft belonging to classes C and D, respectively, flying into and out of an airport in a year.

Table 14. Aircraft classification

Aircraft class	Max. take-off weight (lbs.)	No. of engines
A	12,500 or less	Single
B		Multi
C	12,500 – 300,000	Multi
D	Over 300,000	Multi

A.2 Runway configurations and ASV

The circular provides estimates of ASV based on the particular runway configuration that an airport utilizes 80% of the time that produces the maximum hourly capacity, and it prescribes the ASV for the particular configuration as in Fig. 20.



No.	Runway-use Configuration	Mix Index %(C+3D)	Hourly Capacity Ops/Hr VFR	IFR	Annual S&vice Volume Ops/Yr
12.		0 to 20	197	119	370,000
		21 to 50	149	114	320,000
		51 to 80	126	111	305,000
		81 to 120	111	105	315,000
		121 to 180	103	99	370,000
13.		0 to 20	197	59	355,000
		21 to 50	147	57	275,000
		51 to 80	145	56	270,000
		81 to 120	138	59	295,000
		121 to 180	125	60	350,000

Fig. 20. ASV and runway configurations

A.3 Most-used runways and runway configurations – ASPM data

The Circular describes 19 possible runway configurations to estimate the ASV and hourly capacity under both IFR and VFR conditions at an airport (Fig. 20). In order to determine the most-used runway configurations at an airport the ASPM database was used for 15-minute operations at an airport. This database provides the particular runway configuration used at an airport for every 15-minute period in a day (Table 15). It was also deemed necessary to determine how each runway was used at an airport. For this, the sample data in was approximated as shown in Table 16. It was estimated that all runways in a particular configuration were used equally to conduct arrivals or departures. For example, runway 4R was used in two configurations for arrivals (Table 15). For the first configuration, it shared the arrivals with runway 13R and with 13L in the second. It was estimated that runways 4R and 13R were each used to conduct 692 (=1384/2) arrivals for the particular 15-minute period. And, runways 4R and 13L were each used to conduct 74 (≈147/2) arrivals for the same 15-minute period. On the other hand, only runway 13L was used for all departures in this 15-minute period. Therefore, 4R and 13R have no departures (Table 16). This simple estimation procedure was used to determine the annual arrivals and departures for each runway at an airport.

Table 15. Sample ASPM data for an airport

Runway configurations per 15 minutes	**Arrivals**	**Departures**
4R, 13R | 13L	1384	978
4R, 13L | 13L	147	106

Table 16. Estimate of operations per runway

Runway	**Total Arrivals**	**Total Departures**	**Total Operations**
4R	766	--	766
13R	692	--	692
13L	74	1084	**1158**

Appendix B

Estimating ASV for LGA and NYNJ

LGA's operations were used to validate the Circular, which states that the most-used runway configuration should have been used 80% of time to estimate ASV. But LGA has no such runway configuration. As such, each runway's usage was estimated as described earlier to determine the most-used configuration. For example, in 2007, based on the estimation, runways 22 and 31 at LGA were most used for arrivals whereas all runways were used for approximately the same amount of time for departures and total operations (Table 17). Therefore the most-used configuration for LGA in 2007 was found to be that shown in Fig. 21.

Table 17. Estimates of runway usages at LGA for 2007

Runway	Arrivals	Departures	Total	Arrivals (%)	Departures (%)	Total (%)
4	34115	47282	81397	17.78	24.71	21.24
13	3404	86205	89609	1.77	45.05	23.39
22	104652	1973	106625	54.55	1.03	27.83
31	49179	54767	103946	25.63	28.62	27.13

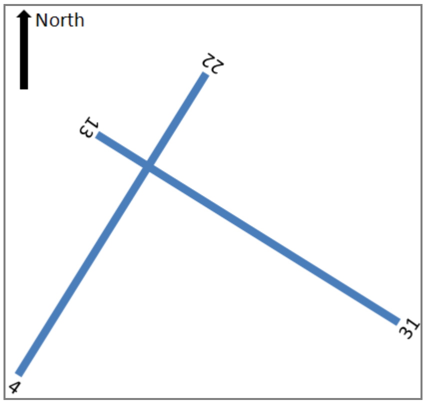


Fig. 21. Runway layout of LGA

Using the Circular, the ASV for LGA's most-used configuration in 2007 (Fig. 21) was determined to be 225,000. The computed ASV values for LGA from 2002 to 2007 are compared against actual data in Table 18. The T-100 database maintained by BTS was used to compile this actual operations data. It can be observed that the Circular always under-estimated LGA's ASV. This can be attributed to the fact that the circular was compiled using the operational and safety standards from the 1980s, which have significantly changed over the years. The ASV of NYNJ was estimated by treating it as a very large airport with widely separated runways. The team only considered EWR, JFK and LGA as the constituent airports of NYNJ and their runways to determine the most-used runway configurations (Table 19). Again, the Circular under-estimates for the same reasons described earlier.

Table 18. Validation of the FAA circular using LGA's data

Year	Data (T-100)	ASV from FAA Circular
2007	377,077	225,000
2006	385,542	225,000
2005	384,906	225,000
2004	385,122	225,000
2003	358,248	225,000
2002	280,575	225,000

Table 19. Estimation of ASV for NYNJ

Year	Data (T-100)	ASV from FAA Circular
2007	1,233,473	225,000
2006	1,184,445	225,000
2005	1,141,250	225,000
2004	1,113,671	225,000
2003	1,016,652	225,000
2002	913,420	225,000

Appendix C

Airline Competition at NYNJ

In addition to the airline redundancy issue in Table 5, further analysis was conducted to gain more insights into metroplex operational dependencies. Airline domestic operations were analyzed to find correlations between a low-cost airline (JetBlue) and those of a regional airline (American Eagle) and a legacy airline (US Airways) at the three major NYNJ airports from 1995 to 2005 (Fig. 22). 125 markets were used for this study to understand the evolution of airline service networks five years before and five years after JetBlue began operations. Note that JetBlue began operations in NYNJ airports starting from JFK in 2000 and did not begin operations at the other two airports until after 2003. These were the markets that had at least 24 flights to NYNJ in the third quarter of 2007, the period when NYNJ experienced some of the worst delays in history. It can be observed that, although American Eagle (AE) and US Airways (US) altered their operations at JFK, their overall presence at NYNJ was unaltered by JetBlue's operations. Note that US Airways discontinued service to JFK in 1999.

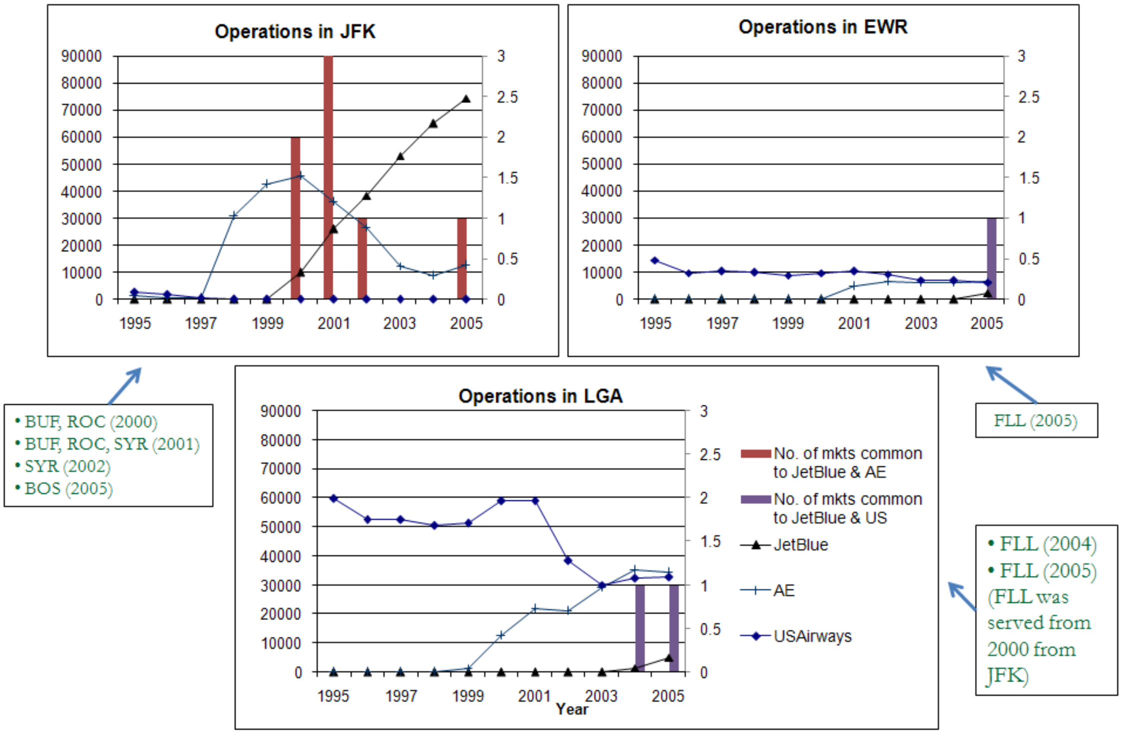
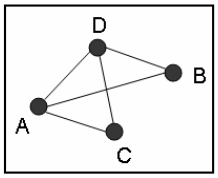


Fig. 22. Another example for metroplex operational dependency

It is to be noted that no direct influence of JetBlue on AE's and US' operations was observed. These airline's networks were also analyzed to find any correlation in the type of markets they served. The red vertical bars in Fig. 22 denote the number of markets common to JetBlue and AE, and the purple bars the markets common to JetBlue and US (these are listed in the boxes pointing to each of the airports' graph). It can be observed that there were very few common markets between JetBlue and AE, and between JetBlue and US. Also, the markets common to JetBlue and AE were small and a short distance from JFK. Only Boston and Ft. Lauderdale (in Florida) were long distance markets served by these airlines. As earlier, no direct correlation between airline operations could be found. One likely explanation is that airlines respond to each other's operations and business models, and though correlations exist, they require a rigorous analysis to be detected.

Appendix D

Glossary of Network Theory Terminology

Network Property	Equation & Sample Calculation
Degree (k): number of links connected to a node. This was denoted as “deg” or “links” in the delay-predictor model. If weights are used on links, it is “dom_traffic”	 $k_A = 3$ for this sample network
Clustering coefficient of a node (C_i): quantifies the closeness of nodes in a given network. It can be used to determine the “robustness” of the network; it has no dimensions.	$C_i = \frac{\text{number of triangles connected to node } i}{\text{number of triples centered on node } i}$ For the sample network above: $C_A = C_D = 2/3$; $C_B = C_C = 1/1 = 1$
Eigen vector centrality of a node (*evc*): quantifies how well a node is connected through its neighbors. It is a measure of the importance of a node in network in terms of the degree of its neighbors.	$A\mathbf{x} = I$, where A is the adjacency matrix depicting the presence of links and $\mathbf{x}$ is the eigen vector of A corresponding to the largest eigen value. For the example network above, $A = \begin{bmatrix} 0\,1\,1\,1 \\ 1\,0\,0\,1 \\ 1\,0\,0\,1 \\ 1\,1\,1\,0 \end{bmatrix}$ x = [0.5573 0.4352 0.4352 0.5573], showing that nodes A and D are more important to the connectivity of the network than B and C.

Appendix E

Glossary

Organizations and Architectures

ATL	Hartsfield-Jackson Atlanta International Airport
ATC	Air Traffic Control
BTS	Bureau of Transportation Statistics
DEN	Denver International Airport
FAA	Federal Aviation Administration
GMU	George Mason University
ICAO	International Civil Aviation Organization
NAS	National Airspace System
PANYNJ	Port Authority of New York & New Jersey
SoS	System-of-systems
TRACON	Terminal Radar Approach Control
WTO	World Trade Organization

Metroplex	Airport (code)
New York/New Jersey (NYNJ)	Newark Liberty International Airport (EWR) John F. Kennedy International Airport (JFK) La Guardia Airport (LGA)
Northern California (NorCal)	San Francisco International Airport (SFO) Metropolitan Oakland International Airport (OAK) Norman Y. Mineta San Jose International Airport (SJC)
Southern California (SoCal)	Los Angeles International Airport (LAX) Long Beach Airport—Daugherty Field (LGB) Ontario International Airport (ONT) John Wayne-Orange County Airport (SNA)
Chicago	Chicago O'Hare International Airport (ORD) Chicago Midway International Airport (MDW) General Mitchell International Airport, Milwaukee, WI (MKE)
Southern Florida	Miami International Airport (MIA) Palm Beach International Airport, West Palm Beach, FL, (PBI) Fort Lauderdale/Hollywood International Airport (FLL)
Washington, DC	Ronald Reagan Washington National Airport (DCA) Washington Dulles International Airport (IAD) Baltimore/Washington International Thurgood Marshall Airport (BWI)

Datasets

ASPM	Aviation System Performance Metrics
LMINET 102	Set of 102 airports used in a queuing network model of the National Airspace System developed by the Logistics Management Institute (LMI)
OEP 35	Data maintained by the FAA on 35 airports as part of the Operational Evolution Partnership program
OPSNET 45	Data maintained by the FAA about operations at 45 airports
T-100	Database maintained by the BTS and includes non-stop segment and on-flight market data

Modeling parameters

arr	arrivals
ASV	Annual Service Volume of an airport
Avg. Clust. Coeff.	Average Clustering Coefficient of a network
BMA	Benevolent Monopolist Airline
CC	Clustering Coefficient of a node in network
$d_{i,j}$	distance between centers of rwy_i and *RR*
$d_{l(i)}$	length dependency of rwy_i
$d_{o(i)}$	orientation dependency of rwy_i
$d_{p(i)}$	proximity dependency of rwy_i
$d_{i,j}$	distance between rwy_i and rwy_j
dep	departures
IFR	Instrument Flight Rules
l_i	length of rwy_i
l_{RR}	length of *RR*
RDM	Runway Dependency Metric
RDM_i	RDM for rwy_i
RDM-A	RDM for an airport
RMD-M	RDM for a metroplex
RR	Reference Runway
rwy	runway
rwy_i	runway *i* at an airport or a metroplex
Rwy_ops_i	number of flights operated from rwy_i
VFR	Visual Flight Rules

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01- 10 - 2010	**2. REPORT TYPE** Contractor Report	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Analysis of Dependencies and Impacts of Metroplex Operations

5a. CONTRACT NUMBER
NNX07AT23A

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
DeLaurentis, Daniel A.; Ayyalasomayajula, Sricharan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
411931.02.71.07.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2010-216853

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 03
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES
This report was prepared by Purdue University under subcontract to George Mason University for NASA under Cooperative Agreement NNX07AT23A.
Langley Technical Monitor: Rosa M. Oseguera-Lohr

14. ABSTRACT

This report documents research performed by Purdue University under subcontract to the George Mason University (GMU) for the Metroplex Operations effort sponsored by NASA's Airportal Project. Purdue University conducted two tasks in support of the larger efforts led by GMU: a) a literature review on metroplex operations followed by identification and analysis of metroplex dependencies, and b) the analysis of impacts of metroplex operations on the larger U.S. domestic airline service network. The tasks are linked in that the ultimate goal is an understanding of the role of dependencies among airports in a metroplex in causing delays both locally and network-wide. The Purdue team has formulated a system-of-systems framework to analyze metroplex dependencies (including simple metrics to quantify them) and develop compact models to predict delays based on network structure. These metrics and models were developed to provide insights for planners to formulate tailored policies and operational strategies that streamline metroplex operations and mitigate delays and congestion.

15. SUBJECT TERMS
Air transportation delays; Air transportation network; Metroplex dependencies; Metroplex operations

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)***
U	U	U	UU	37	(443) 757-5802