ABSTRACT

Title of Document: AN ANALYSIS OF THE RELATIONSHIP BETWEEN TRAFFIC MANAGEMENT INITIATIVES

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This thesis provides an overview of Traffic Management Initiatives (TMI) trends over the years 2009 through 2016, and serves to highlight similarities and differences between four restriction types: Miles-in-Trail (MIT) restrictions, Ground Delay Programs (GDP), Airspace Flow Programs (AFP), and Ground Stops (GS). Yearly and regional patterns are investigated to find temporal and geographic tendencies, which are then compared across restriction types. We use various metrics of severity, which help explore TMI implementation methodology. This research confirms that the causal factors of TMIs are tied closely to their purposes and their locations within the National Airspace System (NAS). Finally, we suggest a method for matching restrictions based on common facilities and overlapping implementation time in order to determine the frequency of concurrent TMIs. The statistics presented in this thesis are meant to supply a "big picture" summary of restrictions implemented in the National Airspace using data recorded in the National Traffic Management Log (NTML).

AN ANALYSIS OF THE RELATIONSHIP BETWEEN
TRAFFIC MANAGEMENT INITIATIVES

By

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List of Abbreviations

AFP	Ground Delay Programs
ARTCC	Air Route Traffic Control Centers
FAA	Federal Aviation Administration
GDP	Ground Delay Programs
GS	Ground Stops
hrs	Hours
MIT	Miles-in-Trail
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAID	Navigational Aid
NTML	National Traffic Management Log
TFM	Traffic Flow Management
TMI	Traffic Management Initiatives
TRACON	Terminal Radar Approach Control Facilities
ZXX	Three letter identifier of US ARTCC. See appendix for full list of center abbreviations

Chapter 1: Introduction

Traffic Management Initiatives (TMIs) are restrictions imposed by the Federal Aviation Administration (FAA) that control the flow of air traffic in the National Airspace System (NAS). When utilized effectively, TMIs will minimize delays caused by external stressors like volume, weather, and equipment outages. The purpose of TMIs is to balance traffic demand with the system's capacity [1].

The different types of TMI that will be explained and analyzed later in this paper are: Miles-in-Trail (MIT) restrictions, Ground Delay Programs (GDP), Airspace Flow Programs (AFP), and Ground Stops (GS). Information about these restrictions is recorded initially by Air Traffic Control facilities, which are also responsible for coordinating with Command Centers and communicating with affected facilities during TMI implementation. We obtain the TMI data through the National Traffic Management Log (NTML), a program that the FAA developed in order to provide a single system for automated coordination, logging, and communication of TMIs throughout the NAS [2]. Prior to the introduction of the NTML, the methods for accomplishing these tasks were highly inefficient and varied from facility to facility. The deployment of the NTML application in 2003 greatly facilitated the ability to collect and compare data across regions and over time. This paper presents statistics obtained through analysis of the NTML for the purpose of exploring the scale, scope, and relationships between different restrictions.

The initial inspiration for this research was the paper published by Rios, which provides aggregate statistics on various TMIs with the goal of improving future traffic flow performance [1]. Of particular interest was his work on analyzing and visualizing

MIT restrictions for 2009 – 2010 because his statistical summaries display the "big picture" of MIT activity in the NAS (like the number of restrictions and the flow of requests across center boundaries). Rios did not include his exact methodology in the literature, so we worked closely with stakeholders in the Operations Analysis Group of the FAA to try to replicate his calculations and apply them to more recent years. His paper is the reason that our time period of interest starts in 2009, despite the NTML having been deployed in 2003: the first years of our analysis mirror the time period of Rios' work. We then chose to adapt this MIT analysis methodology for the other TMI types and to perform the same general procedure on them, thereby producing analogous results that would be possible to compare. Rios displays general statistics about GDP, AFP, and GS, but his approach to them is different than his approach to MIT restrictions, so connections cannot be drawn between them. It is important to note that some of the fields available to us today may not have existed during the publication of Rios' paper, which could account for differences in methodology. For example, Rios linked multiple entries of the same GDP using cumulative start time, which we felt was a tenuous identification field in the event that two restrictions are implemented in different regions at the same time; therefore, we used the "Head ID" string as a unique identifier instead.

Another article that provides a system overview regarding TMI is the IEEE proceedings text by the NASA Ames Research Center [3] . This paper describes how Traffic Flow Management (TFM) decisions were made at the time of publishing (2008) and gives a detailed explanation about national traffic flow management "tools" (aka TMIs). An interesting point that the paper brings up is the varying functions of different TMIs: AFPs are meant to manage traffic flow en route, while GDPs handle constraints on a specific airport, despite both of these restrictions having similar implementation methods and being stored in the same format. The article also discusses “playbook” TMIs, which are restrictions with pre-populated parameters meant to most efficiently handle common conditions based on historical data.   While we do not distinguish between playbook restrictions (which are certainly in our dataset) and manually-entered restrictions, the section is an acknowledgement of the known geographical and chronological trends that we explore in our paper. NASA’s work also gives an overview of the role that MIT restrictions play in regional traffic flow management – again stressing the importance of separating the system geographically for analysis in addition to looking at full system tendencies.

Myers et al. use NTML data to do an in-depth exploration of MIT restrictions, particularly their impact on flights and on GDP restrictions [4]. In their paper, the authors match MIT restrictions with flights using spatial and temporal commonalities, similar to how we match different TMIs with each other. They find that for a sample period of May 2014, 13% of MITs did not involve any flights and 39% of MITs involved 5 or fewer flights. Myers further examines the actual spacing of impacted flights and discovers that many aircraft are spaced further than required. This lack of involved flights and excess spacing indicate that a proportion of MIT restrictions are completely irrelevant. It is essential to understand that while our paper produces objective data about TMIs imposed on the NAS, not all of the restrictions impact air traffic in a practical or meaningful way at all. In a sense, they can be thought of as being invoked to guard against a certain condition (aircraft spaced too closely), but that condition never manifesting itself.

The Myers et al. work is the closest literature we could find on our topic of analyzing the relationship between different restriction types as well. MITs are often viewed as a contributing factor to the non-compliance of flights to GDPs; the theory is that flights that receiving MIT delay are not able to get to their destination in time to land during their assigned arrival slot, which causes additional system delay. However, when Myers et al. compares the en route delay of flights involved in MITs with flights not involved in MITs, they find no statistical difference. They also evaluate the actual arrival time against the slotted arrival time for restricted and non-restricted flight, and discover that there is no clear trend between MIT restrictions and GDP performance – restricted flights arriving at some airports do have poorer arrival compliance, while others do not. Although we do not assess TMI performance, our work does draw similar conclusions in regard to the changeability of GDP and MIT restriction patterns depending on geographical location.

Even in professional applications of operation analysis, the TMI summary statistics are not extensively reported. In the US-Europe Operational Performance comparison report, TMIs are classified into different levels, where only one is used for benchmarking. The specific TMIs are not even distinguished during analysis: the paper states only that 75% of reportable delay is caused by TMIs in the group containing GDP, GS, and AFP restrictions and 8% of reportable delay is generated by the group containing MITs [5]. This assertion agrees with the findings of Myers et al., who also concluded that MITs did not significantly contribute to delay. The comparison report even affirms that their data set has the some of the same attributes that we use as metrics, namely, count and duration of TMIs. This connection is expected since we use the exact same data that the FAA uses, and our collaboration with them on this research project is meant to directly contribute to future versions of the comparison report. In the document's Further Work sections, the FAA states: "Analysis work is ongoing to develop a more detailed understanding of US and European Traffic Management Initiatives, i.e. to reveal differences between: TMI types…" [5]. The concepts explored in this paper do exactly what is called for in industry.

We see that while previous work has looked at summary statistics and the impact of one restriction on another restriction's performance, there is no record of a "big picture" multi-year analysis of NTML restriction data. This paper not only gives insight to the scale of the MIT, GDP, AFP, and GS restrictions, but also looks at the differences and similarities in their temporal and regional trends. The main questions we hope to answer with this research are: Have restriction usage patterns changed over time? If so, where have restrictions changed and what may be the cause of this change? And finally, how are the occurrences of these restrictions related?

Chapter 2: TMIs Background and Data Fields

This section serves to describe the different types of TMIs investigated in the paper and the data fields associated with them. To get a better understanding of the data, we start by examining the NTML database in which they are stored. Some key goals of the NTML are to automate data collection, provide real-time distribution of data, and standardize data to maximize traffic management efficiency. The warehouse archive at the Tech Center (ACY) maintains NTML data as highly normalized relational database tables [6]. The process of data normalization involves organizing data attributes (columns) in a way that reduces redundancy and allows for updates with minimal anomalies introduced [7]. For example, we can see from the sample of the SQL query used to collect GS data in Figure 1 that the views we created in our local environment pulled various fields from different tables of the NTML database. These tables contain distinct categories of data, like: general GS data (which has the start and stop time of the restriction), relational data (like key identifiers used to link entries), and rate data (which contains data about the GS rate). These tables were linked using keys - fields in each table that matched with fields in other tables.

Once the tables are linked (or de-normalized) and copied onto our local schema, we reduce the NTML data to only contain fields of interest for our own performance analysis. The specific filtering and field additions that were performed for each restriction are described in greater detail in the following sub-sections. Due to the high fidelity of the NTML database, especially in the quantitative fields that we use for our analysis, we expect the format of the data to be relatively consistent and have minimal errors due to human entry processing issues [8].

```
CREATE TABLE GS_UMD as

SELECT
GDR.HEADID,GDR.NEWID,
GD.GSID,ROW_NUMBER() OVER (PARTITION BY GDR.HEADID ORDER BY
   GDR.HEADID ASC, GD.GSID ASC, RD.ORIG ASC, RD.HHMM2 ASC) as
   HEADID_SEQ,GD.AIRPORT,GD.ACFT_TYPE,GD.START_TIME,GD.STOP_TIME
   ,MAX(GD.STOP_TIME) OVER (PARTITION BY GDR.HEADID) AS
   MAXSTOP,GD.FACS,GD.CENTER,GD.RATEID,GD.ICCATEGORY,GD.ICCAUSE,
   GD.ICTEXT,GD.ICADVISORY,
LE.TYPE,LE.TYPE_TEXT,LE.LOG_TYPE,LE.LOG_TYPE_TEXT,
RD.HHMM1,RD.HHMM2,(RD.HHMM2 - RD.HHMM1)/60 as
   DUR_HRS_ADD,RD.DLY,RD.ORIG,RD.AAR,RD.USLOT,RD.MPEAKDMD,RD.MAF
   FFLTS,RD.PROGRAMRATE,RD.POPUPFACTOR,RD.YMD
FROM
      NTMLWH.GS_DATA GD,
      NTMLWH.GS_DATA_REL GDR,
      NTMLWH.GS_DATA_ENTRY GDE,
      NTMLWH.ENTRYREL ER,
      NTMLWH.LOG_ENTRY LE,
      NTMLWH.RATES_DATA RD
WHERE
    GDR.NEWID = GD.GSID
AND GDE.GSID = GD.GSID
AND ER.ENTRYID = GDE.ENTRYID
AND LE.LOGID = ER.LOGID
AND RD.RATEID = GD.RATEID
```

NTML warehouse tables

Linking tables with key fields

Figure 1. Sample of query pulling from NTML relational database

Additionally, much of our work looks at patterns in regions with man-made boundaries defined by 3-dimensional points in the airspace. These regions are known as facilities and include Air Route Traffic Control Centers (ARTCC), Terminal Radar Approach Control Facilities (TRACON), Sectors, and Airports. ARTCC are large areas primarily responsible for directing flights during the en route phase of flight. There are 20 continental US ARTCC, denoted by three-letter signifiers starting with Z (e.g. ZDC for the Washington DC ARTCC). See Figure 2 for an illustration of ARTCC boundaries. TRACONS are terminal control centers that direct aircraft during the arrival and departure phases of flight (the transition between cruising and taking-off/landing) [9]; they are located close to large airports and are smaller in geographical area than ARTCC.

Sectors are an even smaller breakdown of airspace that are sometimes found in the facility fields for MIT restrictions, but our analysis does not use them for regional trends.

2.1 Miles-in-Trail (MIT) Restrictions

Miles-in-trail indicate the number of nautical miles required between aircraft "departing an airport, over a fix, at an altitude, through a sector, or on a specific route" [10]. The specific fix, Navigational Aid (NAVAID), airway, sector, or center where the spacing must be implemented is referred to as the National Airspace System (NAS) Element. MIT restrictions are used to distribute traffic into a manageable flow, as well as provide space for additional aircraft (merging or departing) to enter the flow of traffic. For example, standard separation between en route flights is five nautical miles, but traffic managers may increase this value significantly during a weather event to allow for deviations [10].

The MIT fields relevant to our research are described in Table 1 below. The fields in blue are ones that we generated ourselves by parsing or performing calculations on other columns of the database.

Table 1. Description of data fields used in MIT restriction analysis

Field Name	Field Description	Field Example
HEADID	Unique identification string that is common for all modifications to the same restriction	2810993
TYPE	Number indicating restriction action: 4 = Initiate, 5 = Extend, 6 = Modify, 8 = Cancel	4
FRFAC	"From Facility" or Requesting Facility; the facility requesting the MIT spacing.	ZAU
TOFAC	"To Facility" or Providing Facility; the facility which aircraft arriving from must provide MIT. May be more than one facility delimited by a slash.	ZOB or ZOB/ZID
TOFACSINGLE	Single "To Facility" separated into its own entry with all other fields duplicated	ZID

Field Name	Field Description	Field Example
NAS_ELEM	Generally a Fix, NAVAID, or Airway where the MIT spacing must be implemented. May also include airports or sectors. May be multiple slash-delimited elements.	J75 (airway) or BNA/BWG (fixes)
NAS_ELEM_ SINGLE	Single NAS Element separated into its own entry with all other fields duplicated	BWG
RSTN_START	Date and time of restriction start in Greenwich Mean Time (GMT)	01-JAN-09 00:14:00
RSTN_STOP	Date and time of restriction end in Greenwich Mean Time (GMT)	01-JAN-09 01:00:00
RSTN_TRUE_ STOP	Latest non-cancel RSTN_STOP of all restriction entries with the same HeadID	01-JAN-09 03:00:00
DUR_HRS_TOT	Total duration of MIT restriction in hours. Found by subtracting earliest start time from latest non-cancel end time for restrictions with common HeadID	2.77
DUR_HRS_ ADD	Duration of MIT restriction in hours contributing to total by particular entry. For example, an EXTEND entry may add 1 hour to a restriction with the same HeadID	0.77
MITVAL	Number of nautical miles that aircraft must be spaced to comply with restriction	30
STRINGENCY_ MIT_HRS	Product of MITVAL and DUR_HRS_ADD to get stringency in the units of miles-hours	23.00
REASON_CLASS	Cleaned version of the NTML field REASON_TXT, which contains the reason for MIT implementation WX=weather, VOL=volume, RWY=runway	VOL:COMPAC TED DEMAND

2.2 Ground Delay Programs (GDP)

Ground Delay Programs (GDP) are implemented in order to control traffic arriving at an airport where the projected demand is expected to exceed the airport's capacity for a sustained period of time [11]. During GDP execution, aircraft are delayed on the ground at their origin airport and are assigned specific departure times. Limiting the flow of flights into the NAS will consequentially regulate the arrival rate at the impacted destination airport. Lengthy periods of demand exceeding acceptance rate may be the result of reduced airport capacity due to weather conditions like low ceilings, thunderstorms, or wind [10].

We define the “scope” of a GDP as the regions or facilities that must comply with the restriction – that is, areas containing airports with flights destined for the GDP airport. The scope of GDP TMIs can be defined by either distance or by tiers. A distance-based program only affects flights originating within a specific mile radius from the GDP airport (e.g. "Distance - 1200 miles+ZNY") [12]. A tier-based program impacts flights originating in the ARTCC that surround the GDP airport: a first tier program would include all ARTCCs touching the ARTCC in which the GDP airport is contained, while a second tier program would be include all the first tier ARTCCs and the ARTCCs that are adjacent to the first tier ARTCCs. Figure 2 illustrates the scope of a tier-based GDP, where the ARTCC in green contains the impacted airport, the ARTCCs in yellow are those impacted by a first tier program, and the ARTCCs in yellow and in green are those impacted by a second tier restriction. For tier-based GDPs, scope is found in the FACS field and is the GDP equivalent of the Providing Facilities in MIT restrictions.

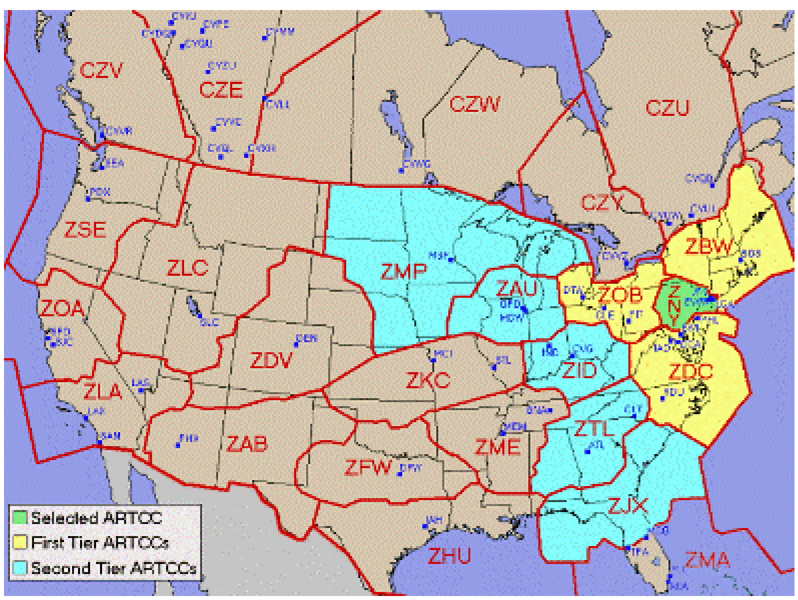

Figure 2. A diagram illustrating first and second tier scope of affected facilities. Diagram from the National Business Aviation Association [12].

Some specific programs have pre-defined centers in their scope. For example, an "All" program would include all continental US ARTCCs and possibly some Canadian facilities. A few examples of standard programs and their ARTCC are listed below [12]:

- Six West - ZAB / ZDV / ZLA / ZLC / ZOA / ZSE
- Ten West - ZAB / ZDV / ZFW / ZHU / ZKC / ZLA / ZLC / ZMP / ZOA / ZSE
- Twelve West - ZAB / ZAU / ZDV / ZFW / ZHU / ZKC / ZLA / ZLC / ZME / ZMP / ZOA / ZSE
- No West - exclude ZAB / ZDV / ZLA / ZLC / ZOA / ZSE
- Ten East – ZBW / ZNY / ZDC / ZJX / ZMA / ZTL / ZME / ZID / ZAU

The NTML generates an entry for every 15 minutes and every hour of a GDP's duration, so a large amount of the data is captured more than once. To get rid of redundancies, we had to aggregate and then filter many of the fields with our own calculations. The fields in blue are those that we generated ourselves using information from other fields of the database.

Table 2. Description of data fields used in GDP restriction analysis

Field Name	**Field Description**	**Field Example**
HEADID	Unique identification string that is common for all modifications to the same restriction. Identical to the GDPID of the first entry of a restriction.	48585
GDPID	Unique identification string that is different for each modification but the same for all bins of the same modification.	48585
HEADID_SEQ	The sequence of HeadID when sorted by bin length (15-min bin first) then by GDPID, then by start time	1
AIRPORT	Three letter identifier of the airport with demand exceeding capacity	SFO
CENTER	ARTCC containing the GDP Airport	ZOA

Field Name	Field Description	Field Example
FACS	Slash-delimited list of ARTCC impacted by GDP restriction for tier-based programs. Flights originating from ARTCC in this field are included in scope of GDP and delayed	ZAB/ZSE/ZFW/ZKC/ZME/ZTL/ZOA/ZLC/ZLA/ZAU/ZMP/ZDV/ZID/ZMA/ZHU/ZJX/ZBW/ZOB/ZDC/ZNY
ETASTART	Date and time of restriction start in Greenwich Mean Time (GMT)	02-JAN-09 17:00:00
ETASTOP	Date and time of restriction end in Greenwich Mean Time (GMT)	03-JAN-09 06:59:00
MAXSTOP	Latest ETASTOP of all restriction entries with the same HeadID	03-JAN-09 07:59:00
DUR_HRS_TOT	Total duration of GDP restriction in hours. Found by subtracting earliest start time from latest end time for restrictions with common HeadID	14.98333
DLY	Average delay in minutes of flights affected by the GDP	36
DLY_AVG	Running average of DLY in reverse HEADID_SEQ order so that the restriction with HEADID_SEQ = 1 has the average delay of all 15-minute bins for the restriction	122.5488
STRING_DLY_TOT	Product of DUR_HRS_TOT and DLY_AVG/60 to get stringency in the units of hrs^2	30.596
ICADVISORY	Impacting condition advisory text, composed of the impacting condition category text and cause text. Essentially equivalent of the MIT reason field	WEATHER / WIND

2.3 Airspace Flow Programs (AFP)

Airspace Flow Programs (AFP) were introduced in the summer of 2006 with the initial goal of “providing enhanced en route traffic management during severe weather events” [10]. AFPs are very similar to GDPs, but they control the flow of aircraft through a volume of airspace instead of traffic arriving at a particular airport [1]. The parameters of AFPs are so similar to GDP that they are stored in the in the same table, but with “XAFP” denoted in the AIRPORT field. Another major difference that affects our regional trend analysis is that AFPs do not have an associated value in the CENTER field of the NTML, so that column is left empty. However, AFP restrictions do have an

ELEMENTDEFINITION field, which contains the geographical data of the associated Flow Constrained Area (FCA). A FCA is an en route region in space with limited throughput capacity as set by the restriction parameters; it is the counterpart to the Airport in a GDP restriction or the NAS Element in a MIT restriction. The FCA shape is stored as a list of latitudes and longitudes encoded in Extensible Markup Language (XML). If these points are plotted and connected, they create the edges of a constrained polygon or the boundary of a constraint line, which aircraft can only pass through at a certain limited rate.

2.4 Ground Stops (GS)

Ground stops (GSs) require all aircraft that meet certain criteria to be held on the ground at their departure airports until the restriction is over. GSs are normally airport specific, where all flights whose destination is the affected airport are stopped, but may be related to a geographical area or to equipment instead. The scope of GSs are tier-based, meaning that they also have a FACS field that lists affected ARTCCs. GSs are essentially GDPs with an acceptance rate of zero.

GSs are implemented in order to severely limit traffic arriving at an airport when the projected demand exceeds the airport's capacity for a short period of time, or when it is necessary to temporarily stop traffic so that longer-term solutions, like GDPs, can be deployed efficiently. Often times GSs are required when events like severe weather, major equipment outages, or catastrophes reduce an airport’s acceptance rate to zero. Because all aircraft affected by a GS are held for the duration of the restriction, there are no values in the delay fields of the GS data set. Therefore, we do not have a separate stringency metric to measure GS severity besides count and duration.

Rios' paper suggests that GSs and GDPs are sometimes used in conjunction, where a GS may be issued during a GDP if conditions worsen or where a GS may be eased into a GDP as the demand and capacity balance out [1]. We plan to explore this assertion in the Chapter 6 below.

The NTML generates an entry for every 15 minutes and every hour of a GS' implementation time, similar to the format of GDP restrictions. The fields in blue are those that we generated ourselves using information from other fields of the database.

Table 3. Description of data fields used in GS restriction analysis

Field Name	**Field Description**	**Field Example**
HEADID	Unique identification string that is common for all modifications to the same restriction. Identical to the GSID of the first entry of a restriction.	61793
GSPID	Unique identification string that is different for each modification but the same for all bins of the same modification.	61793
HEADID_SEQ	The sequence of HeadID when sorted by bin length (15-min bin first) then by GSPID, then by start time.	1
AIRPORT	Three letter identifier of the airport with demand exceeding capacity	SFO
CENTER	ARTCC containing the GS Airport	ZOA
FACS	Slash-delimited list of ARTCC impacted by GS restriction Flights originating from ARTCC in this field are included in scope of GS and stopped at the origin airport	ZSE/ZOA/ZLC/ZLA
START_TIME	Date and time of restriction start in Greenwich Mean Time (GMT)	01-JAN-09 00:43:00
STOP_TIME	Date and time of restriction end in Greenwich Mean Time (GMT)	01-JAN-09 01:45:00
MAXSTOP	Latest STOP_TIME of all restriction entries with the same HeadID	01-JAN-09 01:45:00
DUR_HRS_TOT	Total duration of GDP restriction in hours. Found by subtracting earliest start time from latest end time for restrictions with common HeadID	1.033333
ICADVISORY	Impacting condition advisory text, same information as the GDP field with the same name	WEATHER / WIND

Chapter 3: Comparison Metrics

In order to form a complete representation of MIT, GDP, AFP, and GS activity, we used the daily average count, daily average duration, and daily average stringency as metrics for comparison. Count is the number of restrictions initiated with a unique "Head ID" (an approved identification string). Duration is the number of hours that the restriction was in effect. Stringency is a measure of severity, which captures both the magnitude of the restriction and the length of time that it was in place. For MIT, stringency has the units of MIT-hours and is the product of the MIT value and the Duration. For GDP and AFP, stringency has the units of $hours^2$ and is the product of the Average Delay of the restriction, found by averaging the delay values from the 15 minute bins, and the Duration. Since ground stops are really an all-or-nothing proposition, there is no meaningful way to represent a stringency value for GS.

The daily average values for count, duration and stringency were calculated by summing the values for the time period of interest and dividing that total by the number of days. The NTML data were parsed and filtered according to a set of procedures, which are consistent with methods used in industry:

3.1 Amendments

Amendments that occurred to change the end time or the magnitude of a restriction have the same Head ID and were treated as a continuation of the original restriction. Therefore, these modification, extensions, and cancellations were not counted as new restrictions, but did factor into the calculations for average daily duration and average daily stringency. Cancelled restrictions were only included if the end time occurred after the initiation start time – i.e., if the restriction was in effect for some period of time. MIT restrictions that were passed back to other facilities to distribute encumbrance have unique Head IDs and were thus considered separate restrictions during analysis.

3.2 Multiple Providing Elements

Some MIT restrictions have multiple “to” facilities and/or multiple NAS elements where the MIT spacing occurs. We separated these elements and processed restrictions with unique Head ID, providing facility, and NAS element pairs as different MIT restrictions during the aggregation of our parameters. For GDP, AFP, and GS, the providing facilities were not separated, as these restrictions are implemented in tiers that include multiple centers as a single impacted unit.

3.3 Excluded Elements

Restrictions that had a total duration less than 0 (i.e. that were cancelled before initiation) were also excluded. Only restrictions that had a MIT value greater than 0 and were classified as a type of MIT were included.

Chapter 4: Yearly Trends

If MIT, GDP, AFP, and GS restrictions are strongly correlated, we would expect that the metrics would follow similar patterns of change over time. We investigated the yearly trends of these four restrictions for 2009 through 2016 to see if the severity metrics revealed any patterns. This section serves to examine these changes for the three metrics listed in Chapter 3.

4.1 Daily Average Count

Below is a table and visual representation of the daily average counts for the four restrictions. We notice that the GDP (light blue) and GS (purple) restrictions follow a similar shape and degree of change for all the years of interest, while AFP restrictions (dark blue) remain relatively constant through 2013, then nearly double in 2014. The number of MIT restrictions (red) decreases from 2009 to 2010, and has opposing trends to all other restrictions in 2011 and 2012. MIT restrictions then increase for all years from 2012 through 2015, with particularly dramatic jumps in 2013 and 2015.

Because the magnitude of MIT restrictions is vastly greater than the other restrictions, different axis were utilized in Figure 3, with the MIT restrictions measured by the primary vertical axis on the left, and the GDP, AFP, and GS restrictions measured by the lower-value secondary vertical axis on the right. Although the changes in the daily average count of AFP restrictions seem rather minor, its small scale means that any shifts visible in the graph are significant, which we can see by looking at the percent changes in Table 5.

Table 4. Daily Average Counts by Year for MIT, GDP, AFP, and GS restrictions.

	MIT	GDP	AFP	GS
2009	459.2	3.03	0.35	6.07
2010	434.2	2.42	0.27	4.56
2011	431.3	2.62	0.25	4.95
2012	442.1	2.28	0.22	4.08
2013	486.9	2.73	0.28	4.39
2014	492.4	2.78	0.52	4.58
2015	540.4	2.95	0.58	4.57
2016	526.1	3.04	0.47	4.41

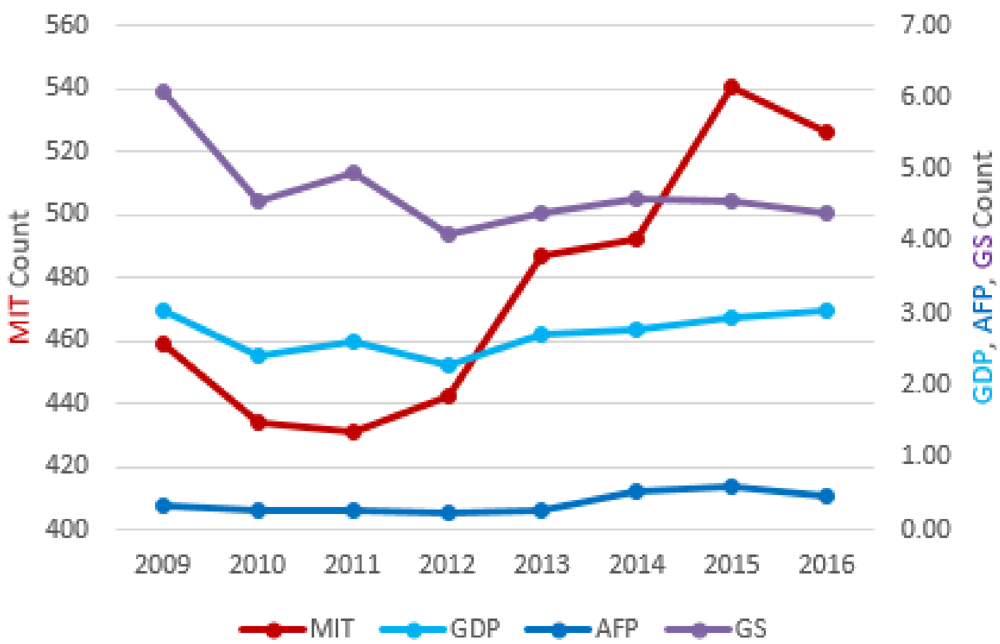

Figure 3. Daily Average Counts by Year for MIT, GDP, AFP, and GS restrictions.

In order to have a standard metric for comparison, we determined the percent change in average daily count between years. The only two years that exhibited the same trend for all four restrictions were 2010, which saw a moderate decrease in the number of all restrictions, and 2014, which saw an increase in the count of all restrictions. In 2014, most of the increases were minor (<5%), except for AFP restrictions, which saw the greatest change in any restriction for any year at 83.8%. MIT and AFP restrictions shared the greatest number of similar yearly trends with 6 out of 7 years fluctuating in the same direction; the one exception was in 2012, where the average daily count decreased for AFP restrictions and increased for MIT restrictions.

Although all of the restrictions decrease the most in 2010, the number of GS restrictions managed to remain much lower than its initial value for all of the following years. This general declining trend in GS could be a result of traffic managers using the other forms of TMI more surgically, in an attempt to avoid the abrupt disruption that a GS causes. GSs are also very expensive to recover from, since aircraft are held at their origin airports, like GDPs, but there is no controlled departure time that can be planned around.

Table 5. (left) Percent change in restrictions from previous year.

Table 6. (right) Number of same-direction yearly trend shifts.

	MIT	GDP	AFP	GS
2010	-5.44%	-20.19%	-21.44%	-24.87%
2011	-0.67%	8.53%	-6.05%	8.47%
2012	2.50%	-13.23%	-14.84%	-17.45%
2013	10.13%	19.78%	29.12%	7.42%
2014	1.13%	2.06%	83.83%	4.47%
2015	9.75%	6.11%	12.75%	-0.24%
2016	-2.65%	3.15%	-18.61%	-3.61%

MIT & GDP	4
MIT & AFP	6
MIT & GS	4
GDP & AFP	5
GDP & GS	5
AFP & GS	5

4.2 Daily Average Duration

We can see that all of the different types of TMI follow the same general directional trends for the years 2009 through 2014, though with different degrees of change. After decreasing significantly in 2010, GDP seem to be fluctuating around a central daily average duration value of 22 hours. MIT durations have a generally increasing trend after 2010 and follow the same shape as MIT counts, with the exception of the duration peak in 2011. GS durations do not exhibit a significant directional trend, while AFP durations had a spike in 2014 that has been gradually decreasing in the years since. The primary and secondary axes in Table 7 were utilized in a similar fashion to the previous section.

Table 7. Daily Average Duration (in Hrs) by Year for MIT, GDP, AFP, and GS restrictions.

	MIT	GDP	AFP	GS
2009	822.1	27.70	2.50	8.59
2010	747.9	21.73	2.07	6.49
2011	776.3	23.16	1.91	7.34
2012	779.6	19.56	1.75	6.31
2013	938.1	24.97	2.28	6.91
2014	992.7	25.38	4.51	7.43
2015	1082.9	21.95	4.30	7.23
2016	1074.3	22.96	3.09	7.20

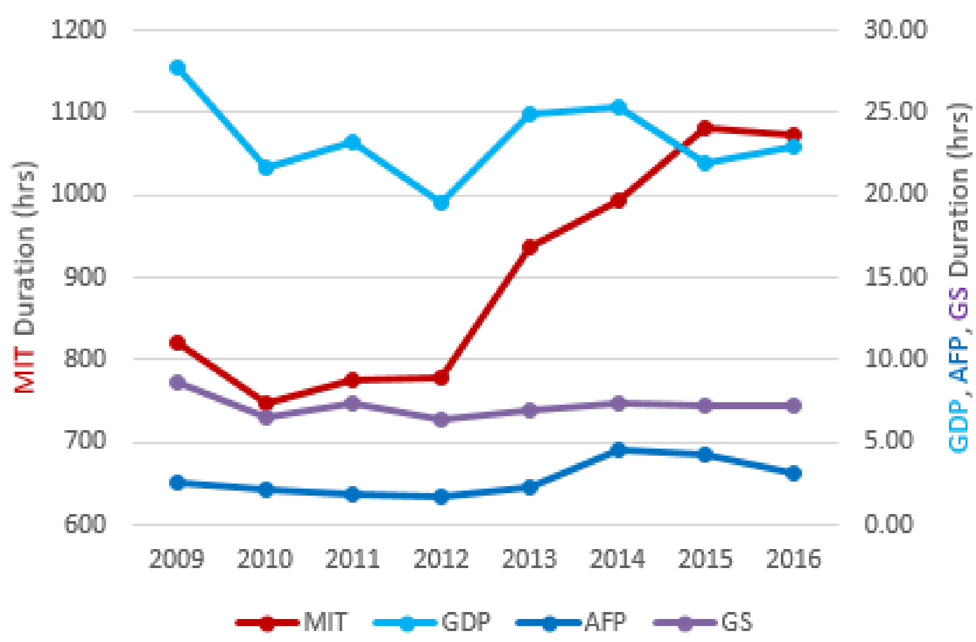

Figure 4. Daily Average Duration (in Hours) by Year for MIT, GDP, AFP, and GS restrictions.

There are three years – 2010, 2013, and 2014 – where all four restriction durations trend in the same direction. For the remaining years, three out of the four restrictions all trend in the same direction. As we can see from Table 6, GS durations have the same trend direction as GDP and AFP durations for 6 of the 7 years of interest. The general increase in MIT restrictions is most likely due to a procedural change implemented in 2013, where certain facilities would call for "routine" MIT restrictions, or restrictions that would last for 24 hours, whether these constraints were truly necessary or not. In these cases, the increase in restrictions may not be an indication of sector overloading, but would reveal a change in traffic manager behavior.

Table 8. (left) Percent change in restrictions from previous year.

Table 9. (right) Number of same-direction yearly trend shifts.

	MIT	GDP	AFP	GS
2010	-9.03%	-21.55%	-17.31%	-24.47%
2011	3.80%	6.58%	-7.45%	13.08%
2012	0.43%	-15.54%	-8.67%	-13.99%
2013	20.33%	27.66%	30.15%	9.41%
2014	5.82%	1.64%	98.15%	7.54%
2015	9.09%	-13.51%	-4.64%	-2.61%
2016	-0.79%	4.60%	-28.03%	-0.41%

MIT & GDP	4
MIT & AFP	4
MIT & GS	5
GDP & AFP	5
GDP & GS	6
AFP & GS	6

4.3 Daily Average Stringency

Due to the "all-or-nothing" nature of GS restrictions, we only look at the stringency for MIT, GDP, and AFP restrictions. We would expect the shape of the stringency graphs to mirror the shape of the duration graphs if the measures of severity (miles-in-trail for MIT restrictions, or hours of delay for GDP/GS restrictions) remained relatively constant between years, which seems to be generally true for all three types of TMI. A good example of the severity metric affecting stringency can be seen in MIT restrictions, where stringency in 2012 is lower than 2010, but duration is higher, meaning that the length of MIT restrictions were longer in 2012, but the required spacing between impacted flights was less. This decrease in required spacing could be due to more accurate instrumentation for tracking aircraft or more efficient methods for directing flights in the NAS.

As we can see from

Table 10, MIT, GDP, and AFP restrictions follow the same stringency trend for the first 3 years, after which MIT and GDP restrictions sharply increase in 2013. For the most recent three years, GDP stringency decreases in 2014 and 2015 then increases in 2016, while MIT stringencies follow the exact opposite trend for those 3 years. AFP restrictions increase noticeably in 2014, then steadily decreased in 2015 and 2016.

Table 10. Daily Average Stringency by Year for MIT, GDP, and AFP restrictions.

	MIT (MIT*hrs)	GDP (hrs^2)	AFP (hrs^2)
2009	16,240	42.04	1.24
2010	14,123	31.59	0.98
2011	14,469	33.98	2.30
2012	14,019	27.48	2.10
2013	18,135	33.75	1.53
2014	18,702	33.05	4.38
2015	20,026	29.49	3.81
2016	19,698	30.70	2.93

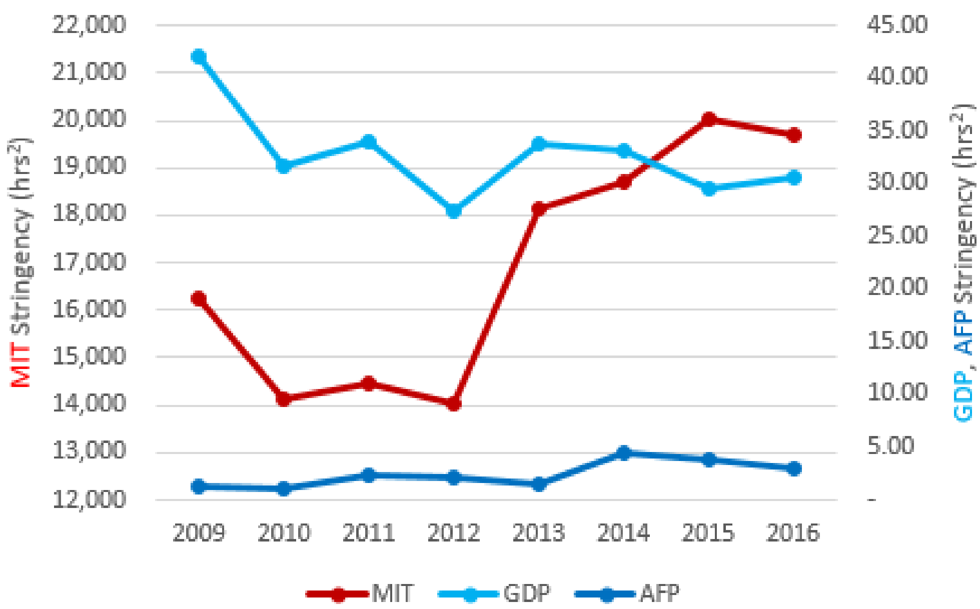

Figure 5. Daily Average Stringency by Year for MIT, GDP, and AFP restrictions.

During the initial three years, all three TMI stringencies trend in the same direction. For the remaining years, two out of the three restrictions trend in the same direction. MIT and AFP share the most similar yearly changes, with 5 out of the seven years trending in the same direction, not quite as many as the more similar pairs for count or duration.

Table 11. (left) Percent change in restrictions from previous year.

Table 12. (right) Number of same-direction yearly trend shifts.

	MIT	GDP	AFP
2010	-13.04%	-24.86%	-20.93%
2011	2.45%	7.57%	134.11%
2012	-3.11%	-19.13%	-8.57%
2013	29.36%	22.82%	-27.35%
2014	3.13%	-2.07%	186.90%
2015	7.08%	-10.77%	-12.99%
2016	-1.64%	4.10%	-23.08%

MIT & GDP	4
MIT & AFP	5
GDP & AFP	4

4.4 Yearly Trend Discussion

In terms of scale, GDP and GS restrictions are similar for count, but significantly different for duration. These two TMI actually switched ranking between the two types of metrics, with GS having a higher average daily count (between 4-6) compared to GDP (2-3 per day), but with GDP having a much higher average daily duration (>19 hours) compared to GS (< 9 hours for all years). This finding is not surprising, as GS is a severe remedy that closes an airport to arrivals, while GDPs at least allow some minimum of traffic. They also share the most common trend directions over the years, with 5 years trending in the same direction for count and 6 for duration. (AFP and GS tie for this highest combination).

It is interesting to see how the nature of the restrictions manifest in the metrics used to measure their severity. We can see that more GS are implemented than GDP, but due to the severe consequences and cost of GS, they are implemented for significantly shorter periods of time. MIT are by far the most popular and arguably the least severe restrictions with a scale hundreds or thousands of times greater than all other restrictions. AFP are the least utilized restriction, possibly for their relatively recent introduction or their highly specific capture criteria. They are also harder to parameterize, as their locations and effects can be difficult to quantify. Air carrier response behavior is also difficult to predict, since carriers could elect to fly around an AFP in lieu of accepting the assigned slot, while they have no such options at destination airports for GDPs.

While it is unfeasible to determine whether yearly changes were caused by factors external to the NAS (like major weather catastrophes) or by procedural shifts (possibly due to new personnel entering the training cycle following the retirement of Reaganadministration traffic managers), we assert that tendencies due to workforce turnover would impact all TMI types equally and comparisons between restrictions would still hold true.

Chapter 5: Regional Trends

For each of the performance metrics, we determined the top five busiest requesting and providing facilities in order to identify any regional tendencies that may have emerged during the years of interest. For the requesting facility, we used the MIT "From Facility" field and the GDP and GS "Center" field. Although the actual requesting facility for GDP / GS restrictions is the impacted airport, we needed analogous fields across the different types of TMIs to evaluate similarities and differences. Therefore, we looked at the ARTCC containing the affected airport for the GDP and GS restrictions during our comparison. For the providing facility, we used the MIT "To Facility Single" field, and parsed out individual facilities from the GDP and GS "Facilities" field. The caveat to this approach is that GDPs whose scopes are distance-based (~70% of GDPs) do not have an entry for the FACS field. Therefore, for this analysis, we are only looking at tier based GDPs (~30% of GDPs), with the assumption that while the values are not accurate, the ranking of impacted centers is correct. This assumption in itself may be off-base if traffic managers in certain regions prefer tier-based restrictions that would over represent adjacent centers. Regardless, GS providing facility values are correct because GSs always use a tier-based scope for their programs. It is important to mention that MIT facilities include TRACONs (like N90 and PCT), while the GDP and GS facilities only include ARTCC centers.

AFP restrictions were not included in this analysis because the impacted regions are polygons or lines drawn in an airspace and the NTML data do not include the center associated with that FCA area. Although AFPs do have a populated "Facilities" field that defines the scope of the TMI, when we extracted the providing facility data, similar to what we did for GDP and GS restrictions, there was no way to distinguish a straightforward set of the top five. Many of the AFP restrictions listed all 20 ARTCC centers in the Facilities field, or a common combination of centers that resulted in the top 5+ facilities all having the same values. We see the repeated values in the GDP column of the providing facility table, which mirrors the issues faced by AFP similarities, but to a lesser extent. For GDP restrictions, identical values were sorted alphabetically, so the top five providing facilities are not objectively definite, but serve the purpose of looking at "big picture" general trends to the degree relevant for this paper.

A more extensive approach for analyzing AFP regional trends would be to map the FCA geometry, find the centers that it is contained in, and use those as the entries for the Requesting Facility field. A similar method could also be done for GDPs, where the ARTCCs that intersect the circle created by the distance radius are used as the Providing Faculties. However, the fact that the NTML data does not include associated ARTCCs for AFPs' flow constrained areas or GDPs' distance-based scopes indicates that these restrictions are likely not used for center capacity analyses in industry.

5.1 Daily Average Count

For the requesting facility count, the top five facilities shared a few commonalities among the three restrictions, but the facility that requested the most restrictions was always different between the MIT restrictions and the GDP and GS restrictions. For all eight years, airports in New York Center (ZNY) requested the most GSs and GDPs. Washington DC Center (ZDC) requested the most MITs for 2009 and 2010, but fell second behind Chicago Center (ZAU) for the remaining six years. Interestingly enough, Chicago Center was not even in the top five list of MIT requestors for 2010 before jumping to the top, while it did remain a consistently high requester of GDPs and GS restrictions for all eight years. Oakland Center (ZOA) reliably requested the second highest number of GDPs, but only broke into the top five requestors of GSs for 2010 and 2011. Los Angeles Center (ZLA) rose into prominence as a requestor for all three restrictions in 2016, starting with a significant number of MIT requests in 2011 onward, which seemed to have bumped Atlanta Center (ZTL) off the top five requesting list for MT restrictions. This shift in the number of restrictions requested from east to west reflects the increased traffic in the west coast corridor of the United States, which could be the result of a culmination of factors: the general increase of trans-continental traffic [5], the expiration of the Wright Amendment in 2014 [13], and the build-up of Delta flights in Seattle [14]. The Wright amendment, which was passed in 1979, limited the destinations and aircraft sizes of flights departing from Love Field in order to promote traffic at the Dallas Ft. Worth airport. The expiration of this legislation meant that Southwest airlines was able to provide non-stop flights from its home base in Texas to airports in California [13]. Delta has been expanding in Seattle to compete with Alaska Airlines in its home base in the Emerald City and could also contribute to the increased west coast traffic [14].

The Providing Facility count did not exhibit trends as clear as the Requesting Facility counts. The top providing facility for MIT restrictions was Indianapolis Center (ZID) in 2009 and 2012 – 2016, and Cleveland Center (ZOB) for 2010 and 2011. These finding agree with our requesting facility conclusions since both ZID and ZOB are adjacent to the topmost MIT requesting facilities (ZDC and ZAU). The providing facilities would be able to provide spacing to aircraft prior to reaching the requesting facility for flights originating from the northeast corridor. There is no discernable pattern of GDP providing facilities, most likely due to the limited number of restrictions included (as described in the introduction of Chapter 5). For GS restrictions, the top provider was Washington DC Center in 2009 – 2012 and 2016, and Cleveland Center in 2013 – 2015. Both of these centers are first tier ARTCC to ZNY and we would expect them to be prominent GS providers.

These differences in regional trends may be due to the nature of the restrictions and the locations of the centers. Centers with a high volume of through traffic would request MITs at a higher rate since MIT restrictions can space flights both en route and near destination airports. GSs are more likely to occur in areas that experience extreme weather (such as snow or heavy thunderstorms), which completely halt the ability of an airport to accept flights. GDPs are likely to originate at airports with high incoming flight rates that still have the capacity to receive aircraft. These geographic features may be why ZAU, which is right in the middle of the country, emerged as a prominent MIT requestor, and why ZOA, which is on the West Coast, appears high on the GDP requestor list, but not on the GS requestor list. ZNY, which contains the three major New York airports, just receives so much destination traffic that GDP and GS must constantly be utilized by airports in that center.

To highlight similarities between restrictions, only centers that appear on the top five list for more than one restriction in the same year are colored. For example, ZOA is not shaded light blue as a GDP requestor in 2009 because the center is not a top requester for MIT or GS in that same year. ZOA is shaded in the following year because it appears on the GS requestor list.

Table 13. List of top 5 Requesting Facilities (left) and Providing Facilities (right) per year by number of restrictions (count)

	FROM FACILITY / CENTER						TO FACILITY / FACILITIES					
	MIT		GDP		GS		MIT		GDP[1]		GS	
2009	ZDC	59.35	ZNY	1.62	ZNY	2.36	ZID	51.71	ZTL	0.803	ZDC	3.20
	ZAU	58.21	ZOA	0.47	ZTL	1.08	ZOB	44.22	ZAU	0.800	ZTL	2.92
	ZTL	49.30	ZBW	0.21	ZAU	0.39	ZBW	32.50	ZID	0.800	ZOB	2.90
	ZNY	39.63	ZAU	0.19	ZDC	0.33	ZNY	32.42	ZMP	0.800	ZJX	2.66
	ZOB	39.42	ZTL	0.18	ZFW	0.25	ZAU	26.18	ZFW	0.797	ZNY	2.58
2010	ZDC	61.97	ZNY	1.08	ZNY	1.50	ZOB	56.84	ZKC	0.641	ZDC	2.43
	ZOB	42.08	ZOA	0.55	ZTL	0.62	ZID	43.21	ZME	0.641	ZOB	2.39
	ZTL	37.17	ZAU	0.21	ZAU	0.51	ZBW	25.34	ZAU	0.638	ZID	2.02
	PCT	34.30	ZBW	0.18	ZDC	0.34	ZNY	25.18	ZID	0.638	ZNY	2.01
	ZNY	30.97	ZTL	0.15	ZOA	0.27	ZAU	22.81	ZTL	0.638	ZBW	1.98
2011	ZAU	70.93	ZNY	1.30	ZNY	2.05	ZOB	52.38	ZDC	0.937	ZDC	3.12
	ZDC	61.39	ZOA	0.50	ZDC	0.57	ZID	43.31	ZTL	0.934	ZOB	3.05
	ZOB	46.70	ZAU	0.22	ZAU	0.52	ZNY	28.75	ZID	0.929	ZNY	2.66
	ZLA	36.61	ZBW	0.20	ZTL	0.47	ZBW	26.59	ZOB	0.926	ZBW	2.57
	PCT	35.63	ZTL	0.09	ZOA	0.22	ZAU	23.11	ZBW	0.923	ZID	2.27
2012	ZAU	67.41	ZNY	1.07	ZNY	1.45	ZID	47.20	ZID	0.732	ZDC	2.21
	ZDC	54.55	ZOA	0.54	ZDC	0.49	ZOB	42.42	ZDC	0.730	ZOB	2.21
	ZOB	49.04	ZAU	0.14	ZTL	0.43	ZDC	29.67	ZAU	0.727	ZNY	1.83
	ZTL	42.94	ZBW	0.10	ZAU	0.39	ZNY	28.28	ZOB	0.727	ZBW	1.78
	ZLA	40.90	ZAB	0.09	ZHU	0.25	ZBW	26.13	ZTL	0.727	ZID	1.71
2013	ZAU	77.11	ZNY	1.35	ZNY	1.62	ZID	51.72	ZFW	1.247	ZOB	2.50
	ZDC	68.62	ZOA	0.48	ZAU	0.45	ZOB	46.22	ZME	1.247	ZDC	2.47
	ZOB	61.82	ZAU	0.24	ZTL	0.45	ZNY	32.61	ZDC	1.244	ZNY	2.07
	ZLA	43.78	ZMA	0.13	ZDC	0.27	ZAU	31.56	ZID	1.244	ZBW	2.02
	PCT	42.87	ZBW	0.11	ZFW	0.20	ZBW	29.58	ZKC	1.244	ZID	1.78

[1] Recall from the Chapter 5 introduction that GDP providing facilities in this table only include tier-based programs and thus have much lower values than expected when compared to the yearly trend count

2014	ZAU	72.33	ZNY	1.26	ZNY	1.70	ZID	50.74	ZDC	1.342	ZOB	2.61
	ZDC	65.72	ZOA	0.54	ZAU	0.49	ZOB	40.68	ZMP	1.340	ZDC	2.60
	ZOB	59.53	ZAU	0.27	ZTL	0.41	ZNY	32.76	ZNY	1.340	ZNY	2.24
	ZLA	47.71	ZMA	0.19	ZDC	0.33	ZDC	31.83	ZID	1.337	ZBW	2.14
	PCT	43.92	ZBW	0.13	ZHU	0.28	ZAU	29.03	ZAU	1.334	ZID	1.74

2015	ZAU	82.15	ZNY	1.15	ZNY	1.56	ZID	58.58	ZDV	0.833	ZOB	2.52
	ZDC	70.39	ZOA	0.42	ZAU	0.42	ZOB	46.88	ZKC	0.833	ZDC	2.48
	ZOB	62.70	ZLA	0.28	ZDC	0.37	ZJX	36.35	ZMP	0.833	ZBW	2.17
	ZLA	53.60	ZMP	0.27	ZTL	0.32	ZNY	33.78	ZDC	0.830	ZNY	2.16
	PCT	42.62	ZAU	0.18	ZHU	0.27	ZAU	33.15	ZFW	0.830	ZID	1.64

2016	ZAU	80.50	ZNY	1.09	ZNY	1.41	ZID	59.16	ZHU	0.962	ZDC	2.11
	ZDC	63.76	ZOA	0.54	ZAU	0.35	ZOB	45.75	ZTL	0.962	ZOB	2.08
	ZOB	58.68	ZLA	0.22	ZTL	0.31	ZJX	40.55	ZAU	0.959	ZNY	1.70
	ZLA	49.63	ZAU	0.20	ZLA	0.30	ZAU	33.77	ZKC	0.959	ZBW	1.66
	ZNY	38.01	ZSE	0.19	ZDC	0.30	ZDC	33.05	ZME	0.959	ZTL	1.29

To have a better visualization of the distribution of daily average counts across facilities, Figure 6 provides a map of the ARTCC shaded by MIT counts for the 2016 calendar year, where a darker greens indicates more restrictions. We can see that providing facility burden seems more geographically distributed than requesting facility burden, and that there is almost a swapping of roles that some facilities play. For example, note how Kansas City center (ZKC) and Albuquerque center (ZAB) transition from low level requestors to mid-level providing facilities. It is clear that ZID provides such a high number of restrictions because it borders the top three facilties that request the most restrictions (ZAU, ZDC, ZOB). These ARTCCs requesting the highest number of restrictions form a barrier to the US northeast corridor, meaning that en route traffic to and from that general zone is highly regulated.

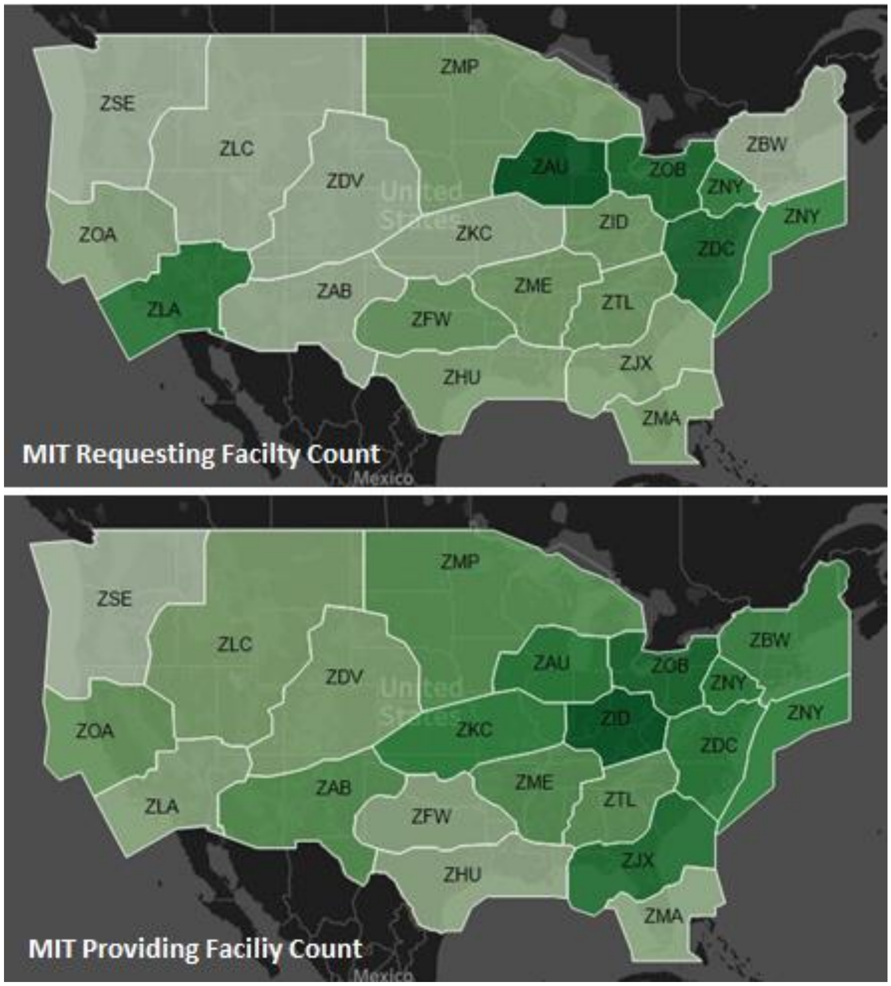

Figure 6. Maps of ARTCC shaded by 2016 MIT requesting facility and providing facility count.

5.2 Daily Average Duration

In terms of duration, New York Center still requests GDP and GS restrictions for the longest amount of time for all eight years. Washington DC remains the center with the longest average MIT restrictions for all years of interest as well. This means that from 2011 – 2016, while Chicago Center requested a greater number of MIT restrictions, Washington DC Center requested MIT restrictions with longer implementation times. Atlanta Center also seemed to have requested longer MIT restrictions, remaining in the top five for duration through 2014 (compared to only 2012 for count). Los Angeles

Center again emerges as a top requestor in 2015 for MIT and GDP restrictions and in 2016 for GS and GDP, likely for the increased traffic mentioned above. The New York TRACON (N90) also appears as a new MIT requesting facility that did not appear in the table for top requestors by count at all.

Jacksonville Center (ZJX) was a prominent providing center for the longer restrictions, showing up in the duration top 5 for both GDP and GS restrictions in 2009. ZJX also ranked in the top providing centers for MIT average duration in 2013 and onward, even rising to the top-most position of provider by duration in 2016. Although Jacksonville Center provided the third highest number of restrictions in 2015 and 2016, it handled around 20 less MIT restrictions per day than the highest providing facility by count (ZID); the fact that ZJX ranks higher than ZID for the most recent four years means that the daily average duration of restrictions provided by ZJX are significantly greater. So much greater in fact, that it is an anomaly that is worth investigating in future work. Deeper scrutiny could determine whether this change is due to methodology – how traffic managers enter restrictions into the traffic management system – or due to actual situational variations, such as weather patterns or increased traffic. This ZJX situation is a testament to the validity of utilizing multiple metrics for analysis in order to determine different aspects of restriction severity and analyze restrictions relationships.

Table 14. List of top 5 Requesting Facilities (left) and Providing Facilities (right) per year by duration of restrictions in hours.

	FROM FACILITY / CENTER						TO FACILITY / FACILITIES					
	MIT		GDP		GS		MIT		GDP[2]		GS	
2009	ZDC	142.07	ZNY	16.11	ZNY	2.77	ZBW	74.97	ZTL	8.95	ZDC	3.72
	N90	95.61	ZOA	3.51	ZTL	1.13	ZNY	74.36	ZAU	8.93	ZTL	3.38
	ZNY	89.20	ZBW	1.82	ZAU	0.43	ZID	72.84	ZID	8.93	ZOB	3.38
	ZAU	86.53	ZTL	1.77	ZDC	0.37	ZOB	69.68	ZMP	8.93	ZJX	3.09
	ZTL	79.93	ZAU	1.75	ZHU	0.28	PCT	54.20	ZJX	8.92	ZNY	3.02
2010	ZDC	145.38	ZNY	10.74	ZNY	1.77	ZOB	77.83	ZKC	7.47	ZDC	2.81
	ZAU	104.01	ZOA	4.61	ZTL	0.65	ZID	57.13	ZME	7.47	ZOB	2.74
	ZTL	78.94	ZAU	2.12	ZAU	0.58	ZNY	56.76	ZAU	7.46	ZID	2.34
	ZNY	70.84	ZBW	1.46	ZDC	0.38	ZBW	56.34	ZID	7.46	ZNY	2.33
	PCT	67.66	ZTL	1.12	ZOA	0.29	PCT	51.16	ZTL	7.46	ZBW	2.30
2011	ZDC	135.58	ZNY	12.53	ZNY	2.39	ZOB	81.11	ZDC	10.43	ZDC	3.62
	ZAU	109.62	ZOA	3.85	ZDC	0.63	ZBW	63.44	ZID	10.42	ZOB	3.52
	ZNY	86.15	ZAU	2.41	ZAU	0.58	ZNY	62.46	ZTL	10.42	ZNY	3.08
	ZTL	76.01	ZBW	1.78	ZTL	0.51	ZID	59.07	ZOB	10.40	ZBW	3.00
	PCT	62.24	ZTL	0.54	ZOA	0.25	ZDC	45.73	ZAU	10.38	ZID	2.65
2012	ZDC	110.89	ZNY	10.52	ZNY	1.73	ZOB	76.29	ZID	8.33	ZOB	2.62
	ZAU	104.99	ZOA	4.66	ZDC	0.57	ZID	64.05	ZDC	8.31	ZDC	2.61
	ZTL	81.80	ZAU	1.28	ZTL	0.48	ZDC	58.36	ZTL	8.30	ZNY	2.17
	ZNY	75.98	ZBW	0.64	ZAU	0.42	ZNY	57.77	ZOB	8.29	ZBW	2.12
	PCT	65.90	ZDC	0.50	ZHU	0.28	ZBW	56.50	ZKC	8.29	ZID	2.05
2013	ZDC	148.22	ZNY	13.60	ZNY	1.96	ZOB	84.01	ZDC	13.97	ZOB	2.99
	ZAU	123.19	ZOA	3.93	ZAU	0.53	ZJX	75.57	ZNY	13.96	ZDC	2.95
	ZNY	99.96	ZAU	2.30	ZTL	0.49	ZNY	74.06	ZFW	13.96	ZNY	2.48
	ZTL	86.32	ZMA	1.24	ZDC	0.33	ZBW	73.53	ZME	13.96	ZBW	2.43
	N90	81.68	ZBW	0.88	ZOA	0.23	ZID	72.81	ZOB	13.96	ZID	2.14
2014	ZDC	133.04	ZNY	12.47	ZNY	2.11	ZOB	83.83	ZDC	14.87	ZOB	3.23
	ZAU	122.62	ZOA	4.53	ZAU	0.59	ZNY	79.61	ZMP	14.82	ZDC	3.21
	ZNY	106.26	ZAU	2.59	ZTL	0.48	ZBW	77.72	ZNY	14.82	ZNY	2.79
	N90	106.07	ZMA	1.82	ZDC	0.40	ZJX	73.85	ZID	14.80	ZBW	2.68
	ZTL	76.89	ZBW	1.10	ZHU	0.33	ZID	73.26	ZOB	14.80	ZID	2.17

[2] Recall from the Chapter 5 introduction that GDP providing facilities in this table only include tier-based programs and thus have much lower values than expected when compared to the yearly trend duration

2015	ZDC	143.45	ZNY	11.11	ZNY	1.97
	ZAU	132.22	ZOA	3.10	ZAU	0.52
	N90	115.17	ZLA	1.53	ZDC	0.46
	ZNY	113.94	ZAU	1.40	ZTL	0.38
	ZLA	79.77	ZBW	1.32	ZHU	0.33

ZOB	90.34	ZMP	9.46	ZOB	3.17
ZNY	83.41	ZKC	9.44	ZDC	3.12
ZJX	83.00	ZFW	9.43	ZBW	2.75
ZID	82.44	ZHU	9.42	ZNY	2.74
ZBW	79.07	ZTL	9.41	ZID	2.08

2016	ZDC	130.08	ZNY	10.35	ZNY	1.76
	ZAU	122.10	ZOA	4.34	ZAU	0.43
	N90	117.68	ZAU	1.42	ZTL	0.38
	ZNY	111.27	ZLA	1.40	ZDC	0.37
	ZOB	84.39	ZBW	1.24	ZLA	0.35

ZJX	90.36	ZHU	10.49	ZDC	2.67
ZID	84.97	ZTL	10.46	ZOB	2.64
ZOB	84.41	ZBW	10.45	ZNY	2.18
ZNY	77.54	ZAU	10.44	ZBW	2.12
ZBW	75.13	ZKC	10.44	ZTL	1.67

5.3 Daily Average Stringency

Stringency exhibits requesting facility regional trends that are similar to duration, with ZDC having the highest MIT stringency and ZNY having the highest GDP stringency for all eight years. Chicago Center and New York center were present as top requestors for both restrictions for all eight years as well. We can see that the New York region requested particularly stringent (either long or widely-spaced) MIT in the years 2014 -2016, where both ZNY and N90 are in the top five most stringent requestors. If we had combined the totals for TRACONS and centers, New York would be considered the region that requested the most stringent MIT restrictions. However, since TRACONS are linked to lower altitudes and terminal (arrival or departure) MITs, while ARTCC are linked to higher altitude and en route MITs, we elected to leave the format as is found in the NTML database.

Boston Center (ZBW) provided more widely-spaced MIT restrictions as we can see from its place at the top of the provider list for the years 2009 – 2012. For 2012 in particular, ZBW was the fifth highest providing facility in count and in duration, yet the first highest in stringency, meaning that the spacing of the MITs that it served must have been particularly large. Jacksonville also rose to the top of the stringency providing facility list earlier in time than duration, taking the top place in 2013 onward, compared to only the 2016 top spot for duration. It is interesting to note that by all three metrics, the GDP providing facilities in 2015 do not seem to have a strong relationship with the other restrictions: for count, only one facility was common with GS restrictions, and for duration and stringency, none of the top facilities matched those of the other restrictions. We see an increase in the count/duration/stringency of GDP affecting Kansas City Center (ZKC), Fort Worth Center (ZFW), and Houston Center (ZHU). These ARTCC are not seen as top Providers for other TMI types but are in the Top 5 Provider lists for all three metrics in 2015. This change could be due to the FAA Metroplex initiative, which was completed for the Houston vicinity in 2015 [15]. The "Optimization of Airspace and Procedures in the Metroplex" program is meant to maximize airspace efficiency in large metropolitan areas, particularly for aircraft arrival and departure paths [16]. It makes sense that these new flows into and out of Houston airports would reduce capacity during initial implementation stages while managers are getting accustomed to them.

Table 15. List of top 5 Requesting Facilities (left) and Providing Facilities (right) per year by stringency of restrictions.

	FROM FACILITY / CENTER				TO FACILITY / FACILITIES			
	MIT (MIT*Hrs)		GDP (Hrs*Hrs)		MIT (MIT*Hrs)		GDP (Hrs*Hrs)[3]	
2009	ZDC	3267	ZNY	25.90	ZBW	1696	ZTL	16.95
	ZNY	1889	ZOA	4.44	ZID	1558	ZAU	16.94
	N90	1657	ZBW	2.82	ZOB	1204	ZID	16.94
	ZAU	1608	ZAU	2.62	ZNY	1180	ZMP	16.92
	ZTL	1564	ZTL	2.14	ZJX	1176	ZJX	16.91

[3] Recall from the Chapter 5 introduction that GDP providing facilities in this table only include tier-based programs and thus have much lower values than expected when compared to the yearly trend stringency

2010	ZDC	3230	ZNY	15.93	ZBW	1344	ZKC	13.38
	ZAU	1881	ZOA	6.26	ZOB	1209	ZAU	13.38
	ZNY	1582	ZAU	3.53	ZID	1159	ZID	13.38
	PCT	1371	ZBW	2.03	ZJX	1084	ZME	13.38
	ZTL	1123	ZTL	1.81	PCT	1069	ZTL	13.38

2011	ZDC	3095	ZNY	19.27	ZBW	1471	ZDC	17.56
	ZAU	2011	ZOA	5.71	ZOB	1324	ZID	17.55
	ZNY	1836	ZAU	3.74	ZID	1196	ZTL	17.54
	PCT	1244	ZBW	2.44	ZJX	1028	ZOB	17.50
	ZOB	1047	ZFW	0.56	ZNY	960	ZKC	17.50

2012	ZDC	2498	ZNY	13.94	ZBW	1290	ZID	14.31
	ZAU	1879	ZOA	7.93	ZID	1254	ZTL	14.26
	ZNY	1640	ZAU	1.85	ZOB	1236	ZDC	14.26
	PCT	1214	ZDC	0.81	ZJX	1162	ZDV	14.25
	ZTL	1129	ZBW	0.61	ZDC	965	ZJX	14.25

2013	ZDC	3491	ZNY	19.19	ZJX	1782	ZFW	20.56
	ZAU	2284	ZOA	5.92	ZBW	1744	ZME	20.56
	ZNY	2200	ZAU	3.24	ZID	1592	ZID	20.55
	PCT	1533	ZBW	0.90	ZOB	1389	ZKC	20.55
	ZOB	1403	ZDV	0.85	ZNY	1171	ZDC	20.54

2014	ZDC	3116	ZNY	18.19	ZJX	1794	ZMP	21.66
	ZNY	2278	ZOA	5.94	ZBW	1761	ZNY	21.63
	ZAU	2215	ZAU	3.32	ZID	1570	ZAU	21.63
	N90	1804	ZBW	1.29	ZOB	1393	ZID	21.62
	ZOB	1494	ZMA	0.82	ZNY	1269	ZOB	21.62

2015	ZDC	3485	ZNY	16.99	ZJX	2059	ZMP	15.92
	ZNY	2404	ZOA	3.77	ZBW	1814	ZKC	15.90
	ZAU	2362	ZAU	2.05	ZID	1775	ZFW	15.90
	N90	1941	ZLA	1.48	ZOB	1511	ZHU	15.87
	ZOB	1701	ZBW	1.43	ZNY	1338	ZDC	15.85

2016	ZDC	3102	ZNY	14.52	ZJX	2176	ZBW	16.98
	ZNY	2302	ZOA	6.05	ZID	1849	ZHU	16.97
	ZAU	2139	ZAU	2.13	ZBW	1662	ZNY	16.97
	N90	1973	ZLA	1.76	ZOB	1420	ZTL	16.96
	ZOB	1942	ZBW	1.40	ZNY	1227	ZAU	16.96

5.4 Requesting Facility Causal Factors

In order to gain insight into why certain regions had a greater need for restrictions, we analyzed the causal factors for the top requesting facilities in 2016. These are the ARTCCs that are requesting more or longer or more severe restrictions due to external stressors, so we hope to find the driving factors behind the greater demand for TMIs. The providing facilities are merely subjected to restrictions and have less of a hand in the reasons for implementation, which is why we focus on the causal factors associated with requesting facilities.

In terms of count (Figure 7), we see that for the top MIT requestor, Chicago Center, "TM Initiatives" is the most common reason for restrictions. This category implies that a large portion of MITs were implemented purely to control traffic with either no specific cause behind them, or causes that were not recorded, for unknown reasons. Even our connections at the FAA tell us that we would need to trawl free text fields or ask traffic managers themselves to discover the true driving factor behind this reason class. The second largest motive for MIT occurrence is volume, meaning that the traffic demand on airspace exceeds the capacity. Following volume is weather, which only accounts for about 11% of MITs – less than a quarter of the number being attributed to the "TM Initiatives" category. In contrast, weather is the most common reason for GDP and GS implementation at ZNY by an overwhelming amount - 93% for GDP and 81% for GS. The next most frequent reason is volume, accounting for only about an eighth of the number of restrictions as weather. When we further break down the weather category, we see that in 2016, wind conditions caused the most GDPs and thunderstorms caused the most GSs. This difference may be due to the characteristics of each weather event: strong winds are intermittent, meaning that airports would still be able to land aircraft during lulls, albeit at a lower rate, while thunderstorms at an airport would prevent landing throughout the duration of the storm.

These findings suggest that MIT are more commonly initiated due to decisions made by air traffic managers, but GDPs and GSs are implemented as a result of stressors that are exogenous to the system, such as inclement weather.

Table 16 shows the category and reason breakdown of GDP counts at ZNY. Note that the "Reason percent" in this table represents the proportion of a reason across all categories, while the weather reason percent in Figure 7 only represents its proportion within the weather category. See the appendices for a full collection of causal tables.

Table 16. Causal factors of GDP at ZNY in 2016, measured by count

Category	**Category Daily Average Count**	**Category %**	**Reason Text**	**Reason Daily Average Count**	**Reason %**
WEATHER	1.01	92.50%	WEATHER:THUNDERSTORMS	0.28962	26.50%
			WEATHER:WIND	0.43169	39.50%
			WEATHER:LOW CEILINGS	0.23224	21.25%
			WEATHER:SNOW-ICE	0.04918	4.50%
			WEATHER:LOW VISIBILITY	0.00820	0.75%
			WEATHER:RAIN	0.00273	0.25%
VOLUME	0.06	5.50%	VOLUME:VOLUME	0.04372	4.00%
			VOLUME:COMPACTED DEMAND	0.01639	1.50%
RUNWAY	0.01	1.00%	RWY:MAINTENANCE	0.00546	0.50%
			RWY:DISABLED AIRCRAFT	0.00273	0.25%
			RWY:CONSTRUCTION	0.00273	0.25%
OTHER	0.01	0.50%	OTHER:SECURITY	0.00273	0.25%
			OTHER:OTHER	0.00273	0.25%
EQUIPMENT	0.00	0.25%	EQUIPMENT:OUTAGE	0.00273	0.25%

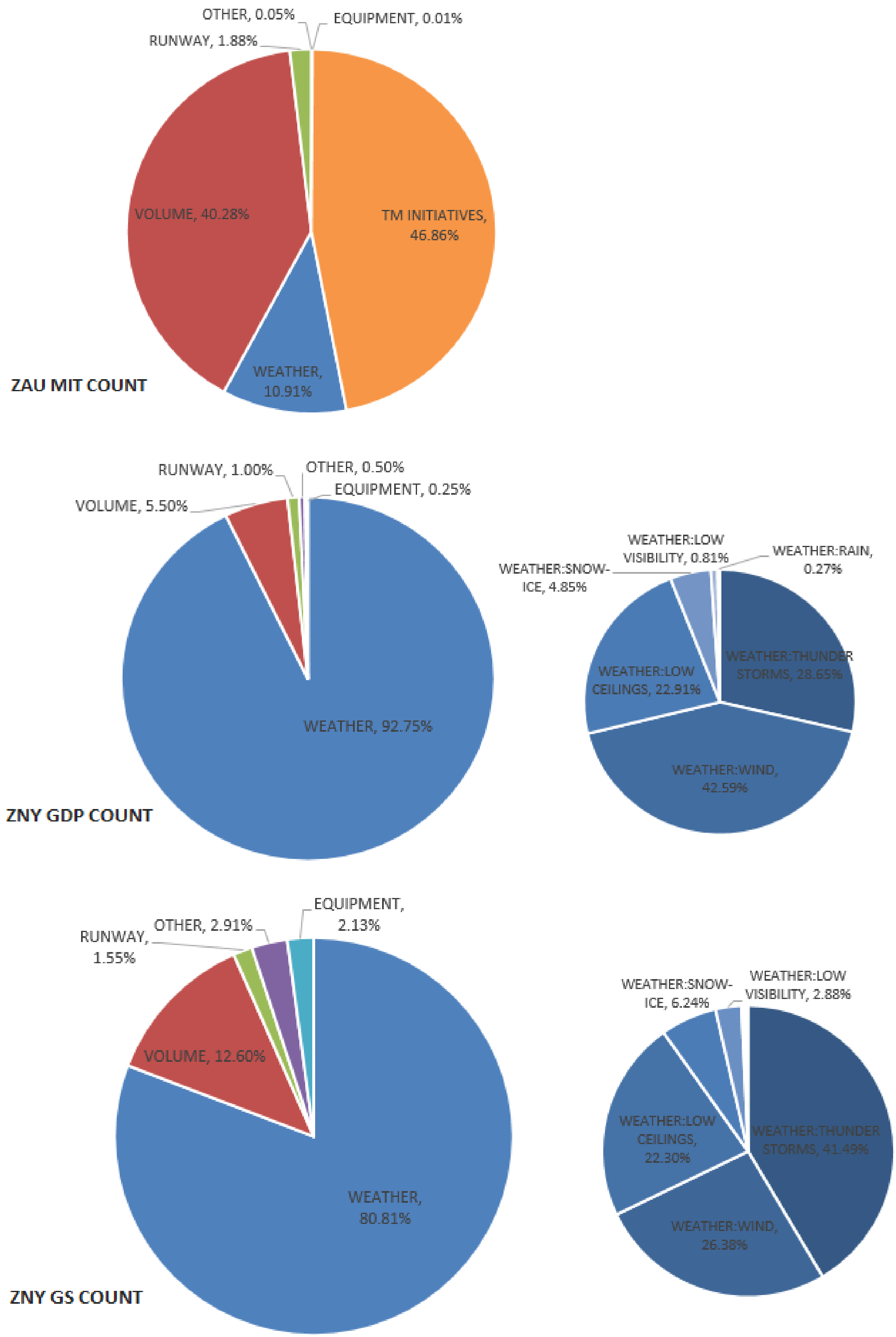

Figure 7. Causal factors of TMI implementation calculated by count

When it comes to daily average duration, ZDC is the top requesting facility, and both volume (66%) and weather (22%) overtake TM Initiatives (10%) as the top causal factors of MITs in 2016. We expect volume to have a prominent influence since MIT restrictions serve to increase spacing of traffic, which would really only be necessary during standard capacity conditions if there is en route congestion due to a high volume of aircraft. Volume may be considered a secondary causal reason, as it often the result of weather in other areas of the country that impact traffic flow in the region of interest. Other restrictions that alter the departure times or trajectories of aircraft also cause facility overloading that would contribute to volume-related MITs as well. The duration of an MIT restriction caused by weather is determined by the duration of its associated weather event, which may impact a region for an extended period of time and decrease airspace capacity. From the pie charts (Figure 8), we know that restrictions linked to volume and weather have significantly longer average implementation than restrictions attributed to TM Initiatives.

For a more in-depth look,

Table 17 displays the average duration per restriction, which is calculated by dividing the daily average duration by the daily average count. We see that the average duration of individual restrictions with the reason TM Initiatives is actually the shortest out of all reasons, even though it is the most prominent one in terms of count. We only calculated these “per restriction” figures for MIT, due to the extreme change in the proportion of causal reasons between daily average count and daily average duration. These numbers help us understand how the distribution of reasons can vary so greatly depending on the metric of measurement.

Table 17. Daily average value of each metric for MIT at ZAU in 2016 separated by reason

	Daily Average Count	Daily Average Duration	Daily Average Stringency	Average Duration per Restriction (hrs)	Average Spacing per Restriction (NM)
TM INITIATIVES	37.72	12.70	242.59	0.34	19.11
WEATHER	8.78	28.51	609.74	3.25	21.39
VOLUME	32.43	85.75	2177.74	2.64	25.40
RUNWAY	1.52	0.62	17.29	0.41	27.82
OTHER	0.04	2.37	52.72	54.32	22.20
EQUIPMENT	0.01	0.12	2.08	11.22	17.00

Weather remains the top cause of GS and GDP restrictions in terms of daily average duration. Further breakdown of the weather reason shows a nearly identical distribution as daily average count, with wind causing the greatest daily average duration of GDPs and thunderstorms causing the greatest daily average duration of GS restrictions. These results are comparable across metrics, which means that most GDP and GS restrictions have similar average durations across the various reasons. Weather may have slightly longer restrictions, as explained above, which we can observe from the marginally higher average daily duration percentages compared to count.

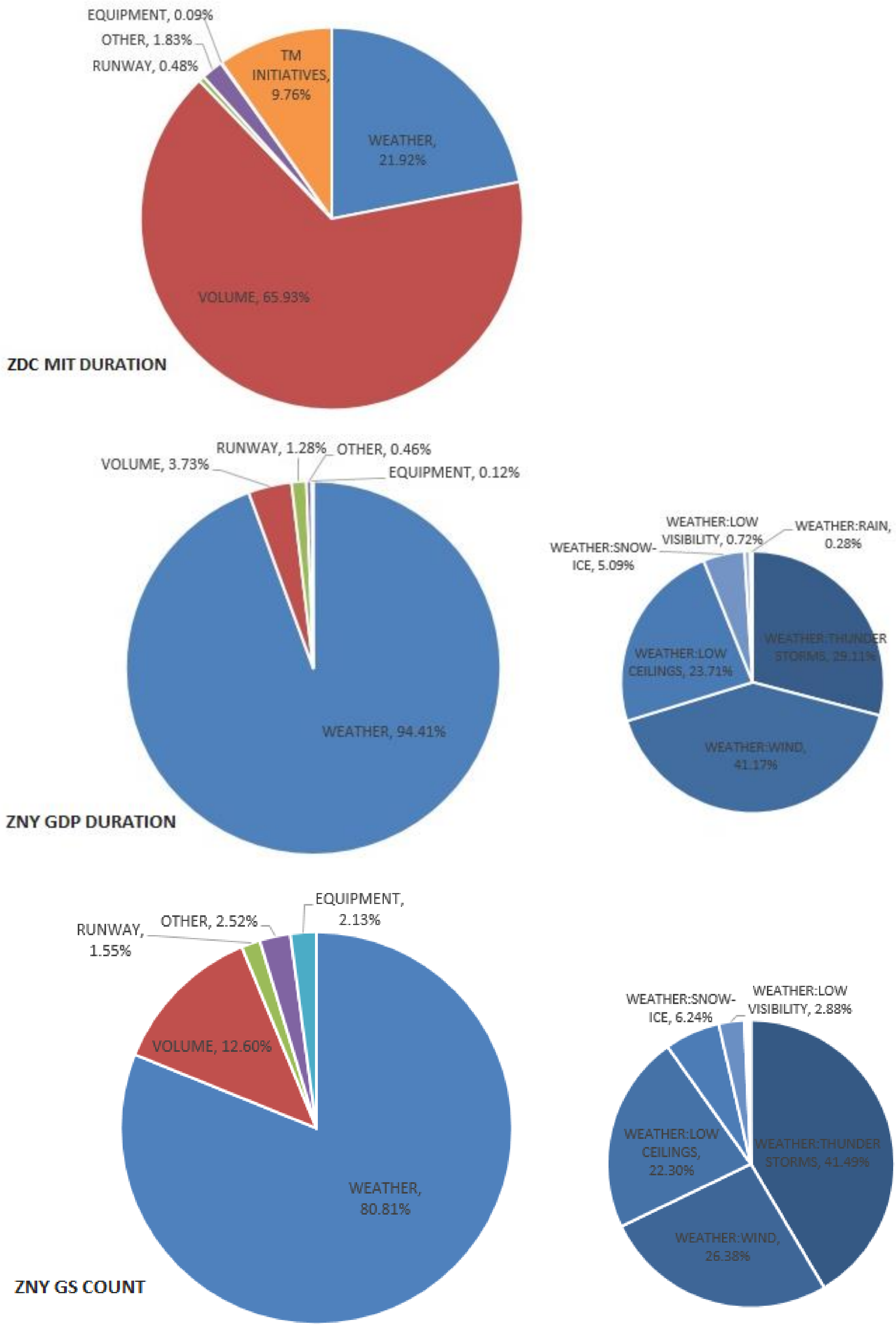

Figure 8. Causal factors of TMI implementation calculated by duration

The distribution of causes for MITs and GDPs based on stringency (Figure 9) closely reflect the patterns that we saw for daily average duration.

Table 17 shows that the range of spacing per restriction is relatively small across all reasons, which would explain the consistency between metrics for MIT restrictions. One noticeable difference is that weather accounts for an even bigger proportion of GDPs, and of those restrictions, thunderstorms surpass wind as the highest ranking cause. This discovery supports the assertion that thunderstorms cause more severe TMIs with higher associated delays. We observed this phenomenon with GS restrictions, which are higher-cost and more severe than GDP, being primarily instigated by thunderstorms.

Analyzing the TMIs by causal factor exhibits the nature and purpose of the restrictions. MITs are meant to regulate en route traffic and thus are more responsive to conditions originating within the NAS, like excessive demand (aka volume), which causes the greatest daily average duration and stringency. It seems that the majority of MITs are not initiated due to necessity, but more to increase NAS efficiency and fine-tune traffic flow, as seen by the prominence of the "TM Initiatives" reason when investigating restrictions by count. Conversely, GDPs and GSs are meant to regulate incoming traffic to a destination airport and are more intensely impacted by uncontrollable factors that are external to the NAS, like weather, which decrease arrival capacity. The delay of GDPs and the occurrence of GSs increase with more severe weather events, since these restrictions actually hold planes on the ground for some period of time, as opposed to just altering aircraft speed or trajectory. During our research into the reasons behind TMIs, we find strong similarities between GDP and GS restrictions, while MIT restrictions seem to be a class of their own – most likely for their differences in function and execution.

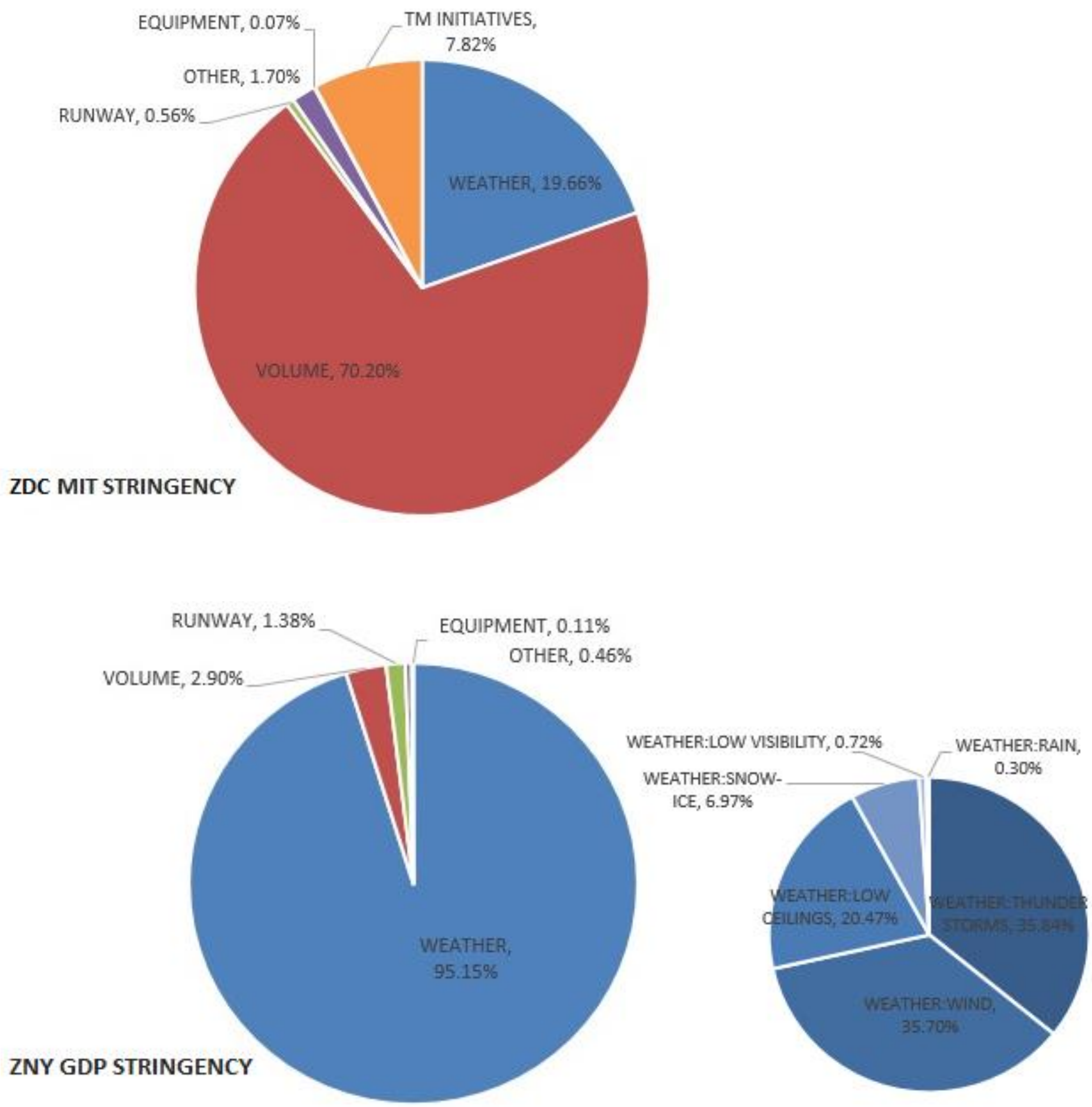

Figure 9. Causal factors of TMI implementation calculated by stringency

Chapter 6: Restriction Matching

While the yearly and regional trends reveal the general changes and correlations between restrictions, they do not tell us whether restrictions occur in the same locations at the same time. This final analysis section matches restrictions based on ARTCC center and implementation time. For MITs to be matched with GDP or GS restrictions, all of the following conditions had to be met:

1. The MIT Requesting Facility matches the field that contains the GDP/GS Center, or the MIT NAS Element name matches the GDP/GS Airport
2. The MIT Providing Facility is listed in the GDP/GS Facilities field
3. The restriction times intersect (overlap is greater than or equal to 0)

These matching criteria face the same weakness as our GDP regional analysis, which is that only tier-based restrictions are captured. As a re-cap from Chapter 5, all GS restrictions have a tier-based scope, but only about 30% of GDP restrictions do. This means that we are not able to compare the magnitude of GDP matching with other restrictions accurately, but can look at trends between years.

Because AFPs are polygons or lines drawn in the airspace and the NTML data do not include the center associated with the FCA area, we attempted to match AFPs with MITs based only on steps 2 and 3 above. This lenient procedure, that lacked a condition for equivalent requesting centers, produced an inaccurately high AFP to MIT pairing rate. We ran the matching algorithm for the year 2009 through 2013 and found that the number of matched AFP and MIT restrictions was somewhere between 20,000 and 27,100 per year – about twice as high as the matching for MIT-GS restrictions, despite there being 10 times more GS restrictions than AFP restrictions. We also tried linking

GDP/GS with AFP based on scope (an exact match in the Facilities field), and although the results were not as unreasonably high as the AFP - MIT matching (see Appendices), we thought that the basis for association was weak and decided not to include AFP in the restriction matching at all. A more extensive approach for analyzing AFP matching would have been to map the FCA geometry, find the centers that it is contained in, and match those centers with the Requesting Facility or Center field. However, since we did not do this in the regional matching section for the previously stated reasons, we elected to keep the methodology similar here.

For matching GDP and GS restrictions together, we used the airport as the common geographical element instead of the facility, since both of these restrictions are airport-based. Due to the issue of matching the Facilities fields for non-tier based GDP restrictions (described above), we did not include a scope criteria and only matched TMI based on two specifications: matching Airport fields and overlapping implementation times.

Lastly, in order to find commonalities between all three restrictions, we took the results of the MIT-GS match and ran them through the GDP-GS matching process. The final list of restrictions that we count in our analysis had the following conditions:

1. The MIT Requesting Facility matches the GS Center or the MIT NAS Element matches the GS Airport
2. The MIT Providing Facility is listed in the GS Facilities field
3. The GS and GDP Airports match
4. All of the restriction times intersect with overlap that is greater than or equal to zero.

Table 18 contains the count of unique matched restriction pairs per year based on the criteria listed above. MITs and GSs have the highest co-occurrence, which is unsurprising since these are the two restriction types with the highest individual counts. For this pair, the trend of matching seems to follow the shape of the GS count graph, with the highest count in 2009. It is interesting to see that although the number of individual MIT and GDP restrictions increased from 2014 – 2016, their co-occurrence actually decreases annually during those years. For MIT and GDP, there is a significant peak in the number of matches in 2013, which happens to be the year that each of those two restrictions increased the most. Bear in mind that these figures only represent the matching of MIT with tier-based GDP and that the number of ARTCC affected by both restrictions at the same time would likely be higher had the providing centers for GDP been determined. There are fewer GDP-GS matches than either of the MIT pairings due to the scale of the TMIs: on average, 400-500 MIT occur per day while only 3-6 GDP/GS occur, meaning that there is a higher probability of multiple MITs occurring in the same facilities at the same time as other restrictions.

For the three-restriction incidence, the downward trend of MIT-GDP matches seems to have a strong impact from 2014-2015, since MIT-GS and GDP-GS occurrences both increase during that year. That is the only year where MIT-GDP-GS occurrence does not trend in the same direction as at least two of the other matching pairs. All four groups have the same fluctuating trend between 2009 and 2013, following which, MIT-

GDP and MIT-GDP-GS matches decrease through 2016, MIT-GDP increase through 2015 then decrease, and GDP-GS stay relatively constant.

Table 18. Number of matched restrictions

	2009	2010	2011	2012	2013	2014	2015	2016
MIT - GDP	5,363	4,286	6,501	4,323	8,542	7,509	5,578	5,477
MIT - GS	12,315	9,197	11,181	8,971	10,444	10,709	11,355	9,458
GDP - GS	796	618	716	491	671	616	633	660
MIT - GDP - GS	1,984	1,443	2,778	1,641	3,142	2,693	2,625	2,130

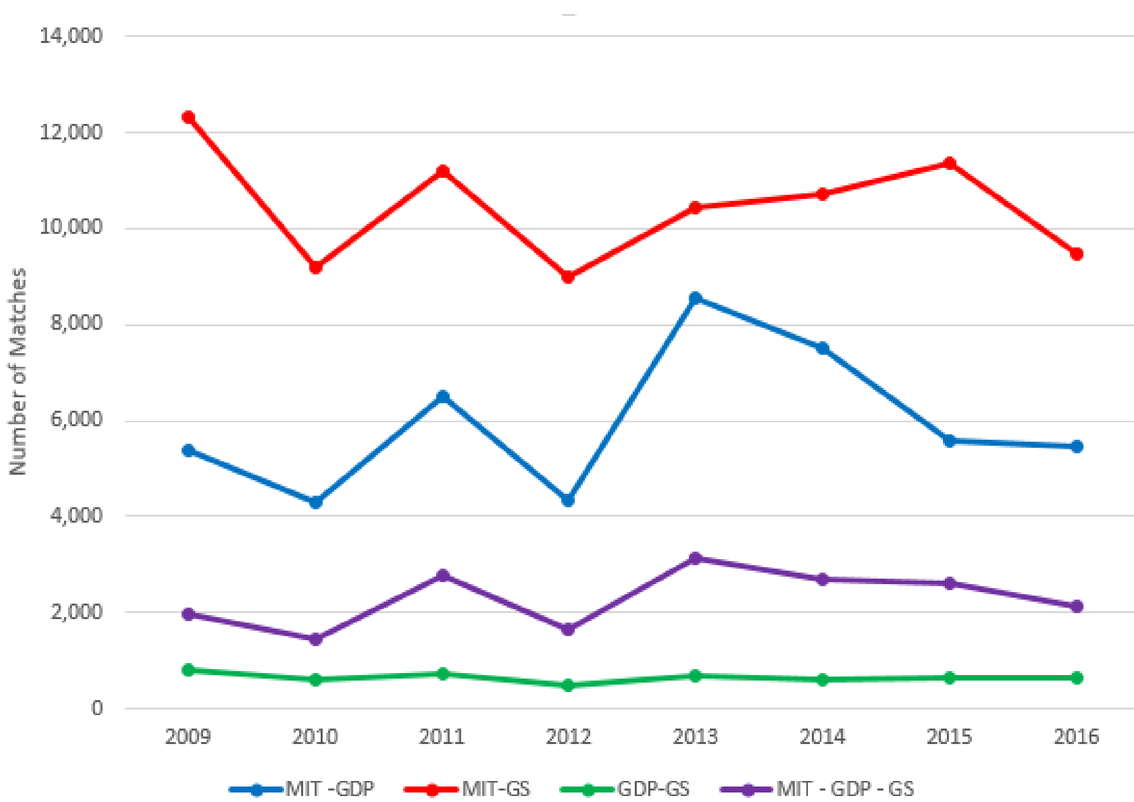

Figure 10. Count of matched restriction occurrences for the years 2009 through 2016

Recall from Chapter 1 that Rios made the assertion stating GDP and GS occur in conjunction or build up/ease into one another [1]. While it seems that the number of matches between these restrictions is low, when we look at the percent of restrictions out of the total number of GDPs and GSs that occur in a year (

Table 19), we see that nearly half of GDPs and over a third of GSs are linked with each other. For reasons like this, we want to look at the proportion and ratio of restrictions that occur simultaneously in order to better illustrate the relationship between them.

Table 19 contains the value of each parameter per year, averaged for 2009 through 2016. We are interested in the number of unique restrictions that are linked to other TMIs, and the percent of the total number of restrictions that those unique restrictions account for. Using the MIT-GDP pair as an example: on average, 4529 unique MIT restrictions were matched with GDP restrictions per year, which accounts for only 2.6% of the total number of MITs that were implemented annually. Since the scales of the different types of TMIs are vastly different, these measures give us a standard way to compare the proportion of matched restrictions.

We also calculated the "duplicate rate" of each TMI type by dividing the total number of pairs by the number of unique restrictions. This value tells us the average number of times each TMI of that type is repeated in the final matched set. For example, the GDP duplicate rate for MIT-GDP matching is 18.01, meaning that each GDP is matched with 18 different MIT restrictions, corresponding to 18 entries with the same GDP restriction in the output dataset. The "match ratio" tells us the proportion of unique TMIs matched for each restriction type, (e.g. for every 13 unique MITs, there is one unique GDP). This match ratio gives us insight to how the different restrictions align.

We can see the that the percent of matched MIT across all events is pretty low - less than 4% - which is expected due to the large number of total MITs initiated per year. We found that about 33% of GDPs and 85% of GSs occur in the same facilities at the same time as MITs. The low GDP matching is likely due to the fact that not all GDP restrictions have associated ARTCCs, while all GSs do because of their tier-based implementation. GDP and GS have a nearly 1:1 matching ratio, with GDP having a slightly higher duplication rate, likely a result of GDP also having a lower count than GS restrictions. As expected, the unique proportion of total restrictions decreased when we matched all three restrictions, with GDP still having the highest duplication rate. These statistics about each type of restriction within the matched sets help us form a better understanding of how TMI are used conjunctively in the NAS.

Table 19. Yearly average data about the individual restrictions for each matched set

MIT -GDP	Unique MIT	4529	Unique GDP	331		
	% Total MIT	2.62%	% Total GDP	33.25%		
	MIT Dup. Rate	1.30	GDP Dup. Rate	18.01		
	MIT-GDP Match Ratio		13.69 : 1			
MIT-GS	Unique MIT	6799	Unique GS	1462		
	% Total MIT	3.92%	% Total GS	85.37%		
	MIT Dup. Rate	1.54	GS Dup. Rate	7.18		
	MIT-GS Match Ratio		4.65 : 1			
GDP-GS	Unique GDP	469	Unique GS	640		
	% Total GDP	47.11%	% Total GS	37.43%		
	GDP Dup. Rate	1.38	GS Dup. Rate	1.02		
	GDP-GS Match Ratio		1 : 1.36			
MIT - GDP - GS	Unique MIT	1484	Unique GDP	185	Unique GS	272
	% Total MIT	0.86%	% Total GDP	18.57%	% Total GS	16.05%
	MIT Dup. Rate	1.54	GDP Dup. Rate	12.37	GS Dup. Rate	8.42
	MIT-GDP-GS Match Ratio		8.02 : 1 : 1.47			

Chapter 7: Conclusions

Overall, this paper gives a broad overview of the general TMI trends by year, by region, and by cause, and serves to highlight commonalities and differences between each of the restrictions. In Chapter 4, we looked at the yearly patterns of four TMIs – MIT, GDP, AFP, and GS – as measured by three different metrics: count, duration, and stringency (a measure of severity). Analyzing the percent change between years revealed trends in system regulation over time (i.e. to what degree each restriction was utilized per year). We found that restrictions decreased in 2010, but either generally increased or leveled out in the years following. The various metrics also provided insight into restriction scale and implementation methodology, since some trends differed depending on the metric. For example, in 2011, MIT count decreased while duration increased, suggesting the use of fewer MIT restrictions with longer effective times. We saw that the daily average count, duration, and stringency for MITs were orders of magnitude higher than for the other TMIs, with AFP being consistently the least prominent. According to our yearly tendency investigation, GDP and GS, AFP and GS, and MIT and AFP had the most number of common directionality between years; the roles of MIT/AFP affecting en route trajectories and GDP/GS affecting airports are likely related to those similarities.

In Chapter 5, we further confirm that the functions of MIT, GDP, and GS restrictions are tied closely to their purposes and their geographical locations, as was suggested by previous literature. MIT restrictions control en-route spacing and are thus more susceptible to issues originating within the NAS, like volume, or excessive demand in the airspace. They are also initiated frequently, yet for a short duration, as a result of traffic-managers' decisions to fine tune traffic for efficiency, which manifests as the "TM

Initiatives" reason. Because they are mostly en route restrictions, MITs are requested in centers that handle a lot of through traffic, either in the middle of the continental US or bordering ARTCC with busy airports. GDPs and GSs are meant to regulate traffic arriving at an impacted airport and are therefore more common in centers with high-demand destinations (like ZNY, which contains the three traffic-heavy New York airports). They are caused mostly by weather, which decreases an airport's capacity to such an extent that airborne holding is ineffective and aircraft must be held on the ground. Since GSs are essentially GDPs with an acceptance rate of zero, they are most often caused by weather events (thunderstorms) that are more severe than those causing GDPs (wind). By matching restrictions based on common facilities and overlapping implementation time (Chapter 6), we found that MITs and GSs had the highest occurrence of matching pairs in ARTCCs, which is expected considered that they are the most commonly initiated TMIs, at least according to our record of daily average TMI counts. GDP and GS restrictions were linked at a nearly 1:1 rate on the airport level, which is more specific than the ARTCC level, with 47% of GDPs and 37% of GSs used in conjunction with each other. The matching method is original work performed for the purpose of this thesis, but it is used to validate Rios assertion that a significant proportion of GDP and GS restrictions are related.

The statistics presented in this paper are meant to provide a "big picture" summary of restrictions implemented in the NAS over the last 8 years using the data recorded in the NTML. We hope that this high level analysis will help researchers understand restriction causes and behavior, with the ultimate goal of assisting the decision-making that will improve the effectiveness of traffic management initiatives.

Chapter 8: Future Work

As we can see from the lack of AFP analyses in Chapters 5 and 6, a major issue with the raw NTML data is that it does not include the centers associated with an AFP's FCA. This absence of information prevented us from comparing facility trends and matching AFPs with other TMIs based on our current methodology. However, it is possible to populate the Center field by mapping the FCA geometry and finding the ARTCC(s) that it intersects with, a task that would be beneficial to pursue in future work. The same could be done to find the values in the Facilities field for distance-based GDPs. We could draw the specified radius of a restriction around the affected airport and determine its intersecting centers. This work would improve the accuracy of the providing facility regional analysis and the GDP-MIT restriction matching. Yet even if both of these tasks are performed, we are still matching based on common ARTCCs, which are fairly large regions. A "true" geographical match would actually link TMIs by the intersections of specific geometries (FCAs, GDP airport radii, GS and MIT ARTCC, etc.) and would provide a higher resolution of restriction association.

Other factors to consider when looking at the relationship between TMIs are season and day of the week. Summer months produce more convective weather and have higher passenger demand, most likely due to the US public education system having an extended summer break [17]. Certain days of the week (like Monday and Friday) have increased demand from business travelers and generate more traffic as well [18]. We could see if all restrictions are impacted similarly during each season or time period of interest, looking at monthly or even weekly trends, especially around travel-heavy times like the holidays. Since we only analyzed at the causal factors of the top centers in 2016, including other years or additional regions may reveal additional trends as well.

In our methodology, we do not consider the “pass back” data field, which indicates whether a TMI is the result of management being handed off to regions upstream of the original traffic issue. As an extension to our current restriction matching procedure, we could investigate the prevalence of pass backs, not just those indicated in the appropriate field, but also the restriction propagation suggested by time and region parameter matching. Furthermore, we could identify routine TMIs based on the similarities between entries (e.g. a three hour MIT restriction implemented at 9AM every Monday), which would allow us to distinguish restrictions reacting to system conditions from those just put in place for insurance. These efforts would help us get a feel for how traffic control is distributed across the NAS and the actual proportion of “essential” (non-routine) restrictions.

Appendices

Table 20. List of ARTCC abbreviations [19]

ZAB	Albuquerque Center	ZKC	Kansas City Center
ZAN	Anchorage Center	ZLA	Los Angeles Center
ZAU	Chicago Center	ZLC	Salt Lake City Center
ZBW	Boston Center	ZMA	Miami Center
ZDC	Washington D.C. Center	ZME	Memphis Center
ZDV	Denver Center	ZMP	Minneapolis Center
ZFW	Fort Worth Center	ZNY	New York Center
ZHN	Honolulu Center	ZOA	Oakland Center
ZHU	Houston Center	ZOB	Cleveland Center
ZID	Indianapolis Center	ZSE	Seattle Center
ZJX	Jacksonville Center	ZTL	Atlanta Center

Table 21. Causal factors of MIT at ZAU in 2016, measured by count

Category	**Category Daily Average Count**	**Category %**	**Reason Text**	**Reason Daily Average Count**	**Reason %**
WEATHER	8.78	10.91%	WEATHER:WIND	3.98	4.94%
			WEATHER:THUNDERSTORMS	3.61	4.48%
			WEATHER:SNOW/ICE	0.42	0.53%
			WEATHER:LOW CEILING	0.31	0.38%
			WEATHER:LOW VISIBILITY	0.24	0.30%
			WEATHER:OTHER	0.17	0.22%
			WEATHER:TURBULENCE	0.04	0.05%
			WEATHER:FOG	0.01	0.01%
VOLUME	32.43	40.28%	VOLUME:COMPACTED DEMAND	12.48	15.51%
			VOLUME:BLENDING STREAMS	8.68	10.78%
			VOLUME:OTHER	5.76	7.15%
			VOLUME:VOLUME	5.36	6.65%
			VOLUME:ENROUTE SECTOR	0.11	0.14%
			VOLUME:SECTOR COMPLEXITY	0.02	0.03%
			VOLUME:ARRIVAL DEMAND	0.01	0.02%
RUNWAY	1.52	1.88%	RWY:OTHER	1.48	1.84%
			RWY:CONSTRUCTION	0.03	0.04%
OTHER	0.04	0.05%	OTHER	0.03	0.04%
			OTHER:MILITARY/VIP OPS	0.01	0.02%
EQUIPMENT	0.01	0.01%	EQUIPMENT:OUTAGE	0.01	0.01%
TM INITIATIVES	37.72	46.86%	TM INITIATIVES:MIT	37.70	46.83%
			TM INITIATIVES:METERING	0.02	0.03%

Table 22. Causal factors of MIT at ZAU in 2016, measured by duration

Category	Category Daily Average Duration	Category %	Reason Text	Reason Daily Average Duration	Reason %
WEATHER	28.51	21.92%	WEATHER:THUNDERSTORMS	19.83	15.24%
			WEATHER:LOW CEILING	3.26	2.51%
			WEATHER:WIND	1.84	1.41%
			WEATHER:OTHER	1.83	1.41%
			WEATHER:TURBULENCE	1.33	1.02%
			WEATHER:SNOW/ICE	0.29	0.23%
			WEATHER:LOW VISIBILITY	0.13	0.10%
VOLUME	85.75	65.93%	VOLUME:COMPACTED DEMAND	37.43	28.78%
			VOLUME:VOLUME	36.68	28.20%
			VOLUME:ARRIVAL DEMAND	4.16	3.20%
			VOLUME:OTHER	3.71	2.85%
			VOLUME:SECTOR COMPLEXITY	1.58	1.21%
			VOLUME:BLENDING STREAMS	1.07	0.82%
			VOLUME:ENROUTE SECTOR	0.94	0.73%
			VOLUME:AIRPORT	0.18	0.14%
RUNWAY	0.62	0.48%	RWY:OTHER	0.42	0.32%
			RWY:CONSTRUCTION	0.20	0.16%
OTHER	2.37	1.83%	OTHER	1.61	1.24%
			OTHER:MILITARY/VIP OPS	0.76	0.59%
EQUIPMENT	0.12	0.09%	EQUIPMENT:OUTAGE	0.12	0.09%
TM INITIATIVES	12.70	9.76%	TM INITIATIVES:METERING	12.24	9.41%
			TM INITIATIVES:MIT	0.46	0.35%

Table 23. Causal factors of MIT at ZAU in 2016, measured by stringency

Category	Category Daily Average Stringency	Category %	Reason Text	Reason Daily Average Stringency	Reason %
WEATHER	609.74	19.66%	WEATHER:THUNDERSTORMS	405.3	13.06%
			WEATHER:LOW CEILING	71.7	2.31%
			WEATHER:WIND	49.8	1.60%
			WEATHER:OTHER	46.4	1.50%
			WEATHER:TURBULENCE	25.0	0.80%
			WEATHER:SNOW/ICE	8.9	0.29%
			WEATHER:LOW VISIBILITY	2.8	0.09%
VOLUME	2177.74	70.20%	VOLUME:COMPACTED DEMAND	997.6	32.16%
			VOLUME:VOLUME	896.2	28.89%
			VOLUME:ARRIVAL DEMAND	120.0	3.87%
			VOLUME:OTHER	73.8	2.38%
			VOLUME:SECTOR COMPLEXITY	42.8	1.38%
			VOLUME:BLENDING STREAMS	22.9	0.74%
			VOLUME:ENROUTE SECTOR	20.0	0.65%
			VOLUME:AIRPORT	4.4	0.14%

RUNWAY	17.29	0.56%	RWY:OTHER	11.4	0.37%
			RWY:CONSTRUCTION	5.9	0.19%
OTHER	52.72	1.70%	OTHER	36.1	1.17%
			OTHER:MILITARY/VIP OPS	16.6	0.53%
EQUIPMENT	2.08	0.07%	EQUIPMENT ISSUE/OUTAGE	2.1	0.07%
TM INITIATIVES	242.59	7.82%	TM INITIATIVES:METERING	230.9	7.44%
			TM INITIATIVES:MIT	11.7	0.38%

Table 24. Causal factors of GDP at ZNY in 2016, measured by duration

Category	**Category Daily Average Duration**	**Category %**	**Reason Text**	**Reason Daily Average Duration**	**Reason %**
WEATHER	0.9414	9.75	WEATHER:THUNDERSTORMS	2.8373	27.41%
			WEATHER:WIND	4.0230	38.86%
			WEATHER:LOW CEILINGS	2.3174	22.39%
			WEATHER:SNOW-ICE	0.4978	4.81%
			WEATHER:LOW VISIBILITY	0.0699	0.68%
			WEATHER:RAIN	0.0273	0.26%
VOLUME	0.0373	0.39	VOLUME:VOLUME	0.3009	2.91%
			VOLUME:COMPACTED DEMAND	0.0857	0.83%
RUNWAY	0.0128	0.13	RWY-TAXI:MAINTENANCE	0.0764	0.74%
			RWY-TAXI:DISABLED AIRCRAFT	0.0372	0.36%
			RWY-TAXI:CONSTRUCTION	0.0190	0.18%
OTHER	0.0046	0.05	OTHER:SECURITY	0.0259	0.25%
			OTHER:OTHER	0.0219	0.21%
EQUIPMENT	0.0012	0.01	EQUIPMENT:OUTAGE	0.0121	0.12%

Table 25. Causal factors of GDP at ZNY in 2016, measured by stringency

Category	**Category Daily Average Stringency**	**Category %**	**Reason Text**	**Reason Daily Average Stringency**	**Reason %**
WEATHER	13.815	95.15%	WEATHER:THUNDERSTORMS	4.951	34.10%
			WEATHER:WIND	4.932	33.97%
			WEATHER:LOW CEILINGS	2.827	19.47%
			WEATHER:SNOW-ICE	0.963	6.63%
			WEATHER:LOW VISIBILITY	0.099	0.68%
			WEATHER:RAIN	0.042	0.29%
VOLUME	0.421	2.90%	VOLUME:VOLUME	0.340	2.34%
			VOLUME:COMPACTED DEMAND	0.080	0.55%
RUNWAY	0.200	1.38%	RWY:MAINTENANCE	0.122	0.84%
			RWY:DISABLED AIRCRAFT	0.063	0.43%
			RWY:CONSTRUCTION	0.015	0.10%
OTHER	0.067	0.46%	OTHER:SECURITY	0.029	0.20%
			OTHER:OTHER	0.038	0.26%
EQUIPMENT	0.016	0.11%	EQUIPMENT:OUTAGE	0.016	0.11%

Table 26. Causal factors of GS at ZNY in 2016, measured by count

Category	Category Daily Average Count	Category %	Reason Text	Reason Daily Average Count	Reason %
WEATHER	1.139	80.81%	WEATHER:THUNDERSTORMS	0.473	33.53%
			WEATHER:WIND	0.301	21.32%
			WEATHER:LOW CEILINGS	0.254	18.02%
			WEATHER:SNOW-ICE	0.071	5.04%
			WEATHER:LOW VISIBILITY	0.033	2.33%
			WEATHER:RUNWAY TREATMENT	0.003	0.19%
			WEATHER:RAIN	0.003	0.19%
			WEATHER:FOG	0.003	0.19%
VOLUME	0.178	12.60%	VOLUME:VOLUME	0.104	7.36%
			VOLUME:COMPACTED DEMAND	0.071	5.04%
			VOLUME:MULTI-TAXI	0.003	0.19%
RUNWAY	0.022	1.55%	RWY:DISABLED AIRCRAFT	0.011	0.78%
			RWY:OBSTRUCTION	0.005	0.39%
			RWY:CONSTRUCTION	0.005	0.39%
OTHER	0.041	2.91%	OTHER:EMERGENCY	0.022	1.55%
			OTHER:OTHER	0.014	0.97%
			OTHER:SECURITY	0.005	0.39%
EQUIPMENT	0.030	2.13%	EQUIPMENT:OUTAGE	0.030	2.13%

Table 27. Causal factors of GS at ZNY in 2016, measured by duration

Category	Category Daily Average Duration	Category %	Reason Text	Reason Daily Average Duration	Reason %
WEATHER	1.438	81.53%	WEATHER:THUNDERSTORMS	0.607	34.41%
			WEATHER:WIND	0.373	21.15%
			WEATHER:LOW CEILINGS	0.316	17.92%
			WEATHER:SNOW-ICE	0.092	5.21%
			WEATHER:LOW VISIBILITY	0.040	2.24%
			WEATHER:RUNWAY TREATMENT	0.004	0.23%
			WEATHER:RAIN	0.003	0.19%
			WEATHER:FOG	0.003	0.18%
VOLUME	0.210	11.90%	VOLUME:VOLUME	0.125	7.07%
			VOLUME:COMPACTED DEMAND	0.083	4.72%
			VOLUME:MULTI-TAXI	0.002	0.11%
RUNWAY	0.026	1.49%	RWY:DISABLED AIRCRAFT	0.014	0.79%
			RWY:OBSTRUCTION	0.007	0.38%
			RWY:CONSTRUCTION	0.006	0.33%
OTHER	0.052	2.94%	OTHER:EMERGENCY	0.027	1.53%
			OTHER:OTHER	0.019	1.09%
			OTHER:SECURITY	0.006	0.32%
EQUIPMENT	0.038	2.13%	EQUIPMENT:OUTAGE	0.038	2.13%

Table 28. Breakdown of restriction matching by year

		2009	2010	2011	2012	2013	2014	2015	2016	AVG
MIT -GDP	Unique MIT	4396	3574	5224	3581	5971	5505	3897	4085	4529
	% Total MIT	2.62%	2.26%	3.32%	2.21%	3.36%	3.06%	1.98%	2.12%	2.62%
	MIT Dup. Rate	1.22	1.20	1.24	1.21	1.43	1.36	1.43	1.34	1.30
	Unique GDP	290	231	337	261	443	457	293	334	331
	% Total GDP	26.24%	26.19%	35.21%	31.52%	44.66%	45.02%	27.21%	29.98%	33.25%
	GDP Dup. Rate	18.49	18.55	19.29	16.56	19.28	16.43	19.04	16.40	18.01
	Match Ratio	15.16 : 1	15.47 : 1	15.5 : 1	13.72 : 1	13.48 : 1	12.05 : 1	13.3 : 1	12.23 : 1	13.69 : 1
MIT-GS	Unique MIT	8453	6066	6799	5947	6649	6735	7467	6274	6799
	% Total MIT	5.04%	3.83%	4.32%	3.68%	3.74%	3.75%	3.79%	3.26%	3.92%
	MIT Dup. Rate	1.46	1.52	1.64	1.51	1.57	1.59	1.52	1.51	1.54
	Unique GS	1891	1369	1621	1283	1343	1457	1425	1307	1462
	% Total GS	85.37%	82.27%	89.81%	86.34%	84.84%	87.14%	85.90%	81.28%	85.37%
	GS Dup. Rate	6.51	6.72	6.90	6.99	7.78	7.35	7.97	7.24	7.18
	Match Ratio	4.47 : 1	4.43 : 1	4.19 : 1	4.64 : 1	4.95 : 1	4.62 : 1	5.24 : 1	4.8 : 1	4.65 : 1
GDP-GS	Unique GDP	559	437	484	361	491	451	459	513	469
	% Total GDP	50.59%	49.55%	50.57%	43.60%	49.50%	44.43%	42.62%	46.05%	47.11%
	GDP Dup. Rate	1.42	1.41	1.48	1.36	1.37	1.37	1.38	1.29	1.38
	Unique GS	790	608	703	484	656	609	624	647	640
	% Total GS	35.67%	36.54%	38.95%	32.57%	41.44%	36.42%	37.61%	40.24%	37.43%
	GS Dup. Rate	1.01	1.02	1.02	1.01	1.02	1.01	1.01	1.02	1.02
	Match Ratio	1 : 1.41	1 : 1.39	1 : 1.45	1 : 1.34	1 : 1.34	1 : 1.35	1 : 1.36	1 : 1.26	1 : 1.36
MIT - GDP - GS	Unique MIT	1407	1049	1812	1115	1919	1727	1490	1354	1484
	% Total MIT	0.84%	0.66%	1.15%	0.69%	1.08%	0.96%	0.76%	0.70%	0.86%
	MIT Dup. Rate	1.41	1.38	1.53	1.47	1.64	1.56	1.76	1.57	1.54
	Unique GDP	168	126	217	138	233	226	184	188	185
	% Total GDP	15.20%	14.29%	22.68%	16.67%	23.49%	22.27%	17.08%	16.88%	18.57%
	GDP Dup. Rate	11.81	11.45	12.80	11.89	13.48	11.92	14.27	11.33	12.37
	Unique GS	258	182	339	196	340	323	287	253	272
	% Total GS	11.65%	10.94%	18.78%	13.19%	21.48%	19.32%	17.30%	15.73%	16.05%
	GS Dup. Rate	7.69	7.93	8.19	8.37	9.24	8.34	9.15	8.42	8.42
	Match Ratio	8.4 : 1 : 1.5	8.3 : 1 : 1.4	8.4 : 1 : 1.6	8.1 : 1 : 1.4	8.2 : 1 : 1.5	7.6 : 1 : 1.4	8.1 : 1 : 1.6	7.2 : 1 : 1.3	8 : 1 : 1.5

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