

## ABSTRACT

## Title of Thesis:

# AN ANALYSIS OF EN ROUTE AIR TRAFFIC MANAGEMENT INITIATIVES

Santiago Javier Sanz, Master of Science, 2018

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Ensuring the safety and efficiency of flights is a large mission the FAA is tasked with. Since the early 2000's the FAA has been working on implementing their next generation air transportation system that aims at modernizing the way flights are managed. Some of the changes brought on by the implementation of next gen include additions and modifications to the time management initiatives (TMIs) that the FAA uses for managing flights. For that reason, the FAA is interested in how these TMIs compare with each other. This document focuses on comparing different TMIs by conducting statistical analysis on the available data and examining the results.

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by

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Thesis submitted to the Faculty of the Graduate School of the  
University of Maryland, College Park, in partial fulfillment  
of the requirements for the degree of

Master of Science

2018

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## Acknowledgements

I would first like to thank my thesis advisor Professor David Lovell of the Department of Civil and Environmental engineering, and the Institute for systems research at University of Maryland. Dr. Lovell was always willing to answer any question I had about my research or writing, and always provided the constructive feedback necessary to perfect my work. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it.

I would also like to thank Dr. Michael Ball of the Smith School of Business and the Institute for Systems Research at the University of Maryland, Dr. Robert Hoffman of Metron Aviation, and the other members of the Nextor II group. Dr. Ball and Dr. Hoffman provided valuable feedback and support throughout, in particular during the time Dr. Lovell was on sabbatical. Additionally, I would like to thank Dr. Lovell, Dr. Ball, and Dr. Mark Austin of the Department of Civil and Environmental engineering, and the Institute for systems research at University of Maryland for taking the time to be a part of my thesis committee.

Furthermore, I would like to thank the analysts at the FAA, in particular Mr. Prabhakar Thyagaragan, Dr. Abbas Afshar, and Ms. Jin Li. Mr. Prabhakar and Dr. Afshar provided loads of industry knowledge as well as pointed me in the right direction for finding information regarding my thesis topic. Additionally, Ms. Li helped me develop the Tableau dashboard with her knowledge and expertise on the ins and outs of Tableau.

Finally, I must express my very profound gratitude to my parents for investing in my education, and providing me with unfailing support and continuous encouragement throughout my years of study, including the process of researching and writing this thesis. Without their support, this accomplishment would not have been possible.

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## List of Abbreviations

FAA	Federal Aviation Administration
TMI	Traffic Management Initiatives
MIT	Miles In Trail
TBM	Time Based Metering
APREQ	Approval Request
DSP	Departure Spacing Program
MINIT	Minutes In Trail
STOP	Departure Stop
NextGen	Next Generation Air Transportation System
NAS	National Airspace System
IFR	Instrument Flight Rules
VFR	Visual Flight Rules
FL	Flight Level
ATC	Air Traffic Control
ADIZ	Air Defense Identification Zone
ATCSCC	Air Traffic Control System Command Center
ARTCC	Air Route Traffic Control Center
TRACON	Terminal Radar Approach Control
ATCT	Air Traffic Control Tower
TBFM	Time Based Flow Management
NTML	National Traffic Management Log
ASPM	Aviation System Performance Metrics

TFMS

Traffic Flow Management Services

## Chapter 1: Introduction

Since the creation and popularization of flight, managing flights has been vital for ensuring safety on the ground and in the air. During the early 2000's, the progressive increase in air travel has caused a significant increase in the amount of delays flights experience. This has caused the Federal Aviation Administration (FAA) to rethink the way it manages flights. The answer the FAA came up with was the Next Generation Air Transportation System (NextGen) to modernize the ways flights are managed. Changes brought about by NextGen include a shift from radar-based navigation to satellite base navigation, as well as improvements to the infrastructure and procedures for flight operations. In particular, the FAA uses various Traffic Management Initiatives (TMIs) to handle situations where congestion or safety concerns necessitate some intervention in the traffic flow. NextGen includes modernization of the suite of TMIs available to traffic managers, with modifications to some to reflect new technology conditions, as well as the addition of new TMIs (TMI) (Joint Planning and Development Office, 2011).

With the addition of new TMIs, and changes in how the various TMIs are implemented by traffic managers, carriers and the FAA are interested in seeing how different TMIs affect flights as well as how the different TMIs used compare against each other. Unfortunately, as of the time of writing, there is no database that records specifically how each TMI that a flight might encounter affects that particular flight. In a step towards mitigating this limitation, analysts at the FAA created a simulation that models flights trajectories based on their schedule to see what TMIs potentially affected which flights. This simulation generates a database of unique flight and

restriction pairings which are coupled with additional data on the flight and restriction. As of the time of this writing, the database is still under development. The research conducted to support this thesis was based on one of the most recent iterations of this database.

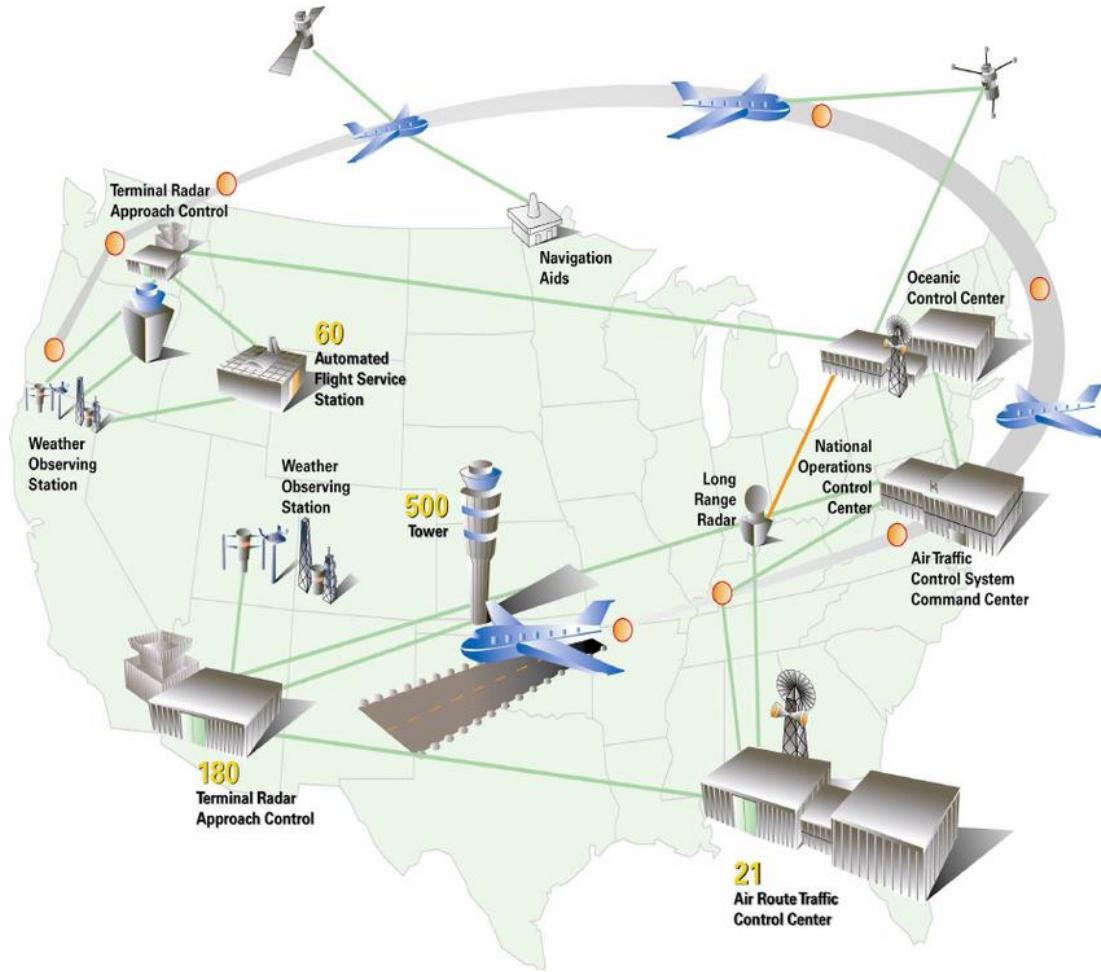
This document begins by presenting the background information necessary to understand the research work that will be covered. This includes a brief discussion of the National Airspace System, the different types and classes of airspace, the different types of air traffic control centers, the typical process of an individual flight, and a description of the official vision for the next generation air transportation system. Following this brief overview, a more detailed overview of the TMIs studied in this research along with the data sources that contain the data used for running the simulation and therefore also used for this research will be provided. Afterwards, a detailed overview of how the simulation works will be provided, along with a description of the Tableau dashboard developed for the FAA to visualize the simulated data. The brunt of this report will cover the methodology of a statistical analysis conducted on an excerpt of the database generated by the simulation. Since the database is still under development, only a small quantity of the data was available; therefore, the statistical analysis conducted was for a small sample. The document ends with a presentation of the results as well as some recommendations for future work.

## Chapter 2: Background

In order for thousands of aircraft to fly simultaneously around the world in a predictable, safe, efficient, and controlled manner, there must be a system in place to manage all the flights that are in the air and on the ground at any given point in time. Any mismanagement could cause fatal incidents to occur, costing the lives of tens if not hundreds of people as well as thousands if not millions of dollars' worth of damage. In the United States, the Federal Aviation Administration (FAA) is the agency in charge of managing traffic throughout the U.S. airspace. Additionally, the FAA is tasked with regulating all aspects of commercial aviation from the construction and operation of airports, to the certification of aircraft. This section will provide a brief overview of how air traffic management works in the United States so that readers can better understand the information presented later in this document.

### 2.1 National Airspace System

For accomplishing the task of managing aircraft on the ground and in the air in the U.S. airspace, the FAA has created the National Airspace System (NAS). According to the Federal Aviation Administration (2017), the NAS is “The common network of U.S. airspace; air navigation facilities, equipment and services, airports or landing areas, aeronautical charts, information and services; rules, regulations and procedures, technical information, and manpower and material. Included are system components shared jointly with the military” (PCG N-1). An illustration of the NAS can be seen in figure 1 below.



*Figure 1: Illustration of the National Airspace System (Jasinevicius, 2010)*

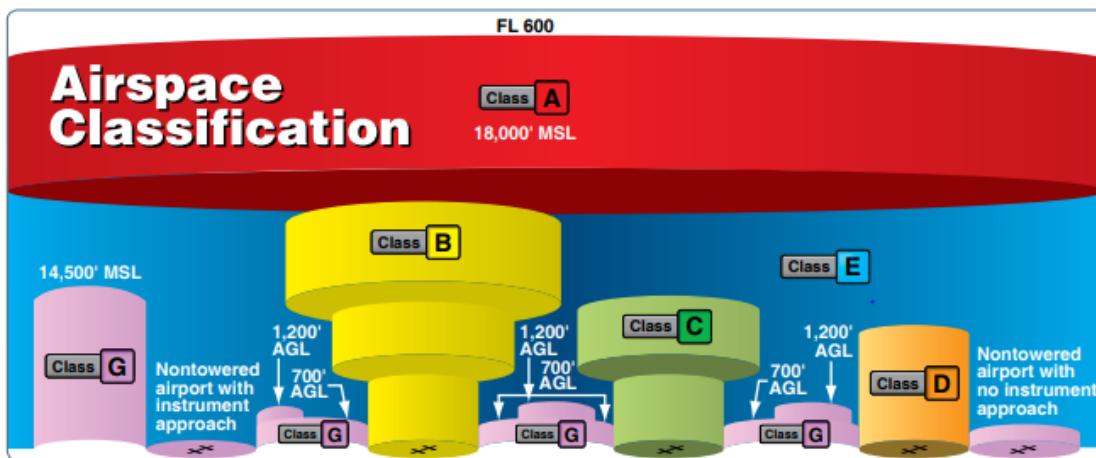
For the purpose of maintaining relevance to the topic of this document, only the aspects of the NAS related to airspace and the management of flights will be covered.

## 2.2 Airspace

To manage flights more effectively, the U.S. Airspace in the NAS is divided into four different types of airspace. These include controlled, uncontrolled, special use, and other. Controlled and uncontrolled airspace are broken down into different classes of airspace. Within these two types of airspace there are six total different classes of

airspace, with controlled airspace being divided into five classes, and uncontrolled airspace constituting a single class by itself.

Controlled airspace is a generic name given to the classes of airspace and defined dimensions within which air traffic control service is provided to planes flying under Instrument Flight Rules (IFR), and Visual Flight Rules (VFR) (CFI Notebook.net, n.d.). As stated above, this type of airspace is divided into five different classes. These include Class A, B, C, D, and E, and can be seen in the figure below.



*Figure 2: Airspace Classes (Federal Aviation Administration, 2016)*

Class A airspace is airspace between the altitudes of 18,000ft at Mean Sea Level (MSL) up to Flight Level (FL) 600. Flight level refers to the vertical altitude, in units of hundreds of feet, at standard pressure. In flight, pilots use a pressure altimeter, a calibrated barometer, which takes the current ambient pressure and using the barometric formula, results in a corresponding altitude. This method of calculating altitude is possible since pressure decreases as altitude increases. This class of airspace also includes the airspace overlaying the waters of the coast of the 48 contiguous states and Alaska up to 12 nautical miles from the coast. In this class,

only airplanes operating under Instrument Flight Rules are allowed. Class B airspace is found surrounding the nation's busiest airports. This area consists of a surface area plus two or more layers that range in altitude from the surface up to 10,000ft MSL.

Class B airspace was designed to contain all published instrument procedures once the aircraft enters the airspace. Additionally, Air Traffic Control (ATC) clearance is required for all aircraft that enter or that are within the bounds of this class.

Furthermore, all cleared aircraft also receive separation service within the airspace.

Class C airspace is the airspace surrounding airports that have operational control towers and are serviced by radar approach control. This class also contains a certain number of IFR operations or passenger enplanements. The geometry for this class consists of a surface with a 5 nautical mile (NM) radius that extends from the ground up to 1200 ft above the airport followed by an outer circle with a radius of 10NM.

Similar to class B airspace, airplanes in this class must also be in constant communication with the ATC. Class D airspace surrounds airports that just have an operational control tower. This class of airspace is in effect from the surface to 2500ft above the elevation of the airport. The area encompassed by this class of airspace is individually tailored and normally designed to contain the procedures when instrument procedures are published. Like class B and C, class D airspace also requires constant communication with the ATC prior to and when within the airspace.

The last class of controlled airspace would be class E. This class consists of all the controlled airspace not classified as class A, B, C, or D. Depending on the location and the other classes of airspace, class E airspace could begin as low as 700ft above the ground or as high as 14500ft and extends up to but not including 18000ft MSL.

Additionally, the airspace above FL600 is also classified as class E airspace. Figure 1 shows a visual description of the different classes of airspace (Federal Aviation Administration, 2016).

Another type of airspace that the FAA defines is uncontrolled airspace. In this kind of airspace, an ATC does not have responsibility or authority over flights in the airspace except for when a temporary control tower is active. For uncontrolled airspace there is only one class, class G. The class G airspace begins at the surface and extends all the way up to the base of class E airspace. For this class of airspace, Visual Flight Rules (VFR) are in effect (Federal Aviation Administration, 2016).

The third type of Airspace defined by the FAA in the NAS would be Special Use Airspace (SUA). This is a designation given to the areas where certain confined activities take place, or where limitations may be placed on aircraft that are not part of those activities. Information about the specifics of each special use airspace can be found on the National Aeronautical Charting Group's en route charts' end panels. The SUA shown on instrument charts includes information on the area name or number, effective altitude, time and weather conditions of operations, the controlling agency, and the chart panel location. SUAs typically consist of six different types of areas. These would include prohibited areas, restricted areas, warning areas, military operation areas, alert areas, and control firing areas (Federal Aviation Administration, 2016).

The last type of airspace the FAA defines would be airspace that is labeled as "other". Other airspace is a term used to refer to airspace that does not fall under controlled, uncontrolled, or special use airspace. This includes, local airport advisory,

military training route, temporary flight restrictions, parachute jump aircraft operations, published VFR routes, terminal radar service area, national security area, air defense identification zone (ADIZ), intercept procedures, flight restricted zones, special awareness training required for VFR pilots flying within 60 miles of Washington DC, wildlife areas/wilderness areas/national parks, and requests to operate above 2000ft AGL, National Oceanic and Atmospheric Administration marine areas off the coast with requirements to fly above 2000ft AGL, and tethered balloons for observation and weather recordings that extend on cables up to 60,000ft (Federal Aviation Administration, 2016).

### 2.3 Air Traffic Control Facilities

Now that the different types and classes of airspace have been briefly described, it is important to understand the different types of facilities that are in service for managing air traffic throughout the NAS. Having a brief understanding of the different types and classes of airspace helps visualize how the airspace is structured. In turn, understanding the facilities helps show how each distinct class of airspace is controlled. Overall, there are four different types of facilities. These would include the Air Traffic Control System Command Center, Air Route Traffic Control Centers, Terminal Radar Approach Control, and Air Traffic Control Towers.

The Air Traffic Control System Command Center (ATCSCC) is the facility that is in charge of overseeing the air traffic control system as a whole. Located in Warrenton, VA, this is the facility that is responsible for the strategic aspects of the NAS. Additionally, this facility will modify traffic flows and rates when congestion,

weather, equipment outages, or runway closures occur, or when other operational conditions affect the NAS.

Another type of facility would be Air Route Traffic Control Centers (ARTCC). Throughout the U.S., there are twenty-one ARTCCs. The geographic coverage of these centers can be seen on the map in Figure 2 below.



*Figure 3: ARTCC Boundaries Map (Fetter, n.d.)*

Each one of these twenty-one ARTCC's oversees its respective geographical area. All twenty-one ARTCC areas are further divided into sectors. The main purpose of the ARTCCs is to provide air traffic control to airplanes operating in IFR flight plans within controlled airspace usually during the en route phase of flight. When the controller workload and equipment capabilities permit, an ARTCC can also provide advisory or assistance service to planes flying under VFR.

The third type of facility that is used to manage the air traffic across the NAS would be the Terminal Radar Approach Control (TRACONs). The purpose of these

centers is to provide approach and departure service for both IFR and VFR flights, and to provide service to those aircraft transitioning through the terminal's airspace. TRACONs use both radar and non-radar separation.

The last facilities that are used to manage air traffic are the Air Traffic Control Towers (ATCT). These facilities use radar and visual observation to keep track of the aircraft under their control. The ATCTs are in charge of providing traffic advisories, spacing, sequencing, and separation services to both VFR and IFR aircraft operating near an airport. Each one of these facilities plays an integral role in ensuring the efficiency and safety of flights (Federal Aviation Administration, 2018a).

#### 2.4 Process of a Typical Flight

To better understand the process of flying in the national airspace it is necessary to combine the information presented above relating to the types and classes of airspace with the information relating to the different facilities used by the FAA to manage flights. This will provide a better picture of the process. The process of flying through the U.S. airspace is composed of seven parts that will be explained in further detail in this section. These parts include pre-flight, taxi, departure, en route, descent, approach, and landing. All these parts are associated with the different facilities and the different classes of airspace.

Before a flight can move from its gate there are a series of steps that the pilots must complete. This is known as the pre-flight part of the flight. During this part, the pilots must complete a thorough plane inspection to ensure the plane is flight worthy. Then, they must file a flight plan. In the ATCT, the controllers review the flight plan,

create a flight progress strip, and grant clearance to the pilot to be able to conduct that flight plan (Freudenrich, 2001).

After the pre-flight portion of the flight is completed, the pilot communicates with the ATCT for permission to begin the pushback, thereby beginning the Taxi portion of the flight. During this portion, the ground controller directs the pilot to push back. The plane is then pushed back from the gate by the ground crew operating the tug. Once unhitched, the pilot taxis the plane to the correct runway. At this point, the ground controller passes the plane to the local controller. When the airspace is clear, the local controller gives the pilot clearance to take off. At this point, the plane speeds down the runway (Freudenrich, 2001).

While the aircraft is taking off, the Local controller passes the flight to the departure controller in the TRACON. The departure controller gives the pilot instructions appropriate to maintain a safe distance between other ascending aircraft. Additionally, the departure controller makes sure the plane is following regular ascent corridors through the airspace of the TRACON. After the plane leaves the TRACON, the departure controller passes the flight to the controllers at the ARTCCs (Freudenrich, 2001).

Once the aircraft passes to the hands of the controllers at the ARTCCs, the flight has officially entered the en route phase. During this phase of flight, the pilot is in communication with the controllers at the ARTCCs, who oversee the pilots to ensure they maintain safe separation between aircraft, as well as coordinating activities with other sectors or centers. The controller is also responsible for providing the pilots updates about the weather and the air traffic. As the plane flies in the class

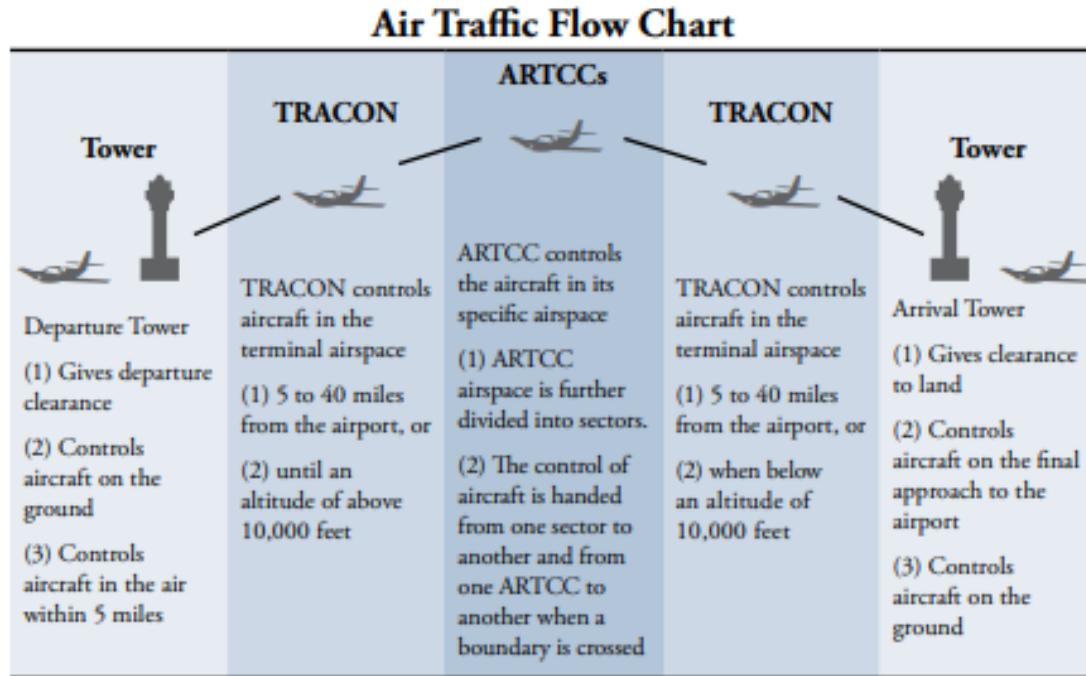
A airspace, the flight gets passed on from sector to sector, and from center to center (Freudenrich, 2001).

When the airplane approaches its destination, the flight enters the descent phase. In this phase, the center controllers will instruct the pilot on when s/he can safely decrease altitude within the class A airspace. The center controller then merges all descending aircraft into a single file line to prepare them for landing. If the airport is congested, the center controller will place the plane in a holding pattern until a spot becomes available in the landing queue (Freudenrich, 2001).

On leaving the center adjacent to the TRACON's airspace, the flight enters the approach phase. In this phase, the center controller passes the flight to the controllers in the TRACON. The approach controller in the TRACON instructs the pilot to adjust his heading, speed, and altitude to line up with the standard approach corridors. When the plane is within 10 miles of the runway, the approach controller passes the flight on to the ATCT (Freudenrich, 2001).

At this point, the flight enters its final phase. This would be the landing phase. During this phase, the pilot prepares to land the aircraft. The local controller provides the aircraft with weather condition updates, as well as ensures the descending aircraft are maintaining adequate spacing. When the plane is close enough to land, the local controller gives the pilot clearance to land. Once the plane touches down, the local controller directs the plane to the taxiway where the flight is then passed to the ground controller. The ground controller then directs the plane to the proper gate where the passengers can begin to deplane, officially ending the flight. To better

visualize the process of flight Figure 3 below provides a visual of when the different facilities are in use (Freudenrich, 2001).

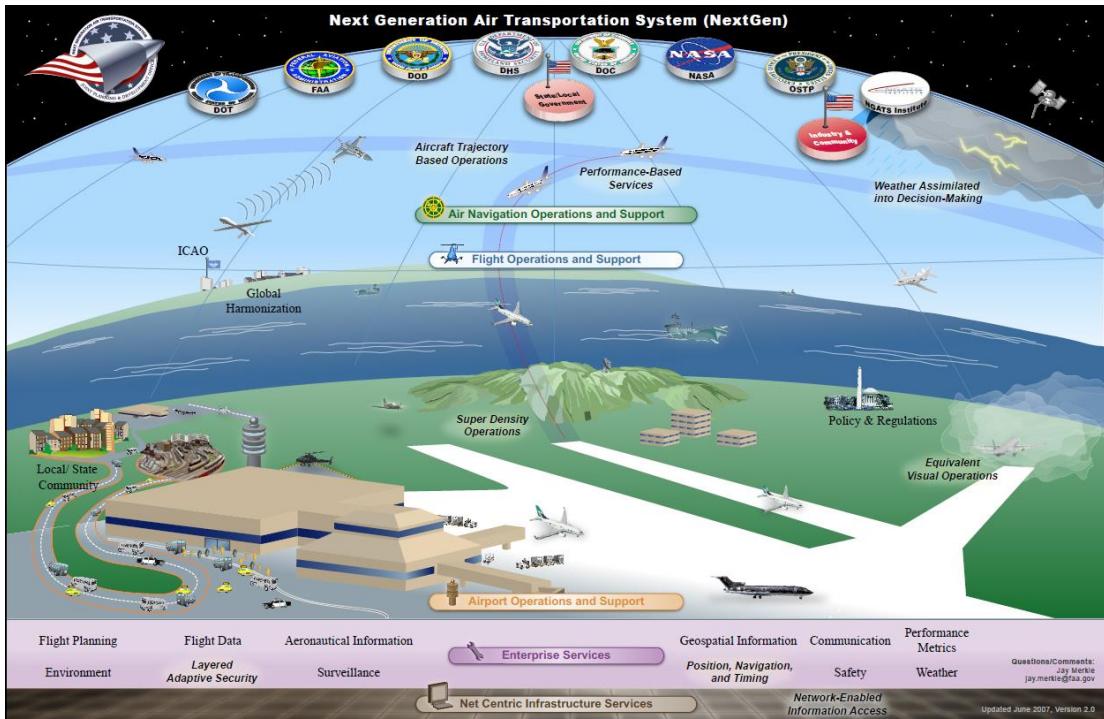


*Figure 4: Facilities used during particular phases of flight (Federal Aviation Administration, 2009)*

Since the process of flight presented above is a rather simplified one, it is important to briefly emphasize the fact that flights might encounter factors that affect their flight plan. These factors include the airspace classified as “other” in the form of temporary flight restrictions, SUAs, and traffic management initiatives (TMIs). Temporary flight restrictions might appear when there is a temporary hazardous condition such as a storm or a forest fire. These restrictions either reduce the flow of traffic through the area or require reroutes to avoid the area completely. Even though SUAs are filed in advance for the most part, they can still cause certain flights to deviate from their most efficient route. Lastly, TMIs can cause flights to be delayed. Since this document focuses on TMIs and their effect, the section below will go into more detail on TMIs.

## 2.5 Next Generation Air Transportation System

During the early 2000's it became evident that the current flight management structure had reached its capacity and would not be capable of handling the projected increase in demand. Additionally, the legacy system was not capable of processing information in real time. Because of these facts, there was a call to modernize the air transportation system. Beginning in 2007, the changes to the air transportation system began to roll out, and it is projected that all major components will be in place by 2025 (Joint Planning and Development Office, 2011). The new modernized system switched from radar-based to GPS satellite-based navigation, and it also promised to improve how the NAS users see, navigate, and communicate. To be more exact, there are six goals for the next generation air transportation system. These goals include ensuring that the U.S. retains its leadership in global aviation, expanding the capacity of the legacy system, ensuring safety, protecting the environment, ensuring national defense, and securing the nation. Additionally, there are nine characteristics that were determined the system will have according to the *Concept of Operations for the Next Generation Air Transportation System* written by the Joint Planning and Development Office (2011). Figure 5 below shows a visualization of the NextGen.



*Figure 5: Illustration of NextGen (Joint Planning and Development Office, 2011)*

The first key characteristic is that the system must be user focused. This means that the system should tailor information to the users as well as provide flexibility. Another characteristic of the system is that it should provide distributed decision making. That means that the system should allow for the quick access and exchange of information so that a system wide collaborative decision-making process can take place to inform the decisions of the stakeholders. Next, the system should also have an integrated safety management system. This will use a formal top-down, business-like approach to manage safety risk. The next characteristic presented would be international harmonization. This would mean collaborating with other nations to identify best practices in standards and procedures to ensure a safe and secure global air transportation system. The next key characteristic would be taking best advantage of human and automation capabilities, respectively. In other words, allowing humans

to do what they do best, while at the same time allowing computers to do what they do best. Automated systems would acquire, compile, monitor, evaluate, and exchange the information, while the humans would make the decisions based on the data presented to them. To further help with the decision-making process, another characteristic of the system would be integrating weather operations. This would allow for a single authoritative source to be used for the weather, as well as allow weather to be integrated into the decision-oriented automation and human decision-making processes. Another characteristic of the system is that it would have an environmental management framework. This would use new technology, procedures and policies such as intelligent flight planning and improved flight management to reduce the impact on community noise, local air quality, and local water quality; reduce energy use; and reduce climate effects. Another key characteristic of the system is that it should be robust and resilient, meaning that it should be able to remain operational when major outages, natural disasters, security threats, or other unusual circumstances occur. Lastly, the system should be scalable, and should be able to accommodate increasing air traffic as well as adapt to changes in demand in the short or long term even when not predicted. When all the major systems are in place, the next generation air transportation system should be capable of taking on any increase in demand as well as provide a more efficient intuitive and easier to use system (Joint Planning and Development Office, 2011).

## Chapter 3: Traffic Management Initiatives

To manage flights and prevent excessive congestion, the FAA implements different Traffic Management Initiatives (TMI), which are programs and tools used throughout the different phases of flight to control the flow of flights throughout the NAS. These initiatives can be implemented either on the ground; or en route. The specific TMI is selected based on the specific condition, and the flight management equipment that is located at the facility. Since the Next Generation air transportation system is slowly being rolled out, not all facilities are equipped with the ability to use certain TMIs. There are several TMIs the FAA implements, but for the purpose of this document only six will be explained in further detail. These include MIT, MINIT, APREQ, DSP, STOP, and TBM.

MIT refers to Miles-in-Trail. This is a method the FAA uses to space aircraft by requiring a certain minimum number of miles of separation between aircraft. This TMI is usually implemented on departing flights, over a fix, at a specific altitude, through a sector, or on a specific route. The purpose of TMIs is to manage the flow of air traffic into an amount that is manageable by a facility, as well as for providing enough space for flights to merge into the traffic flow. An example of when an MIT TMI may be used would be during a weather event where the separation between flights may be increased substantially from the standard separation of five nautical miles to allow for deviations (National Business Aviation Association, n.d.).

Similar to MIT's, air traffic controllers might sometimes use MINIT TMIs, which stands for Minutes in Trail. Like miles in trail, minutes in trail TMIs provide a minimum spacing between aircraft, but unlike MITs, the spacing is provided in

minutes instead of miles. MINIT TMIs are usually used when aircraft are operating in an environment where radar is not present, or when transitioning to or from a non-radar environment; in other words, when it happens to be more convenient to measure intervals of time rather than intervals of space. They are also used if additional spacing is necessary due to aircraft deviating around weather (National Business Aviation Association, n.d.).

The next TMI that is a part of the data used in this document is APREQ. This stands for approval request and is also known as Call for Release (CFR). APREQs are tactical departure scheduling practices, which are combined efforts between the ATCT and the Center control over head. The tower computes the earliest departure time for a flight based on the conditions on the ground and then passes this data to the center, which then uses a decision support tool to find the next available open slot at the merge point in the overhead flow. This time slot is then passed back to the ATCT, which then proceeds to monitor the situation on the ground to see if the time slot can be met. If the time slot cannot be met the process repeats, but if it can, the flight might need to be held in the departure queue to meet the slotted departure time (National Aeronautical and Space Administration, 2017). It should be noted that APREQs are only necessary when a significant overhead flow happens to coincide with the location of an airport, and this is not common in the U.S.

Another TMI that is found in the data used for this document is DSP. This stands for departure spacing program or departure sequencing program. DSP is a tool that has been designed to improve the departure traffic scheduling and coordination efficiency. The main task of the DSP TMIs is to evaluate flight schedules and routes

from airports that participate in the DSP, calculate departure fix demand/loading, and assign departure time windows based on projected fix crossing times. This tool is also capable of automating the coordination of schedules and clearances between facilities (Doble et al., 2009).

The next TMI in the list of TMIs used in this document would be STOP. This TMI is also known as departure stops. STOP restrictions usually occur when there is a problem at the departure airport preventing planes from taking off, such as adverse weather conditions. During these situations the planes will be held on the ground and will not be allowed to take off. Once the situation is resolved departures will continue.

The TMI TBM, which stands for Time Based Metering, is a tool that is a part of time – based flow management (TBFM). This is a technology and a method that is used to adjust capacity/demand at certain airports, departure fixes, arrival fixes and en route points across the NAS. In contrast, TBM is the specific automated tool that is used for planning efficient flight trajectories. It works by calculating the ETA to the outer meter arc, meter fix, final approach fix, and runway threshold. The system then tells the pilot these times to ensure they arrive to a specific point at a specific time. This system refreshes itself to accommodate changes in the flow of flights (Federal Aviation Administration, 2009).

## Chapter 4: Data Sources

For the research presented in this document, data were queried from three different databases. These databases include NTML, ASPM, and TFMS flight plans, each of which is described in detail below. They contain information pertaining to the six traffic management initiatives described above, information about flights and their performance, and information with respect to their flight plan. These three sources were used to create a combined table that conveniently displays information from all three sources in one location. In addition to details about the data sources, the rest of this chapter also contains information pertaining to how these data were used for this research.

### 4.1 NTML

NTML stands for National Traffic Management Log. This is an application developed by the FAA that when deployed provides a single point of entry, automated data collection, and distribution of NAS operational data, which includes information on TMIs and restrictions, across the traffic flow management system. The deployment of NTML eliminates the need for controllers to place phone calls to different facilities to coordinate restrictions or TMIs. Instead, there is now a coordination of log data between U.S air traffic facilities over the traffic flow management system national network and FTI mission support network that allow FAA employees to quickly and consistently provide operational log reporting. All the data available in the NTML database has been entered by controllers in ARTCCs, TRACONs, ATCSCC, and ATCTs. After a certain time period, the data available in the NTML database are

archived in a different database named the NTML warehouse. These data are then used to conduct analysis of the NAS, data manipulation, and for reporting capabilities (CSC, 2015). The table below shows an excerpt of NTML data.

HEADID	ENTRYID	RSTN_ACFT_TYPE	RSTN_APRT_TYPE	RSTN_APRT	RSTN_NAS_ELEMENT	RSTN_LAT	RSTN_LON	RSTN_ALT	RSTN_START_TIME	RSTN_END_TIME	SCHEDULEID	TRAJ_ACFT_TYPE
6952613	285485868	ALL	DEPARTURE	TEB; MMU; CDW	TEB	40.848722	-74.06225		6/1/2017 15:30	6/1/2017 18:00	215	GLF4
6952613	285485868	ALL	DEPARTURE	TEB; MMU; CDW	TEB	40.848722	-74.06225		6/1/2017 15:30	6/1/2017 18:00	417	C560
6952394	285468566	JETS	ENROUTE	JFK	JFK	40.632889	-73.77139		6/1/2017 11:30	6/1/2017 12:45	767	CRJ2
6951248	285467616	ALL	ARRIVAL	JFK	CAMRN	40.017303	-73.86106		6/1/2017 11:14	6/1/2017 12:05	767	CRJ2
6951244	285467586	ALL	ARRIVAL	JFK	CAMRN	40.017303	-73.86106		6/1/2017 11:13	6/1/2017 12:03	767	CRJ2
6952303	285470670	ALL	ARRIVAL	LGA	RBV	40.202402	-74.49503		6/1/2017 12:04	6/1/2017 13:34	771	CRJ9
6952301	285470331	ALL	ARRIVAL	LGA	COBUS	40.055833	-74.80991		6/1/2017 12:02	6/1/2017 13:33	771	CRJ9
6952303	285477467	ALL	ARRIVAL	LGA	RBV	40.202402	-74.49503		6/1/2017 13:34	6/1/2017 17:56	979	CRJ2
6952301	285477424	ALL	ARRIVAL	LGA	COBUS	40.055833	-74.80991		6/1/2017 13:33	6/1/2017 17:49	979	CRJ2
6952793	285498873	ALL	ENROUTE	LGA	LGA	40.783716	-73.8686		6/1/2017 19:00	6/2/2017 2:00	980	CRJ9
6952754	285499149	ALL	ARRIVAL	LGA	LGA	40.783716	-73.8686		6/1/2017 19:00	6/2/2017 2:00	980	CRJ9
6952631	285488532	ALL	ENROUTE	LGA	ETG	41.21495	-78.14276		6/1/2017 16:30	6/1/2017 17:30	1316	CRJ9
6952630	285490872	ALL	ENROUTE	LGA	ETG	41.21495	-78.14276		6/1/2017 17:00	6/1/2017 17:26	1316	CRJ9
6952317	285478550	ALL	ARRIVAL	LGA	LIZZI	40.665661	-75.14879		6/1/2017 13:46	6/1/2017 17:56	1316	CRJ9
6952300	285477749	ALL	ARRIVAL	LGA	LIZZI	40.665661	-75.14879		6/1/2017 13:37	6/1/2017 17:50	1316	CRJ9

## 4.2 ASPM

ASPM stands for Aviation System Performance Metrics. This is an online access system that provides data on flights to and from ASPM airports, 77 of which are currently equipped, and all flights by ASPM carriers, currently more than 35. This would include all IFR traffic and potentially some VFR traffic. Additionally, it also includes ASPM carrier flights to non ASPM domestic and international airports.

(Federal Aviation administration, 2018d)

ASPM data can be grouped into two different groupings. These would be efficiency counts, and metric counts. Efficiency counts is the group that captures all traffic handled by the air traffic controllers at ASPM equipped airports. These records might have some missing data. Metric counts are the basis of delay calculations displayed in the analysis and individual flight modules. These data must be fully specified records.

(Federal Aviation administration, 2018d)

In addition to providing data on flights, the ASPM data base also provides information on airport weather, runway configurations, and airport arrival and departure rates. The combination of flight data and airport data provides an image of the air traffic activity for the ASPM airports and carriers. Although some of this data is accessible to the public, there is a significant portion of the database that is password restricted. Figure 6 below shows a view of the ASPM online access page.

(Federal Aviation administration, 2018d)

*Figure 6: ASPM Online Access Page (Federal Aviation Administration, 2018d)*

### 4.3 Flight Schedules

In order to obtain the flight schedules, the FAA's SWIM information sharing platform is used. The acronym SWIM stands for System Wide Information management. This is a platform that was designed to meet the Next Gen requirement of data sharing, while providing the right information to the right people at the right time. SWIM allows for users to have a single point of access for the data they need, while making it simple for producers to publish the data only once.

Within the SWIM platform, the flight schedules are extracted from TFMS data. TFMS stands for Traffic Flow Management Services. This is a data exchange system that processes flight data in order to assemble all the data onto one record per flight. Airlines upload the flight schedules onto TFMS through the FAA's SWIM. Once in the database, the historic flight schedules, flight plans, and other information about flights can be extracted. Figure 7 below shows an sample of data from the TFMS flight schedules. (Federal Aviation Administration, 2018f)

ID_NUM	ACT_DATE	ACID	FLIGHT_INDEX	TKT_CARRIER_ICAO	OP_CARRIER_ICAO	TKT_FLTNO	OP_FLTNO	TAILNUM	FLIGHT_PLAN_TYPE	OUT_TIME	OUT_TIME_FLAG	OFF_TIME
215	20170601	WWI42	206371						ORIGINAL_FLIGHT	6/1/2017 17:33	COMPUTED	6/1/2017 17:45
417	20170601	LIV600	232109						ORIGINAL_FLIGHT	6/1/2017 16:18	COMPUTED	6/1/2017 16:30
767	20170601	EDV3616	132810						ORIGINAL_FLIGHT	6/1/2017 10:47	COMPUTED	6/1/2017 11:00
767	20170601	EDV3616	132810						ORIGINAL_FLIGHT	6/1/2017 10:47	COMPUTED	6/1/2017 11:00
767	20170601	EDV3616	132810						ORIGINAL_FLIGHT	6/1/2017 10:47	COMPUTED	6/1/2017 11:00
771	20170601	EDV3498	133936						ORIGINAL_FLIGHT	6/1/2017 11:00	COMPUTED	6/1/2017 11:09
771	20170601	EDV3498	133936						ORIGINAL_FLIGHT	6/1/2017 11:00	COMPUTED	6/1/2017 11:09
979	20170601	EDV3942	164489						ORIGINAL_FLIGHT	6/1/2017 16:44	COMPUTED	6/1/2017 16:55
979	20170601	EDV3942	164489						ORIGINAL_FLIGHT	6/1/2017 16:44	COMPUTED	6/1/2017 16:55
980	20170601	EDV3945	201723						ORIGINAL_FLIGHT	6/1/2017 23:31	COMPUTED	6/1/2017 23:41
980	20170601	EDV3945	201723						ORIGINAL_FLIGHT	6/1/2017 23:31	COMPUTED	6/1/2017 23:41
1316	20170601	EDV3472	158468						ORIGINAL_FLIGHT	6/1/2017 15:57	COMPUTED	6/1/2017 16:09
1316	20170601	EDV3472	158468						ORIGINAL_FLIGHT	6/1/2017 15:57	COMPUTED	6/1/2017 16:09

## Chapter 5: Simulation

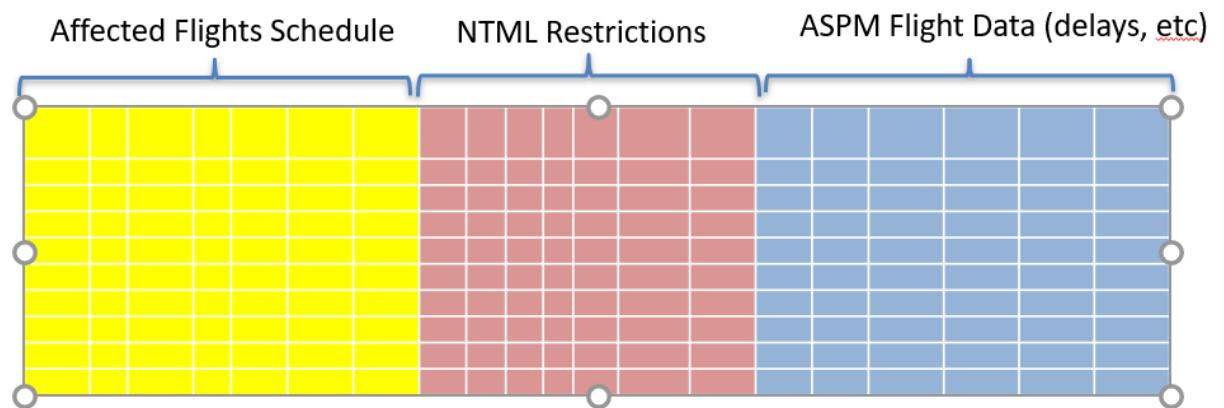
One of the largest novelties of the research performed for this document is the ability to see which flights are affected by what TMIs. Unfortunately, the FAA does not record, for each flight, a complete record of its experience, to include a trajectory record and details of any TMIs it may have been subjected to along the way. Nevertheless, it is extremely useful to be able to estimate details of TMI participation in order to make claims about their usefulness, efficacy, etc. Since the FAA does not have information on what TMIs affect specific flights, a simulation had to be created to model the trajectories of flights. For this simulation the three databases described in the section above, ASPM, NTML, and TFMS flight schedules were joined together into one table that relates restrictions to flights. The idea behind the simulation is that given a trajectory record and historical information on TMIs, it is possible to identify which TMIs a flight must have encountered, or been potentially subject to. It is not possible to identify exactly what effect a particular TMI had on a flight. For example, a flight encountering a miles-in-trail restriction might already have had sufficient spacing between it and a leading aircraft; therefore, no additional steps were necessary to create spacing. If this had not been the case, then some delay would have been necessary to stretch the path of the following aircraft in order to bring it into compliance with the MIT restriction. It is not possible with this simulation to identify which situation occurred for any particular flight, so only gross estimates of TMI effects are possible.

This simulation was in a way similar to the simulation presented in the work “Predicting Aircraft Trajectory Choice – A Nominal Route Approach” by Liu,

Hansen, Lovell, and Ball (2018). Their report focused on clustering trajectories and then observing three features; convective weather, wind, and MIT restrictions, to be able to predict the trajectory an aircraft will take. Even though this document does not focus on predicting trajectories for flights, the generation of the trajectories, as well as the method used to see if the trajectories encountered MIT restrictions, are very similar to how analysts at the FAA generated flight trajectories to see what TMIs flights encountered.

There are some steps that must be taken to run the simulation. The first step is to generate the flight plans for the selected time period. Then, all NTML restrictions are extracted from the NTML database for the same time period. Once that is done, the trajectory modeler is run, combining the generated flight plans with the NTML data. When running the simulation, if the trajectory crosses over a NAS element, at a relevant altitude, between the restriction start and end time, that has imposed a TMI, the flight is considered to have been affected by that TMI. All affected flights are recorded and stored in order to eventually be uploaded to the database. After running the simulation, there is a certain amount of post processing that must take place. First, all output files, schedules, and restrictions must be uploaded to the database. Then, schedules are joined to add additional flight plan information. After that, restrictions are joined to include additional information on restrictions. And lastly, ASPM data are merged to include flight delay measures. Once all these steps have taken place, the database is ready to be used to analyze trends and answer analytical questions that might arise. Figure 4 below depicts a visual of how the data in the database are

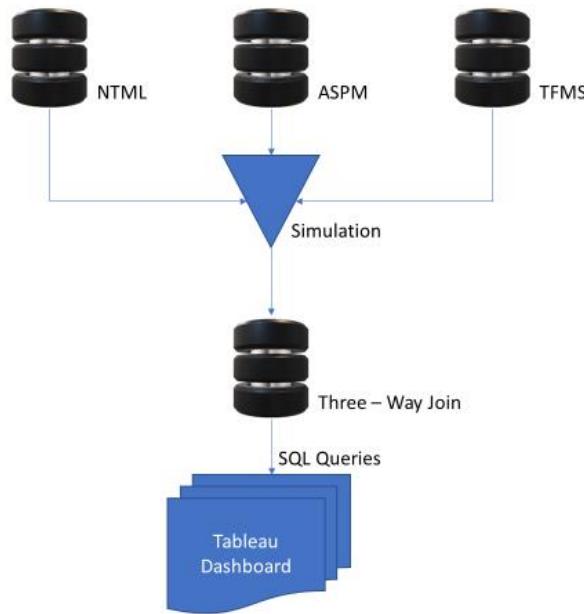
arranged (Afshar, 2018).



**Figure 7:** Three - Way Join Table Breakdown (Afshar, 2018)

## Chapter 6: Tableau Dashboard

Once the three – way join database was created, the data could be used to perform analyses and show different trends. In order to do so, an interactive dashboard was developed using the Tableau software. The Tableau dashboard visualizes the data to allow for a simpler way to identify trends that occur. This dashboard will allow FAA personnel to visualize the effectiveness and compare the performance of the different TMI's available in the simulated three – way join database. Figure 5 below shows how the three – way join table was created and how Tableau accesses the database to create the dashboard.

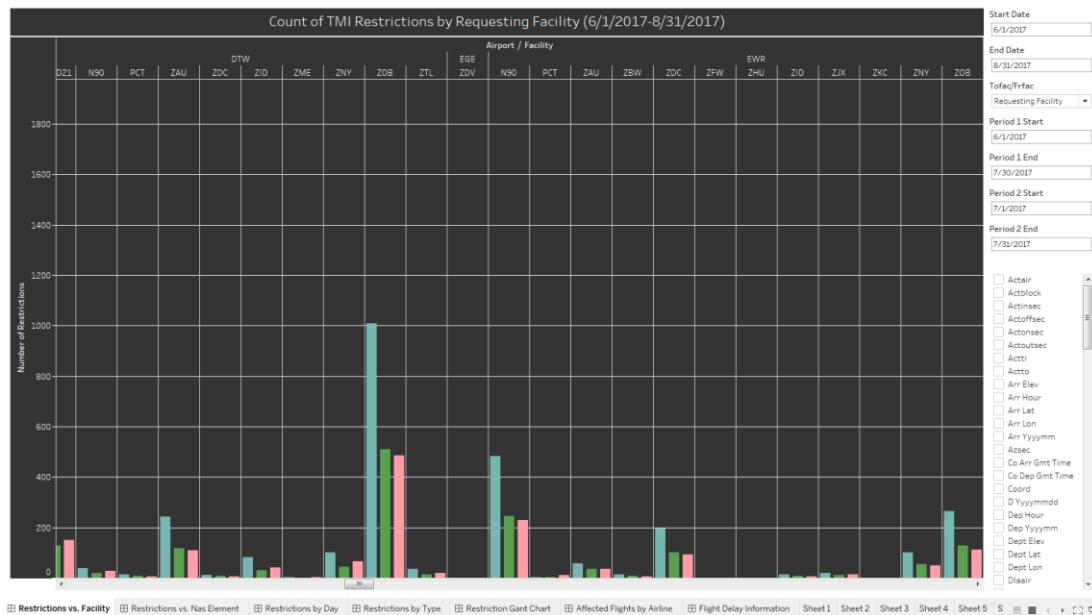


**Figure 8: Tableau Workflow Diagram**

The dashboard created consists of seven different sheets. Before delving into the sheets, there are some options that must first be selected on the first sheet. The first option would be selecting between the facilities that request TMIs, and those that provide the TMIs. Then, the time periods to compare must be selected as well. The

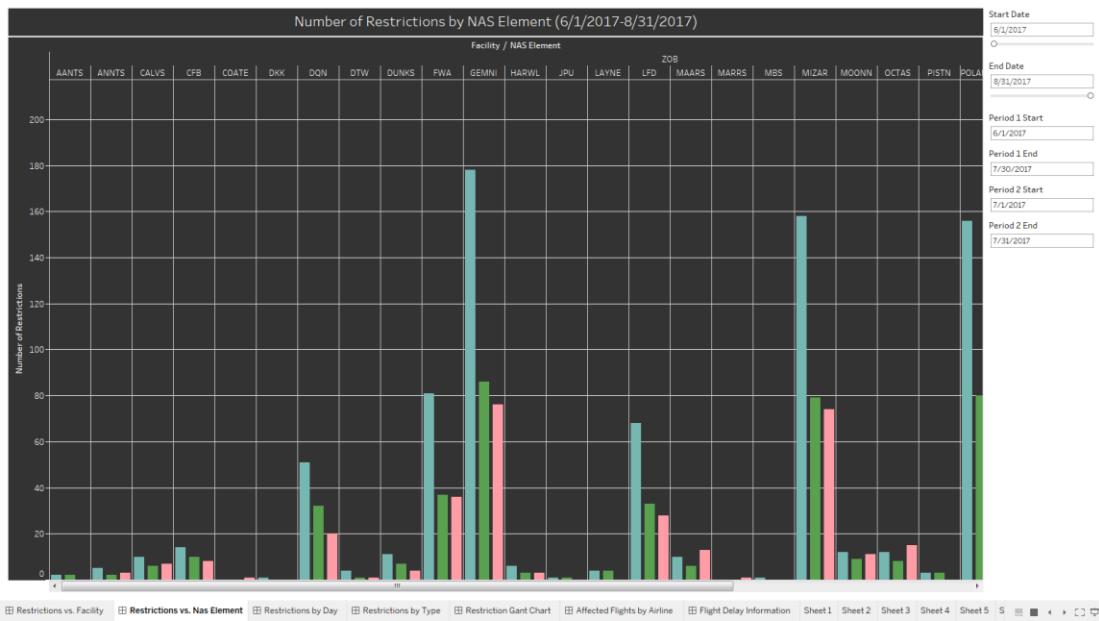
dashboard allows up to three different time periods to be selected for comparison purposes. These options determine the starting points for the linear drill down of the data available in the three – way join database. It is worth pointing out that this is one possible way of presenting the data, and that there are other ways of accomplishing the same task.

The first chart in the dashboard displays the count of the TMI restrictions by facility for either the Requesting or the Providing facilities. For this chart it is possible to show a comparison of the number of restrictions by facility for up to three different time periods. This chart also allows you to sort the facilities from greatest to least numbers of restrictions in order to see which facilities request restrictions the most, as well as see which facilities are providing restrictions the most. Since this is an interactive graph, a specific facility must be clicked on to drill down, move on to the next sheet, and see more specific data. Below is a screenshot of the first chart.



**Figure 9: Count of TMI Restrictions vs. Requesting Facility**

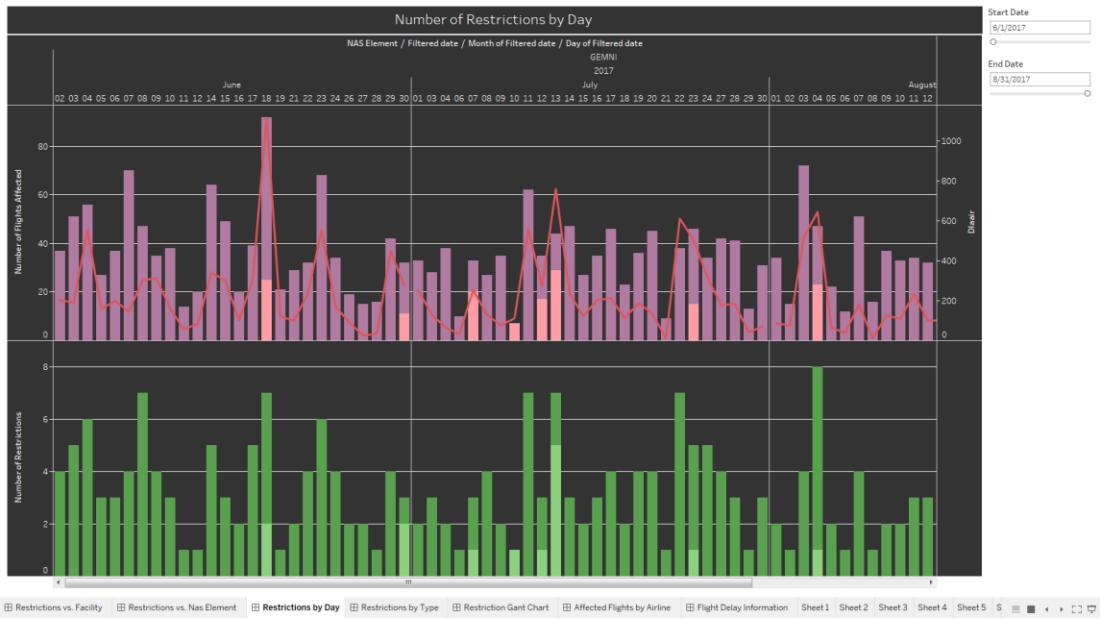
After the time periods and either requesting or providing facilities are selected, and a particular facility is clicked on, the chart on the next sheet displays the number of restrictions by individual NAS elements within the selected facility. Like the previous sheet, this chart can compare up to three different time periods. Again, it is possible to sort the data for NAS elements in the selected facility from the greatest to least number of restrictions. In order to move on to the next sheet a particular NAS element must be clicked on. Below is a visual of the chart described above.



**Figure 10: Number of Restrictions vs. NAS Element**

Following the chart above, the graph on the third sheet presents substantially more information than the previous two charts. The top portion of the chart shows the number of flights affected by each individual restriction for a specific day, and for a specific element in a specific facility. Information relating to specific flights are the results of the simulation, therefore the number of flights affected is a simulated value and not an actual value. Additionally, the top chart also shows the total air delay by day for a specific element of a specific facility. The lower portion of the graph shows

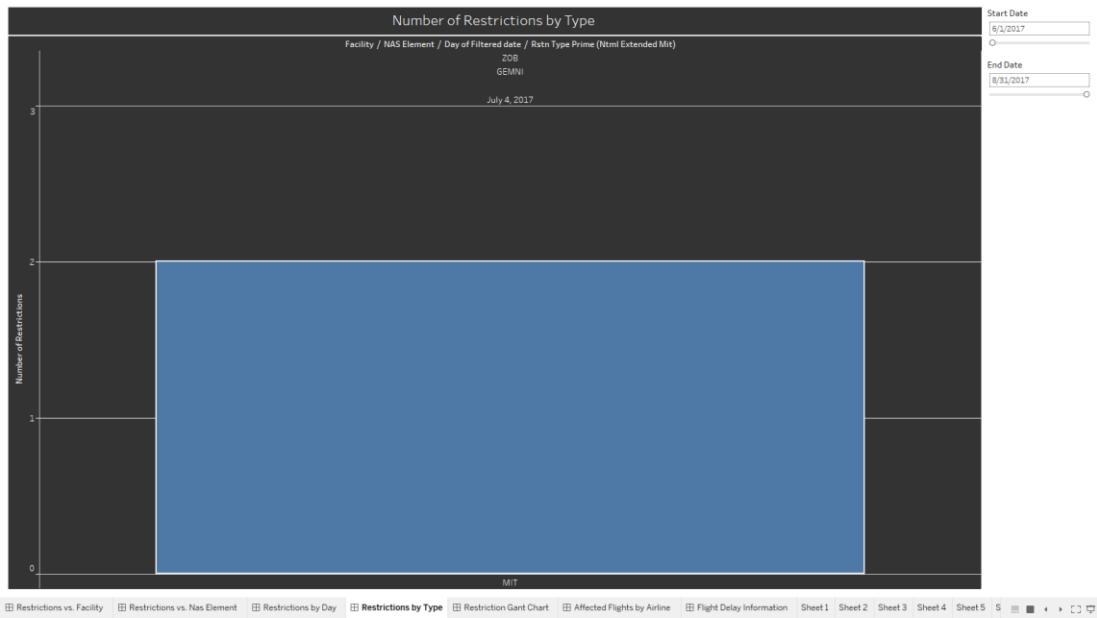
the number of restrictions by day for a specific element of a specific facility. Each different type of restriction used on a particular day, differentiated by the different colors in the bars, and the number of flights affected by the restriction as well as the number of restrictions used, is visible on the bar graphs. These values can be seen by hovering the mouse over any of the bars. In order to drill down to the next level of data, a particular bar for a particular day must be clicked on. The third chart in the linear progression can be seen below.



**Figure 11:** Number of Restrictions and Flights Affected by Day

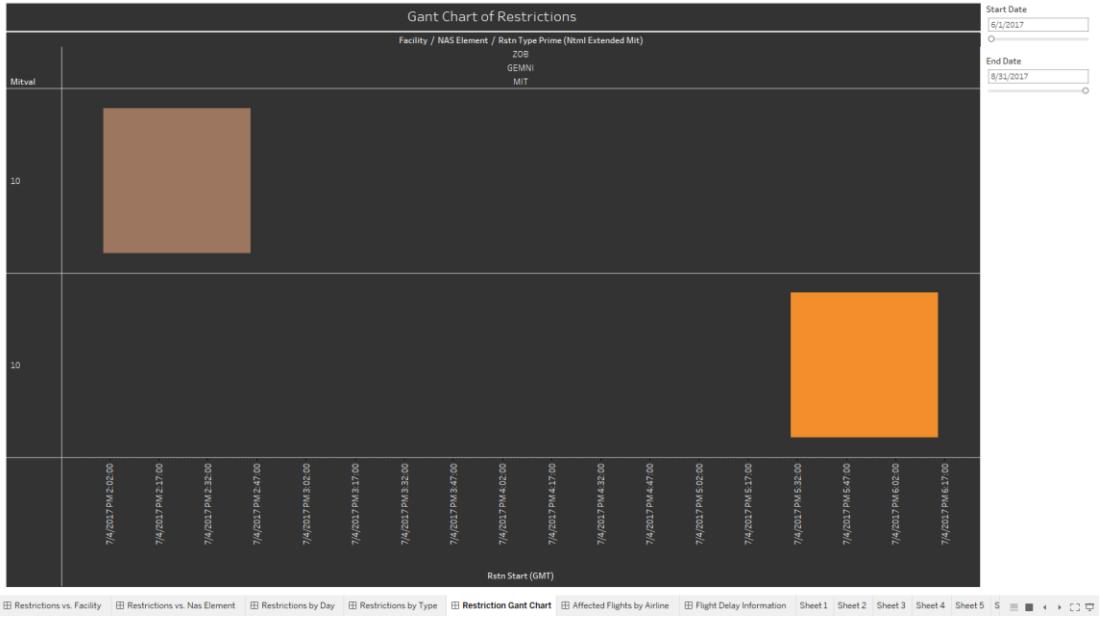
After a particular type of restriction on a specific day is selected, the next chart on sheet four is displayed. This chart is effectively a zoomed – in version of the second graph in the previous sheet. The chart displays the number of restrictions of a specific type for the selected day that were implemented. In addition, this graph can easily be modified to display all the other types of restrictions implemented on the selected day in separate bars, with each bar showing the number of restrictions for each different type. As with the previous graphs, the chart will drill down and progress to the next

sheet when a bar is clicked on. The graph on sheet four described above can be seen in the image below.



*Figure 12: Number of Restrictions by Type*

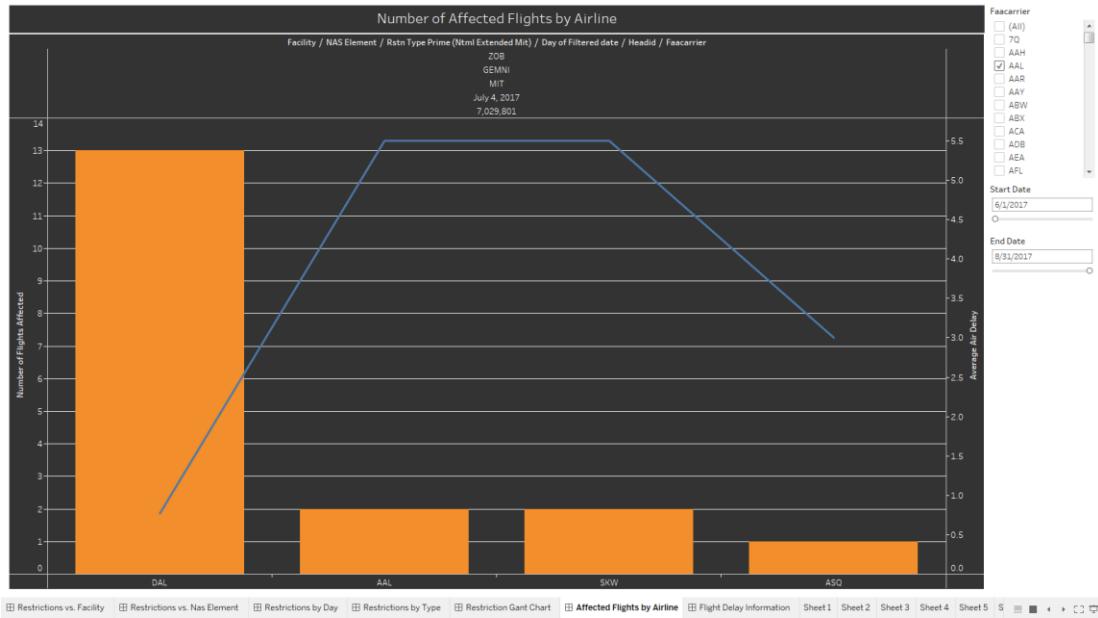
When the bar with a particular type of restriction in sheet four is clicked on, a Gantt chart with the individual restrictions of the specific type selected are displayed. The displayed Gantt chart in sheet five shows a timeline with each specific restriction and its duration represented as blocks of variable widths. In addition, when the MIT type of restriction is selected, the graph will display the MIT value in a column on the left-hand side. When the cursor is hovered over the blocks, the specific information of each block, including the duration in fractions of a day, will be displayed. Similar to the other graphs, clicking on a particular restriction in sheet five will drill down to the next chart. A visual of sheet five can be seen below.



**Figure 13:** Gant Chart of Restrictions

Once a specific restriction from sheet five has been clicked on, the information is drilled down further in sheet six. This sheet provides a bar graph showing the number of flights that were affected by the selected restriction for each airline. Again, it is possible to sort the airlines by greatest to least number of affected flights. Additionally, this graph also shows the average air delay by airline for the particular restriction under consideration. This is represented by a line graph connecting all the air delay values that is superimposed over the bar graph. The right Y axis displays the values for air delay, while the left Y axis displays the values for the number of flights affected. Since this information is generated by running the simulation described above, the numbers of flights affected by airline are the estimates produced by running the simulation, and not actual values. With that being said, the average flight delay only takes into account the affected flights generated by the simulation and not all flights including those that do not encounter any delays. Like all the previous graphs, clicking on any of the bars will drill down the information on sheet six and

present sheet seven, the final sheet of this dashboard, which presents data about the flights that were affected by the selected restriction.



**Figure 14:** Number of Affected Flights by Airline

The last chart of the dashboard on sheet seven departs from the graph format that the previous six graphs have followed. This sheet displays a list of all the flights that were affected by the selected restriction for a selected airline. Listed on the spreadsheet are the flight numbers, departure location, arrival location, aircraft type, departure time, and arrival time of the aircrafts affected by the selected restriction for the selected airline. Additionally, the sheet displays the air delay experienced by each flight as well as the total air delay experienced by all flights of the selected airline for the selected restriction. This sheet can be seen in the visual below.

Affected Flights Information							
Facility / NAS Element / Rsn Type Prime [Ntnl Extended Min] / Day of Filtered date / Fccarrier / Headid / Rsn Sta							
ZOB	GEMINI						
	MIT						
	July 4, 2017						
	DAL						
	7029801						
	07/04/2017 17:30						
	07/04/2017 18:18						
Acid	Dep Locid	Arr Locid	Etms	Aircraft Type	Out Time	In Time	
DAL98	DCA	DTW	M090		07/04/2017 16:45	07/04/2017 18:18	
DAL1063	ATL	DTW	M088		07/04/2017 16:28	07/04/2017 18:26	2.00
DAL1233	BWI	DTW	M090		07/04/2017 17:10	07/04/2017 18:39	1.00
DAL1390	PBI	DTW	M088		07/04/2017 15:53	07/04/2017 18:52	0.00
DAL1559	TPA	DTW	B752		07/04/2017 15:52	07/04/2017 18:26	0.00
DAL2013	MCO	DTW	B739		07/04/2017 16:04	07/04/2017 18:45	0.00
DAL2494	CLT	DTW	A320		07/04/2017 17:00	07/04/2017 18:44	2.00
DAL2903	PHL	DTW	A319		07/04/2017 16:30	07/04/2017 18:06	0.00
EDV3324	ORF	DTW	CRJ2		07/04/2017 16:29	07/04/2017 18:16	3.00
EDV3447	CAK	DTW	CRJ2		07/04/2017 17:34	07/04/2017 18:29	0.00
EDV3464	RDU	DTW	CRJ9		07/04/2017 16:28	07/04/2017 18:12	0.00
GS6181	MYR	DTW	CRJ7		07/04/2017 16:15	07/04/2017 18:15	0.00
GS6296	IAD	DTW	CRJ7		07/04/2017 16:55	07/04/2017 18:32	2.00
Total Delay by Restriction							
						10.00	

Restrictions vs. Facility   
  Restrictions vs. Nas Element   
  Restrictions by Day   
  Restrictions by Type   
  Restriction Gant Chart   
  Affected Flights by Airline   
  Flight Delay Information   
 [Sheet 1](#) | [Sheet 2](#) | [Sheet 3](#) | [Sheet 4](#) | [Sheet 5](#) | [S](#) | [«](#) | [»](#) | [»»](#) | [»»»](#)

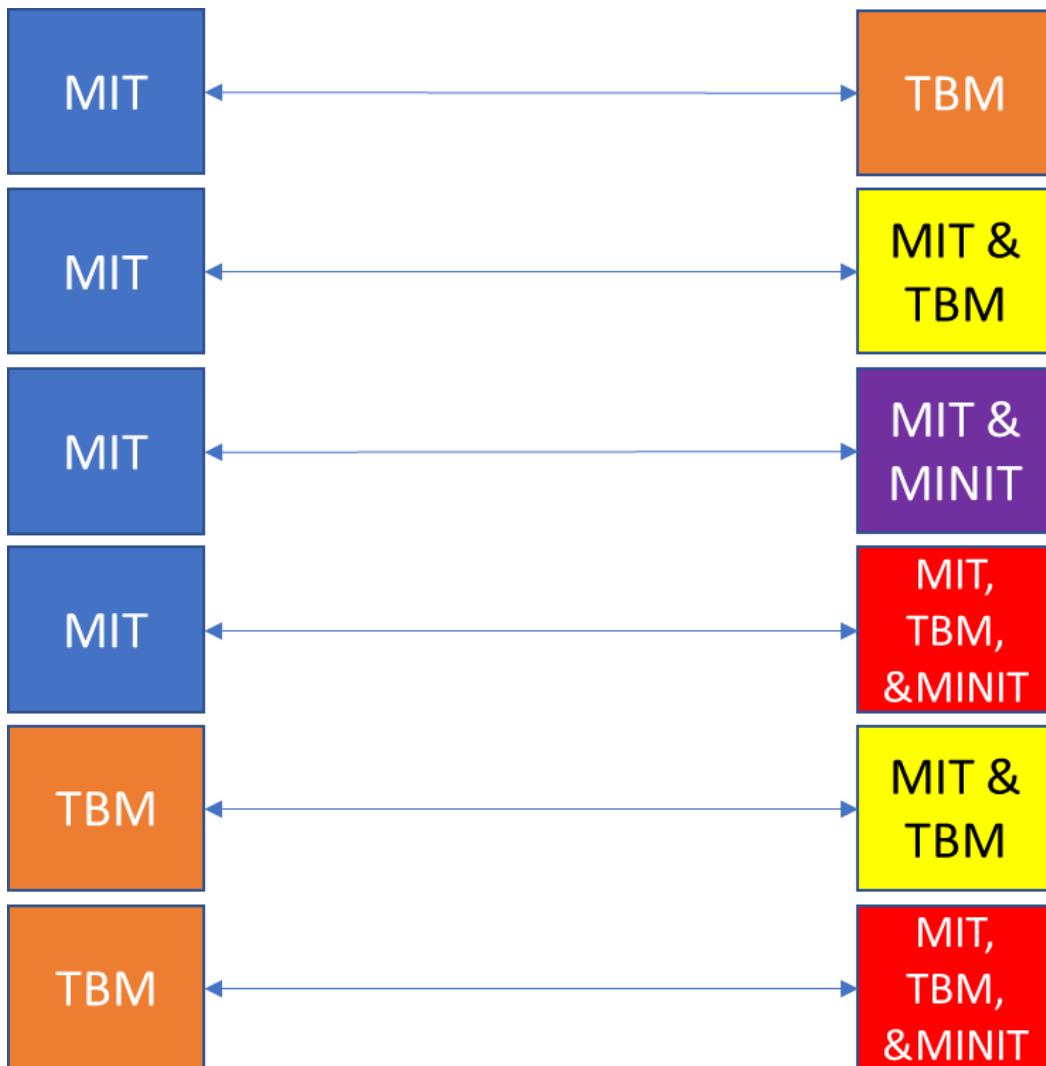
**Figure 15:** List of Affected Flights with Additional Information

## Chapter 7: Statistical Analysis of the Three – Way Join Data

With the creation of the three – way join data table combining ASPM, NTML, and flight plan data, an analysis of how the available TMIs in the table affect flights can be performed. This analysis consists of several steps that will be explained in further detail in this section. The first step was to filter the data table and generate cases for the TMIs a flight might encounter. After the filtering was complete, statistical calculations were conducted on comparisons between pairs of separate cases. Lastly, the statistical results of the different comparisons conducted were evaluated for statistical significance. Since there was a significant number of combinations possible, only six comparisons were created with five cases selected for the sake of brevity. The focus of this document is to present a methodology that can be applied to future iterations of the three – way join table that might vary from the version used for this analysis.

With that being said, the five cases of focus will be: flights that encounter only MIT restrictions, flights that encounter only TBM restrictions, flights that encounter MIT and TBM restrictions only, flights that encounter MIT and MINIT restrictions only, and flights that encounter MIT, TBM, and MINIT restrictions. The six comparisons that will be examined in further detail in this section include: flights that encounter MIT restrictions versus flights that encounter TBM restrictions, flights that encounter MIT restrictions versus flights that encounter MIT and TBM restrictions, flights that encounter TBM restrictions versus flights that encounter MIT and TBM restrictions, flights that encounter MIT restrictions versus flights that encounter MIT and MINIT, flights that encounter MIT restrictions versus flights that encounter MIT and MINIT, flights that encounter MIT restrictions versus flights that

encounter MIT, TBM, and MINIT restrictions, and flights that encounter TBM restrictions versus flights that encounter MIT, TBM, and MINIT restrictions. All cases and comparisons can be visualized in the figure below. The reasoning for selecting these cases and comparisons is that interest was expressed in this analysis by engineers at the FAA. Furthermore, MIT, TBM, and MINIT restrictions were selected due to their similarity in nature since these three types of restrictions take place in the en route phase of flight and in theory could be interchanged.



*Figure 16: Cases and Comparisons Analyzed*

## 7.1 Data Filtration

When it came time to analyze the three – way join table, the first step performed was to filter the data by extracting flights according to the combinations of different types of flight restrictions they encountered. Since this was the first iteration of the three – way join table, only a limited sample of data that encompassed two days was available. As a result, the emphasis in this thesis will be on the processes that can be followed to conduct various types of analysis, and the types of results that one might be able to obtain, rather than the reliability of the specific results themselves. Nonetheless, even for a small data set, it will be demonstrated that numerous interesting results were statistically significant at the 95% confidence level. Table 1 shows an excerpt of the data that shows the columns of importance for conducting the analysis. The definition of each data field seen in Table 1 can be found in the appendix. Only those fields of interest that are seen in Table 1 are defined for the sake of brevity even though the actual three – way join table contains close to two hundred different data fields.

ID_NUM	ACT_DATE	ACID	FLIGHT_IN	ETMS_AIR	HEADID	FAACARRI	DLASCHOI	DLAFOUO	DLAEDCT	DLATO	DLASCHOI	DLAFOFF	DLAIR	DLATI	DLABLOCK	DLASCHAF	DLAPARF	RSTN_TYP
5	20170602	EDV4065	234578	CRJ9	6955271	DAL	0	0	0	0	0	0	0	0	0	0	0	0 MIT
5	20170602	EDV4065	234578	CRJ9	6955270	DAL	0	0	0	0	0	0	0	0	0	0	0	0 MIT
6	20170601	EDV3754	159286	CRJ9	6952370	DAL	0	0	0	8.5	1	1	0	3	0	0	0	0 TBM
6	20170601	EDV3754	159286	CRJ9	6952296	DAL	0	0	0	8.5	1	1	0	3	0	0	0	0 TBM
6	20170601	EDV3754	159286	CRJ9	6952290	DAL	0	0	0	8.5	1	1	0	3	0	0	0	0 TBM
6	20170601	EDV3754	159286	CRJ9	6952289	DAL	0	0	0	8.5	1	1	0	3	0	0	0	0 TBM
7	20170602	FDX981	355968	A306	6955310	FDX	4	4	0	0	3	3	0	1.5	0	0	0	0 MIT
7	20170602	FDX981	355968	A306	6955296	FDX	4	4	0	0	3	3	0	1.5	0	0	0	0 TBM
12	20170601	EDV3517	149179	CRJ9	6952660	DAL	144	0	0	4	148	3	0	0	0	127	0	0 MIT
10	20170601	EDV3517	149179	CRJ9	6952551	DAL	144	0	0	4	148	3	0	0	0	127	0	0 MIT
44	20170601	EJA644	207100	C56X	6952515	EJA	25	25	0	4.5	30	30	7	0	11	36	36 APREQ	
45	20170601	FDX656	154866	MD11	6952459	FDX	43	43	0	0.4	43	43	0	7.3	0	43	43 APREQ	
72	20170601	EDV3900	135580	CRJ2	6952275	DAL	0	0	0	4.7	0	0	2	2.9	0	0	0	0 MIT
75	20170601	EDV3614	190275	CRJ9	6952793	DAL	0	0	4	5.5	4	4	0	5.7	0	0	0	0 MIT
75	20170601	EDV3614	190275	CRJ9	6952754	DAL	0	0	4	5.5	4	4	0	5.7	0	0	0	0 TBM

*Table 1: Three - Way join table excerpt*

The first column is an identifying number used to identify different flights. Because these data covered only a 2-day period, these ID numbers were unique across flights, so it was possible to use them as identifiers. When looking at a larger sample, this

number would not be a unique identifier for the flights since these numbers are eventually reused. More generally, in order to uniquely identify flights, a combination of the next three columns would be needed: the date, the airline and flight number combination, and flight index. Following these columns, the next three include the airframe used, the unique identifier for restrictions, and the carrier. The next eleven columns contain all the recorded delay information pertaining to each flight. This includes the gate delay relative to schedule, the gate delay relative to flight plan, the taxi – out delay, the departure delay relative to schedule, the departure delay relative to flight plan, the air delay, the taxi – in delay, the block delay, the arrival delay relative to schedule, and the arrival delay relative to flight plan. The last column of relevance from the three – way join table would be the column listing the type of restrictions encountered by each flight. Each row in the data represents one different restriction; therefore, there could be multiple rows with the same flight number.

Since the Identifying number can be used as a unique identifier for each flight in this particular case, the rows were first sorted by ID number. After the rows were sorted, the built-in filters were used to display restrictions of a particular type. The restrictions of a particular type were later copied and pasted onto separate sheets. In total six sheets were created for the six different, individual types of TMIs. Following this step, VBA code was written and used to create six more sheets to display the flights that were only affected by a single type of TMI. The code copied the original sheet, and deleted entries whose ID number was also found in other sheets for other TMIs. In the end, this left the sheets only with flights that were affected by one and only one TMI. A modified version of the same algorithm was also responsible for

finding flights that were affected by only two TMIs. Lastly, four more sheets were created to separate flights that were affected by three TMIs: MIT, TBM, and one of the four other types of TMIs. The reason why MITs and TBMs are so highly emphasized is because the FAA expressed interest in examining and comparing the effects of MIT and TBM restrictions. Furthermore, these TMIs are conceptually directly comparable because they affect flights in the en route phase. Below is the algorithm used.

- 
- **Do While** ((ID num on Sheet A row I  $\neq$  0) And (ID num on Sheet B row J  $\neq$  0))
    - **If** (ID num on Sheet A row I = ID num on Sheet B row J) Then
      - **Do While** (ID num on Sheet A row I = ID number on Sheet A row I)
        - **Copy** Row I and past on new Sheet
        - **Delete** Row I from Sheet A
      - **Loop**
      - **Do While** (ID num on Sheet B row J = ID number on Sheet B row J)
        - **Copy** Row J and past on new Sheet
        - **Delete** Row J from Sheet B
      - **Loop**
    - **Else**
      - **If** (ID num on Sheet A row I < ID num on Sheet B row J) Then
        - **Do While** (ID num on Sheet A row I = ID number on Sheet A row I)
          - **Increase** the value of I by one
        - **Loop**
      - **Else**
        - **Do While** (ID num on Sheet B row J = ID number on Sheet B row J)
          - **Increase** value of J by one
        - **Loop**
      - **End If**
    - **End If**
  - **Loop**
- 

**Algorithm 1:** Data Filter for generating cases

Effectively, what this algorithm does is compare two sheets and eliminate flights that encounter more than one kind of delay. If any of the combinations of interest are found, the code takes the row and pastes it in its appropriate new sheet. If no combinations of interest are found, the algorithm moves onto the next line of the sheet whose ID number is the lowest. This algorithm is used multiple times within the code to generate sheets with the individual restrictions as well as the combinations of restrictions of interest.

## 7.2 Statistical Calculations

Once the data were filtered and separated into different sheets for each particular case, statistical calculations were conducted to compare different cases to each other. First, the mean, variance, and standard deviation were calculated for every different type of delay present in the three – way join data table under every single TMI filtered case. An excerpt of the data containing only the mean values calculated for most cases can be seen in Table 3 below. In particular, it is interesting to note that many of the average delay statistics vary considerably across the different single TMI cases. It is useful to determine if these represent statistical happenstance, particularly since this is a fairly small data set, so the variances should be relatively large, or if these are indeed distinctions between the different circumstances.

To test the differences in the mean, a two-sided  $t$ -test for the differences in the means was conducted. It cannot be guaranteed that the normal assumption implicit in that test is satisfied; however, we know that the delay data comes from a complicated process that has many contributing factors, most of which probably act in an additive

fashion. Hence, at least qualitatively, a Central Limit Theorem argument might be invoked.

Because the data comes from populations of different sizes and different variances, the Welch – Satterthwaite equation (Welch, 1947) is used to determine the effective number of degrees of freedom with which to apply the test:

$$v = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(\frac{S_1^2}{n_1}\right)^2}{n_1-1} + \frac{\left(\frac{S_2^2}{n_2}\right)^2}{n_2-1}} \quad (1)$$

where  $n_1$  and  $n_2$  are the sample sizes of the two different TMI types, and  $S_1^2$  and  $S_2^2$  are their variances, respectively. Since this computation typically results in a non-integer value, it was rounded up to the nearest integer to produce a conservative estimate.

Essentially, we are testing the null hypothesis that the means of the two statistics are the same. One way to do this is to construct the confidence interval at the chosen confidence level and see if it contains zero. Equation (2) shows the confidence interval, where  $\bar{X}_1$  and  $\bar{X}_2$  are the two sample means, and  $t_{v,\alpha/2}$  is the appropriate t-statistic for  $v$  degrees of freedom, as calculated in equation (1), and a confidence level of  $1 - \alpha$ . In this case, a confidence level of 95% is chosen, so  $\alpha = 5\%$ .

$$(\bar{X}_1 - \bar{X}_2) \pm t_{v,\alpha/2} \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}} \quad (2)$$

Table 2 shows the confidence intervals for the delays of all the case comparisons that were examined.

Confidence Interval (95%)	Only MIT & Only TBM		Only MIT & Only MIT and TBM		Only TBM & Only MIT and TBM	
	LCL	UCL	LCL	UCL	LCL	UCL
Air delay	1.50E+00	2.02E+00	-0.37	0.19	-2.00	-1.68
Gate Delay Schedule	1.87E+00	4.20E+00	2.41	4.51	-0.69	1.55
Gate Delay flight plan	1.95E+00	3.37E+00	1.40	2.83	-1.19	0.10
Taxi Out Delay	1.84	2.46	0.83	1.50	-1.29	-0.68
Departure Delay Schedule	4.02	6.47	3.47	5.74	-1.83	0.55
Departure Delay Flight Plan	3.64	5.23	1.90	3.53	-2.47	-0.97
Taxi In Delay	0.94	1.31	0.31	0.72	-0.78	-0.44
Block Delay	2.71	3.45	1.56	2.34	-1.40	-0.86
Arrival Delay Schedule	4.48	6.90	3.96	6.19	-1.74	0.51
Arrival Delay Flight Plan	4.27	5.85	2.48	4.11	-2.46	-1.08
<hr/>						
Confidence Interval (95%)	Only MIT & MIT TBM and MINIT		Only TBM & MIT TBM and MINIT		Only MIT and Only MIT & MINIT	
	LCL	UCL	LCL	UCL	LCL	UCL
Air delay	0.33	1.03	-1.34	-0.81	0.41	1.21
Gate Delay Schedule	-14.19	-9.56	-17.25	-12.56	-13.02	-8.85
Gate Delay flight plan	-10.08	-6.73	-12.71	-9.42	-9.29	-6.38
Taxi Out Delay	-1.51	-0.48	-3.63	-2.65	-3.95	-2.67
Departure Delay Schedule	-15.61	-10.77	-20.88	-15.99	-16.65	-12.24
Departure Delay Flight Plan	-11.99	-8.38	-16.39	-12.84	-13.57	-10.29
Taxi In Delay	0.39	0.98	-0.71	-0.16	1.79	2.29
Block Delay	2.39	3.27	-0.59	0.09	-1.30	-0.11
Arrival Delay Schedule	-9.62	-5.07	-15.32	-10.75	-13.00	-8.73
Arrival Delay Flight Plan	-6.28	-2.91	-11.28	-8.03	-9.71	-6.52

*Table 2: Confidence Intervals for Examined Case Comparisons*

While the confidence interval allows us to test the null hypothesis for a given confidence level, it is also useful to compute the *p*-values, which essentially tell us at what level of confidence, or lower, the test would have demonstrated statistical significance. In order to compute the *p* values, the test statistic *T* was computed using equation 3 below. After the *T* statistic was found for each case comparison, the value of the *T* statistic and the degrees of freedom were inserted into the excel function T.DIST.2T(*T Statistic, Degrees of Freedom*), which generated the *p*-values for a two tailed *T* test. If the null hypothesis is rejected, whenever zero is not in the confidence interval, or equivalently, when the *p*-value of the two-sided test is less than  $1 - \alpha$ , it can be concluded that the means of the two cases compared vary by a statistically significant amount.

$$T = \frac{\bar{X} - \bar{Y} - 0}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (3)$$

One last metric used for comparison purposes was the probability that flights encounter delays of over 15 minutes. This is a metric that is commonly used by the FAA for analytical purposes. Since the samples sizes for the data examined were large enough, the probability of flights encountering delays greater than 15 minutes was estimated using the sample proportion. To calculate the standard proportion, all the flights that encountered delays greater than 15 minutes were found for each case, and that number was then divided by the sample size for the case. One last point to note is that for all the calculation relying on distributions it is assumed that both population distributions are normal, and that the two random samples are selected independently of one another.

### 7.3 Statistical Results

All the statistical calculations computed using the formulas and methods described above were arranged in a table for easy comparison. This was performed for all cases with individual TMIs as well as for a select number of cases with pairs and triples. The table below is an excerpt from the Excel sheet that contains all the average delays for all the cases. Since there was a large number of combinations possible to run comparisons, and since the focus of this document is to provide a methodology for comparing the effects of TMIs, only a few were selected. Since the FAA expressed interest in MITs and TBMs, only those TMIs that take place in the en route phase of flight were selected for the comparisons. Since these TMIs take place in the en route phase, only air delay will be looked at, since it is difficult if not impossible to be able

to infer how delays that occur in the en route phase affect planes on the ground. The fields that were used for the comparisons are highlighted in the table below.

Average Delays	Only MIT Average (X-bar) (min)	Only TBM Average (X-bar) (min)	Only APREQ Average (X-bar) (min)	Only DSP Average (X-bar) (min)	Only MIT and MINIT Average (X-bar) (min)
Air delay	4.29	2.53	2.72	2.09	3.48
Gate Delay Schedule	14.43	11.40	12.62	7.60	25.37
Gate Delay flight plan	9.49	6.83	9.11	4.75	17.33
Taxi Out Delay	7.51	5.36	7.81	3.00	10.82
Departure Delay Schedule	20.35	15.10	18.67	9.41	34.79
Departure Delay Flight Plan	14.52	10.08	15.03	6.47	26.45
Taxi In Delay	4.35	3.22	2.39	2.23	2.30
Block Delay	5.54	2.46	4.09	1.37	6.25
Arrival Delay Schedule	17.04	11.35	14.01	6.06	27.90
Arrival Delay Flight Plan	11.97	6.91	10.50	3.74	20.09
Sample number	9375	8483	3935	167	1824
Average Delays	Only MINIT Average (X-bar) (min)	Only STOP Average (X-bar) (min)	Only MIT and TBM Average (X-bar) (min)	MIT TBM & MINIT Average (X-bar) (min)	
Air delay	1.50	2.12	4.37	3.60	
Gate Delay Schedule	8.67	15.59	10.97	26.31	
Gate Delay flight plan	6.75	15.12	7.37	17.90	
Taxi Out Delay	8.35	4.72	6.34	8.50	
Departure Delay Schedule	16.42	19.53	15.74	33.54	
Departure Delay Flight Plan	14.50	19.06	11.80	24.70	
Taxi In Delay	1.33	2.65	3.83	3.66	
Block Delay	3.33	0.88	3.59	2.71	
Arrival Delay Schedule	9.50	14.47	11.96	24.38	
Arrival Delay Flight Plan	7.58	14.24	8.68	16.56	
Sample number	12	17	7315	1878	

**Table 3: Average Delays (min)**

From looking at the table above there are some interesting inferences that can be suggested. One observation is that the average air delay experienced by flights that only encounter MITs is substantially larger than the air delay experienced by flights that encounter only one of the other types of restrictions. Also, the average air delay of the other cases does not approximate the amount of air delay experience by the case with only MITs until the cases with either two or three TMIs that include MITs are looked at. For further inspections, the table below provides the variance, standard deviation, and the probability that the air delay encountered is greater than 15 minutes in addition to the average air delay for the cases of interest. From looking at these data, one interesting point to note is that the variance and standard deviation for air delay of flights that encounter only MIT restrictions are significantly larger than for all the other cases. In addition, the probability of having a delay greater than 15

minutes is also significantly larger. These facts show that flights that encounter only MIT restrictions can experience significantly larger delays, and perhaps less predictable delays, given the large variance

Air delay	Average(X-bar) (min)	Variance (min^2)	Standard Deviation (min)	Probability x>15
Only MIT	4.29	145.33	12.06	0.058
Only TBM	2.53	16.3	4.04	0.015
Only MIT and TBM	4.37	34.55	5.88	0.049
MIT TBM and MINIT	3.6	29.75	5.45	0.03
Only MIT and MINIT	3.48	48.61	6.97	0.057

*Table 4: Average, Variance, Standard Deviation, and Probability for cases to be examined*

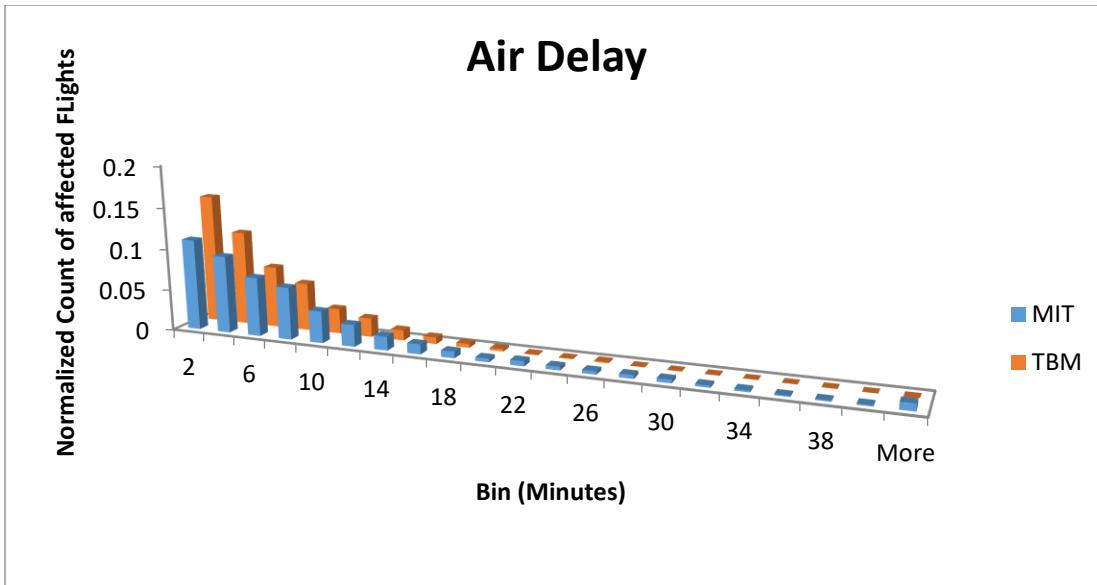
The values in the table above were used to calculate the confidence interval and  $p$  value for the selected comparisons. These can be seen in the table below. It can be seen that most comparisons between cases result in rejection of the null hypothesis, which is that the difference in means is equal to zero. This means that there is a statistically significant difference between mean air delay of most comparisons examined. The only comparison that was examined that failed to reject the null hypothesis was the comparison between the only MIT and only MIT and TBM cases. All these comparisons will be examined in greater detail in the following subsections.

Air delay	Confidence Interval (95%)		P - Value
	LCL	UCL	
Only MIT vs. Only TBM	1.50	2.02	3.93E-40
Only MIT & Only MIT and TBM	-0.37	0.19	0.54
Only TBM & Only MIT and TBM	-2.00	-1.68	4.55E-111
Only MIT & MIT TBM and MINIT	0.33	1.03	1.18E-04
Only TBM & MIT TBM and MINIT	-1.34	-0.81	1.16E-15
Only MIT & Only MIT and MINIT	0.41	1.21	8.10E-05

*Table 5: Confidence intervals and p values for examined comparisons*

#### 7.4 Case Comparison 1: MIT vs. TBM

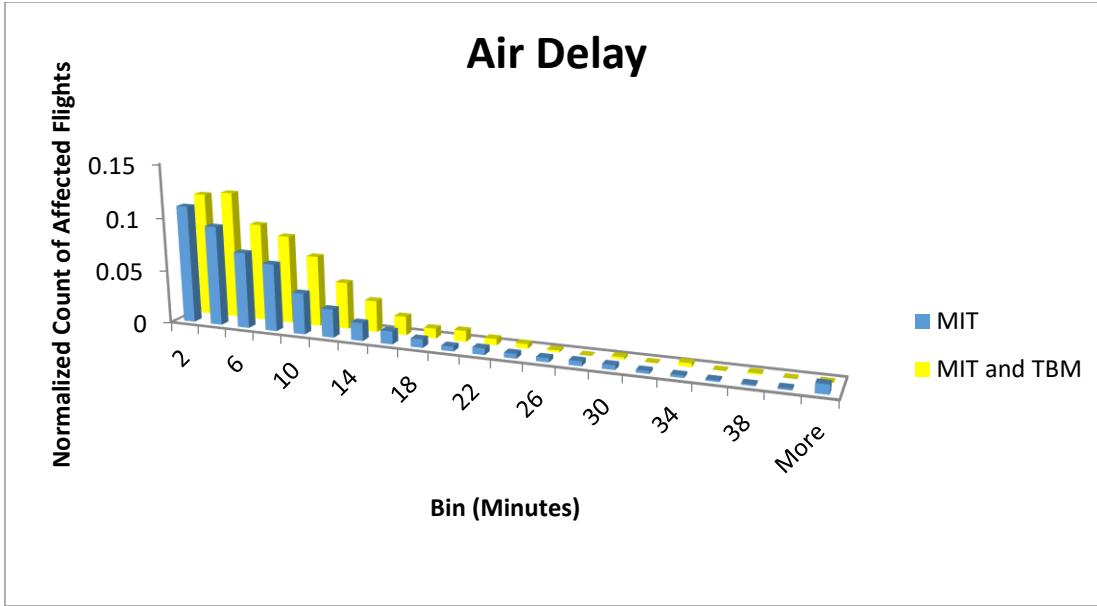
The first case comparison that will be examined is a comparison between only MIT versus only TBM restrictions. The histogram presented below in Figure 17 helps visualize the data presented in the previous section. As stated above, the only MIT case experiences a much larger average air delay than the only TBM case. This can be seen in the graph at the tail end. The histogram for only MIT has a large tail, subsumed in the “more” category, that contains many more flights that are delayed over 40 minutes than the histogram for only TBM. In fact, if the raw data are examined, there are flights that experience delays as large as hundreds of minutes, which explains the large variance and standard deviation. On the other hand, the only TBM histogram shows that there are more flights in this case that experience delays between 2 to 6 minutes compared to the flights that encounter only MIT restrictions. There are some plausible reasonings for such results. One explanation is that since TBMs are a newer type of TMI, they work better at fine tuning the flow of flights while MITs, since they have been around for a longer period of time, are a more brute force method for spacing flights. Another explanation for why the histograms look as they do is that when the weather gets bad, TBMs are discontinued and replaced with MITs, since TBMs work by making projections on flights and these projections cannot be made accurately enough in the presence of adverse weather.



**Figure 17:** MIT vs. TBM Histogram

### 7.5 Case Comparison 2: MIT vs. MIT and TBM

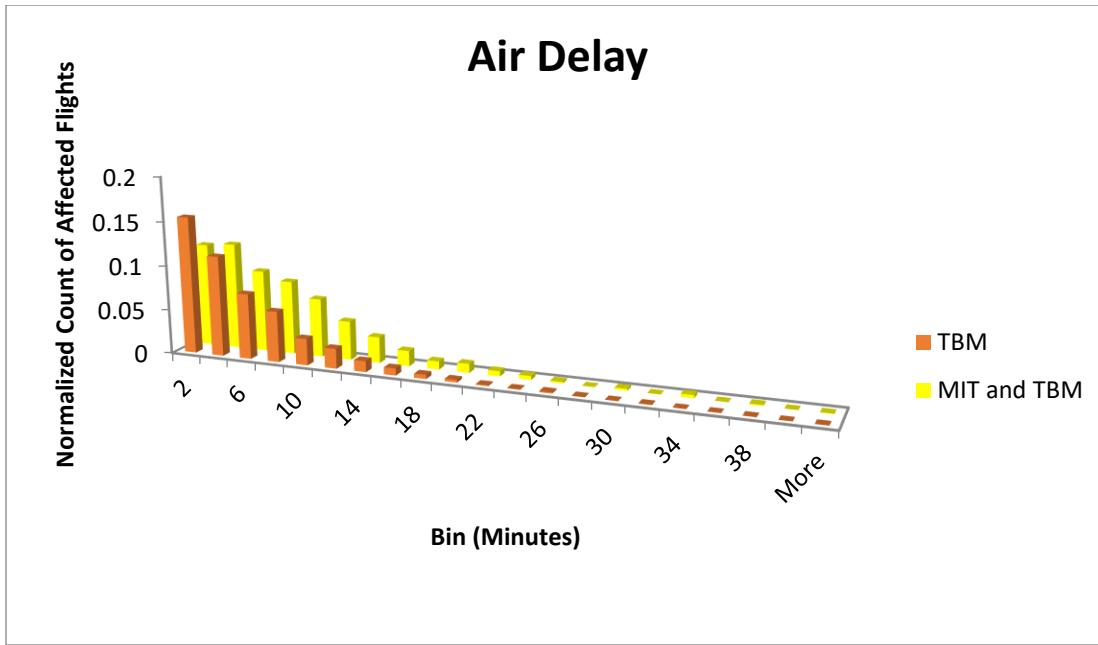
The second case comparison looks at the differences between the only MIT and the only MIT and TBM case. Out of all the cases examined, this is the only case that fails to reject the null hypothesis. From looking at the histogram, it is visible that the graph of MIT and TBM contains more flights that encounter delays between 2 and 22 minutes, while the graph for only MIT has more flights that encounter delay above 22 minutes. When looking at the means, which can be seen in Table 4, both means are relatively close to each other meaning that the larger tail of the only MIT graph offsets the larger amount of MIT and TBM flights that encounter delays under 22 minutes. One additional point to make is that the variance is significantly larger for flights that encounter only MIT restrictions. Even though the difference in means for this case are not statistically significant, this case still helps to shows that the average air delay experienced by flights that encounter more than one type of TMI is less than the sum of the average air delay for the only MIT and only TBM cases.



*Figure 18: MIT vs. MIT and TBM Histogram*

### 7.6 Case Comparison 3: TBM vs. MIT and TBM

The third case comparison looked at is the case between flights that encounter only TBMs and flights that encounter both MIT and TBM restrictions. Figure 19 shows that flights that encounter only TBM restrictions experience a smaller amount of delays, while flights that encounter both MIT and TBM experience more delays between 4 and 24 minutes. In this comparison, the difference in means between both cases is statistically significant. This difference could be due to the fact that TBM restrictions just fine tune flights, and are only effective when the weather is clear, while flights that encounter both MIT and TBM might fly through areas that are not equipped with TBM, or areas where TBM has been deactivated due to the conditions, therefore increasing the amount of air delay they experience.



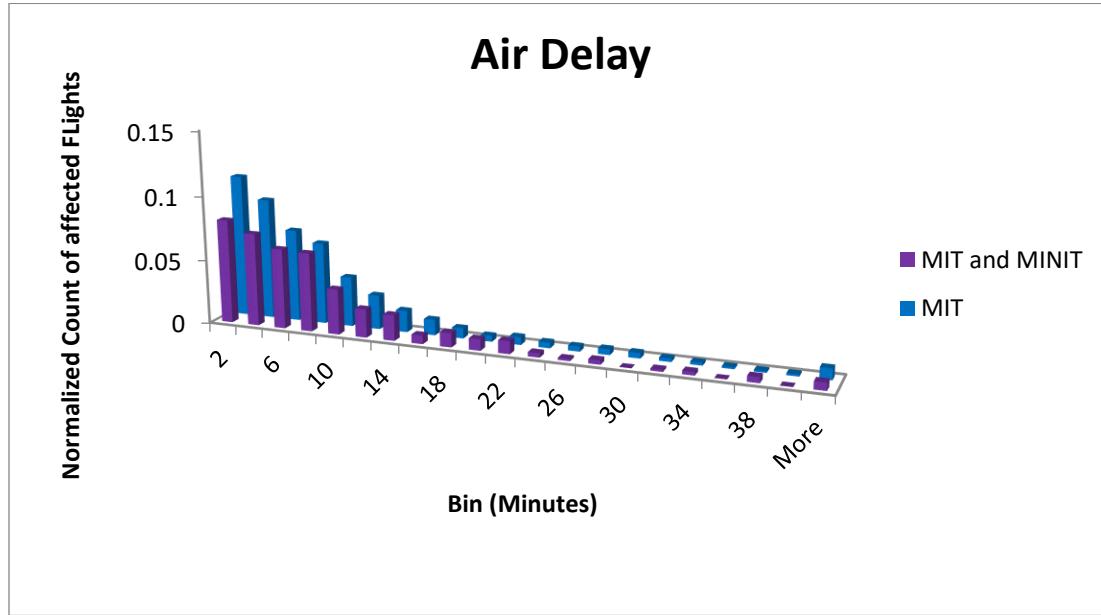
*Figure 19: TBM vs. MIT and TBM Histogram*

### 7.7 Case Comparison 4: MIT vs. MIT and MINIT

The next case comparison to be examined is the case between flights that encounter only MIT restrictions and flights that encounter both MIT and MINIT restrictions.

Examining the histogram in Figure 20 shows that flights that encounter MIT and MINIT restrictions have most of their delays between 2 and 14 minutes with a small secondary increase in delays between 18 and 22 minutes. The histogram of MIT and MINIT restrictions also shows that there are a significant number of flights that encounter over 40 minutes of delays. In comparison, flights that encounter only MIT restrictions have a substantially greater number of flights that encounter delays over 40 minutes. When looking at the averages, flights that encounter both MIT and MINIT restrictions have a lower average delay than the flights that encounter only MIT restrictions. This can be seen in Table 4. One inference that can be made from this finding is that flights that encounter a combination of TMIs do not necessarily

experience greater delays than the sum of flights that encounter only MIT and only MINIT restrictions. Additionally, by looking at the other cases it is visible that the average air delay for flights that encounter only TBM restrictions is significantly lower than flights that encounter any other combination of restrictions.



*Figure 20: MIT vs. MIT and MINIT Histogram*

### 7.8 Case Comparison 5: MIT vs. MIT, TBM, and MINIT

Another case comparison that was looked at was the comparison between flights that encountered only MIT restrictions versus the flights that encountered MIT, TBM, and MINIT restrictions. The case for MIT, TBM, and MINIT has a greater amount of flights that encounter delays between 6 to 12 minutes, while the case for only MIT has a longer tail. This can be seen in Figure 21 below. When comparing the average delays, which can be seen in Table 4, it is visible that the case for MIT, TBM, and MINIT has a lower average delay than the case for only MIT. From the statistical analysis conducted, the difference of means between both of these cases is

statistically significant. It is also worth noting that just because a flight encounters more than one type of TMI, flights need not encounter a greater amount of delay.

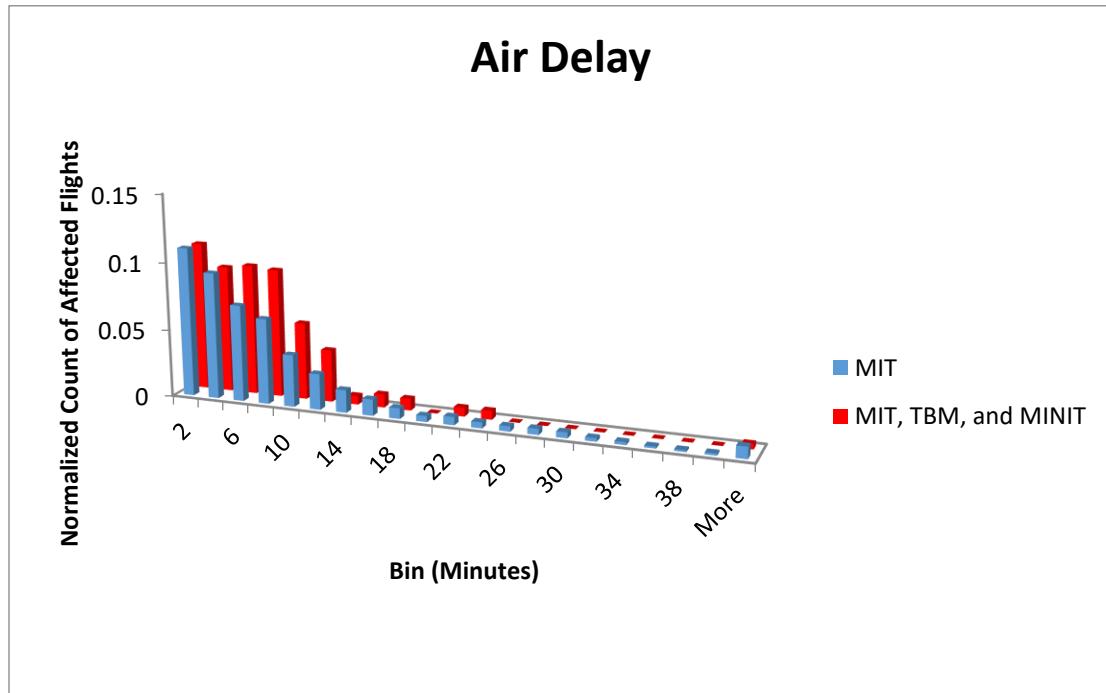


Figure 2I: MIT vs. MIT, TBM, and MINIT Histogram

### 7.9 Case Comparison 6: TBM vs. MIT, TBM, and MINIT

The last case comparison that was looked at was the comparison between flights that encountered only TBM restrictions versus flights that encountered MIT, TBM and MINIT restrictions. It is visible in the histogram in Figure 22 that the differences in means between these two cases are statistically significant. The histogram below displays the distribution of the delays encountered by each case. For flights under the Only MIT case, the numbers of flights that encounter delays are concentrated around the 2 to 4 minute region with a flat trailing edge. On the other hand, the flights under the MIT, TBM, and MINIT case encounter a greater amount of delays between 6 to

12 minutes. It's also worth mentioning that the case MIT, TBM and MINIT has a bit of a tail in the over 40 minute column.

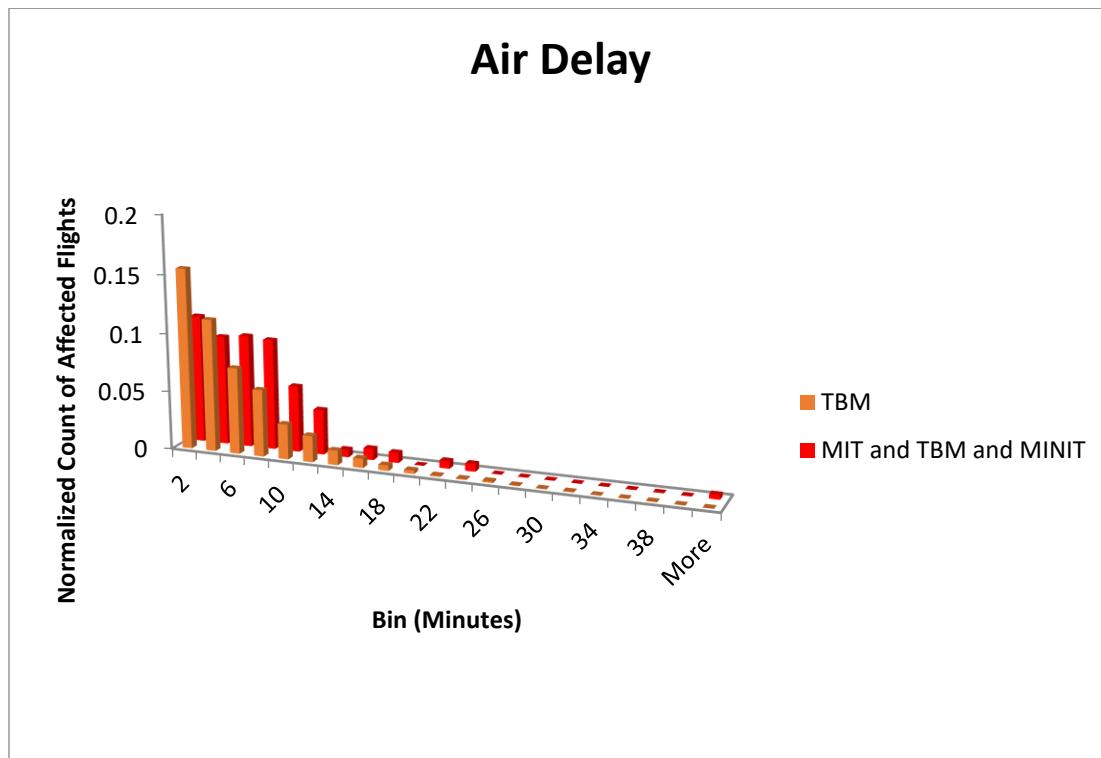


Figure 22: TBM vs. MIT, TBM, and MINIT

## Chapter 8: Conclusion

Managing air traffic throughout the NAS is a very complex and tedious task that takes a lot of people and infrastructure. In recent years, the FAA has been working on modernizing and upgrading the ways air traffic is managed through their NextGen plan. As part of this plan, there have been additions to the type of TMIs that are used to manage the flow of flights. For this and many other reasons, airlines are interested in how TMIs affect flights, if flights that encounter more than one TMI or more than one type of TMI experience greater delays, and if certain TMIs affect airlines differently. Since the FAA does not record what flights are affected by what TMIs, analysts at the FAA had to create a simulation that would simulate a model of the flight schedule. This in turn generated a rough estimate of which flights were affected by which TMIs. The creation of this database is the first time that flights have been related to the TMIs they encountered during flight.

Since the creation of this database is still in the development phase, only a small preliminary sample that encompassed two days' worth of data was available for use. These data were filtered appropriately, and summary statistics were generated. With these values, different comparisons between cases were created. In order to find the difference between the two means of two selected cases, the two tailed T test was used to find the confidence interval as well as find the corresponding P values. Additionally, the probability that the air delay is greater than 15 minutes was also calculated, since this is a metric that is commonly used by the FAA. After all these calculations were computed, histograms for each case comparison were created in order to visualize the distribution of air delay.

By looking at the results from the statistical analysis as well as looking at the histograms there are several inferences that can be made. One inference to point out is that flights that encounter MIT restrictions see the greatest amount of air delay. In addition, the cases for flights that encounter more than one type of TMI that also encounter MIT restrictions also see a greater amount of air delay. Another inference that can be made from the analysis is that MITs have a greater variance than any of the other cases. This could be due to the fact that MITs are used during all conditions while some TMIs such as TBM are used only during good weather.

Since the data generated by the simulation only presents a rough estimate of which flights are affected by specific TMIs, the statistical analysis performed on these cases would also be a rough estimate. Therefore, for more accurate results, the FAA should work on creating a method to record this information. By recording this information, more accurate analysis could be conducted.

## Chapter 9: Future Work

Since this is the first time that flights are paired with flight restrictions, there is additional work that can be done in the future to examine the effects of TMIs. One example of what could be done would be to follow the methodology presented in this document to create a comparison between the cases that were not examined. Some interesting comparisons would be comparing flights that encountered TMIs that take place both on the ground and in the air versus flights that encounter TMIs in the air only and flights that encounter TMIs on the ground only. With this comparison, the other delay metrics can be used, in addition to air delay.

Another example of future work that could be done would be to examine the effects of TMIs at individual ARTCCs or at individual sectors. This could be done by following the same methodology but only taking the flights that cross a specific ARTCC or sector. Selecting one ARTCC or sector will show what TMIs they are using as well as the specific delay information for the specific area selected. This could also be performed for airports as well. In addition to this, specific cases can be compared for different airports.

One of the goals of the FAA is to expand the three – way join table to include data for the previous three years. Once this is complete, it would be possible to follow the methodology presented in this document to be able to not only compare two different cases for the same time period, but also to compare two or more different years for one case, or compare two different cases year after year. This will show any changes in the use of TMIs as well as show whether or not the average delays are increasing, decreasing, or staying the same.

Lastly, having an actual record of how flights are affected by TMIs instead of running a simulation to obtain these flights would be useful for being able to see the exact effects TMIs have on flights. For this, the FAA would have to make changes to their existing way of recording information. When flights are passed from center to center, information pertaining to the TMIs the flight encounters should be recorded along with the other relevant flight data that is already recorded.

## Appendices

ID_NUM	ID Number
ACT_DATE	Date of action
ACID	Airline and flight number identified by traffic flow management system
FLIGHT_INDEX	ETMS generated fight Identifier or new identifier created during ATA lab enhancement process
ETMS_AIRCRAFT_TYPE	Enhanced Traffic Management System Aircraft type/airplane used
HEADID	Database identifier for a specific restriction
FAACARRIER	Airline code
DLASCHOUT	Gate Delay in Minutes based on schedule
DLAFFOUT	Gate delay in minutes based on flight plan
DLAEDCT	EDCT hold in minutes
DLATO	Taxi out Delay minutes
DLASCHOFF	Airport Departure delay minutes based on schedule
DLAFFOFF	Airport departure delay minutes based on flight plan
DLAIR	airborne delay minutes
DLATI	Taxi in delay in minutes
DLABLOCK	Block Delay Minutes
DLASCHARR	Arrival delay in minutes compared to scheduled
DLAFFPARR	Arrival delay in minutes compared to flight plan



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