ABSTRACT

Title of Thesis: IMPACT ASSESSMENT OF DYNAMIC SLOT EXCHANGE IN AIR TRAFFIC MANAGEMENT

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Since the inception of Collaborative Decision Making (CDM), the Federal Aviation Administration and the airlines have been striving to improve utilization of critical resources such as arrival slots and reduce flight delays during Ground Delay Programs. Two of the mechanisms that have been implemented for increasing utilization at resource-constrained airports are those of Compression and Slot Credit Substitution (SCS). SCS is a conditional, dynamic means of inter-airline slot exchange while compression can be considered a static means of achieving slot utilization.

This thesis will be an attempt to develop theoretical models to understand the performance of compression to slot exchange requests from airlines. This thesis will also address the trends in these slot exchange procedures, the benefits in terms of delay savings realized by the airlines, and avenues for future applications for improving efficiency of the National Airspace System.

IMPACT ASSESSMENT OF DYNAMIC SLOT EXCHANGE IN AIR TRAFFIC MANAGEMENT

By

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Dedication

I would like to dedicate this endeavor to my parents, sister and brother-in-law who have been the constant driving force in my pursuit for education.

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First, I will like to express my gratitude to Dr. Michael Ball for all his guidance, encouragement and unending patience throughout the course of my work at NEXTOR. Working with him has been extremely educational and enjoyable.

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List of Abbreviations

AAR	Airport Acceptance Rate
ADL	Aggregate Demand List
AOC	Airline Operation Centers
ATC	Air Traffic Control
ATCSCC	Air Traffic Control System Command Center
ATFM	Air Traffic Flow Management
CDM	Collaborative Decision Making
CR	Collaborative Routing
CTA	Controlled Time of Arrival
CTD	Controlled Time of Departure
ECR	EDCT Change Request
EDCT	Estimated Departure Clearance Time
ERTD	Earliest Runway Time of Departure
ERTA	Earliest Runway Time of Arrival
ETMS	Enhanced Traffic Management System
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
GDP	Ground Delay Program
GDPE	Ground Delay Program Enhancements
NAS	National Airspace System
NEXTOR	National Center of Excellence for Aviation Operations Research

OAG	Official Airline Guide
RBS	Ration-By-Schedule
RCI	Rate Control Index
SCS	Slot Credit Substitution
SGTD	Scheduled Gate Time of Departure
SSE	Sum of Square Errors

Airports

ATL	Atlanta William B. Hartsfield Airport
BOS	Logan International Airport
EWR	Newark International Airport
LGA	LaGuardia Airport
ORD	Chicago-O’Hare International Airport
PHL	Philadelphia International Airport
SFO	San Francisco International Airport

Airlines

AAL	American Airlines
COA	Continental Airlines
DAL	Delta Airlines
NWA	North-West Airlines
TRS	Airtran Airways
UAL	United Airlines
USA	US Airways
FDX	Federal Express

Chapter 1: INTRODUCTION

1.1 Air Traffic Overview

Air traffic in the continental United States has seen impressive growth in the past few decades. It has evolved from being a small industry into a key economic driver employing over 1.7 million people in the United States [1]. In spite of setbacks caused by recent events such as 9/11, the SARS epidemic and the continuing war in Iraq, there are no signs of abatement. Indeed, current projections indicate that air traffic will grow at an annual rate of 3 - 5% over the next 12 years [2].

Unfortunately, the growth in air traffic in the United States has not been marked by a corresponding increase in airport resources. As a result, the level of congestion has risen, leading to staggering delays during peak periods of activity. These delays result in substantial costs: In 2000 the delays attributable to the Air Traffic Control (ATC) system have cost the industry and its passengers and shippers a record $6.5 billion, not including downstream costs on other sectors of the economy [3]. The disproportion between stagnating capacity and ever-increasing demand has (and will have) enormous consequences on the performance of the air transportation system.

Not surprisingly, the current levels of delay and the projected growth in demand have led to a large number of initiatives that intend to alleviate congestion. These initiatives are both varied and abundant. Some airports are considering increases in capacity by building new runways. Other initiatives consider the potential of demand management measures, such as the use of auctions at LaGuardia Airport [4]. In addition, the FAA has implemented (and is considering) procedural changes during the management of daily operations which aim at increasing flexibility. A short-term strategy for reducing or eliminating air traffic jamming is by adopting the Ground Delay Programs. The Ground Delay Program (GDP), first established in 1981, is a mechanism used to decrease the rate of incoming flights into an airport when it is projected (due to weather forecast for instance) that arrival demand will exceed capacity.

1.2 Air Traffic Management

In the U.S., the Federal Aviation Administration (FAA) is responsible for the coordination of air traffic across the National Airspace System (NAS). Its primary task is the enforcement of proper separation requirements in the controlled airspace. This tactical separation service in real-time collision detection and avoidance is provided by the network of Air Traffic Control (ATC) centers across the United States. It coordinates the movement of aircrafts through the system of vast network of air traffic controllers. The secondary task of the FAA is to ensure the efficiency of the NAS, which is referred to as Air Traffic Flow Management (ATFM). Figure 1.1 shows the interactions between the different divisions of ATM.

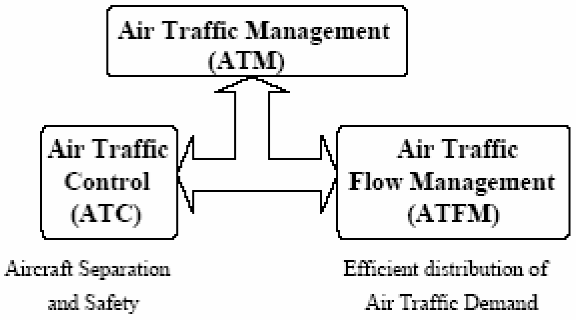

Figure 1.1: ATM Components

1.2.1 Air Traffic Flow Management (ATFM)

The strategic ATFM functions performed by the FAA are primarily coordinated by the Air Traffic Control System Command Center (ATCSCC). The ATCSCC continuously monitors current and projected demand within the NAS and identifies system constraints or other conditions (e.g. weather) that may affect the smooth running of the system. The ATCSCC tries to mitigate the effects of predicted congestion in the airspace.

1.2.2 Collaborative Decision Making (CDM)

The Collaborative Decision Making (CDM) Program was formed in 1995 as a joint government/industry initiative to develop new technology and procedures to ensure a safe and efficient National Airspace System beneficial for all the stakeholders (the aviation community and the flying public) [6 and 7] . The CDM Program focuses on several air traffic management initiatives and is not a single goal, but a philosophy of business. It is based on the belief that air traffic flow management can be improved if there is a closer collaboration between the FAA and the airlines and other airspace users, with large benefits for all involved parties. This collaboration takes the shape of mutual exchange of data and more flexible and efficient collaborative procedures.

The collaboration between government and industry was born out of the FAA's need for real-time operational information from the airlines and the airlines' desire to gain more control over their operations during a GDP, especially in matters with economic consequences [8]. The initial operational implementation of CDM had been aimed at the development of operational procedures and decision support tools for implementing and managing Ground Delay Programs (GDPs). CDM strives to achieve transparency in information exchange by generating better information from various sources, distributing the same information to the FAA and the NAS users, and allowing NAS users to collaborate with the FAA traffic flow managers in the formulation of flow management actions. Some of the CDM programs that have gained acceptance among the air traffic community are as follows:

- Improved Estimated Departure Clearance Time (EDCT) Compliance: For arriving at the destination airport on-time, a flight has to be EDCT compliant, i.e., the flight should take-off within a 10-minute departure window. CDM has been providing airlines with real-time airport arrival information and has encouraged airlines to focus on EDCT compliance in a collaborative manner.
- Improved Predictability: CDM has made a concerted effort to improve the accuracy of flight departure predictions.
- Enhanced GDP Performance: The Rate Control Index (RCI) measures the flow of air traffic into an airport and compares it to the targeted flow that was set by the traffic flow managers at the ATCSCC during a GDP.
- Reduced Near-Term GDP Cancellations: The combination of improved demand information and the power run feature of Flight Scheduling Monitor (software used to coordinate GDP planning) that allow ATCSCC personnel to delay the implementation of a GDP to the last possible minute decrease the number of near-term cancellations.

- Compression Benefits: A compression algorithm maximizes the use of slots vacated by cancelled or delayed flights.
- Increased User Equity: The use of the Official Airline Guide (OAG) as a priority list for the Ration-By-Schedule (RBS) sets the standards for more equity between the airlines, as opposed to real-time estimated time of arrival (ETA).
- Tailored GDPs through Revisions: Prior to CDM, the ATCSCC did not have the ability to modify GDP parameters such as scope, duration or the associated Airport Acceptance Rate (AAR).

The success of these initial CDM efforts has highlighted the potential benefits of increased collaboration in ATFM, and led to a number of projects that aim to enhance the basic application of CDM to GDPs. These procedures present a significant move towards decentralized Air Traffic Flow Management.

The resource allocation schemes implemented under CDM have addressed these issues through a fundamental change in the allocation of airport capacity. Rather than an assignment of individual flights to arrival slots, the central paradigm under CDM is that the slots are allocated to airlines. This led to the introduction of two new allocation mechanisms, Ration-By-Schedule (RBS) and Compression.

1.2.3 Ground Delay Programs (GDP)

The Federal Aviation Administration (FAA) implemented collaborative procedures along with the primary stakeholders, the airlines, for managing demand-capacity imbalances in the NAS. The Ground Delay Programs (GDPs) is one of the key initiatives used by the ATCSCC in reducing congestion. The program is initiated when an airport is unable to handle air traffic because of high demand for airport resources and airport capacity constraints. This is typically due to a reduction in the airport's arrival capacity under bad weather. In a GDP, flights bound for congested airports are delayed on the ground at their origination airport, so as to balance the total number of arrivals with the reduced capacity at the airport under consideration. The underlying motivation is that, as long as a delay is unavoidable, it is both safer and cheaper for the flight to absorb the delay on the ground before take-off.

The demand-capacity imbalances that usually occur at airports due to bad weather are difficult to forecast. It is difficult to forecast capacity issues even 1-2 hours prior to the implementation of a GDP. In spite of the uncertainty in the airport capacity profile, the ATCSCC assumes a deterministic capacity profile and plans GDP accordingly.

For modeling GDP, the capacity constraints at the airport are considered in the allocation of arrival slots for the flights. After assigning the arrival slots to the flights, the departures of the flights from the origination airport are constructed. Ground delay is computed from the difference between the original time of departure and the controlled time of departure. Two significant classes of flights destined for the arrival airport are exempted during GDP. Flights that are already in the air are exempted. Also, flights originating at airports greater than a certain distance away from the GDP airport are exempted because of the uncertainties in the length of the GDP.

1.2.4 Ration-By-Schedule (RBS)

The concept of RBS is very simple. RBS assigns flights to slot on a first-scheduled first-served basis ordered according to their original scheduled time of arrival as published in the Official Airline Guide (OAG) [10]. The end result of RBS should not be viewed as an assignment of slots to flights but rather as an assignment of slots to airlines.

Suppose that at La Guardia Airport (LGA), the nominal Arrival Acceptance Rate (AAR) is 30 flights per hour under fair weather conditions. Under a GDP, the AAR of the airport drops to 15 flights per hour. The flights are moved accordingly to accommodate the lower AAR. The visual representation of the RBS process is provided in Table 1.1.

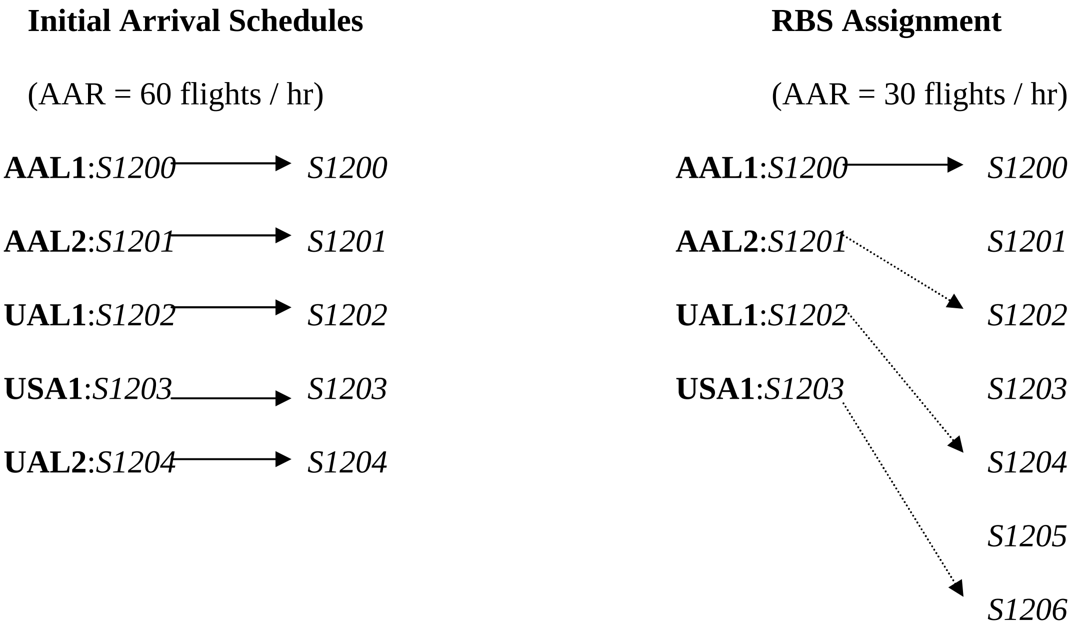

Figure 1.2: Slot assignment based on Ration-By-Schedule

1.2.5 Intra-Airline Substitution

In the intra-airline substitution process, an airline can cancel or swap one of its earlier flights which had been assigned an arrival slot under GDP through the ration-by-schedule procedure, and can then move other flights as their slots permit. The substitution procedure is adopted by the airline presumably to manage its internal economic objectives of reducing delays of its critical flights in exchange for increasing the delays of some of its non-critical flights. The airline does not have to interact with the FAA in the construction of this substitution process, except to inform the FAA of its decisions.

An example of an intra-airline substitution process has been illustrated in Figure 1.3. The prefix ‘S’ in front of the hour refers to arrival slot of the flight. American Airlines is willing to cancel an earlier flight, AAL2, to reduce delays of some of its other economically important flights during a GDP.

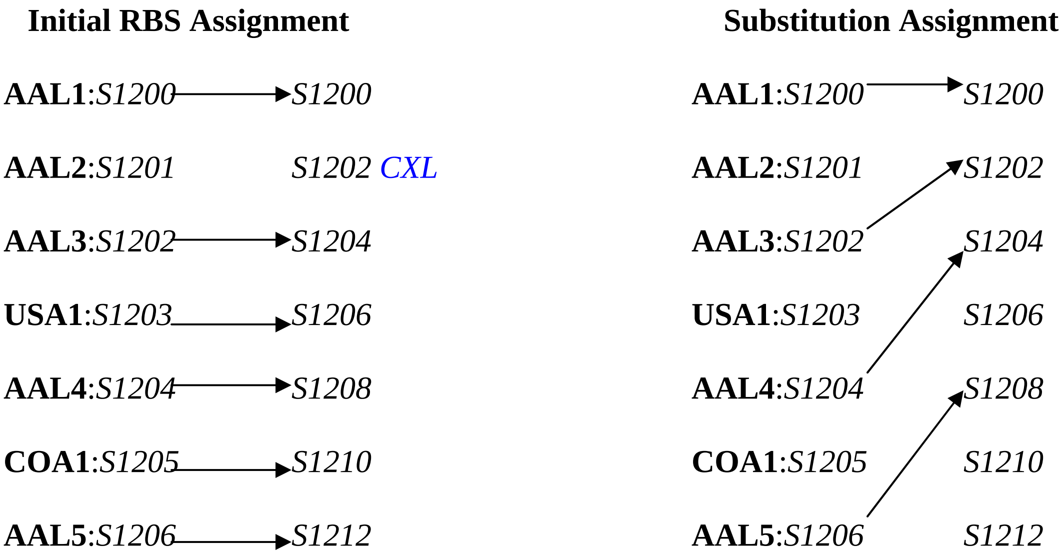

Figure 1.3: Intra-airline substitution

Due to the cancellation of its flight AAL2, American Airlines is able to move up the arrival slots of its flights AAL3, AAL4 and AAL5. In this example, AAL3 and AAL4 are moved to slots that correspond to their actual arrival times under fair-weather conditions. Other airlines’ slots are unaffected by these transactions.

1.2.6 Compression

After the airlines have conducted the internal cancellation and reassignment of their flights, there will be “holes” in the arrival schedules that an airline is unable to fill through internal substitutions. In this case, the airline requires assistance from the FAA for filling these vacant slots. These “holes” or vacant slots are filled by the ATCSCC by running the compression algorithm, which shifts all the flights up in the schedule to fill the “holes” in the arrival schedules during GDP. The presumption behind compression is that it will be acceptable to an airline to have any of its flights accelerated in the GDP schedule, except that the flights cannot be moved into slots earlier than their original, non-GDP scheduled time of arrival. Compression has been in operation across the NAS since 1998 as a means to improve airport resource utilization. A detailed description of compression is provided in Chapter 2.

1.2.7 Slot Credit Substitution (SCS)

In recent times, the air traffic management has shifted from using static models for demand management to more dynamic, adaptive models. Due to certain limitations of compression caused because of the ATCSCC’s reluctance to run compression, which will be discussed in detail in Chapter 2, Slot Credit Substitution (SCS) has been adopted as a means to improve resource utilization under GDP. In the case of SCS, an airline is willing to give up one of its arrival slots but in return will like to move up one of its other critical flights into a lot vacated by another airline and reduce delays for this flight. SCS essentially is similar to compression in moving up flights but is more “transaction oriented” rather than a “batch process”.

1.3 Problem Description

As mentioned in the above section, SCS and compression are different means of achieving increased airport resource utilization under GDP. Flight delays can be reduced through either of these two programs. SCS is an adaptive, dynamic means of improved utilization of airport resources. Compression, on the other hand, is considered a static means of achieving increased slot utilization.

This thesis will be an attempt to develop theoretical models to understand the performance of compression to slot exchange requests from airlines. Some of the questions that are addressed in this thesis are:

- What are the underlying factors that affect the benefits obtained from these two procedures?
- What are the trends witnessed in these slot exchange methods and the benefits in terms of delay savings realized by the airlines?
- Under what conditions will compression be able to provide a performance similar to that obtained through Slot Credit Substitution?
- What can be an appropriate metric to evaluate the benefits obtained from these procedures?
- Are there other avenues where the concepts learned from these procedures be adopted for improving efficiency of the NAS?

1.4 Literature Review

Extensive literature review was conducted for all the different models that had been adopted by the ATCSCC for air traffic management at resource-constrained airports during a GDP. For a better understanding of the slot exchange methods, it is imperative that the concepts behind CDM philosophy are studied and researched.

One of the earliest discussions on CDM could be found in the article by Wambsganss (1996) [11]. The article talks about the value created across the NAS through information exchange between the stakeholders of NAS. The article, published in the *Air Traffic Control Quarterly,* lists the advantages of Collaborative Decision Making (CDM) for the FAA, the airlines and the flying public. In 1998, Ball et al. [9], prepared a document on the preliminary assessment of CDM implementation. In this document, a comprehensive outlook on the impact of information distribution and common situational awareness on decision making and the ability of airlines to make economic resource allocation decisions to solve capacity-demand imbalance is provided. The impact assessment of the different CDM technologies and paradigms was also conducted.

Ball et al. in their presentation in June 2000 discuss the positive impact of CDM on the quality of information and its distribution through increased accuracy of flight departures and the submission of more timely flight cancellation notices. This article also discusses the application of CDM philosophies to other areas of air traffic management such as Collaborative Routing (CR). Conference papers [4] from Air Traffic Management Conference, ATM 2001 at Santa Fe, were referred for the impact of CDM initiatives on operational improvement of air traffic.

As CDM had grown through the years, the need for future direction of CDM concepts was realized. Ball et al. (2001) discuss the future directions in collaborative decision making. This paper reviews on-going and proposed CDM research streams. The topic areas included in this paper are on ground delay program enhancements, collaborative routing, performance monitoring and analysis, collaborative resource allocation mechanisms, game theory models for analyzing CDM procedures and information exchange, collaborative information collection and distribution. Slot Credit Substitution is one of the newer concepts that have been implemented under the CDM umbrella. This document was used to understand the future course of actions for CDM.

Vossen (2002) discusses fair allocation of airport resources during GDP using models such as Ration-By-Schedule and introduces methods that may be used to manage the allocation of resources dynamically. This paper includes concepts regarding one-for-one and two-for-two slot trades which have been the basis behind newer concepts such as Slot Credit Substitution. This paper also discusses compression in detail and its potential to improve slot utilization across the NAS. Compression was implemented at the ATCSCC in 1998 and can be considered a mature algorithm for enhancing slot utilization.

Literature review for compression was obtained from Metron Aviation Inc.. This website is a rich source of literature on compression and also contains data related to compression benefits.

Slot Credit Substitution was implemented in NAS in May 2003. Due to the relative newness of the slot exchange method, there has been a dearth of information on this procedure. A basic understanding of SCS method was gained through various

PowerPoint slides obtained from a number of disparate sources. In [12], Roger Beatty of American Airlines had presented to the CDM A&D sub group meeting the basic concepts of SCS and the desirability of this model as a public policy goal. Another important document that was studied for calculation of SCS benefits is by Justin Voshell of Metron Aviation, Inc. ([13] and [14])

1.5 Organization of Thesis

Chapter 2 provides the reader with details on the compression and SCS procedures and examples of how the benefits obtained from each of these procedures can be calculated. This chapter also talks about the philosophy behind the implementation of compression and the limitations of this process that led to reduced information exchange between the ATCSCC and the airlines. SCS was adopted by the ATCSCC to circumvent the drawbacks of compression and provide airlines more control over the decision making process.

In Chapter 3, we develop theoretical models based on the ability of compression to influence the inter-airline slot exchange request submissions. We try to understand the factors that affect the successful processing of SCS requests and compression. We assume a particular distribution of exchange requests to the ATCSCC and try to understand the implications of running compression at various intervals of time. Sensitivity analysis is conducted to determine the effects of changes in various parameters on the benefits obtained from SCS and compression. The models created are applied to real-world inter-airline exchange requests to understand the ability of the models to provide benefits to airlines.

Chapter 4 contains information on the sources of data and preparation of data that was undertaken before further impact assessment could be done for SCS and compression.

Chapter 5 discusses means of creating metrics for comparison of SCS and compression benefits. It also provides information on the trends in the industry, adoption rates in the industry, airline behavior through the years towards these slot exchange schemes and the future of these procedures.

In Chapter 6, the main contributions of this thesis are summarized. We also evaluate other areas in air traffic management where the concepts behind these models can be ported for increased efficiency in the system.

Chapter 2: BACKGROUND

Compression and Slot Credit Substitution (hereafter referred to as SCS) are key elements under FAA's Collaborative Decision Making (CDM) and Ground Delay Program Enhancement (GDPE) programs. These procedures have been adopted by the FAA for improved utilization of critical airport resources during Ground Delay Programs. This chapter discusses these slot exchange mechanisms in detail.

2.1 Compression

Compression is a slot optimization and utilization procedure used by the FAA Air Traffic Control System Command Center (ATCSCC) to ensure that valuable airport resources such as arrival slots do not go unused during a Ground Delay Program (GDP). During a GDP, airlines cancel and delay their flights and, thus, create vacant arrival slots at the destination airport. The slot is vacated by the airline when it determines that the slot can not be utilized through simple intra-airline substitution process. The compression algorithm that is run by the ATCSCC at regular intervals identifies these open arrival slots and moves other flights up thus reducing their delays. Compression always attempts to fill an open slot by moving a flight which belongs to a CDM-participating airline that can benefit from the slot. If there are no flights of the CDM-participating airline, then the slot is made available to all the other flights. Compression also tries to give preference to the flights of the airline that vacated the slot to be moved up. The basic philosophy behind compression is that the airline that vacates the slot is paid back for the released slots encouraging the airlines to provide the ATCSCC information on their flight cancellations. The cycle of decision making in the case of compression as given in Figure 2.1 [10]:

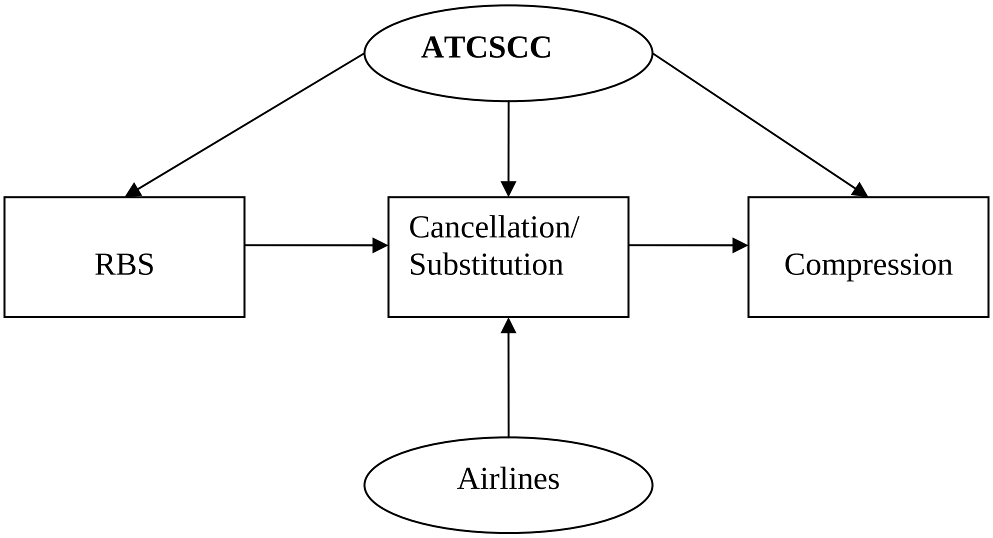

Figure 2.1: Cycle of Decision-making for Compression

Air Traffic Control System Command Center (ATCSCC) plays an important role in the decision-making process. ATCSCC implements the Ration-by-schedule procedure. The airlines try to construct intra-airline substitutions. If these substitutions are not feasible, the airlines provide their cancellation information to the ATCSCC. Once this information reaches the command center, the airlines wait for ATCSCC to run compression which will benefit their flights.

A conceptual overview of the compression algorithm for a known set of flights is provided below:

Step 1: Flights are ordered according to their schedule. Open slots are determined.

Step 2: The owner of the open slot is determined and the following rules are used to fill the slot.

2.1 The flights from any other CDM participating airline are used to assign to the slot. If there is no such flight, go to Step 2.2 else to Step 3.

2.2 Other non-CDM participating flights are considered for the open slots. If there is no such flight, go to Step 2.2 else to Step 3.

2.3 If there are no flights that can be assigned then return to Step 1 and select the next open slot.

Step 3: The slot assignments of the flights are swapped and Step 2 is repeated.

The extent to which a flight can be moved up will be limited by its scheduled time of departure. Moreover it is assumed that a flight cannot be moved down from its position in the current schedule.

An example of the compression process is illustrated below in Figure 2.2.

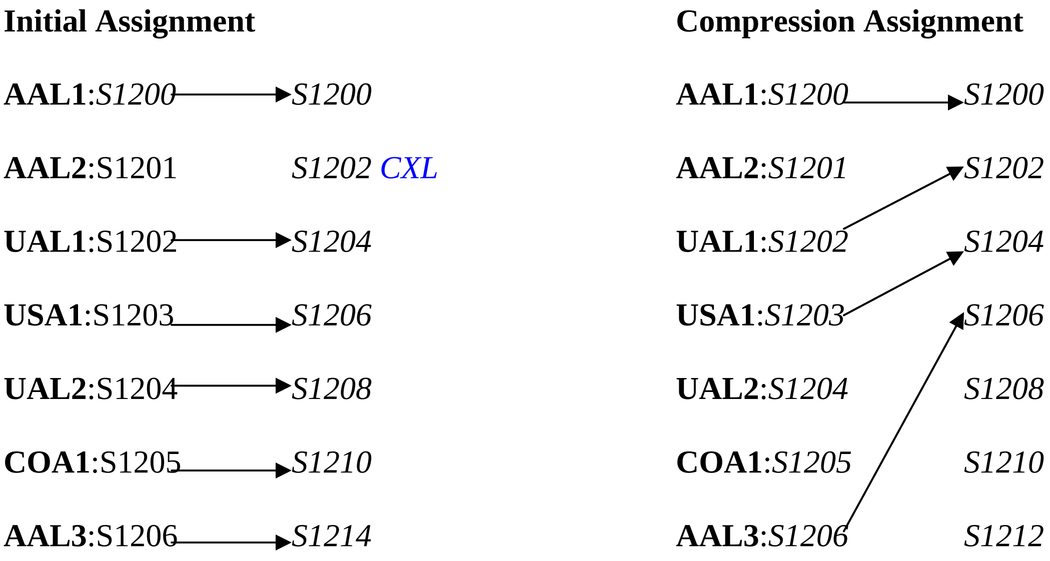

Figure 2.2: Compression Example

American Airlines cancels its flight AAL2. American Airlines is not able to substitute the slot with one of its other flights. When the ATCSCC runs compression, the flights of other CDM participating airlines are moved up till it becomes possible for American Airlines to schedule one of its flights to a vacant slot. In this case, United Airlines flight UAL1 and US Airways flight USA1 are moved up till it becomes possible for American Airlines to utilize a slot for its next flight AAL3.

2.2 Slot Credit Substitution

Slot Credit Substitution (SCS) is a dynamic slot swapping tool that provides the airlines with the flexibility of substituting flights and gain credit for releasing an earlier slot. The substituting airline benefits by getting rewarded with an earlier slot by virtue of its relinquishing the arrival slot of one of its other flight. SCS resembles a combination of the substitution and compression processes within a GDP.

SCS is a conditional request, i.e., an airline is willing to cancel one of its earlier flights only if it is able to get a replacement slot that it desires. SCS is initiated by the airlines under three different circumstances:

- When an airline cancels a flight but is not able to move any of its other flights to the vacated slot to reduce delays for later flights because of a gap in their schedule.
- When an airline has a flight that cannot make its Expected Departure Clearance Times (EDCT) and there are no other flights in its schedule that can fit into that slot.
- When an airline wants to protect a critical flight that will otherwise be canceled, because it has no other slots in its schedule that the flight will fit into.

SCS was instituted in the ATCSCC with the release of the Enhanced Traffic Management System (ETMS) 7.6. This release of ETMS was implemented in the ATCSCC in May

2003 and since then has been able to handle SCS requests. SCS is made possible among the airlines by a bridging process that links the Airline Operation Centers (AOCs) with the FAA ATCSCC.

The general flow of an SCS process is that the airline submits its request for slot exchange to ETMS. The airline is willing to cancel one of its flights provided that it is able to secure an arrival slot later in the GDP. The substitution chain is constructed using flights of airlines that are not under the control of the airline requesting SCS. ETMS attempts to create a bridge using other users' flights which is a process similar to compression. If successful, ETMS responds positively to the requester and notifies other users whose flights have been moved up and generates an updated ADL file. It is necessary that all the involved airlines are actively participating in the substitution process. The "bridge" flights are flights of the airlines that are moved up in the SCS process. It is possible for the airlines to prevent their flights from being considered in any pending SCS requests by not participating in the SCS processes. This will prevent the SCS process from interfering with the internal GDP management by the airlines. The following flow chart shows the process of decision-making by the ATCSCC and the industry.

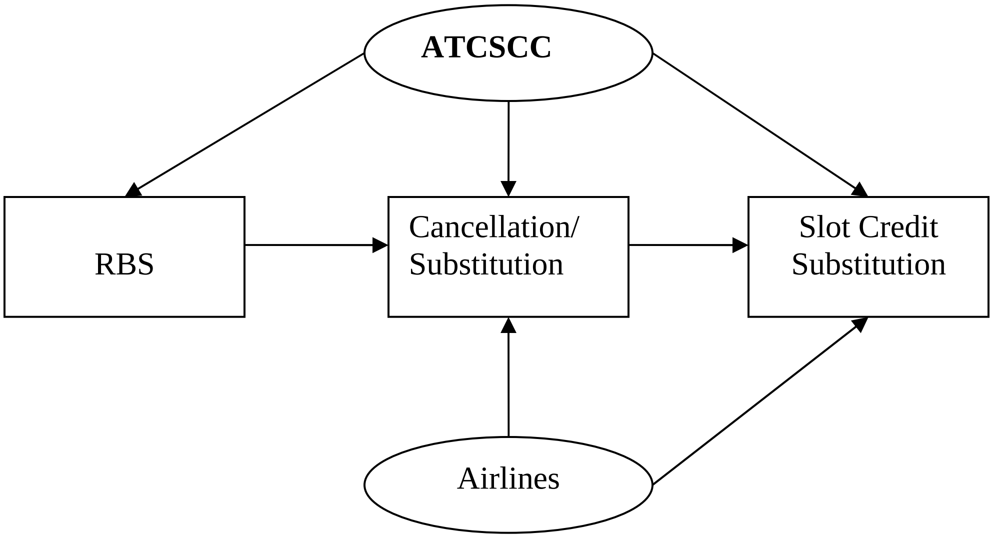

Figure 2.3: Cycle of Decision-making for Slot Credit Substitution

As can be seen, the ATCSCC initiates RBS. The airlines are willing to cancel their flights only if the ATCSCC provides another slot in return that they will be able to utilize. The ATCSCC, in collaboration with the airlines, try to create a substitution chain. As is apparent from the chart, the process of SCS is a more collaborative approach to decision making compared to compression.

The “bridging benefit” of the transaction is the total delay savings given to the bridging flights in the transaction. The “bridging benefit” can also be termed as the primary delay savings achieved through SCS. Once the bridging process is completed, it is possible that the requesting carrier will be able to make further substitutions with its other flights. Because these substitutions were enabled by the SCS transaction, this benefit is termed ‘substitution benefit’ of the transaction. These further slot exchanges done by the carrier are also termed ‘cascading effect’ of the substitution benefit. For our analysis, we consider the primary delay savings obtained from bridging as the benefits obtained from SCS.

For a flight to be eligible for bridging, it must meet the following criteria.

- The flight must not be cancelled, active, or completed.
- The flight must not be ground stopped.
- The flight must not be a Pop-up.
- The flight must have an Earliest Runway Time of Departure (ERTD) later than the minimum notification time (30 minutes). This will provide users with the ability to remain in compliance with the +/- 5 minute EDCT rule.
- A flight cannot be moved beyond its Earliest Runway Time of Arrival (ERTA).

An example of an SCS transaction is illustrated in Figure 2.4 below.

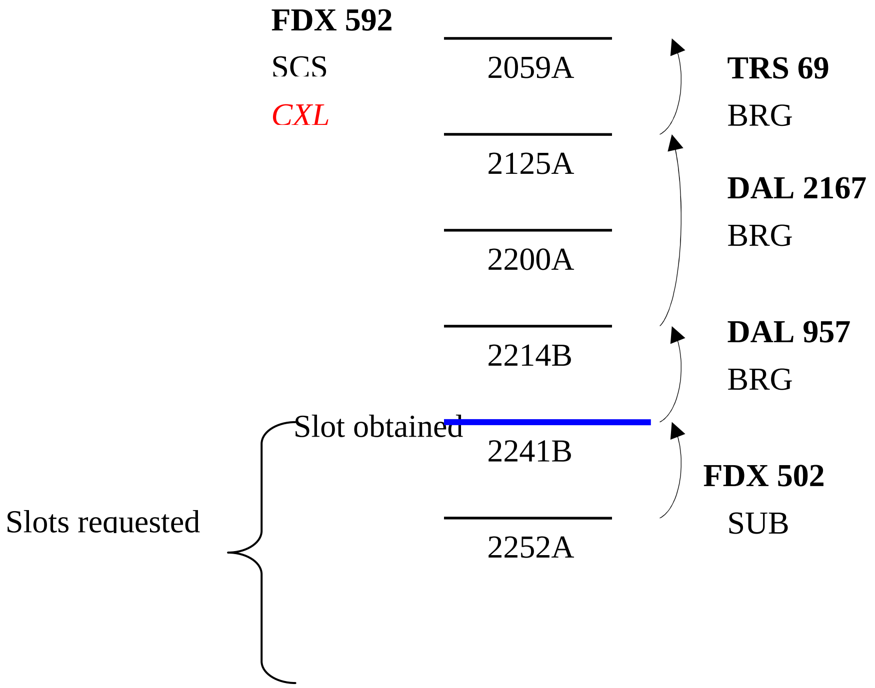

Figure 2.4: Slot Credit Substitution Example

Federal Express (FDX) submits an SCS message to the ATCSCC stating its interest in relinquishing slot 2059A and instead requests a window of slots that it will be able to utilize. Once ETMS receives this request, it tries to create a substitution chain using the flights of other airlines in the schedule. Airtran Airlines (TRS69) and Delta Airlines (DAL2167 and DAL957) flights are willing to move their flights up and hence facilitate the creation of the bridge. The ‘bridging benefit’ achieved through SCS will be the overall delay savings obtained by the bridge flights which in this case are TRS69, DAL2167 and DAL957. Substitution of FDX502 to slot 2241B enables Federal Express to create ‘cascade effects’ in terms of substitution among its own flights. In this case, Federal Express substitutes its flight FDX502 into slot 2241B and thus gains substitution benefits. The full benefit obtained from the slot exchange process will be the aggregation of “bridging” and “cascading” benefits.

2.3 Compression over simple substitution models

In this section, we discuss the benefits realized through compression over simple substitution processes adopted by airlines. This will provide an insight into the philosophy behind the implementation of compression by the FAA.

Simple substitution process is used by the airlines to move flights into an open slot made available by the same airline which owns the slot first. Airlines were using this capability prior to Collaborative Decision Making (CDM). Any airline can cancel its flight which had been assigned an arrival slot in a GDP and move another one of its flights up to fill the open slot. Even though an airline achieves benefits using the simple substitution process, some airlines did not implement this capability and so did not do the substitutions. Also, even though an airline may have the capability to use the substitution process, it was sometimes difficult for the airline to capitalize on every opportunity for substitution. There have been frequent instances when slots went unused because the airline that owned the slot did not substitute one of their flights to fill it. This was especially pronounced during severe weather events when it was difficult for the airlines to stay on top of its substitution process.

Compression was adopted by the FAA as a means to reduce delays across all the flights. Compression provided a tool for the ATCSCC to do these substitutions for the airlines resulting in overall delay reductions across all of their flights. Also, compression provided a means for the airlines to benefit in terms of delay reductions on flights that could not be moved up to the slot vacated by the canceled flight of the airline.

A detailed analysis had been conducted at Metron Aviation to determine the benefits obtained from substitution and compression for all compression cycles between September 8, 1998 and March 17, 1999 [15]. The results from this analysis showed that over all of these compression cycles, 66% of the compression benefits could have been achieved theoretically by intra-airline substitution process if the airlines had initiated the process and 34% of the compression benefits could never have been achieved without compression.

2.4 Limitations of Compression

After compression was implemented by the ATCSCC as a slot utilization procedure, there were certain situations when compression did not provide benefits to the airlines canceling their flights in the hopes that arrival slots will be compressed by the FAA [16]. The airlines that had cancelled their flights in the hopes that their other flights will be moved up did not achieve the delay savings. ATCSCC did not run compression regularly as they perceive that there will be an increased demand for airport resources due to pop-up and general aviation flights. This became a major stumbling block to CDM because if the ATCSCC does not compress regularly, then airlines do not get the full benefit of compression, and airlines partially lose the incentive to cancel flights.

Suppose that the ATCSCC issues a Ground Delay Program, and fifteen flights are scheduled to arrive during a particular hour in the GDP also called GDP-hour. The airlines that have a slot during that GDP-hour cancel their flight intentionally in the hopes that when compression is run their other economically important flights will be moved up, reducing their overall delays. The airlines want the ATCSCC to run compression since there are open slots available. The ATCSCC, on the other hand, does not compress the flights as it expects pop-ups and does not want to create an overbooking scenario. This is a situation where the airlines see open slots and want compression, but the ATCSCC sees excess demand and does not want to compress. The airline will see that its sacrifice of canceling a flight was in vain, and believes that it does not pay to cancel a flight in hopes that compression will be run. All airlines suffer because potential cancellations are not made, and excess demand is not reduced which could have been reduced if compression could be counted on.

2.5 Advantages of SCS

One of the primary benefits from Slot Credit Substitution (SCS) is the even slot-for-slot exchange. There is an increased system stability/ predictability compared to compression. SCS creates a smoother GDP traffic flow, improves Airport Arrival Rate (AAR) and EDCT compliance and improves capacity utilization during GDP. Due to a bulk of the onus of substitution falling on the airlines, the workload for the ATCSCC is significantly lower than in compression. Other benefits to the command center are in terms of decreased need for compression and reduced EDCT Change Request (ECR), requests submitted due to missed EDCTs. The airlines benefit from the flexibility provided in canceling and substituting their flights. Critical flights of the airlines can be accommodated in the schedules. Some of the system benefits obtained from SCS are increased predictability, improved airline business decisions in terms of more economically suitable cancellation choices, improved passenger throughput, improved slot control management, improved user EDCT compliance and reduced delays for all airlines. If compression can be counted on, airlines with multiple flights are encouraged to cancel their flights and combine passengers. This is not only a good solution for the airline, but it benefits all airlines since the overall demand is reduced at the congested airport. But, the technology requirements for processing SCS messages are higher. The increased collaboration among the airlines and the ATCSCC will increase the overheads of constructing an efficient slot exchange scheme.

In summary, there are advantages and drawbacks of each of the two slot exchange mechanisms. Compression has its own inherent advantages in terms of the airlines ability to focus on other activities to reduce delays than spend their efforts on creating a substitution chain. On the other hand, airlines have to depend on the ATCSCC to run compression to realize delay benefits. Under Slot Credit Substitution the airlines take control of creating the substitution requirements in order to maximize their internal economic objectives.

Chapter 3: THEORETICAL MODELING

This chapter describes theoretical models that are constructed to evaluate Slot Credit Substitution (SCS) and compression. The models will assist in determining the benefits in terms of delay savings that can be achieved through SCS and compression. Our notion is that as the frequency of compression increases, the benefits obtained from compression will be comparable to that from SCS.

On initial analysis, it appears that compression is a batch optimization process while SCS is a one-for-one exchange process. In a Slot Credit Substitution, an airline is willing to cancel or delay one of its flights in exchange for delay savings for one of its other flights. Compression, on the other hand, can be viewed as a batch slot optimization process where the ATCSCC gathers cancellation and delay information of the airlines and then runs compression to improve slot utilization. There are situations in the real world where batching the exchange of resources increases optimization due to the choices it provides in comparison to one-for-one exchange of resources. Compression does not provide any additional advantage inherent to batch optimization processes. This is because when compressed, the flights are moved up the slots in accordance with their schedules.

Let us say that there are two flights X and Y that have their scheduled arrivals at 1400 and 1420 hours respectively. When compressed, both the flights will be moved up proportionately, that is, if X moves up to an arrival slot at 1340, Y will move up 20 minutes to the arrival slot at 1400 hours. Compression does not provide any additional savings beyond what can be achieved through one-for-one exchange. It does not have any underlying optimization criteria to enhance delay savings and will imitate SCS benefits when run frequently. This is in line with our notion that frequent compression runs will provide similar results to those from SCS.

3.1 Factors Influencing Success of Slot Credit Substitution

For SCS to succeed there are some important considerations that need to be taken into account. The following example illustrates these factors. Figure 3.1 shows the arrival slots allotted to the flights under fair weather conditions as well as slots allotted after a GDP has been initiated at the destination airport. Under GDP, the capacity at the destination airport has dropped by 50%. United Airlines (UAL) has requested slot exchange under SCS for its flight UAL02 and the ATCSCC has found willing airlines whose flights can be moved up to construct the slot exchange. American Airlines flight AAL11 and Delta Airlines flight DAL01 are the “bridge” flights for this exchange. The

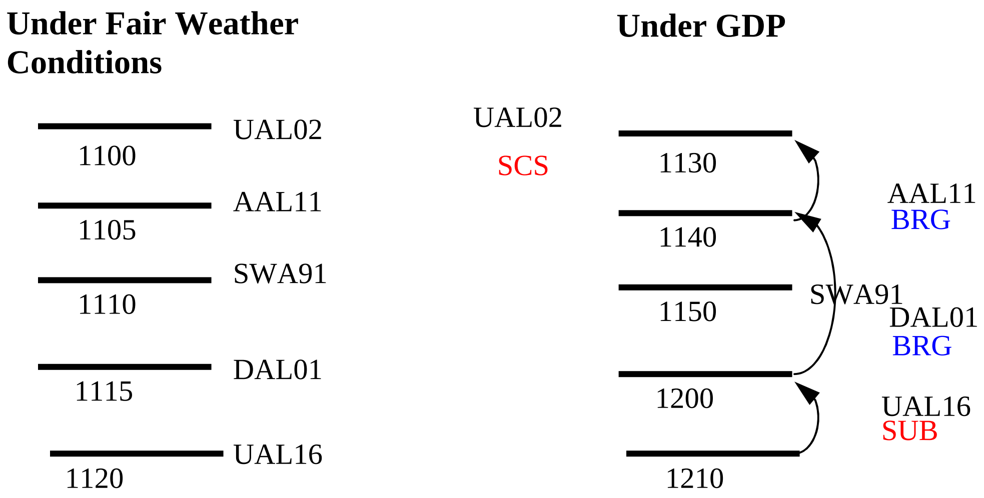

Figure 3.1: Factors influencing success of SCS

Controlled Time of Departures (CTDs) of the involved flights are changed. AAL11 arrives at 1130, DAL01 arrives at 1140, SWA91 retains its original CTD and UAL16 gets a CTD of 1200.

Table 3.1 contains information on the departure times of the flights from their origination airport after GDP has been implemented at the destination airport. Scheduled Gate Time of Departure (SGTD) refers to the departure time of the flight from its origination airport under fair weather conditions. Controlled Time of Departure (CTD) is defined as the time at which the flight will depart from the origination airport after RBS algorithm has been initiated at the destination airport. CTD of the flights after the SCS exchanges refers to the time at which the flights have to depart to make it to the arrival slots that have been allocated to the flights after the exchanges. The airborne time is the time required by the flight to reach its destination which is assumed to be a constant. Note that the CTD of the flights after the SCS exchanges cannot be earlier than SGTD.

Table 3.1: Sample of flights for analyzing factors influencing SCS

	SGTD	CTD	Airborne time	CTD after SCS exchanges
UAL02	10:00	10:30	1 hr	11:00
AAL11	09:55	10:30	2 hr 50 min	10:25
SWA91	08:10	08:50	3 hr	08:50
DAL01	09:15	10:00	2 hr	09:40

- **Timeliness of request for slot exchange:** The time at which the airline submits its request to place a flight for substitution will have an impact on the success of substitution. If the request is submitted too close to the actual time of departure of the flight then there may not be enough flights of other carriers willing to exchange slots in such a short duration of time. The longer the time between the submission of request and the departure time of flight, the choices for slot exchanges increase. There is a high likelihood that some of the flights that could have been used in the substitution process may have already taken off and are not available for substitution. In the above example, if UAL, the airline requesting the slot exchange, had submitted its request at 0900, then the ATCSCC will be able to perform the exchanges, as the CTDs of the involved flights will still be after 0900. On the other hand, if UAL had submitted its request at 1000, by then DAL01 would have been airborne. The latest time by which DAL01 has to depart to make it to the 1140 arrival slot would be 0940. So the exchange of slots will not be feasible.

- **Controlled Time of Departure of ‘bridge’ flights:** The controlled departure times of the ‘bridge’ flights should be later than the time when the slot exchange is requested. As can be seen in the example, for the SCS substitution to succeed, it is necessary that the CTDs of the flights prior to the slot exchange, after taking into account the upward movement in CTDs, should be later than the time at which the SCS request is submitted.
- **Scheduled Gate Time of Arrival of flights:** Another factor that needs to be considered in the success of SCS is that the “bridge” flights cannot be moved to an arrival slot earlier than their scheduled gate time of arrival under fair weather conditions (non-GDP conditions). In the example above, it is not possible to

move flights AAL11 and DAL01 to an arrival slot that will require the flight to take-off from its origination airport earlier than its SGTD.

- **Expiration of SCS request:** The SCS message that is sent by the airlines has an expiration period. If the request is not fulfilled within a specific timeframe, then the substitution process cannot be executed. As in the example provided earlier, if the SCS request submitted at 0900 is not processed by 0940, then it will not be possible to do the slot exchanges because flight DAL01 has to take-off by 0940 to be able to reach the destination at 1140.

3.2 Factors Influencing Success of Compression

There are certain factors that need to be considered in order for compression to succeed.

- **Controlled Time of Departure of the flights:** The CTDs of the flights that are moved up should be later than when compression is initiated otherwise flights will be airborne before compression is run and the slot trades cannot be accomplished.
- **Scheduled Gate Time of Arrival of flights:** The extent to which the flights used in the compression process can be moved up is determined by the scheduled times of arrival of these flights. It is not possible to place the flight in a slot that is earlier than its scheduled arrival slot.

3.3 Model Development

Conceptual models are created to understand the ability of compression to capture the inter-airline slot exchange messages. Our initial analysis is to evaluate the percentage of inter-airline slot exchange requests that can be captured through compression based on the frequency at which compression is run. The inter-airline slot exchange requests are predominantly submitted as SCS messages. SCS mechanisms were implemented in the NAS starting from May 2003. Due to the relative newness of this mechanism, there were not many incidences of these requests in the NAS. So, we constructed the models assuming a hypothetical distribution of arrival of slot-exchange requests.

3.3.1 Model 1: Fixed “Window of influence” model

The fixed “window of influence” model is a theoretical model constructed to simulate the ability of compression to have an impact on slot exchange transactions that occur at the ATCSCC. The “window of influence” is a time period prior to compression where the slot exchange requests submitted by the airlines are impacted by compression. In this window, airlines cancel their flights and can expect to obtain benefits through the upward movement of their flights from compression. The “window of influence” is a reflection of the airlines’ trust of compression. The diagram below provides the visual representation of the concept of “window of influence” and its ability to provide benefits to the airlines.

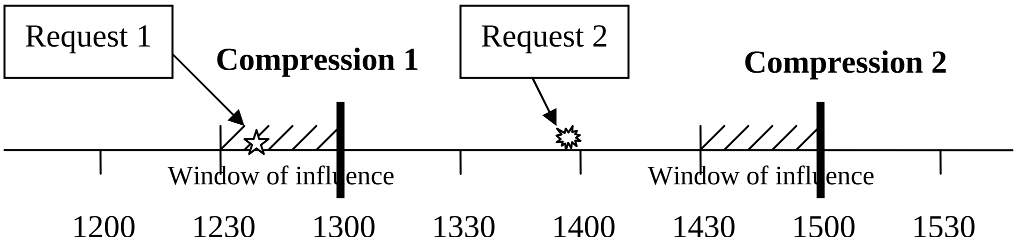

Figure 3.2: Compression “Window of influence”

Compression is run at 1300 and 1500 hours and as seen in Figure 3.2 its “window of influence” is for a period of 30-minutes from 1230 – 1300 and 1430 – 1500 hours respectively. Request 1 arrives at the ATCSCC during the “window of influence” of compression. In this case, compression will be able to create a substitution chain that benefits all the involved flights. On the other hand, Request 2 arrives at the ATCSCC much earlier than the time when compression is run and so will not achieve the desired benefits from compression.

Based on our analysis, the Poisson process will be the best way to model the requests. For every 5 –minute time interval, we assume that the number of requests submitted by the airlines follow a Poisson process. The following criteria have to be considered in creating the Poisson process [17]:

- The occurrences can be counted in whole numbers;
- The occurrences are independent, so that one occurrence neither diminishes nor increases the chance of another;
- The average frequency of occurrence for the time period in question is known and that frequency is small for the period of observation;

We assume that compression has a 30- minute “window of influence”. Depending on the frequency at which compression is run, the ability of compression to provide benefits will change. Scenarios were created for compression run at ½, 1, 2 and 3 hour intervals.

3.3.1.1 Sensitivity Analysis

Sensitivity analysis of the model is conducted by changing the parameters used in the development of the model. Some of the parameters that are changed are:

- The mean of the Poisson process.
- The duration of “window of influence”.

Analysis is conducted to understand the effect of changes in the mean of the Poisson process. When compression is run every 30 minutes, the ability of compression to capture exchange messages is 100% because the duration of the “window of influence” is the same as the frequency of compression. As seen in the Figure 3.3, for the three different scenarios created with varying means, the ability of compression to capture slot exchange messages for different frequencies of compression remains nearly the same. As the frequency of compression decreases, the ability of compression to capture these exchange requests drop. This is due to the fact that the window of influence of compression remains the same while the interval between two consecutive compressions keeps increasing. We can conclude that the mean of the distribution does not have a significant impact on the ability of compression to capture the slot exchange messages.

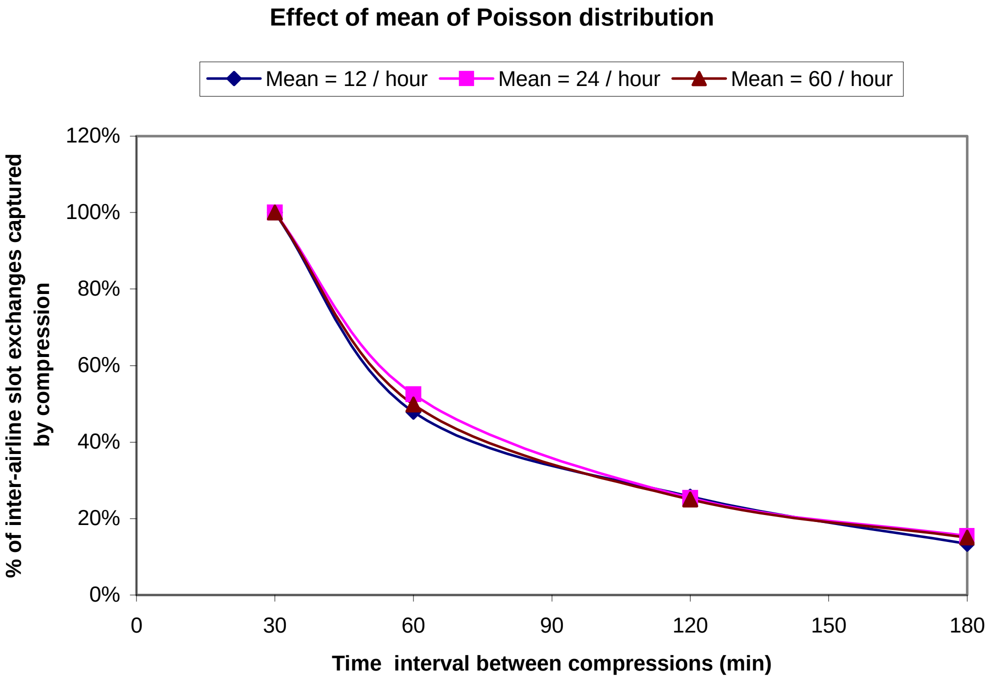

Figure 3.3: Effect of mean of Poisson distribution

Models are created to understand the effect of changes in the duration of the compression “window of influence”. Two scenarios for 30-minute and 15-minute compression window are created and the results plotted as in Figure 3.4. When compression is run every 3 hours, the number of slot exchange messages captured by compression approach similar values. We can conclude that as the time interval between compressions decreases, the ability of compression to capture the messages declines much faster in the case of “window of influence” of 15 minutes. This is in line with our supposition that increase in the “window of influence” of compression enhances its ability to construct increased savings.

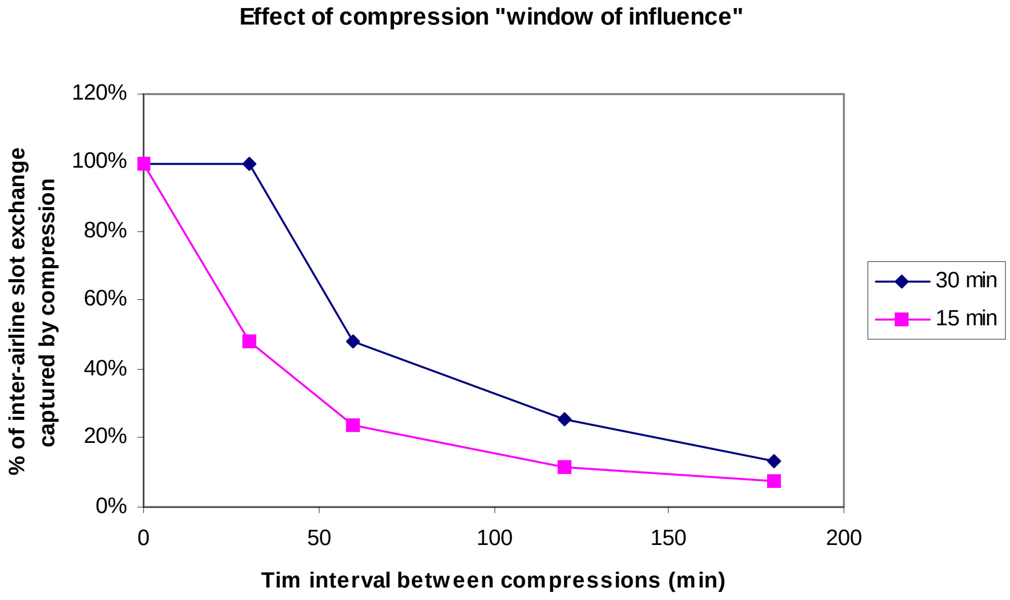

Figure 3.4: Effect of compression “window of influence”

3.3.1.2 Curve fitting

The model developed using the Poisson process shows a decline in the ability of compression to provide benefits similar to SCS when compression is run less frequently. In the previous section, the ability of compression to capture the slot exchange messages for various frequencies of compression was constructed assuming a 30-minute window of influence. Equation is generated for compression effectiveness under 30 minute “window of influence”. A third degree polynomial equation provides the best fit for this plot. This equation will be used in the next section to simulate the ability of compression to capture the slot exchange messages in real world situations. For the example using 30- minute window of influence, the equation was determined to be

$$y = -6 * 10^{-7} (x-30)^3 + 0.0002* (x-30)^2 - 0.0206* (x-30) + 1$$

where y = % of inter-airline slot exchange messages captured by compression;

x = time interval between compressions.

3.3.2 Model 2: Acceptance Lead Time Model

The slot exchange messages are submitted to the Air Traffic Control System Command Center (ATCSCC) by the airlines and the ATCSCC tries to construct the substitution chain. There is a certain time duration by when the exchange process has to be completed otherwise one of the involved flights will be airborne. Let us define the time by when the slot exchange chain has to be constructed by the ATCSCC to be the Earliest Revised Departure Time (ERDT). This corresponds to the revised departure time of the earliest of the involved flights in the exchange process. A visual representation of the model is provided in Figure 3.6. The "window of influence" parameter is not a determining factor in the creation of this model.

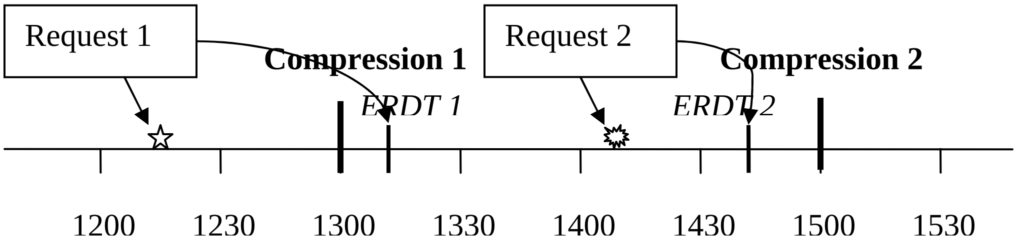

Figure 3.6: Compression with Uniform distribution of revised time of departures

Let us consider a flight that submits a slot-exchange message and has the earliest revised time of departure of the bridge flights later than the time when compression is to be run at 1300 hours. In the diagram above, Request 1 will be captured by compression as all the involved flights have their departure times later to the time when compression is run. All the flights will be benefited from compression. On the other hand, in the case of Request 2, one of the bridge flights has its revised departure time earlier than 1500 hours. When compression is run at 1500 hours, one of the bridge flights will already be airborne and so compression will not be able to construct the slot exchange process.

For the construction of the model, we assume a Poisson process for the submission of requests. The earliest revised departure times are assumed to have a uniform distribution. Sometimes when a flight misses its EDCT time, it requests the command center for an EDCT Change Request (ECR) and gets a departure slot later than 10 minutes. This was the criteria used for the lower bound of the uniform distribution and is assumed to be 10 minutes. The upper bound of the uniform distribution is varied at 60, 90, 120, and 180 minutes. For different compression intervals, the ability of compression to capture these slot exchange messages is studied. The plot in Figure 3.7 shows the ability of compression to capture these messages.

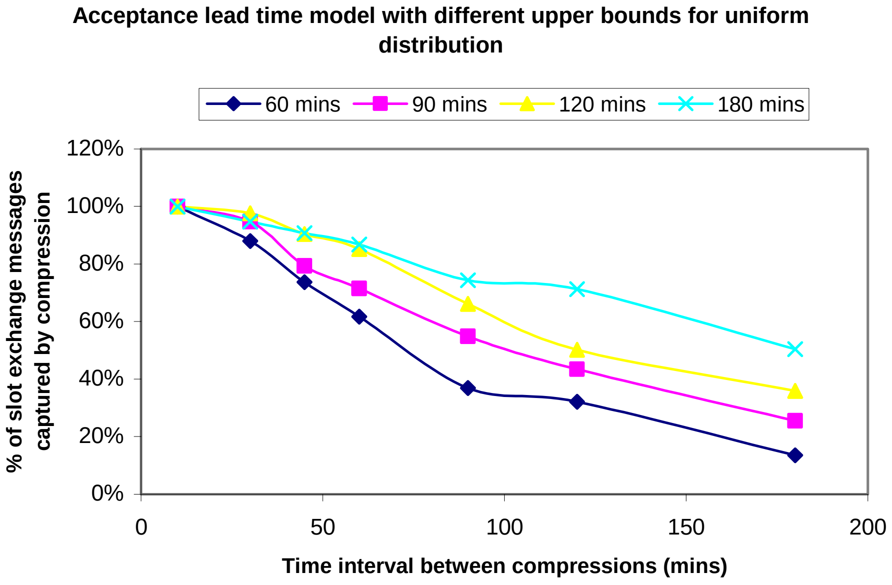

Figure 3.7: Effect of revised time of departure of flights on compression

As observed, the ability of compression to capture the messages declines as the compression interval increases but the reduction is more gradual than observed in the previous model. Theoretically, if the upper bound of the distribution had been “infinite” then all the messages would have been captured by compression, independent of the frequency of compression. On the other hand, as the upper bound approaches the lower bound of 10 minutes, fewer slot exchange messages will be captured by compression.

3.3.3 Slot exchange messages from real-world situations

We use real world slot exchange messages to replace the Poisson process for messages used in the previous sections. The real-world messages are used to evaluate the robustness of the model. For our analysis, airports that had a significant number of inter-airline slot exchange messages submitted to the ATCSCC during GDP were considered. As the SCS procedure is still in its infancy, not many GDP instances can be found that had a number of these messages. During the period May 2003 and March 2004 there were three instances when there were relatively high numbers of these messages. Table 3.2 shows the airports, the dates and the number of SCS messages on those days.

Table 3.2: Real-world situations of SCS messages

Airport	Date	# of slot exchange messages during GDP
ORD	01/04/2004	6
LGA	09/03/2003	16
ATL	02/26/2004	25

On Jan 4, 2004, GDP was initiated at ORD. There were 6 slot exchange messages submitted by the airlines to the ATCSCC. We use the fixed "window of influence" model to determine the ability of compression to capture these messages. It was found that the revised time of departures of all the affected flights were more than two hours later for all the instances. So, the acceptance lead time model could not be applied. The following plot shows the hourly distribution of messages at ORD.

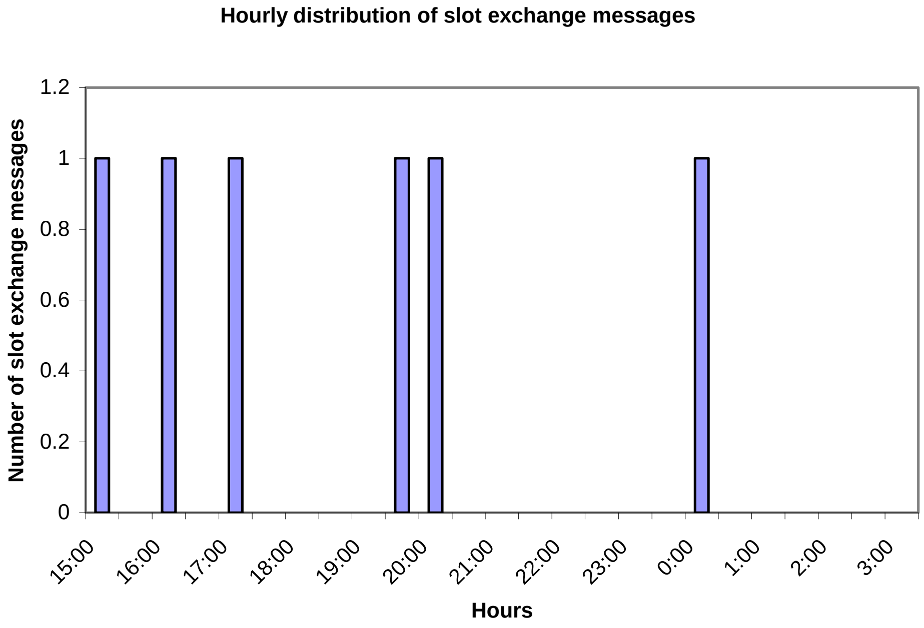

Figure 3.8: Hourly distribution of slot-exchange messages at ORD

The distribution shows that SCS messages are received from the airlines at random intervals. A model is created to evaluate the ability of compression to capture these messages from the airlines. Scenarios are created by varying the compression frequency and assuming a "window of influence" of 30 minutes. Using the equation created in Model 1, we construct the model to validate the results.

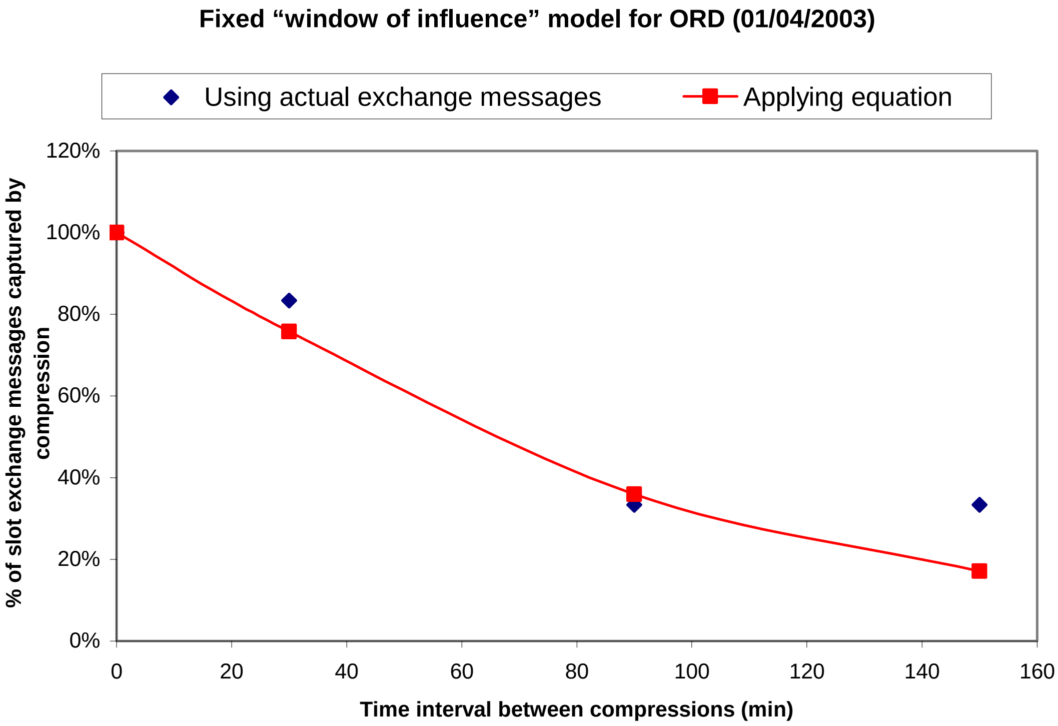

Figure 3.9: Fixed “window of influence” model for ORD (01/04/2003)

As seen in the plot in Figure 3.9, the equation represented by the line fits the data obtained for ORD with a Sum of Square Error (SSE) of 0.8%.

Similarly, two other GDP instances were considered for our analysis that had significant slot exchange messages submitted by the airlines. As seen in Table 3.2, LGA and ATL had 25 and 16 slot exchange messages submitted to the ATCSCC respectively. The distribution of the slot exchange messages are staggered for the instances at LGA and ATL.

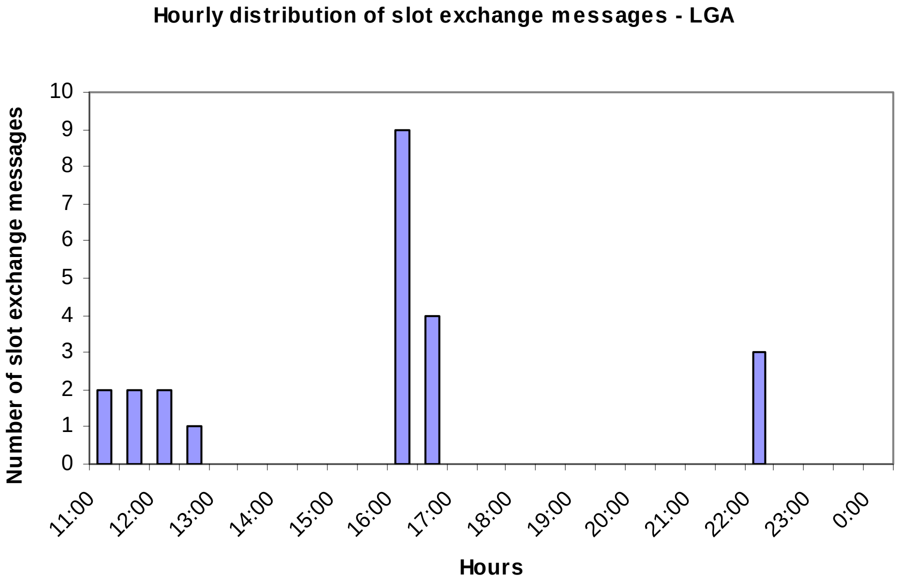

Figure 3.10: Hourly distribution of slot-exchange messages at LGA

The ability of the equation developed in the previous section to capture these messages is evaluated. As seen in the Figure 3.11, the SSE in the case of LGA is 2.13 %.

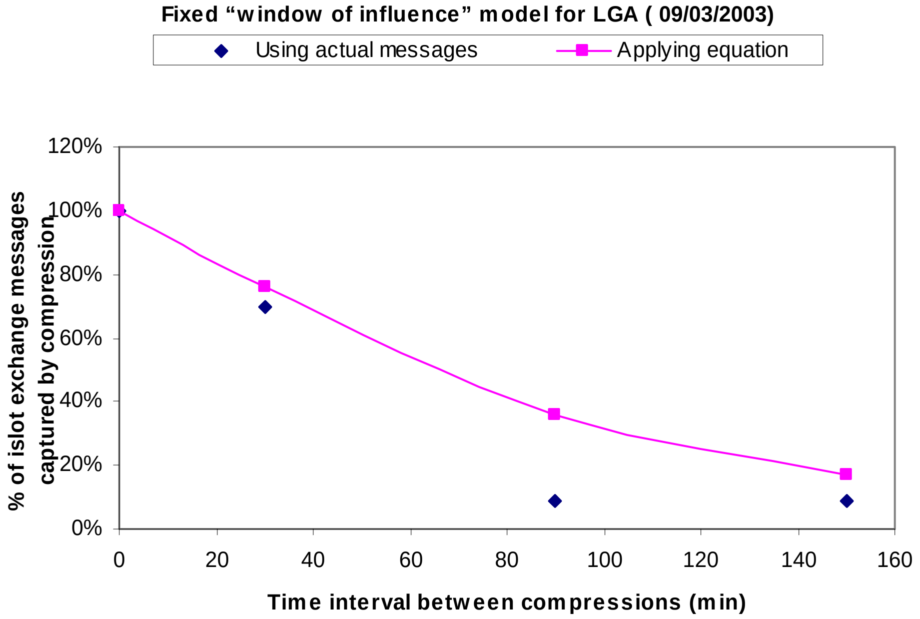

Figure 3.11: Fixed “window of influence” model for LGA (09/03/2003)

Similarly, the hourly distribution of slot exchange messages at ATL on Feb 26, 2004 was analyzed.

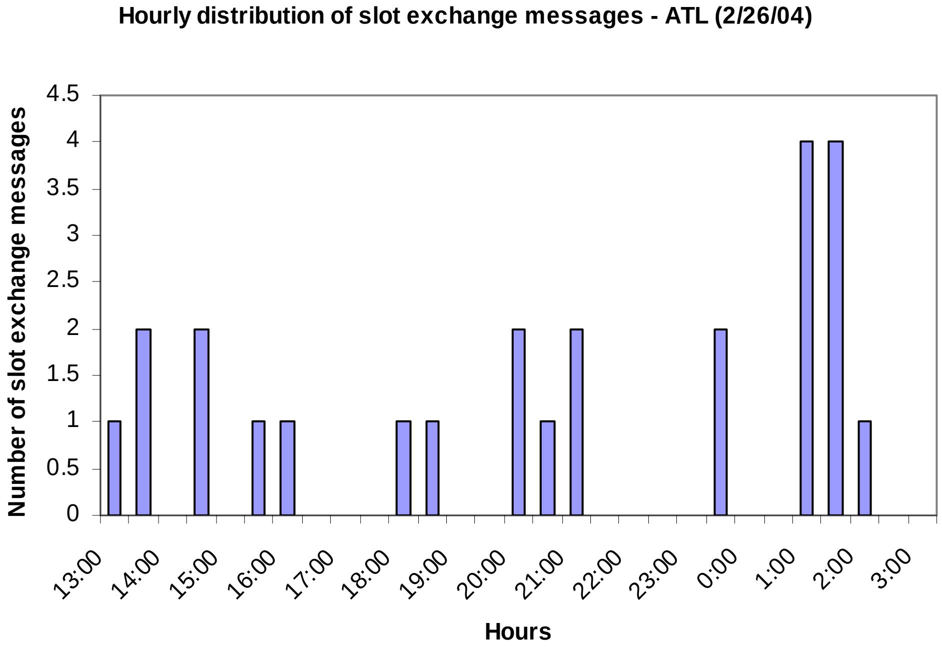

Figure 3.12: Hourly distribution of slot-exchange messages at ATL

The ability of the compression equation to capture the actual exchange messages in this GDP at ATL decreases as the number of compressions run by the ATCSCC is higher. The Sum of Squared Errors in this case was found to be 5.05%.

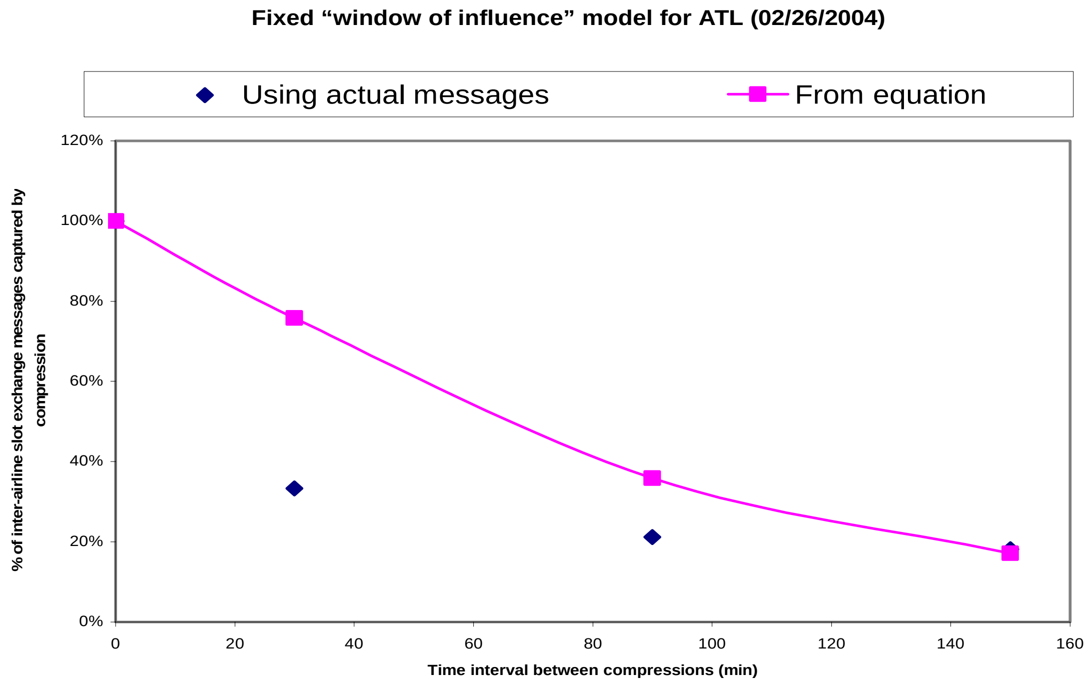

Figure 3.13: Fixed “window of influence” model for ATL (02/26/2004)

The models that were developed in this chapter provide us an insight into the operations of the real-time, conditional transaction oriented process (SCS) and the periodic, batch process (Compression). The periodic, batch processing procedure in case of compression may not be able to capture all the slot exchange messages. SCS is a reactive process where the ATCSCC has to make dynamic, real-time exchanges for the airline requesting the exchange. If compression is run by the ATCSCC, it will be able to provide results similar to that achieved from SCS process.

Chapter 4: DATA ANALYSIS

4.1 Data Sources

The Aggregate Demand List (ADL) [18] and databases obtained from Metron Aviation [2] have been the primary sources of data used for the analysis of Slot Credit Substitution (SCS) and Compression benefits. The ADL is primarily composed of data extracted from the Collaborative Decision Making (CDM) hub site databases, which are maintained with a combination of OAG data, airline-provided flight data messages from Airline Operational Control centers (AOCs), NAS messages generated from the ATC system, and issued ground delays. The hub site is maintained at Volpe National Transportation Systems Center, a federal organization within the U.S. Department of Transportation. Volpe processes the information from the various sources and generates CDM strings consisting of ADLs to each of the CDM participants [19]. The flow of information within the ATC framework is shown in the diagram below. The ADL also includes GDP-specific data entered by the traffic management specialist.

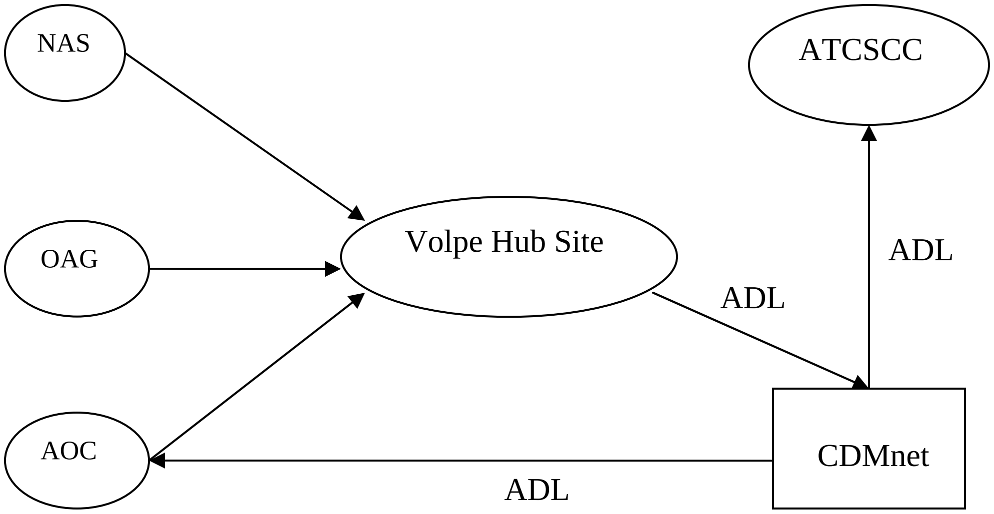

Figure 4.1: Generation of ADL files and their distribution

The ADL file is created for all operations at a single airport for a particular day. As of November 2002, the ADL file has approximately 78 fields for every flight record. Each record contains a comprehensive set of flight status information. Each flight record usually corresponds to a unique flight; however, two or more records for a single flight imply that the flight has undergone changes in its operation and the most recent record will provide the accurate information about the flight. The ADL is updated with latest airline information every five minutes. This implies that there might be transactions that occur in between two ADL updates which might not be reflected in the files. A preliminary study conducted in October 2003 over a two-week period estimated that only 3% of the SCS, ECR or EDCT messages were sent in-between ADL updates. [20] To put it in perspective, 97 % of the ADL records show accurate airline transactional changes without excluding information.

Metron databases were used as a source for analyzing compression benefits. It has a compilation of number of databases and this was used as a source for data. Extensive data has been archived at their website and provides useful information on compression benefits. Data is available at this website starting from 1998 when compression processes were implemented in NAS to recent past.

4.2 Data Preparation

4.2.1 Slot Credit Substitution (SCS)

The successful processing of an SCS request is dependant on the existence of other flights being able to fill the unused capacity by accepting delay reductions. These flights that are moved up are termed ‘bridge’ flights and are used for the calculation of primary delay savings from SCS. ADL files contain these bridging flights used for delay savings. A brief description of the fields of interest in the ADL file is as below:

1. ACID: Aircraft ID (flight identifier)

   This field identifies the flight as it is filed on its NAS flight plan.

2. ETD: Estimated Time of Departure

   The ETD is the best, estimated runway departure time considering all data sources. The time is preceded by a prefix indicating the status of the flight.

3. ETA: Estimated Time of Arrival

   The ETA is the best, estimated runway arrival time. This time is prefixed to indicate the status of the flight. The values of some of the prefix are E when time has been estimated, C when time is estimated but the flight is controlled in a GDP and A when time is from a NAS termination message or actual arrival time of the flight.

4. CTD: Controlled Time of Departure

   CTD is the current controlled departure time (EDCT) for a flight. This is the departure time for the flight under GDP.

5. CTA: Controlled Time of Arrival

   CTA is the current controlled arrival time (EDCT) for a flight. This will be the arrival time allotted to the flight at the destination airport under GDP conditions.

6. CTL_TYPE: Control Type

   If a flight is controlled (i.e., has a CTD and CTA), CTL_TYPE indicates the specific source of the current CTD/ CTA. The possible sources are:

   - GDP – an initial GDP, an extension, or a revision
   - COMP – compression
   - SUB – a regular airline substitution message
   - SCS – an airline slot credit substitution message
   - BRG – a bridge created to handle a slot credit substitution request

7. CTL_EXMPT: Control Exempt Flag

   If a flight is controlled (i.e., has a CTD and CTA), CTL_EXMPT indicates whether the flight is “exempt” from modifications under GDP.

8. MAJOR: Major carrier

   For CDM members, indicates the carrier that has substitution for the flight.

The ADL files are huge datasets. Relevant data from these files are gleaned for SCS analysis. The data is further modified and some of the fields are changed to enable ease of calculation of benefits.

A cross-section of a modified ADL file containing bridging transaction is provided below. The data shows the sequence of ADL updates for flight CAA421 which is used as a bridge flight. Some of the fields have been modified for better understanding of the ADL updates.

Table 4.1: Cross-section of ADL file

ACID	MAJOR	ASLOT	CTL_EXMPT	ETA	ETD	CTA	CTD	CTL_TYPE
CAA421	CAA	-	-	E17:51	S17:05	-	-	-
CAA421	CAA	1850B	-	C18:50	S18:04	18:50	18:04	GDP
CAA421	CAA	1847A	-	C18:47	S18:01	18:47	18:01	GDP
CAA421	CAA	1806A	-	C18:06	S17:20	18:06	17:20	BRG
CAA421	CAA	1820B	-	C18:20	S17:34	18:20	17:34	BRG
CAA421	CAA	1826A	Y	E18:23	A17:39	18:26	17:34	GDP
CAA421	CAA	1826A	Y	E18:25	A17:39	18:26	17:34	GDP
CAA421	CAA	1826A	Y	E18:25	A17:39	18:26	17:34	GDP
CAA421	CAA	1826A	Y	E18:29	A17:39	18:26	17:34	GDP

In the above table, the flight CAA421 has an initial ETD at 17:05 and reaches its destination airport at 17:51. GDP is clamped at the destination airport which changes the arrival pattern of flights at the airport. All the flights arriving during GDP are delayed and their departure and arrival times get shifted. The controlled time of departure (CTD) and controlled time of arrival (CTA) of flight CAA421 are 18:04 and 18:50 respectively. The flight does not have its CTL_EXMPT field enabled which means that the flight is available to undergo the substitution process. An SCS request is sent by one of the other CDM participating airline to ATCSCC. Upon receiving the SCS request, the ATCSCC attempts to create a substitution chain and since CAA421 is available for substitution uses the flight in the process of substitution. The CTL_TYPE of the flight changes from ‘GDP’ to ‘BRG’ in the next ADL update. The flight gets moved up to the arrival slot at 18:06 and in the process benefits with a delay savings of 41 minutes. Once the flight takes off, the CTL_EXMPT field gets updated with ‘Y’ which implies that the flight is no longer available for any further substitution. Similarly, other flights that undergo bridging will benefit from the substitution process. An aggregation of all these benefits across flights for a month provides the benefits achieved from SCS requests in that month.

4.1.2 Compression

Data for compression is obtained from Metron databases [2]. Metron Aviation has been gathering the information on compression and the benefits in terms of delay savings that are obtained from the airlines at the various airports. These resources were tapped for analyzing the savings achieved from compression. Compression benefits have been calculated from the upward movement of flights to fill the slot vacated by cancellation.

Chapter 5: ANALYSIS OF SLOT EXCHANGE PARADIGMS

This chapter will be an analysis on the trends in the airline industry in terms of adoption of the slot exchange methods and the ability of these mechanisms to provide delay savings to the airlines. We will also formulate appropriate metrics to evaluate the benefits received from the slot exchange models.

The NAS consists of 32 major airports and a number of smaller airports spread across the country. These constitute a large network of interlinked airports. Delays in an airport can cause a ripple effect affecting all the other airports throughout the NAS. This effect is especially pronounced in the case of some of the larger airports. The throughput in these airports has a major impact all across the NAS. For conducting our analysis, it is necessary that we consider some of the major airports for our analysis along with our analysis of the NAS.

To determine the airports for our analysis, we use GDP-hour as a measure to compare the distribution of GDPs across the major airports. A GDP-hour is a unit of measure used to define the duration of GDP in hours. For example, a GDP that is initiated at 0400 pm and lasts till 0900 pm will have a GDP-hour of 5. An aggregation of hours of GDPs at an airport is used as a measure of comparison. Airports are accordingly selected that have an impact on the health of the NAS. GDP-hours at the airports are calculated for a period from Jan 2002 to Feb 2004. As observed in Figure 5.1, among the 32 major airports, six of the airports experienced 84% of the GDPs in terms of GDP-hours. These were Atlanta, Newark International, La Guardia Airport, Chicago O'Hare and San Francisco. The GDP-hours at these airports range from 8% at PHL (Philadelphia) to about 22% at ORD (Chicago O'Hare). The rest of the airports had very low number of

GDPs in terms of GDP-hours with Boston leading the rest of the airports with 2.1% of the total NAS GDP-hours. So, in addition to conducting NAS-wide evaluation of impact of compression and SCS, we also consider these six airports for a comprehensive analysis.

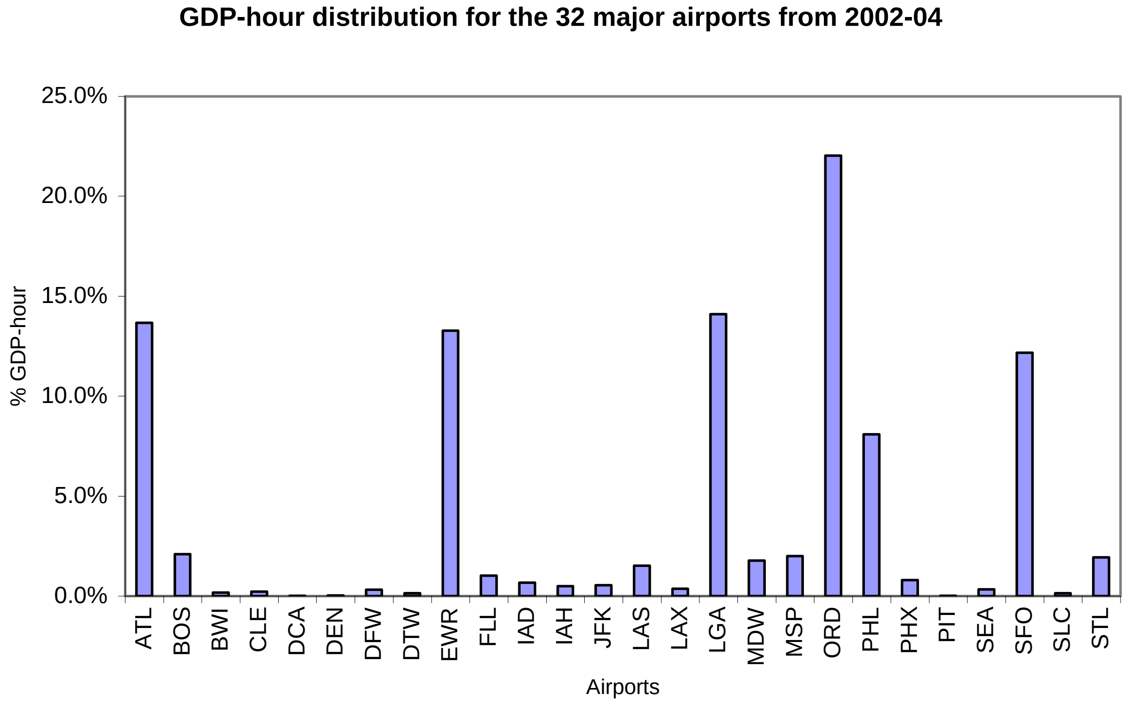

Figure 5.1: GDP-hour distribution for the 32 major airports from 2002-04

5.1 Trend analysis

An analysis is conducted to understand the trends in compression and SCS messages. Before getting into the trends in these slot exchange mechanisms, we determine the trends in GDPs.

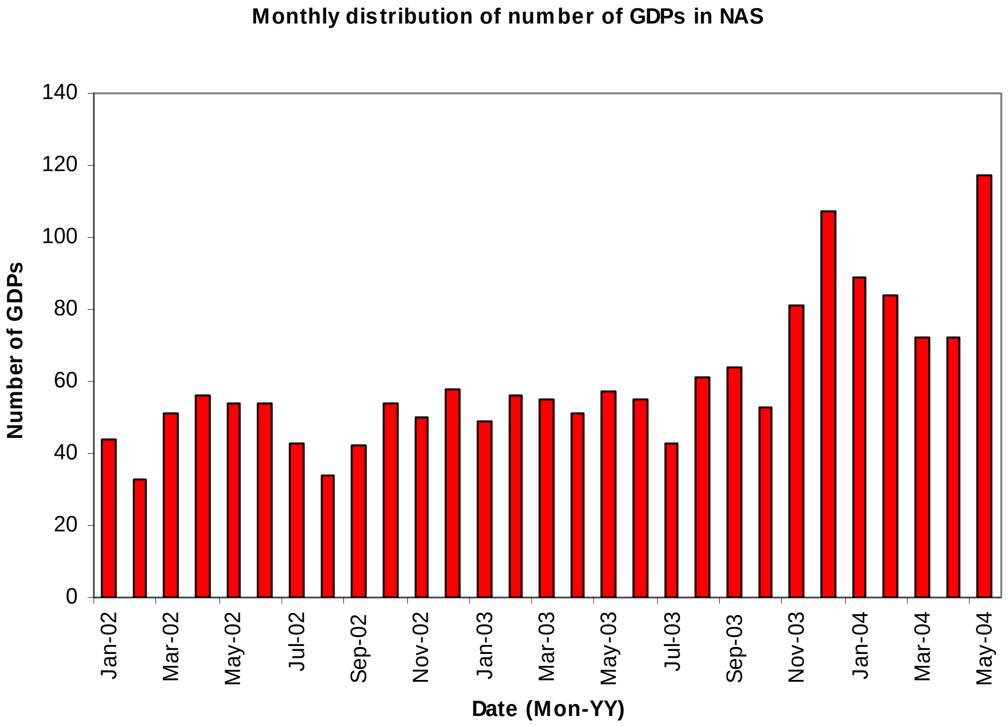

Figure 5.2: Monthly distribution of number of GDPs in NAS

As observed in Figure 5.2, the numbers of GDPs across the NAS from Jan 2002 to Feb 2004 vary from month to month. There appears to be no seasonality in the number of GDPs per month. Of late, the number of GDPs has increased starting October 2003. An evaluation of the number of GDP-hours reveals that the number of hours of GDP across the NAS in a month has increased. This is substantiated by the plot in Figure 5.3.

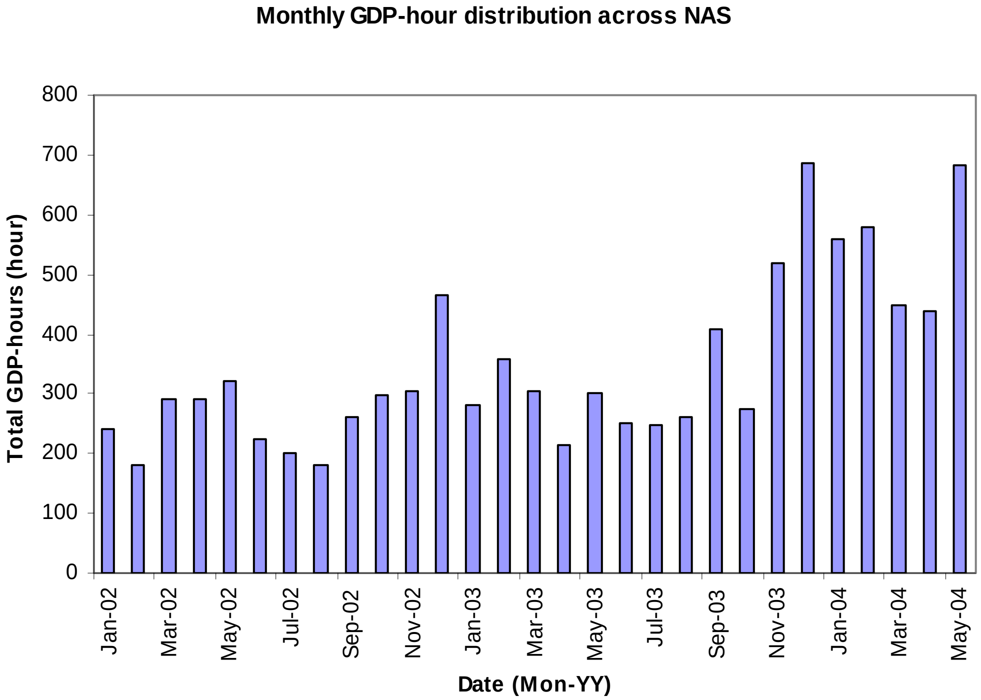

Figure 5.3: Monthly GDP-hour distribution across NAS

5.1.1 Trends in Compression

Preliminary investigation was conducted to understand the trends in compression. For the analysis, compression information from Jan 2002 to Feb 2004 was gathered. The plot in Figure 5.4 shows the time series plot of number of compressions per month across the National Airspace System (NAS) as well as that of the number of GDP- hours.

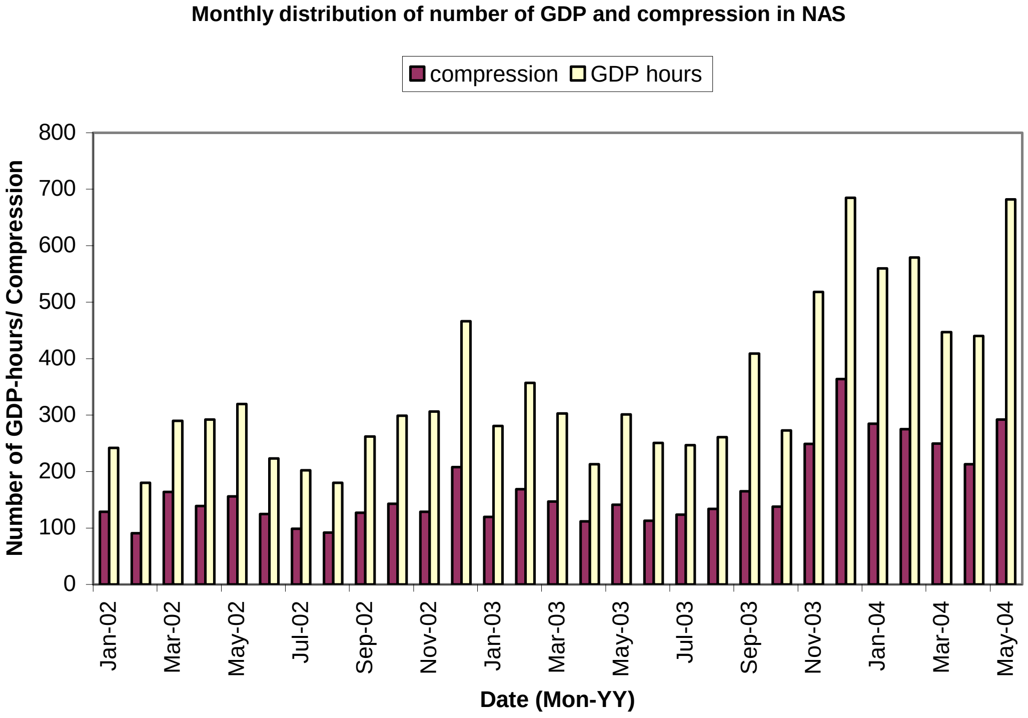

Figure 5.4: Monthly distribution of number of GDPs and compression in NAS

The number of compressions over time has not changed dramatically but has shown an increasing trend lately in the past few months peaking in December 2003. On closer inspection, we can see a direct correlation between increases in GDP-hours with the increase in compressions. The number of GDP-hours has increased through time. Regression analysis was conducted to understand the dependence of the number of compressions on the number of GDPs in a month. As observed (Figure 5.5), the dependence of the number of compressions on GDPs is high. The regression equation was found to be

Number of compressions = 5.05 + 0.47 * Number of GDP-hours

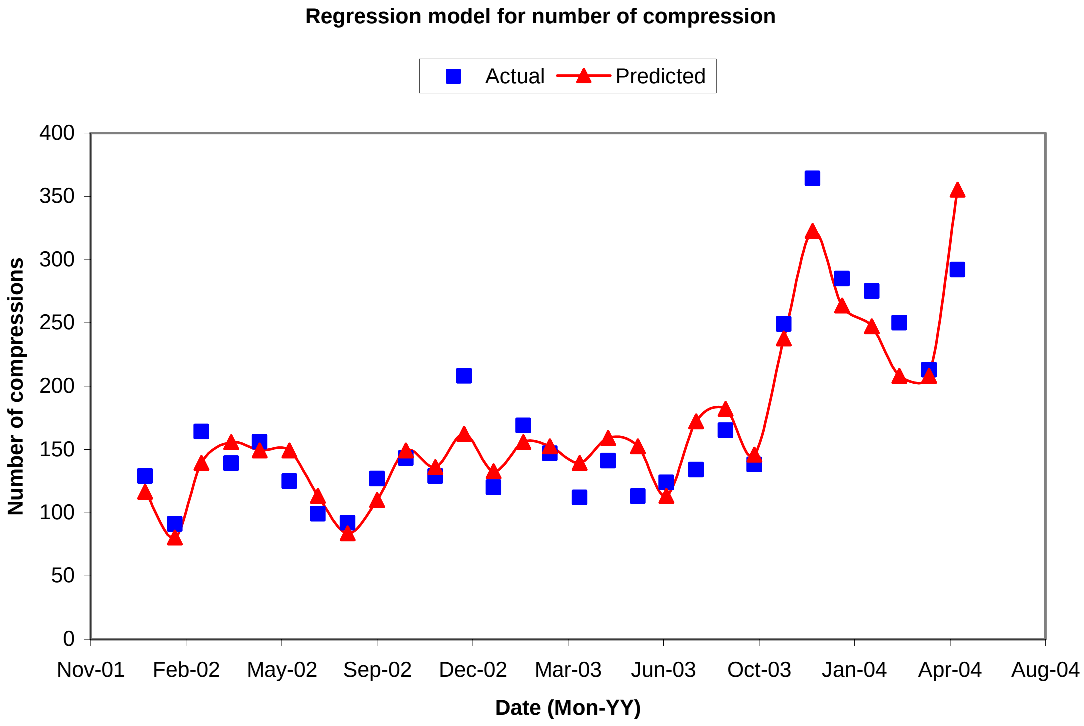

Figure 5.5: Regression model for number of compressions

The other analysis that was conducted was to understand the effect of length of GDP on number of compressions. Our evaluation of the trend showed the following result as shown in Figure 5.6. The number of compressions increases with the length of GDP but the increase is not proportional. On an average, the number of compression runs for a 4-hour GDP is close to 2 whereas the number of compressions run for a 10-hour GDP is close to 4. This implies that the ATCSCC does not run compression at regular intervals. As the length of GDP increases, the rate of increase in number of compressions declines. If compression had been initiated at regular intervals during a GDP then the increase in number of compressions per GDP-hour would have been higher. Analysis of compression information for the six airports did not show any significant difference from that of the NAS.

Figure 5.6: Distribution of average number of compressions with length of GDP

5.1.2 Trends in Slot Credit Substitution

Slot Credit Substitution was adopted throughout the NAS starting May 2003 as a dynamic slot exchange model. Time series analysis (Figure 5.7) of the number of SCS messages that were submitted with the ATCSCC shows an increase in messages received through time.

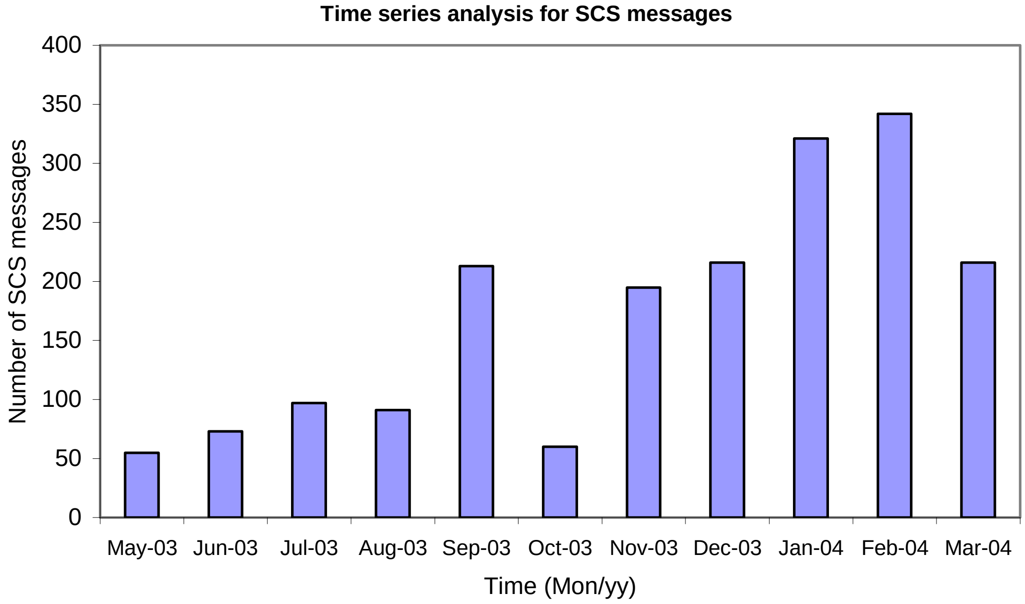

Figure 5.7: Monthly number of SCS messages across NAS

The increase in the number of SCS messages received by the ATCSCC can be attributable to the airlines getting comfortable with the internal mechanisms of SCS. Also, being a conditional slot-exchange mechanism, the airlines have been able to achieve positive delay savings from this procedure and so have gradually increased the adoption of SCS. From the graph it can also be concluded that SCS is still in its growth phase and has a lot of potential to grow through the years.

Similar increasing trends were observed at the six airports under consideration. The adoption rates of the airlines showed a gradual increasing trend. As seen in Figure 5.8, AirTran Airways (TRS) and Delta Airlines (DAL) are leading the rest of the major airlines in their adoption of SCS as a viable mechanism for delay reduction.

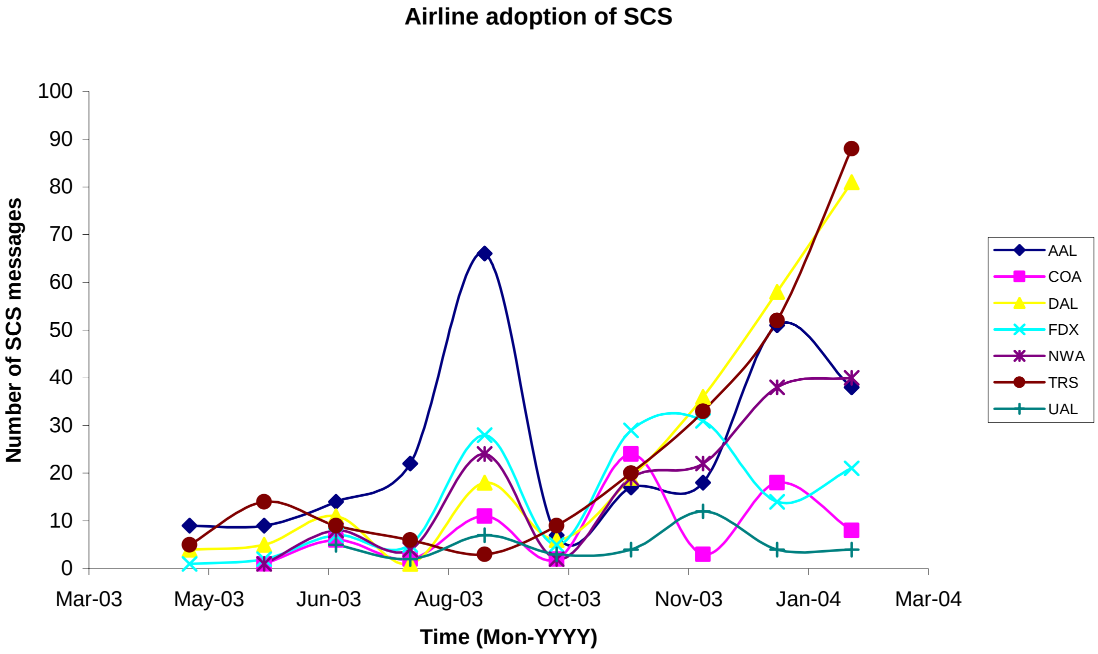

Figure 5.8: Airline adoption of SCS

An analysis of SCS messages from the airports (Figure 5.9) shows that ATL and ORD have had higher SCS submissions than other airports. ATL has shown increased SCS activity because of its being the hub for Delta Airlines which was shown in the earlier graph to be an early-adopter of SCS. The increased SCS activity at ORD can be attributed to the higher incidences of GDP at the airport, the higher volume of air traffic activity and its being the hub for some of the major airlines.

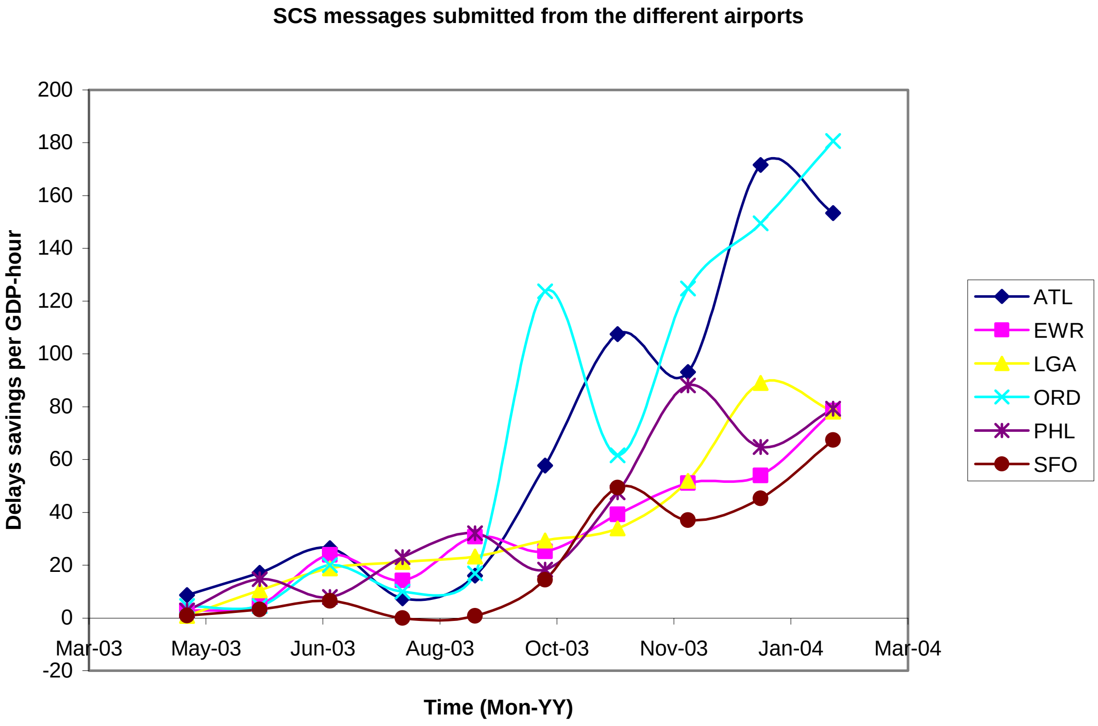

Figure 5.9: SCS message pattern submitted from the different airports

In the case of compression, the ATCSCC had been responsible for initiating this process with minimal changes required in the airline systems. Also, compression had been in place since the beginning of CDM. On the other hand, SCS is a highly collaborative approach to slot utilization and requires a higher involvement on the part of the airlines. The airlines need to have the necessary technology and the expertise to migrate to the SCS procedures. Due to the increased learning curve for the airlines, the adoption of SCS had been slow.

5.2 Metrics Development

To understand the benefits obtained from each of the two slot exchange schemes, appropriate metrics were developed. Different metrics were developed and evaluated to provide an objective baseline for comparison of benefits. Some of the terms that will be used throughout the development of the metrics have been defined as under.

Bridge flights – Bridge flights are the flights of airlines other than the airline that initiated the slot exchange process that are moved up their schedules. This movement of flights is necessary for the initiator airline to obtain a slot that it will be able to use for substitution.

Delay savings – This unit of measure is defined as the number of minutes of delay that have been reduced due to the upward movement of the flights through compression and SCS procedures.

5.2.1. Total delay savings

This metric is defined as the aggregation of minutes of delay reductions experienced due to either of the two slot exchange mechanisms. For an objective analysis of the savings, delay savings across a month was considered. Benefits obtained from compression will be the sum of all the delay reductions due to upward movement of flights into vacant slots when compression is initiated. SCS benefits were calculated considering the upward movement of the bridge flights. Compression has been in existence since 1998 when CDM was implemented, while SCS was implemented in 2003. Being a more mature, proven slot exchange scheme, the benefits achieved from compression are much higher than those from SCS substitution.

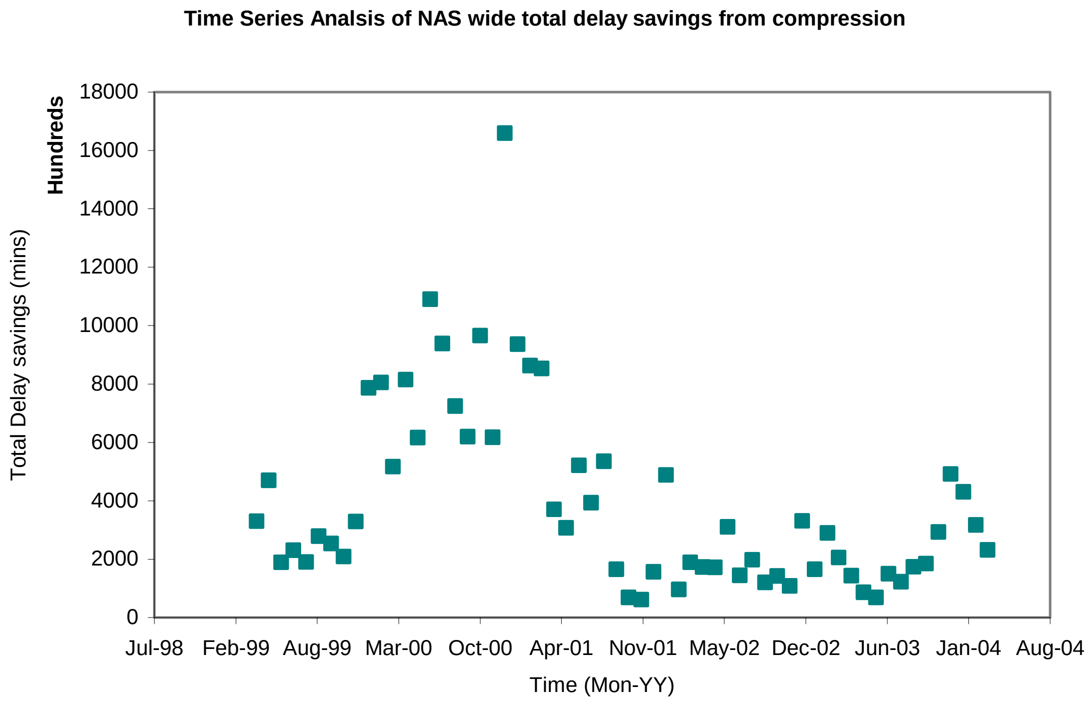

Figure 5.10: Time series analysis of total delay savings from compression

It is observed from Figure 5.10 that there had been a heady growth in delay savings achieved through compression in the early stages of its implementation from April 99 to July 2000. From July 2000 to May 2003, the total delay savings obtained from compression have shown a decline. This can be attributed to a lot of different factors including reduction in air traffic demand due to the terror strikes on September 11, 2001.

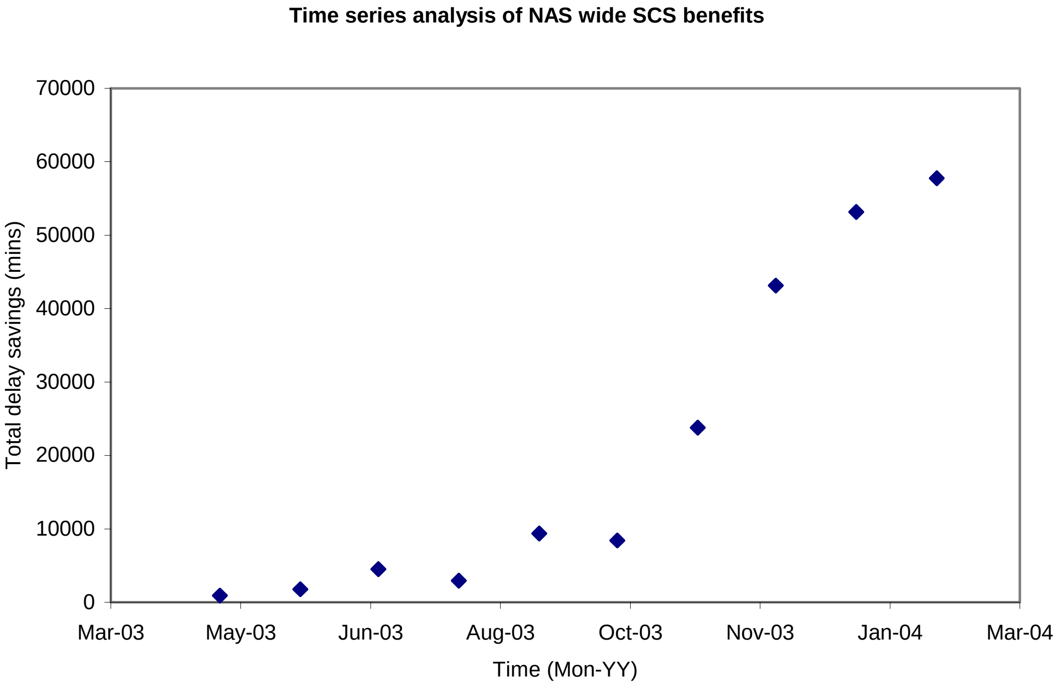

Figure 5.11: Time series analysis of total delay savings from SCS

The times series analysis of NAS wide SCS benefits (Figure 5.11) shows an increase in delay savings for the airlines. In the initial months of SCS, the benefits received by the airlines were low as the slot exchange requests submitted by the airlines were also low. The increased familiarity of the airlines with the technology and the process has led to increased SCS messages and delay savings.

Other means of normalizing the delay savings obtained from these procedures is considered. Delay savings are dependent on the number of GDPs and the number of GDP-hours. So, the savings obtained from these slot exchange schemes were normalized using number of GDPs and number of GDP-hours.

5.2.2 Delay savings per GDP

Another metric that is used to compare the benefits achieved from compression and SCS is delay savings per GDP. This metric for benefit evaluation is calculated by aggregating the monthly delay savings for the major NAS airports and dividing by the number of GDPs across NAS in that month.

Delay savings per GDP = (Total delay savings (min) / Number of GDPs)

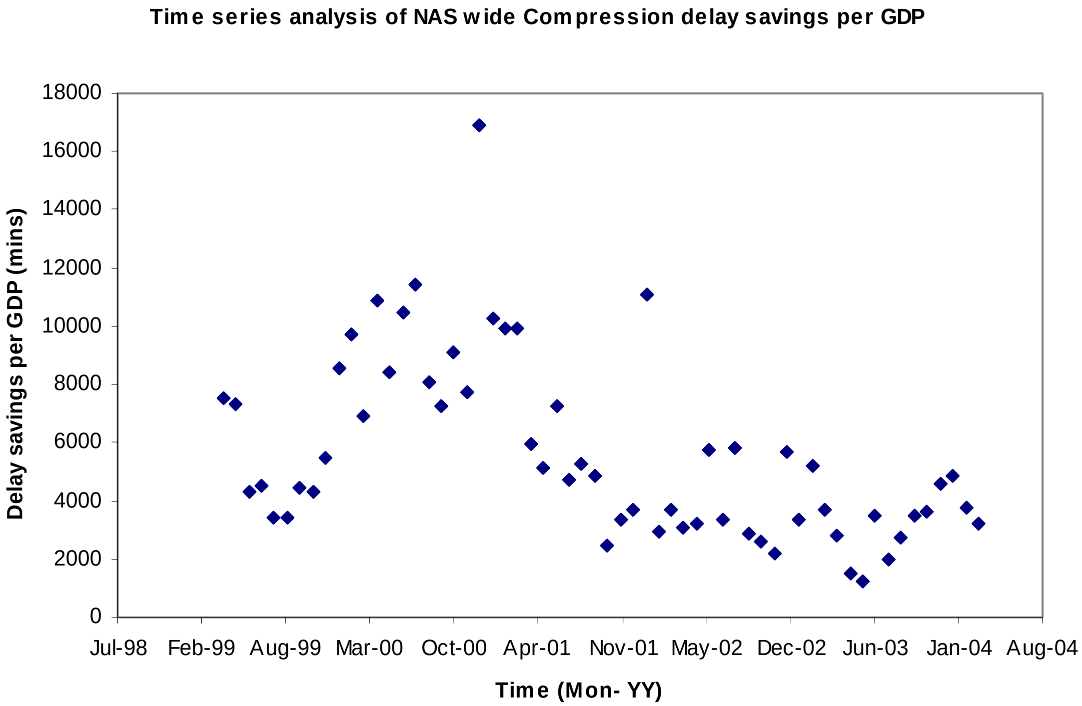

Figure 5.12: Time series analysis of compression delay savings per GDP

The time series analysis for compression delay savings shows the same pattern as in the case of the earlier metric using total delay savings. As seen in Figure 5.12, the increased savings between August 1999 and December 2000 using this metric is less pronounced than obtained from the total delay savings metric.

Similarly, the metric is used for calculation of benefits for Slot Credit Substitution (SCS). Again, this metric shows an increase in the benefits achieved from SCS. The following plot (Figure 5.13) shows the trend in benefits obtained from SCS using this metric.

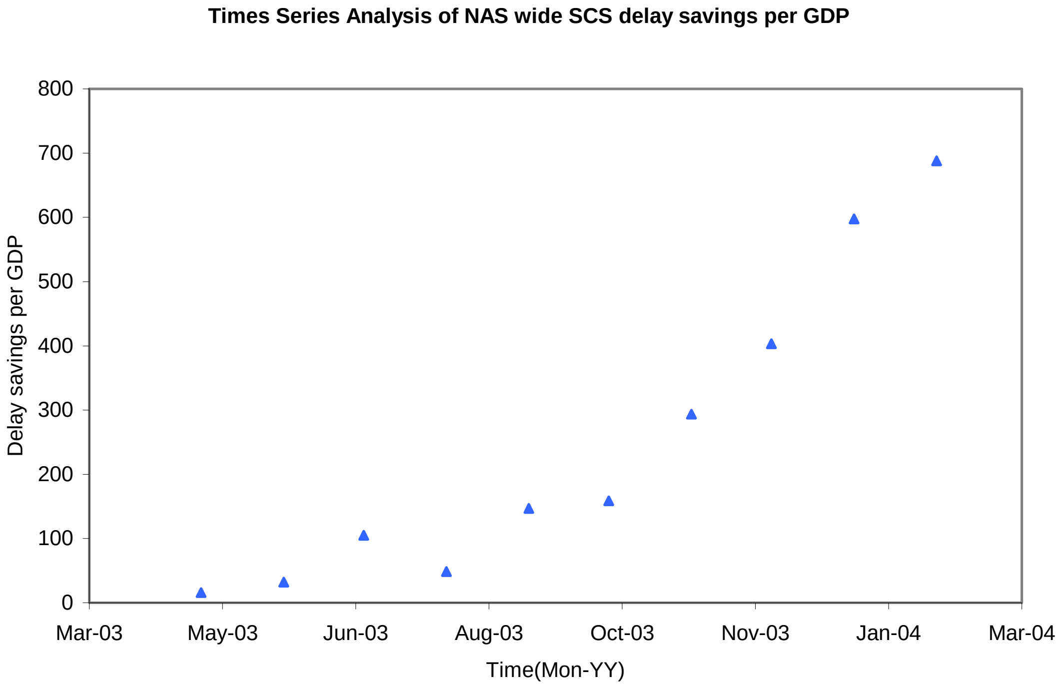

Figure 5.13: Time series analysis of delay savings per GDP from SCS

5.2.3 Delay savings per GDP-hour

This metric on delay savings per GDP-hour tries to create a standard for comparing the benefits achieved from SCS and compression. The metric of delay savings per GDP-hour over a month for the whole NAS is calculated using the following formula.

Delay savings per GDP-hour = Total delay savings / (Total number of GDPs *
Number of hours in a GDP)

In the case of compression, we see a gradual increase, a steady decline and again an increase in delay savings achieved per GDP-hour. One can also observe that the delay savings per GDP-hour from compression does not show a sharp increase and decline as was seen in the other two metrics discussed earlier. The trend is much smoother in this metric.

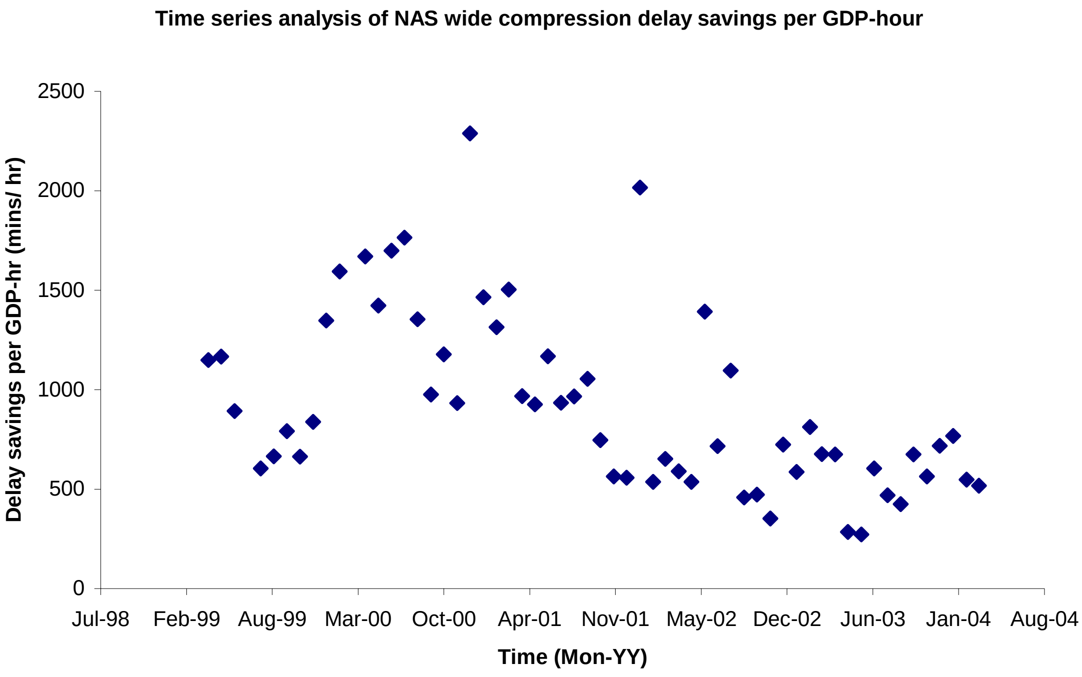

Figure 5.14: Time series analysis of delay savings per GDP-hour from Compression

When compression delay savings are aggregated over quarters (Figure 5.15), the trend line shows a smooth decrease in overall NAS savings and starting May 2003, when SCS was implemented in the NAS, compression benefits are on the rise.

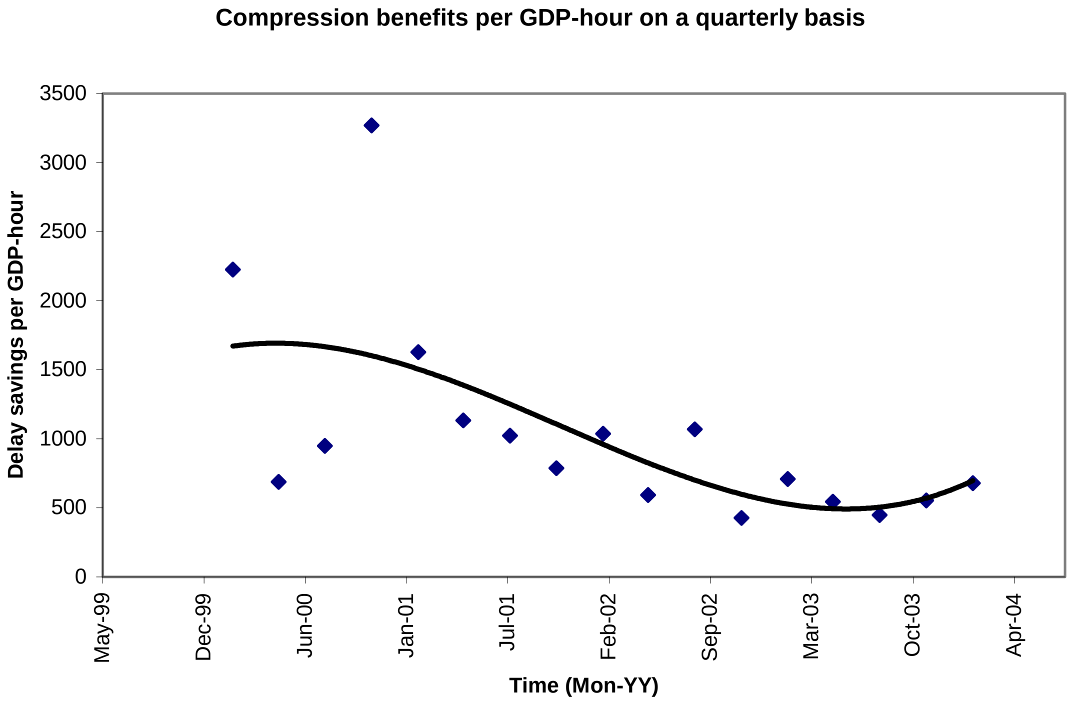

Figure 5.15: Quarterly distribution of delay savings per GDP-hour from Compression

Similarly, SCS provides an increase in delay savings per GDP-hour. As seen in the plot in Figure 5.16, SCS benefits have increased through the months. The increased delay savings is partly due to the increase in number of slot exchange requests submitted by the airlines and their willingness to submit accurate information about their cancellations. The additional benefit from this metric of delay savings per GDP-hour is that it creates a baseline for our benefits analysis from each of the slot exchange process.

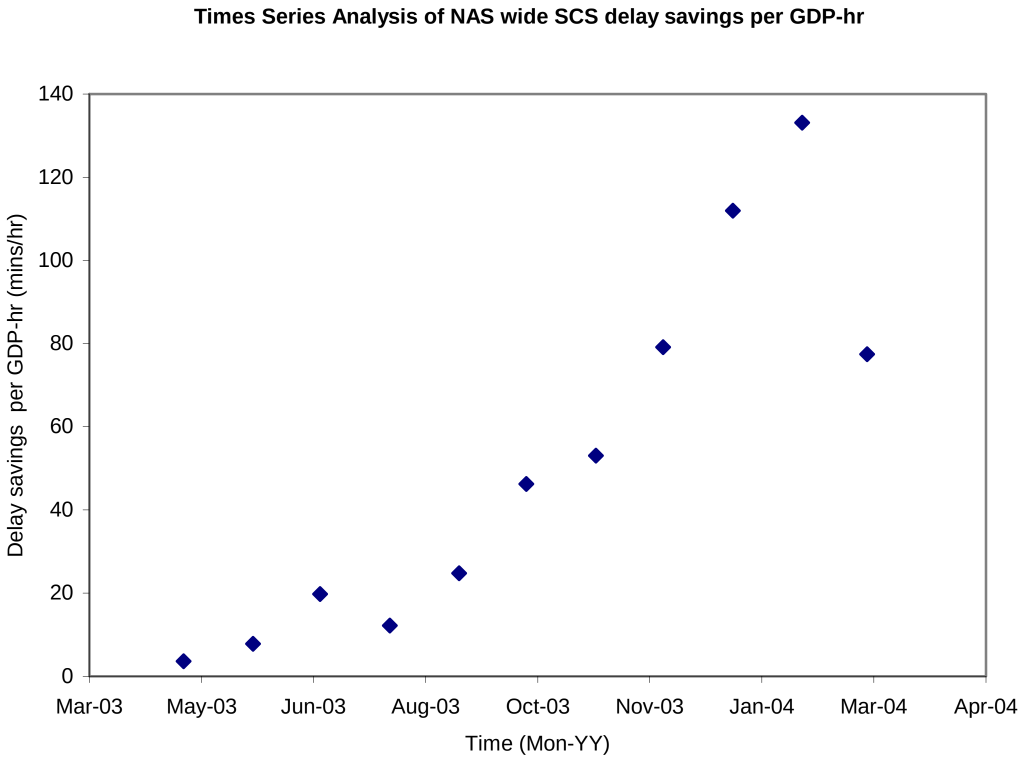

Figure 5.16: Time series analysis of delay savings per GDP-hour from SCS

The following graph (Figure 5.17) shows the delay savings obtained from compression and SCS from May 2003 when SCS was implemented across the NAS. A cross section of the benefits obtained starting from May 2003 shows the heady growth in delay savings experienced through both the slot exchange mechanisms. SCS is still in its early stages and so the benefits are much lower. From the graph we conclude that the benefits from compression have increased after the implementation of SCS.

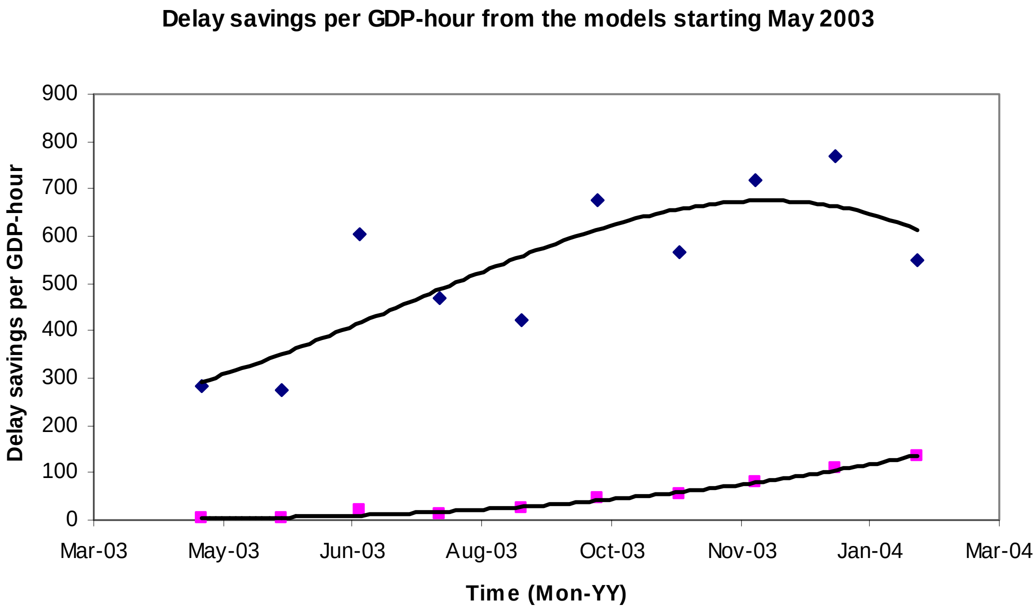

Figure 5.17: Delay savings per GDP-hour from Compression and SCS starting May 2003

To compare the delay reductions achieved through the two models, the benefits obtained from the models were superimposed on a single graph (Figure 5.18).

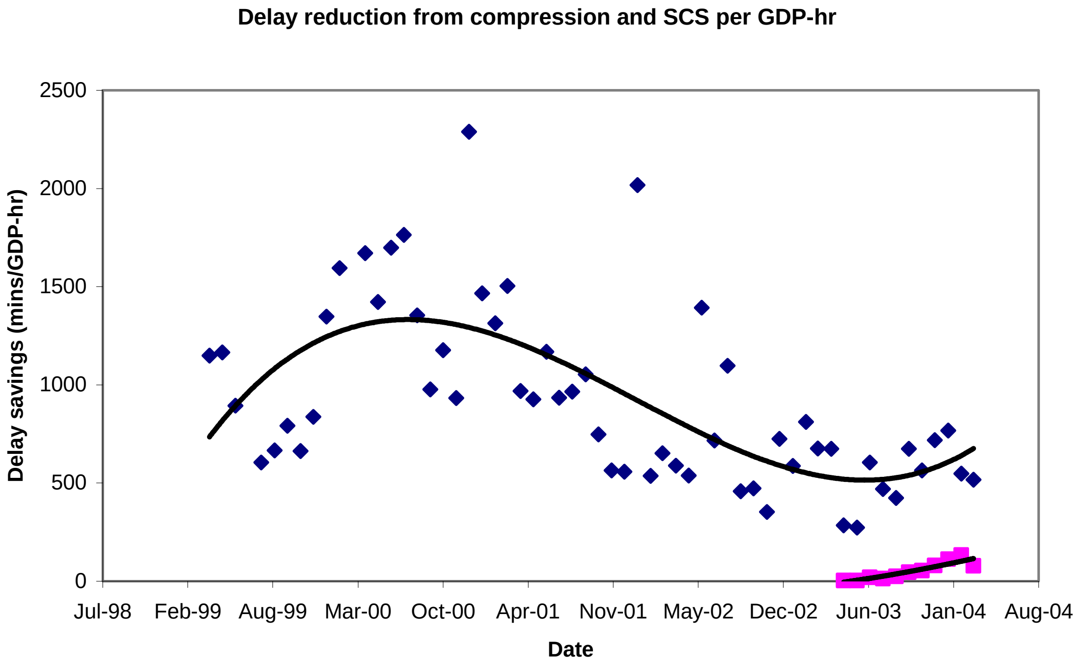

Figure 5.18: Delay savings per GDP-hour from Compression and SCS

As had been observed earlier, starting with the implementation of SCS across NAS, there had been a growth in the benefits achieved from compression.

To summarize, the benefits obtained from compression have improved after the implementation of SCS. SCS implementation is still in its infancy but is definitely bound to grow as airline adoption of the procedure increases.

Chapter 6: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusions

Each of the two slot exchange mechanisms has their inherent advantages and drawbacks. SCS is a dynamic, adaptive slot utilization technique where the onus of the slot exchange falls on the airlines. The airlines have increased maneuverability on choosing slots to forgo and slots that it will like to receive in return. This model allows the airlines to construct slot exchange schemes that boost the internal economics of the airlines. In case of compression, the ATCSCC bears the responsibility of running the process.

The implementation of SCS has increased airline adoption of SCS as a viable solution for delay savings. They are more willing to submit their cancellation information to the ATCSCC as they experience the benefits they obtain from this procedure. This has led to an increase in compression benefits. Compression and SCS complement each other in improving delay benefits. There is immense potential for the airlines to receive benefits from SCS and there will be heady growth in adoption of SCS in future.

6.2 Future research

One of the potential future research topics will be the evaluation of the benefits obtained by airlines through cascading benefits from SCS. Cascading benefit is defined as the benefits obtained by an airline through intra-airline substitution which has been made feasible through SCS. Once the airline that initiated the SCS process receives a slot that it will be able to use, it can conduct substitutions within its fleet of airlines. The benefits obtained through the SCS process as well as the cascading benefits can be considered the overall benefit achieved from SCS.

Two year down the line, these slot exchange procedures will be used by the airlines actively and regularly for reducing delays of their critical flights as well as enhancing their internal economics of operation. Further analysis on comparison and SCS benefits and trends will be an interesting topic for future research.

6.3 Future applications

The underlying philosophy behind these slot exchange paradigms can be applied to other aspects of air traffic management. Delays and resource utilization at the airports can be increased through adoption of these models in other areas of ATM. After closer inspection, we were able to determine the following areas for future applications

These procedures can be used for increased gate utilization at the heavily resource constrained airports. The gates can be considered similar to the arrival slots. There are instances when an airline might not be using the gate for its operations due to unforeseen circumstances such as repair and maintenance of the aircraft. In these cases, the airline will provide the FAA with information on its inability to use a gate and so that gate can be used for accommodating a flight that has just landed and is waiting on the tarmac for a gate. This reduces passenger delays as the passengers will be able to disembark at their scheduled times instead of accruing delays during taxi- in.

The SCS and compression procedures can be implemented at the gate personnel level. Sometimes, due to delays in loading passengers at the gates, the airline misses its departure slot and hence the arrival slot at the destination airport. In this case, it will be possible for the gate personnel to send a request for exchange of slots and thus the problem can be resolved effectively much earlier.

The underlying algorithms can be used by the ATCSSC in case a flight misses its EDCT time. Estimated Departure Clearance Time or EDCT time is issued to a flight to indicate when it can expect to receive departure clearance. EDCTs are issued as part of Traffic Management Programs, such as a Ground Delay Program (GDP). If an airline misses its EDCT time, it sends a message to the ATCSCC requesting another departure slot. The ATCSCC then attempts to create a substitution of flights for utilization of the unutilized slot.

There are a number of avenues where the concepts derived from these slot exchange models can be used for improved air traffic management and decision support. The air traffic management paradigms are shifting from static models to more dynamic, collaborative mechanisms. For optimized utilization of resources, there is increased collaboration between the Federal Aviation Administration and the airlines. A combination of batch optimization procedures with the collaborative models can provide improved benefits for all the NAS stakeholders.

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