NASA/TM–2015-218700

Benefits Assessment for Single-Airport Tactical Runway Configuration Management Tool (TRCM)

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March 2015

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Nomenclature

ASPM   =   Aviation System Performance Metrics

CADRS   =   Combined Arrival/Departure Runway Scheduling

DFW   =   Dallas-Fort Worth International Airport

FAA   =   Federal Aviation Administration

FD   =   Flow Direction

JFK   =   John F. Kennedy International Airport

JPDO   =   Joint Planning and Development Office

MEM   =   Memphis International Airport

MSE   =   Metroplex Simulation Environment

NAS   =   National Airspace System

NextGen   =   Next Generation Air Transportation System

RCM   =   Runway Configuration Management

RU   =   Runway Usage

SORM   =   System-Oriented Runway Management

SRCM   =   Strategic Runway Configuration Management

TRCM   =   Tactical Runway Configuration Management

Introduction

The System-Oriented Runway Management (SORM) concept was developed as part of the Airspace Systems Program (ASP) Concepts and Technology Development (CTD) Project, and is composed of two basic capabilities: Runway Configuration Management (RCM), and Combined Arrival/Departure Runway Scheduling (CADRS). RCM is the process of designating active runways, monitoring the active runway configuration for suitability given existing factors, and predicting future configuration changes; CADRS is the process of distributing arrivals and departures across active runways based on local airport and National Airspace System (NAS) goals.

The central component in the SORM concept is a tool for taking into account all the various factors and producing a recommendation for what would be the optimal runway configuration, runway use strategy, and aircraft sequence, considering as many of the relevant factors required in making this type of decision, and user preferences, if feasible. Three separate tools were initially envisioned for this research area, corresponding to the time scale in which they would operate: Strategic RCM (SRCM), with a planning horizon on the order of several hours, Tactical RCM (TRCM), with a planning horizon on the order of 90 minutes, and CADRS, with a planning horizon on the order of 15-30 minutes[1]. Algorithm development was initiated in all three of these areas, but the most fully-developed to date is the TRCM algorithm.

Earlier studies took a high-level approach to benefits, estimating aggregate benefits across most of the major airports in the National Airspace Systems (NAS), for both RCM and CADRS [2]. Other studies estimated the benefit of RCM and CADRS using various methods of re-sequencing arrivals to reduce delays[3,4], or better balancing of arrival fixes[5,6]. Additional studies looked at different methods for performing the optimization involved in selecting the best Runway Configuration Plan (RCP) to use[7-10].

Most of these previous studies were high-level or generic in nature (not focusing on specific airports), and benefits were aggregated for the entire NAS, with relatively low fidelity simulation of SORM functions and aircraft trajectories. For SORM research, a more detailed benefits assessment of RCM and CADRS for specific airports or metroplexes is needed.

Benefit mechanisms and metrics

Benefits that may be attributed to TRCM use include:

- Increased capacity due to better selection of configuration, runway use, and timing of configuration change
- More efficient ground and airborne operations due to better balancing of arrivals/departures among runways and fixes (increased throughput)
- Reduced delays due to reduced time in departure queues, more efficient route through TRACON airspace

These benefits would apply to the NAS level as well as for the individual aircraft or operator. For the airport operator, benefits result from being able to maintain a more predictable schedule, increased throughput (more flights per day, more passengers per day), and fewer delays. At the metroplex (or regional level), as well as at the NAS level, it is anticipated that benefits would be similar to those at the individual airport level. For this study, only benefits at a single airport are investigated.

To assess these benefits, the effect of the TRCM tool on other metrics can be measured, by comparing timing of flights achieved through conventional means (using historical data) versus what is achieved when using runway configuration plans from the TRCM tool. This could be measured as the amount of time it takes for a flight to transit a given amount of airspace (the transit time), and leads to other metrics such as delays and fuel used. In addition,

other metrics such as queue length and amount of airborne transit time vs transit time on the surface can be compared. It is important to note that, because the benefit is considered at the system level (i.e., not for individual flights), some flights might sustain a greater delay with the TRCM-generated schedule, if it results in a net benefit for the airport as a whole.

Objective of Study

The objective for this study is to conduct a benefits assessment using metrics related to the discussed benefit mechanisms, through simulations conducted with and without TRCM at specific airports, using the TRCM tool and specific airport adaptations.

The objective function of the TRCM tool seeks to minimize transit time, i.e. for arrivals, the amount of time required for a flight to transit from the arrival fix to the "spot" (the location on the airport surface between the movement area and non-movement area, where control is transferred from ground controllers to ramp controllers; ATC is responsible for all aircraft on the movement area); for departures the transit time is from the spot to the departure fix. The TRCM algorithm looks for the airport configuration that results in the shortest transit time for all flights in a particular time interval, thus transit time is the primary metric for the benefits assessment; other metrics are also considered. As a follow-up to the initial benefits assessment, a secondary analysis of underlying effects that contribute to the resulting benefits was also conducted, including sensitivity analysis on key parameters. Traffic data from the year 2009-2010 was used, so the resulting benefits are for current-day demand levels only.

Method of test

The test method consists of comparing results from simulations using the TRCM-generated runway configuration schedule, versus a baseline case; the baseline case consists of results from simulations using the historical runway configuration schedule. The historical information was obtained using the Federal Aviation Administration's (FAA) Aviation System Performance Metrics (ASPM) online database, accessible through the FAA's Operations and Performance Data website[11]. The same demand data were used for both the baseline and TRCM cases; this set of data consisted of twelve days of historical data from each of the airports studied. Further details of the TRCM tool, simulation tool, airport environments, and demand data are included in this section.

The software used for this study is sometimes referred to as SORM, but the particular function of interest for this study is the single-airport TRCM algorithm. Also included in the software package used for this study is the Metroplex Simulation Environment (MSE), which simulates aircraft operations resulting from using a given runway configuration schedule. Both of these programs were developed by Mosaic ATM under contract to NASA [Contract # NNL09AA02B]. The two parts of the software package are described here.

Figure 1 gives an overview of how the SORM software operates. The *SORM Manager* alternates the control between planning and execution cycles. During the planning cycle (labeled *Planning in TRCM*), it uses the TRCM algorithm with a low fidelity fast-time simulation to plan for the next 90 minutes. After each iteration of the planning cycle, the SORM software then operates in the execution cycle (the *Execution in MSE*) simulating the airborne and taxi routes for individual aircraft entirely using a higher fidelity simulation environment, called the Metroplex Simulation Environment (MSE). These alternating cycles continue until all flights under study are simulated.
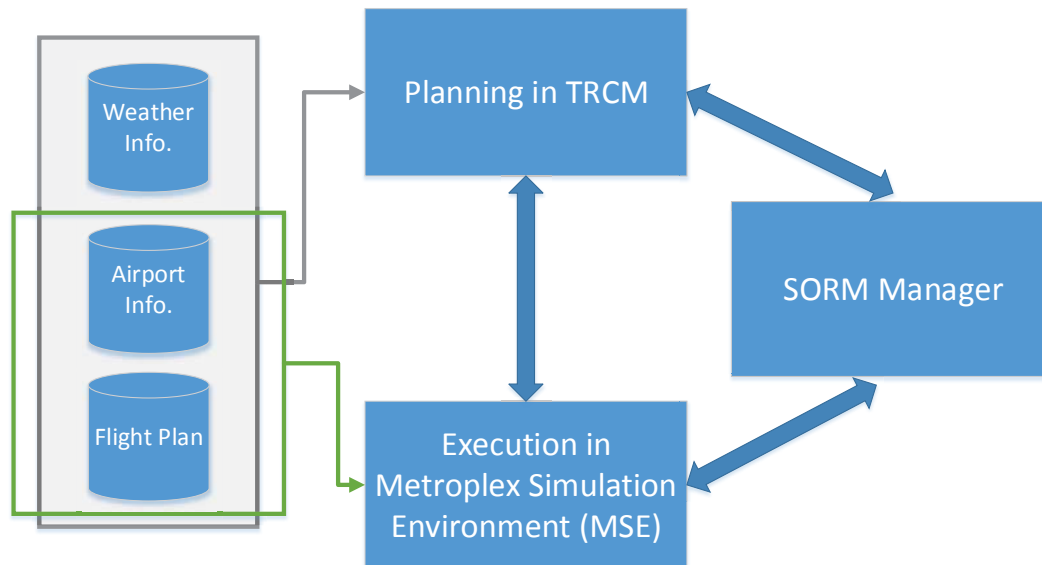
Figure 1. Overview of the current SORM software.

Tactical Runway Configuration Management

The TRCM algorithm takes as input a set of flights for a period of time (currently 90 minutes, but this parameter can be changed if needed), and produces a recommended runway configuration to use for a given time interval (currently 15 minutes); the recommended configuration is the one that results in lower overall transit times for the given airport and time period. In an operational environment these time intervals would be adjusted based on weather and traffic conditions or other factors unique to a given facility.

The current software requires three types of inputs, which are weather information, airport information, and flight plans. Weather information includes wind speed and wind direction. Airport information includes layout of terminals, spots, runways, arrival fixes, departure fixes, and their associated latitude and longitude coordinates, available runway configurations, and the current active runway configuration schedule. Flight plan includes flight ID, departure and destination airports, assigned departure or arrival fix, scheduled arrival time at fix, and scheduled departure time at gate.

The TRCM algorithm uses an enumerative search of all available runway configurations to find the one that minimizes the total transit time across all flights in the given time interval. During the enumerative search, the low fidelity simulation environment is used to calculate the total transit time (the objective value). The algorithm trades off the airborne, taxi, and queue (departing aircraft only) time durations in its search for the minimum total time. Transit time durations are computed using great circle distances for all airborne and taxi routes, along with their corresponding speeds. Wind speed and direction are taken into account to penalize runway configurations that should not be used during unfavorable wind conditions. This is accomplished by adding a penalty to the total transit time. The algorithm output provides: the optimum (minimum total transit time) runway configuration; the time at which the optimum configuration should be used; the first flight on the optimum configuration; and the last flight on the current configuration.

The TRCM software runs entirely within the MSE, which provides feedback on updated flight trajectories for use in the next planning cycle. The current algorithm, however, recommends a change from the current to the optimum configuration even if there is only a total transit time saving of as low as 1 second, or there is as few as one aircraft benefiting from the change. In an operational environment, this could result in excessive number of configuration changes, thus it is necessary to investigate if an additional parameter could be used to determine whether or not to recommend a configuration change.

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Metroplex Simulation Environment

The MSE is a self-contained platform for conducting fast-time simulation of many flights in a given airspace. For this study, the airspace consists of a particular airport environment, including the surface operations and flight between the runway and a given airborne fix. For arrivals, the fix is one of three or four waypoints used as part of the arrival route for arriving flights; for departures, there are numerous fixes that can be used, depending on the intended direction of flight after the aircraft departs the runway. The airport information, flight plan, and runway configuration determined in the most recent TRCM planning cycle are used as inputs to simulate the arrival and departure operations. The MSE includes details of the airport surface operations using node-link connections replicating the actual airport surface layout. It also incorporates aircraft-specific airborne and taxi speed profiles. The MSE records the status of flights, including all simulated flight routes and their time stamps at all predetermined surface nodes. Performance metrics can be post-processed and computed from the MSE flight's records. The current MSE does not take any wind information into account during the simulation of arrival and departure operations. Table 1 compares some of the features and scope of the low fidelity fast-time simulation used in the planning process and the higher fidelity MSE used for simulating operations.

Table 1. Comparison of TRCM (low fidelity) and MSE simulations

Features	Low fidelity planning simulation	Higher fidelity MSE
Usage phase of the software	Determine the optimum runway schedule (planning).	Execute the recommended optimum runway schedule (executing) and records all flight's status for the next planning iteration, and for metric post-processing.
Assumptions	1. Weather (wind) information is used to penalize configurations that are not operable under the certain weather conditions.	1. No weather (wind) information is used during the simulation of the arrival and departure operations.
	2. No runway crossing constraint.	2. Actual runway crossing constraints are simulated.
	3. A predefined constant for taxi speed for all aircraft.	3. Aircraft-specific taxi-speed profiles.
	4. A predefined constant for airborne speed for all aircraft.	4. Aircraft-specific airborne-speed profiles.

Airport Environments

The three airport environments used for this study are Memphis International Airport (MEM), John F. Kennedy International Airport (JFK), and Dallas-Ft. Worth International Airport (DFW); these are depicted by the airport diagrams shown in Figure 2. MEM was selected to provide the SORM research team with data for comparison for a planned field evaluation of TRCM; JFK was used because it had previously been identified as the primary airport of interest for SORM studies; DFW was chosen due to its higher traffic volume and more complex ground operations.

MEM (Figure 2a) has three parallel runways in a North/South orientation (18R/36L, 18C/36C, and 18L/36R) and one East/West runway (9/27) on the north side of the airport. JFK (Figure 2b) has two sets of parallel runways, one set in a Northwest/Southeast orientation (13R/31L and 13L/31R), and the other in a Northeast/Southwest orientation (4L/22R and 4R/22L). DFW (Figure 2c) has five parallel runways in a North/South orientation (18R/36L, 18L/36R, 17R/35L, 17C/35C, and 17L/35R), and two parallel runways in a Northwest/Southeast orientation (13R/31L and 13L/31R). Runway configurations evaluated in this study were the most frequently used, based on historical data

from ASPM. For this study, there were four different (unique) combinations of runway usage identified for inclusion in the evaluation for MEM, 10 combinations at DFW, and 20 combinations at JFK. Note that this does not represent all the possible combinations in which the runways could be used at each of these facilities; however they represent the configurations most commonly used at these facilities.
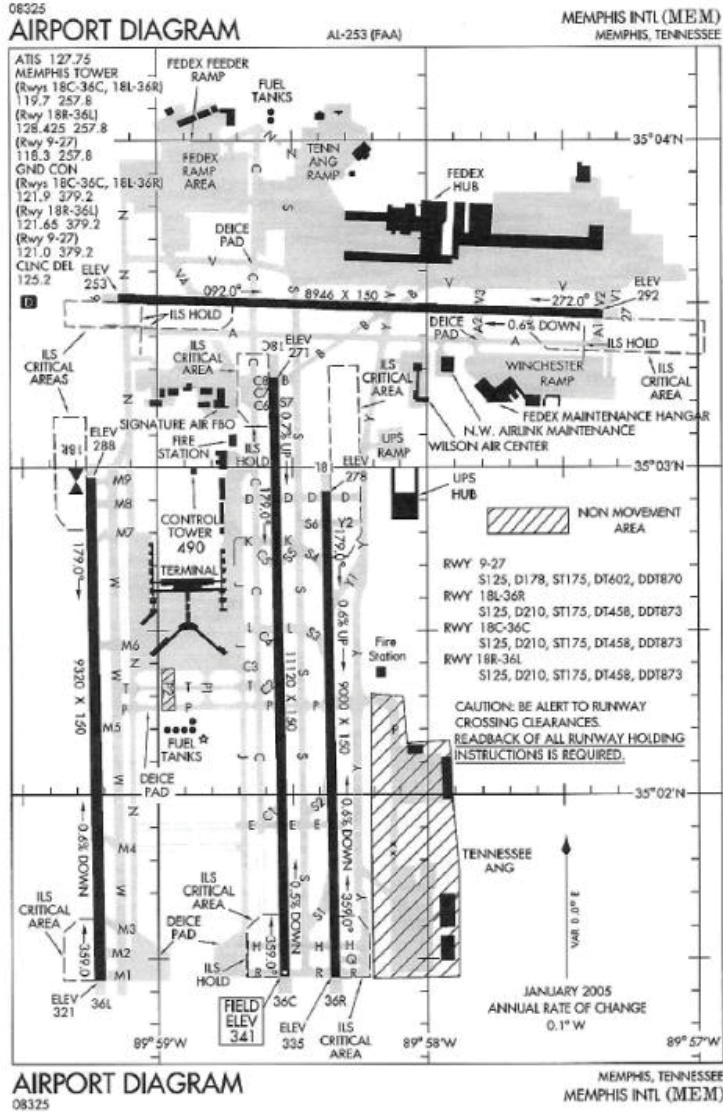
a) Memphis International airport (MEM)
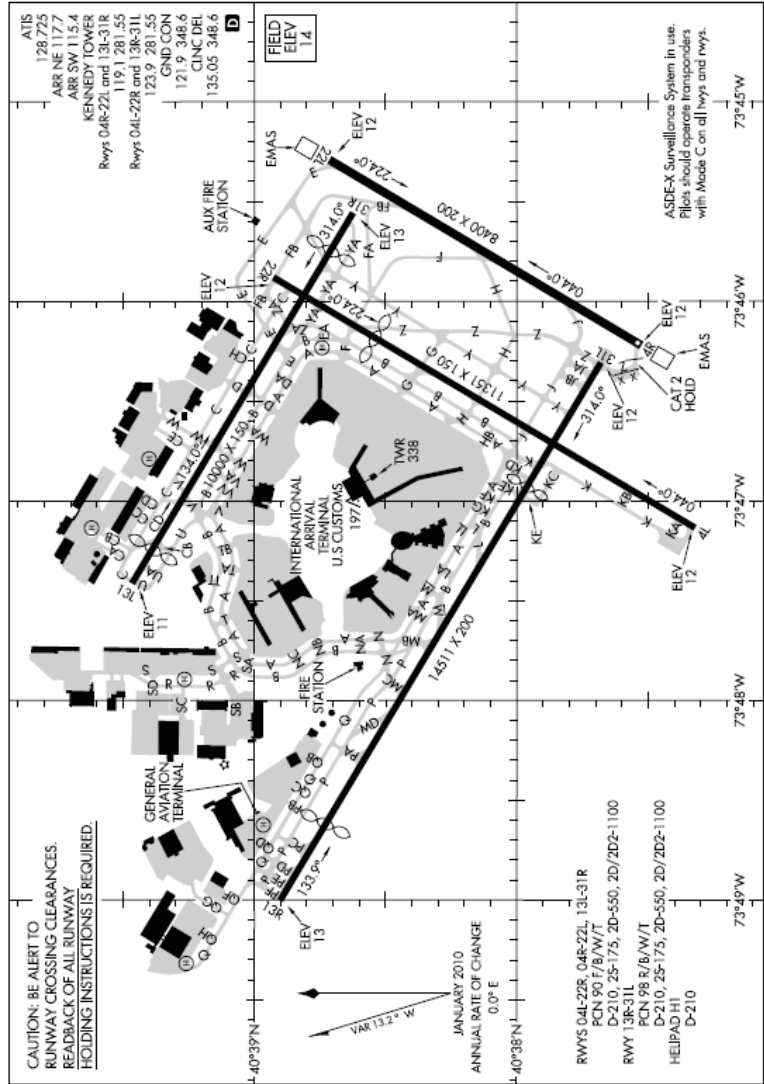
b) New York / John F. Kennedy International airport (JFK)
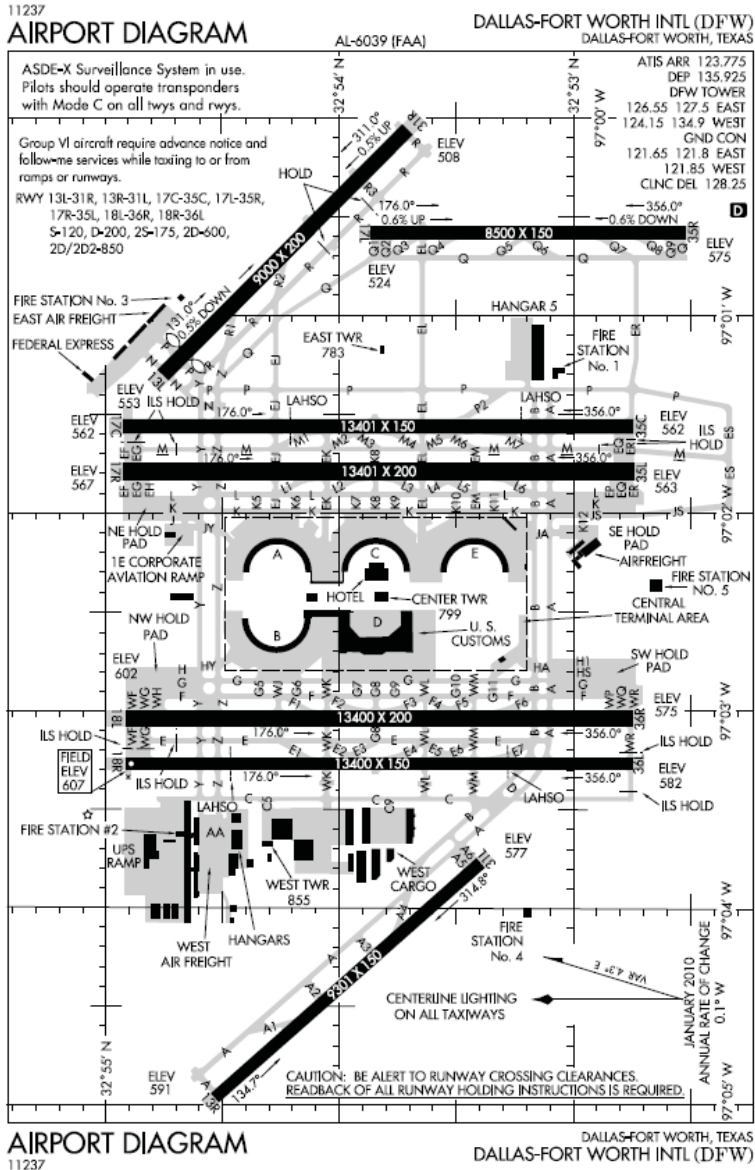
c) Dallas-Ft. Worth International airport (DFW)

Figure 2. Airport Diagrams for (a) Memphis, (b) New York / John F. Kennedy, and (c) Dallas-Ft. Worth airports, respectively (image courtesy of FAA)

Demand Data

A range of conditions for test runs is needed in order to cover some of the primary factors that could affect the resulting benefits. The demand data used for this study comprised a set of historical data that covers the period of Fiscal Year 2010 (October 1, 2009 through September 30, 2010), which was adopted and recommended by the Joint Planning and Development Office (JPDO) for NextGen research. These days were identified by the FAA as capturing trends in seasonal variations in aviation performance in the NAS for that year, using a method developed to minimize differences in predicted and actual levels of desired performance metrics at the daily level[12]. Simulation

runs conducted using historical configurations are considered the Baseline cases, and those using the TRCM-generated configurations are called TRCM runs; for each data file (each day), results from the TRCM run were compared with the corresponding Baseline case to assess the benefits.

The set of days from which the data were obtained are listed in Table 2, along with the number of operations that took place at each of the three airports. Note that the number of operations is less than what would be obtained from a query of ASPM, because the full set of operations is pared down to remove unscheduled flights that are not relevant (such as general aviation and military flights), and other flights with invalid data, and to adjust for different time zones in order to obtain a 24-hour sample. However, the resulting demand data, although less than the full ASPM number, still reflects the relative levels of demand – i.e., which days had higher demand than others, in proper proportions.

Table 2. Dates for historical data used for analysis.

Index Number	Date	Week Day	MEM		JFK		DFW	
			Dep	Arr	Dep	Arr	Dep	Arr
1	10/6/2009	Tuesday	468	500	480	428	756	779
2	10/17/2009	Saturday	300	314	502	449	721	738
3	11/20/2009	Friday	455	535	545	528	851	862
4	1/10/2010	Sunday	343	307	520	507	824	820
5	3/9/2010	Tuesday	461	534	515	503	865	852
6	3/25/2010	Thursday	492	549	555	527	869	863
7	5/6/2010	Thursday	494	556	536	491	882	884
8	5/18/2010	Tuesday	490	542	515	485	873	875
9	6/5/2010	Saturday	309	326	529	480	756	767
10	7/3/2010	Saturday	338	350	561	525	756	770
11	7/13/2010	Tuesday	494	556	521	495	878	881
12	7/22/2010	Thursday	501	554	593	565	903	904

For the twelve sample days used, the day with the highest demand level was July 22, 2010 for all three airports; the day with the lowest demand level was October 17, 2009 for both MEM and DFW, but for JFK it was October 6, 2009. The ratio of low to high demand varied greatly for the three airports; for JFK, demand on the lowest day was 77% of demand on the highest day; for DFW the lowest day was 82% of the highest; for MEM the lowest was 58% of the highest. The large variation in demand levels for MEM can be attributed to the fact that FedEx is the largest airline operating at MEM, sometimes comprising over 40% of the day's traffic; on days when there are not many FedEx flights (usually Friday and Saturday nights), the volume of traffic drops dramatically. For the days that follow (Saturday and Sunday), demand was often under 65% of the maximum value. This unique profile of traffic demand can have a significant effect on benefits.

Historic traffic demand for the entire year obtained from ASPM also showed very different profiles for the three airports. Daily demand for MEM was consistently at either of two levels, averaging around 800 operations per day when there were no FedEx flights, and 1100 operations per day when FedEx had their normal level of operations. At JFK for the year traffic was generally in the range of 1000-2000 operations per day, with most days between 1000-1500 operations, and an observable seasonal variation (lower in winter months, higher in summer months). DFW demand was more consistent, with demand levels between 1500-2000 operations for 10 of the 12 days (the remainder were scattered on the higher side).

Results and Discussion

The major parameters used for characterizing benefits are: transit time, departure queue length, fuel use, and throughput. An additional parameter that is considered important from a user interface standpoint is the runway configuration schedule that is generated by TRCM; of particular interest are the type and number of changes in runway configuration that are recommended. Each of these parameters is examined separately in this section. Additionally, a sensitivity study was conducted on the parameters of interest, with respect to the effect of changes in the number of configuration changes conducted per day; this analysis is also presented.

Transit Time

Figure 3 shows the difference in average transit times for all days at the three airports, separated by arrivals and departures. The differences were computed as Baseline minus TRCM, thus a bar above the zero-line represents a benefit; bars that extend below the zero-line indicate a negative benefit, or penalty.

Upon inspection, it can be seen that most of the bars for MEM are above the zero-line, indicating a transit time benefit for arrivals and departures at MEM; for many days this benefit was substantially over one minute, especially for the departures. The average transit time benefit for MEM for these twelve days was 33.8s for arrivals and 95.8s for departures.

For JFK the arrivals also showed reduced transit times for most of the days (average of 147.4s); however the departures were distributed both above and below, with a net negative (-18.1s) for the twelve days. For DFW the results were somewhat less clear. For most of the days the arrivals showed a positive benefit (average for arrivals was 20.5s), but the average for departures was lower, but still positive (3.2s), also indicating a priority for arrivals over departures. The net average (combining arrivals and departures) over the twelve days was positive for all three airports, although substantially less so for DFW than for the other two. These results are summarized in Table 3.

For MEM departures, the benefit was almost three times that for arrivals – in large part due to the shortened taxi time required for aircraft that are located at the north end of the runways, which consists almost entirely of FedEx aircraft, when the flow direction is changed to South Flow. It is important to note that the baseline for this is from historic data, which may not be entirely accurate with regards to what configuration was actually used, especially for short periods of time during the night. Subject matter experts that were consulted on this question indicated that, most likely the flow direction would have been changed more often than what was reflected in the ASPM database. Thus, it is very possible that the flow direction was changed (winds and other factors allowing), but the change was not reflected in the ASPM database; this would mean that the Baseline case would have many more flights with shorter taxi times than what was simulated based on ASPM data, and computed transit time benefits could be lower than what is shown in the table.

For JFK, the transit time benefit is much greater for arrivals than departures; departures usually do not have as much variation in their flight path, thus there is less opportunity for it to be shortened to improve the transit time. For arrivals, however, a more favorable runway configuration could greatly reduce the flight part of the transit time, which is proportionally greater than the surface transit time for arrivals.This would very likely be the case at most airports. At MEM, the high concentration of FedEx flights affects not only the magnitude of the benefit, but also where the benefit is realized – in the case of FedEx, a shorter taxi time would result in a much greater overall benefit for departures, because a significant proportion of daily operations are FedEx flights. During three different periods on most days, FedEx departures are coordinated to occur one immediately after another. Because they all originate from the FedEx location on the north side of the airport, they would all benefit from shorter taxi times due to a more favorable runway configuration. In contrast the arrivals are more scattered and often arrive from different directions, so the benefit is not as concentrated; however, there are periods (such as early morning) where an arrival stream would also benefit from timely runway configuration changes.
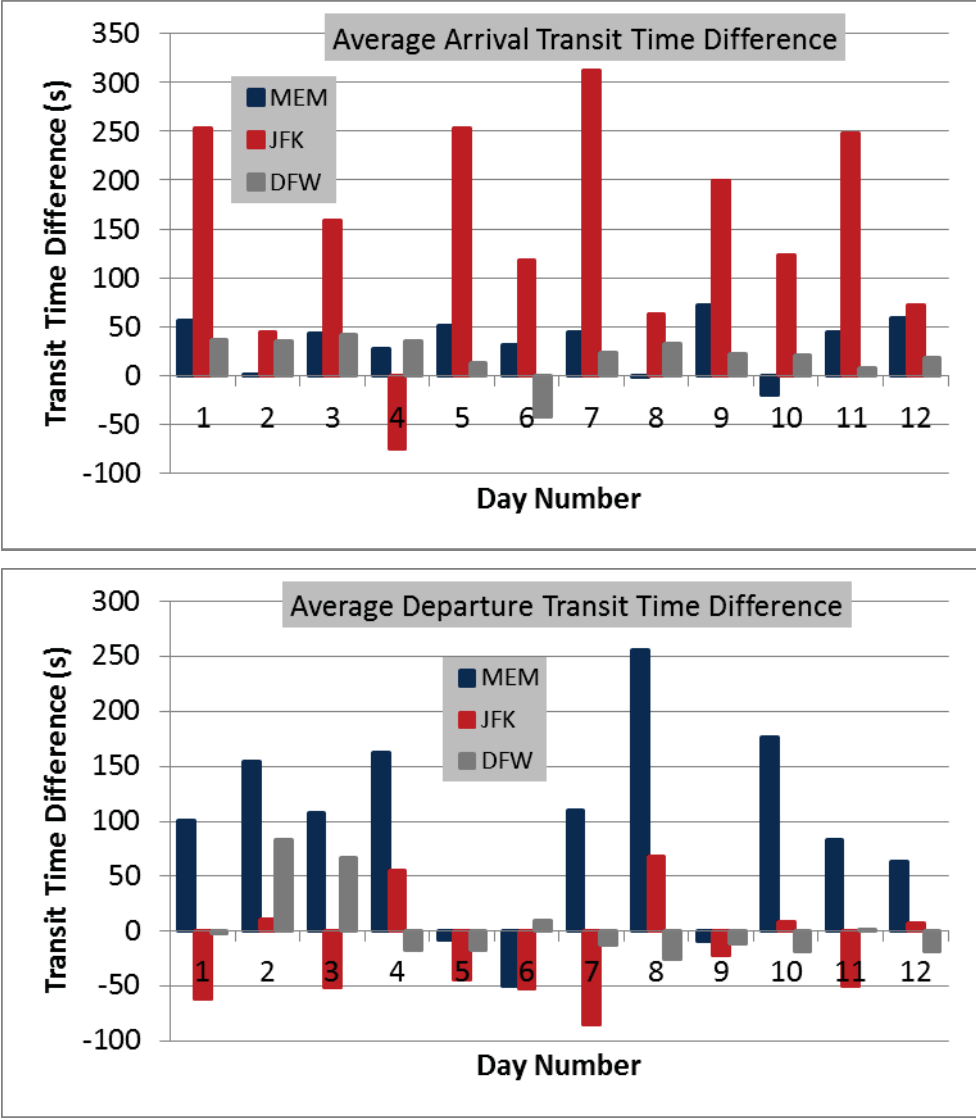
Figure 3. Mean transit time benefit (Baseline-TRCM), arrivals and departures, all airports and days

At DFW, the mixed results could indicate that the TRCM algorithm requires modification to accommodate the more complex surface traffic operations. Specifically, the runway layout and terminal locations require many aircraft to cross runways during their ground movements. Although the computed transit time includes surface operations and the objective function of the TRCM algorithm seeks to minimize transit time, it is possible that the time required for surface operations is not adequately taken into account during the planning phase of the TRCM tool, in particular the time required to wait when crossing an active runway. This is likely due to the lower-fidelity estimate of transit time that is used by the TRCM algorithm to determine whether or not a given runway configuration would provide more benefit than the existing one. If the TRCM planning estimate does not take into account runway crossings, this could result in a much longer actual transit time during the simulation phase. A way of correcting this could be by adding a penalty to the transit time estimate used in the planning phase when multiple crossings of active runways are required, such that it would make a change in flow direction less beneficial if it resulted in an increase in the number of runway crossings over an existing configuration. In none of these cases do the transit time benefits appear to be connected to variations in demand levels. In particular at MEM, where low-demand days are approximately 40% lower than high-demand days, there does not seem to be a relationship to transit time benefit.

Table 3. Average reduction in mean transit time (baseline minus TRCM) overall all days

Airport	Arrivals Transit Time Reduction (s)	Departures Transit Time Reduction (s)
MEM	33.8 (2.1%)	95.8 (7.2%)
JFK	147.4 (8.4%)	-18.1 (-1.5%)
DFW	20.5 (1.3%)	3.2 (0.3%)

Understanding how these benefits were distributed on a day-by-day basis can provide further insight into these results; this is shown in the figures below. Figure 4 shows the percent (over baseline case) average transit time benefit separately for arrivals and departures for each of the twelve days. On days when the arrival benefit was low (less than 2%) or negative, the departure benefit was high (greater than 10%). On most of the other days, a similar trend was seen, although not as extreme – i.e., a day with an arrival benefit lower than the overall mean for arrivals usually had a departure benefit that was higher than the overall mean for departures, and vice versa. This indicates that there is a trade-off of benefits, rather than an even distribution; on most of the days studied, the departures at MEM benefited more than arrivals, on two days (#5 and #9) arrivals benefited more than departures, and on only one day (#12) were the benefits close to evenly shared. This supports the overall results that showed a greater benefit for departures than for arrivals at MEM.
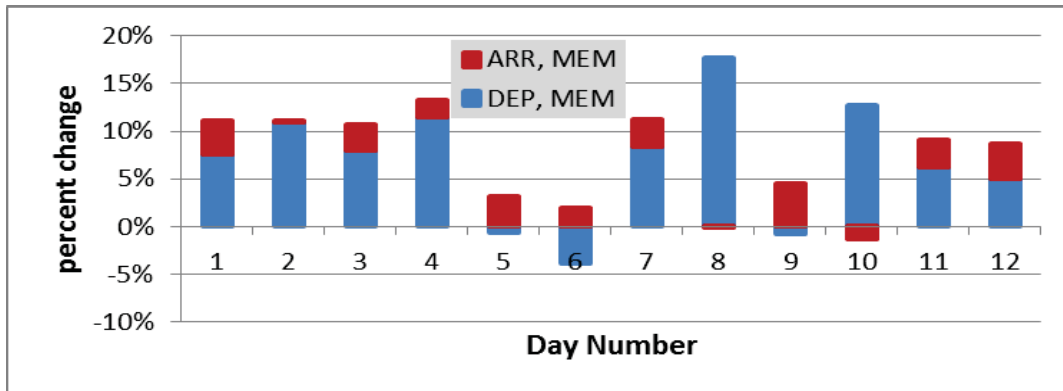
Figure 4. Daily percent benefit (over baseline) at MEM

A similar trend is seen at JFK (Figure 5) as at MEM, but reversed for arrivals and departures; i.e., on the days where the arrival benefit was considerably higher (greater than 10%), the departure benefit was lower than its overall mean, in most of those cases a penalty (negative benefit). On one day (#8) the percent benefit is more evenly shared; for a single day (#4) there was a benefit for departures and penalty for arrivals. This supports the overall results that showed a greater benefit for arrivals than for departures at JFK.
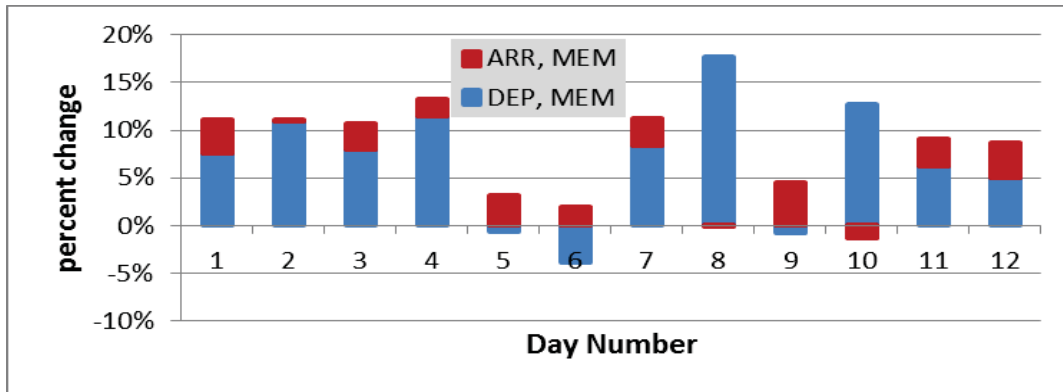
Figure 5. Daily percent benefit (over baseline) at JFK

At DFW (Figure 6) the daily benefits are more evenly split between arrivals and departures, although there are two days (#2 and #3) where the departures benefited considerably more than the arrivals, and one day (#1) where arrivals benefited considerably more than departures. On all but one day (#6), arrivals had a positive benefit, although not very large (most days it was around 2% or less); there were two days (#2 and #3) with substantial departure benefits, but most of the rest of the days had a penalty. This would indicate that, for the days studied at DFW, there was a relatively small but fairly consistent benefit to arrivals, and a smaller, but also consistent, penalty to departures.
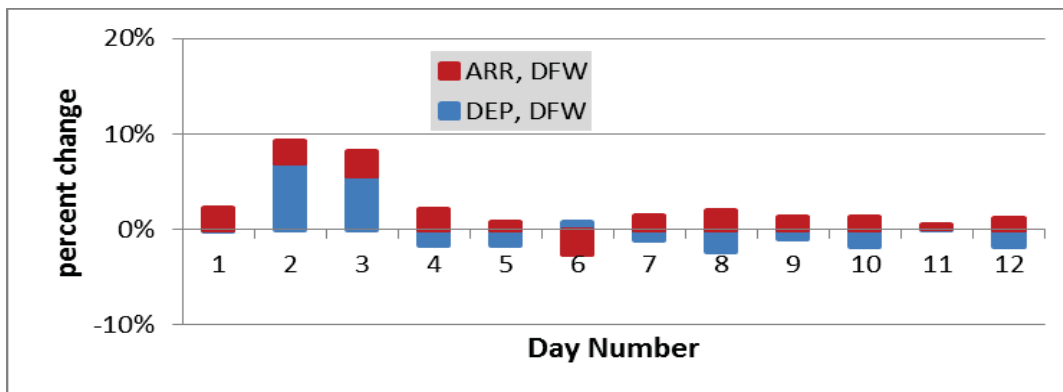
Figure 6. Daily percent benefit (over baseline) at DFW

It is also helpful to understand what contributed to some of these results, by breaking down the transit time benefits to examine the airborne and surface contributions. Figure 7 shows the total transit time benefit (for all days) for each of the three airports, broken down into flight and taxi segments. The flight segment includes time between wheels-off the runway and the departure fix (for departures), or between the arrival fix and wheels-on the runway (for arrivals). The taxi segment includes time between the spot and wheels-off (for departures) and between wheels-on and the spot (for arrivals). Thus any additional stops on the surface would be contained in the "taxi time" bars on these plots.

The figure shows that at MEM there were benefits on both the surface and airborne segments for both arrivals and departures, with the greatest contribution from taxi time for departures. For JFK, the largest contribution for arrivals came from flight time, but there was also a substantial contribution from taxi time; for JFK departures, the substantial deduction from departure taxi operations more than offset the benefit from departure flight time. For DFW, the arrivals had a substantial benefit during flight time, with a small offset during taxi operations; for DFW departures, the benefit was very small from both flight and taxi operations.

Overall, these results indicate that TRCM provides a benefit to arrivals in most cases, and less of a benefit to departures. In the case of MEM, the large benefit to departures is related to the unique nature of operations there, where large numbers of flights depart during a short period of time when the FedEx flights depart during early-morning hours. In this case, a configuration that benefits FedEx departures (departing to the south) would substantially reduce taxi time, resulting in a much higher taxi time benefit for departures than could be achievable for other airports that do not have this type of operation. Also observed for all the airports is that the flight time benefit is generally higher for arrivals than for departures, is because arrivals spend more time in flight than departures, both in actual time and as a percent of transit time (the flight time would contribute more to computation of transit time benefit).
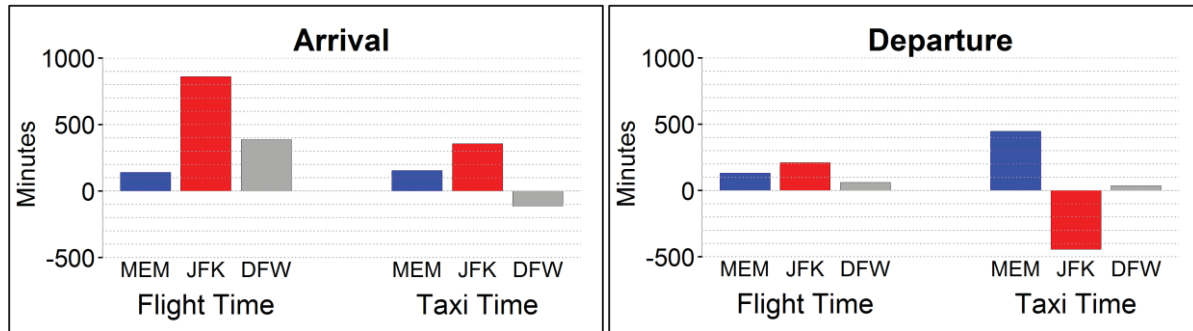

Figure 7. Flight and surface transit time benefit contributions for MEM, JFK, and DFW

During some of the runs, there were a few arrivals that took excessively long paths while taxiing back to gate, or that remained fixed on a spot for no apparent reason; this indicates that there are problems with the ground simulation logic which probably contributed to the resulting penalty. This, as well as the cause for the large penalty in departure taxi times for JFK, needs to be inspected more carefully and any existing problems resolved prior to conducting additional simulations. However, it highlights the importance of having accurate modeling of both flight and surface operations.

Inspection of transit time benefits on a day-by-day basis can provide insight, and is shown in the next sections separately for each airport. In each of these sections, the transit time benefits are further broken down to observe how the mean Baseline transit times differed from mean TRCM times on a daily basis, and how the contributions from flight and surface operations affected the benefits separately for arrivals and departures, as reported in Figure 7 above. This is shown in the following sets of figures.

Memphis International Airport (MEM)

Figure 8 shows the breakdown for MEM. The flight segment includes time between wheels-off the runway and the departure fix (for departures), or between the arrival fix and wheels-on the runway (for arrivals). The surface segment includes time between the spot and wheels-off (for departures) and between wheels-on and the spot (for arrivals). In the figure, A refers to arrivals and D refers to departures. Thus any stops during taxiing would be contained in the "surface" bars on these plots.
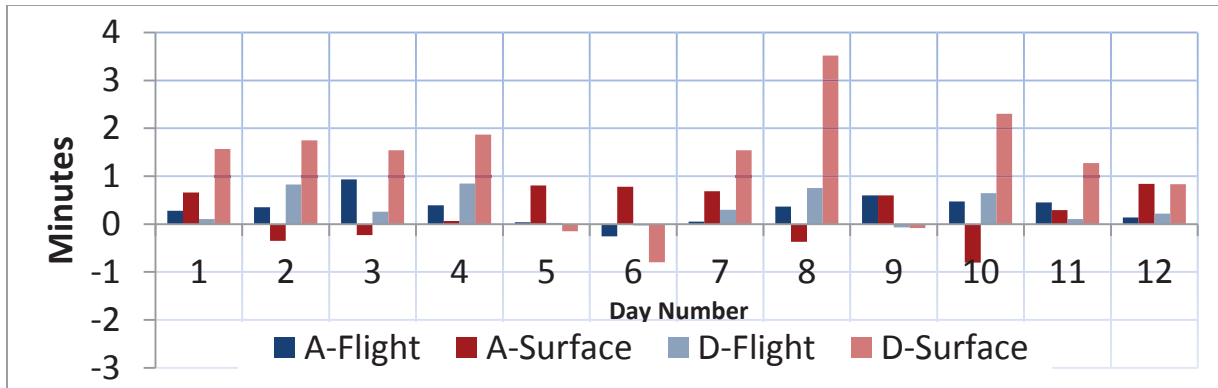
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Figure 8. Daily flight and surface time benefit contributions for MEM

Days that showed an overall benefit for departures (days #1, 2, 3, 4, 7, 8, 10, 11, and 12 from Figure 4) corresponded to large benefits for the surface (Figure 8). Departure penalties on days #5 and #6 came largely from surface penalties. The net arrival penalty on day #10 came largely from a net penalty on the surface. In general, the surface benefit (or penalty) dominated the overall arrival and departure benefits (or penalties).

Because benefit is defined as the baseline minus TRCM cases, its day-to-day variation includes contributions from both baseline and TRCM results, so it is useful to look at these individually. Day-to-day variation in transit times for the baseline and TRCM cases are shown in Figure 9, where it can be seen that the transit times for the baseline departures fluctuated the most (or had the widest range) among the four series shown. Figure 10 and Figure 11 show the breakdown of this daily transit time into flight and surface segments. For each pair of lines (Baseline and TRCM), it can be seen that the baseline case has more fluctuations than the TRCM case. Also, comparing the variation in flight versus surface times in Figure 11, the flight times seem to have fewer fluctuations than the surface times, and departures (Figure 11b) have more fluctuations than arrivals (Figure 11a).

Standard deviations of all daily series were calculated and reported in Figure 12. Similar to observations from the daily results, the baseline generally had higher variations than the TRCM case (i.e., about twice the TRCM standard deviation), except for flight time of arrivals. This is expected because the TRCM algorithm does not differentiate by the type of operation (arrivals or departures) in determining a runway schedule, while the baseline schedules may be based on different objectives determined by the user (that are not be reflected in the TRCM model). This difference in objectives could result in what appears to be a preference towards either arrivals or departures. Also from Figure 12, it can be seen that the surface had higher variations than flight times, and that departures had twice the standard deviation in surface time as arrivals.

Variation in benefits are mainly a reflection of variations resulting from use of the baseline schedule rather than the TRCM schedule. This series of plots can be summarize in three points: 1) the majority of day-to-day fluctuations in transit time comes from baseline cases; 2) departures had more variation than arrivals; and 3) the majority of variations in baseline departures largely came from their surface component.
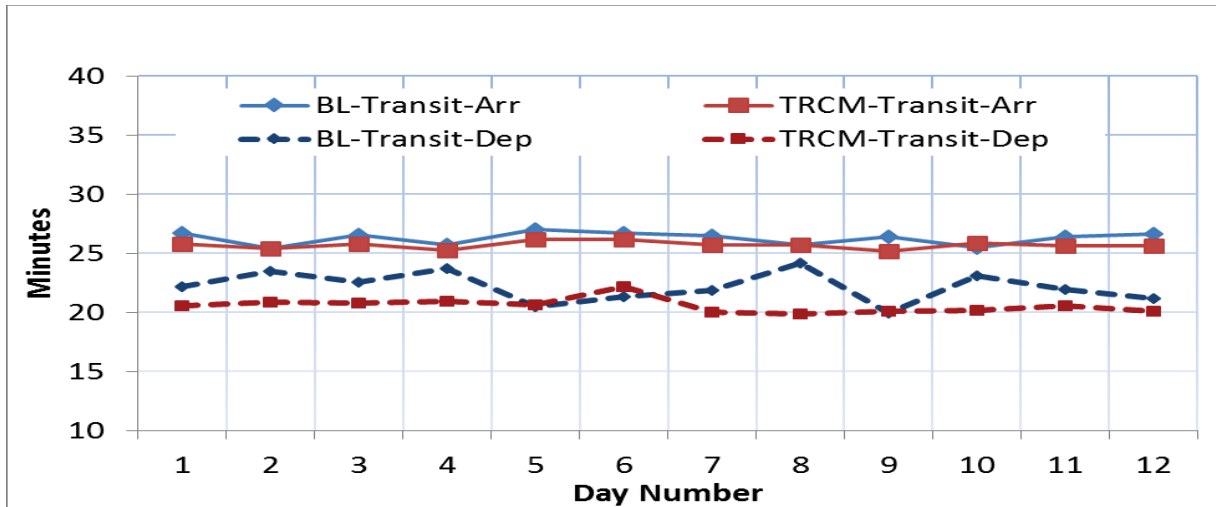
Figure 9. Daily transit times for the baseline (BL) and TRCM cases at MEM, by type of operation
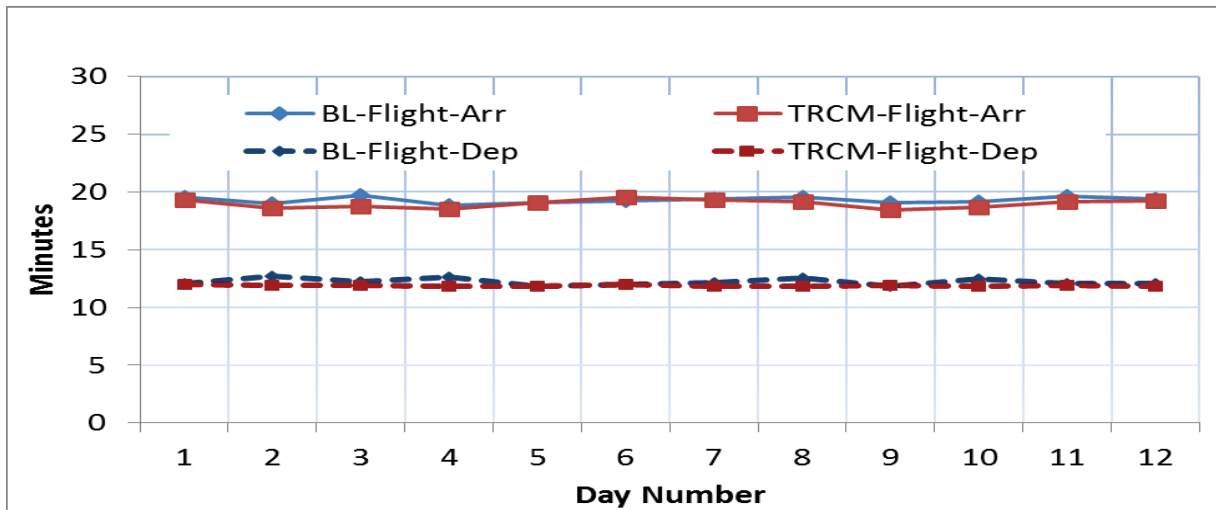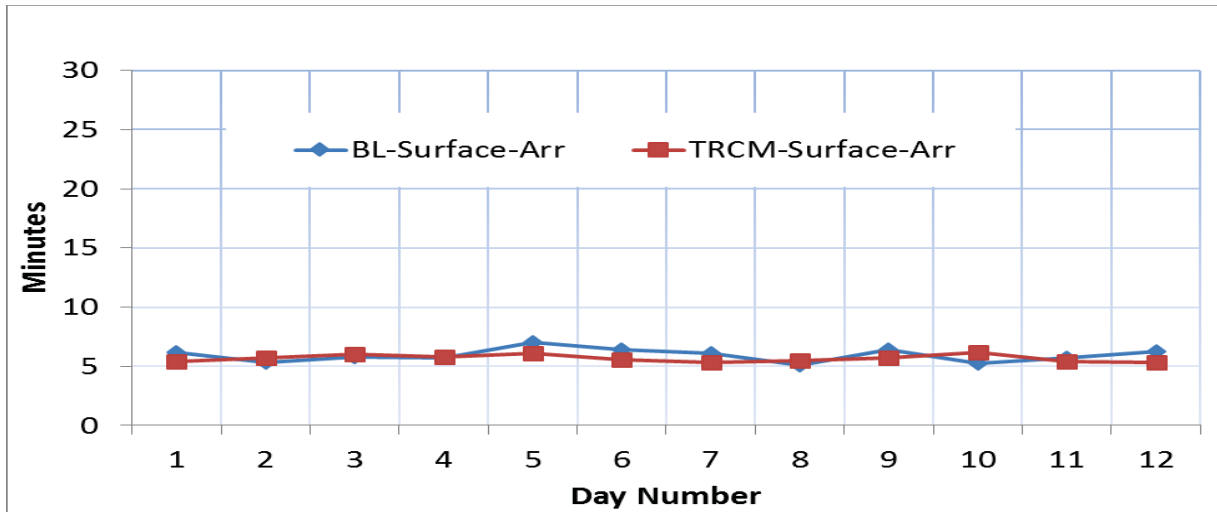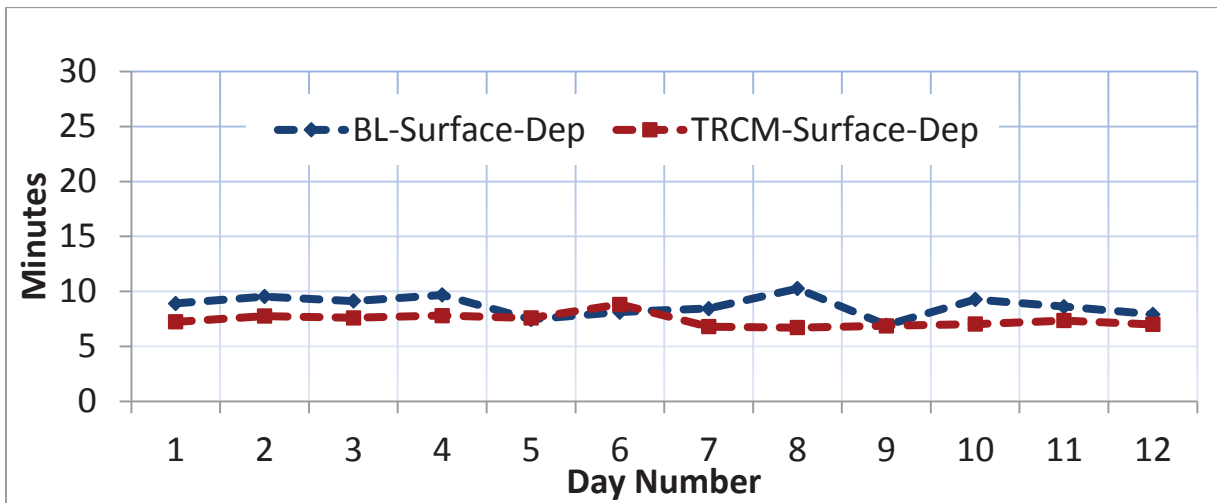

Figure 10. Daily flight times for the baseline (BL) and TRCM cases at MEM, by type of operation

(a) Arrivals

(b) Departures

Figure 11. Daily surface times for the baseline (BL) and TRCM cases at MEM, by type of operation
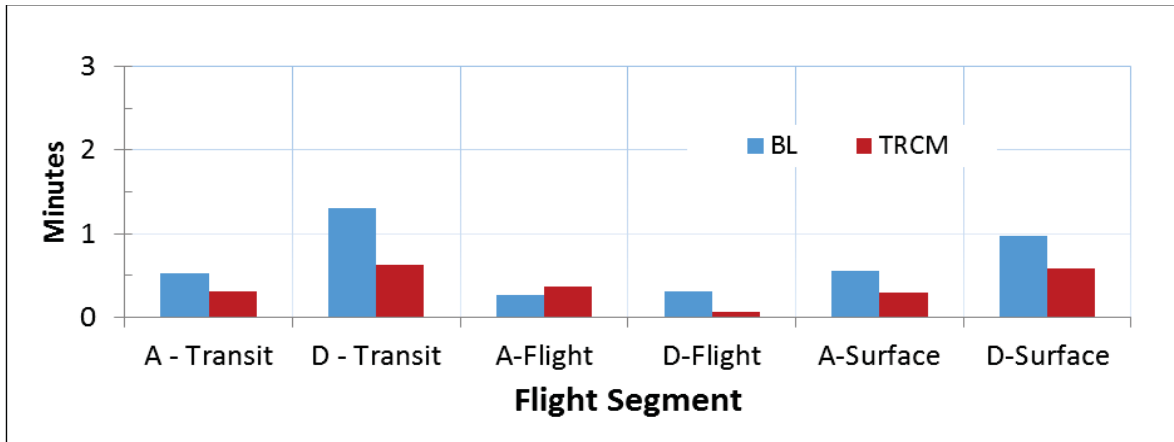
Figure 12. Overall standard deviations of transit, flight, and surface times at MEM

John F. Kennedy Internation Airport (JFK)

Referring back to Figure 5, and as shown in Figure 13, departure penalties (days #1, 3, 5, 6, 7, 9, and 11) corresponded with large departure surface penalties. The arrival penalty on day #4 came largely from a net penalty during the flight segment. For JFK cases, arrival benefits (and penalties) are largely from the flight segment, while departure benefits (and penalties) are generally from the surface segment.
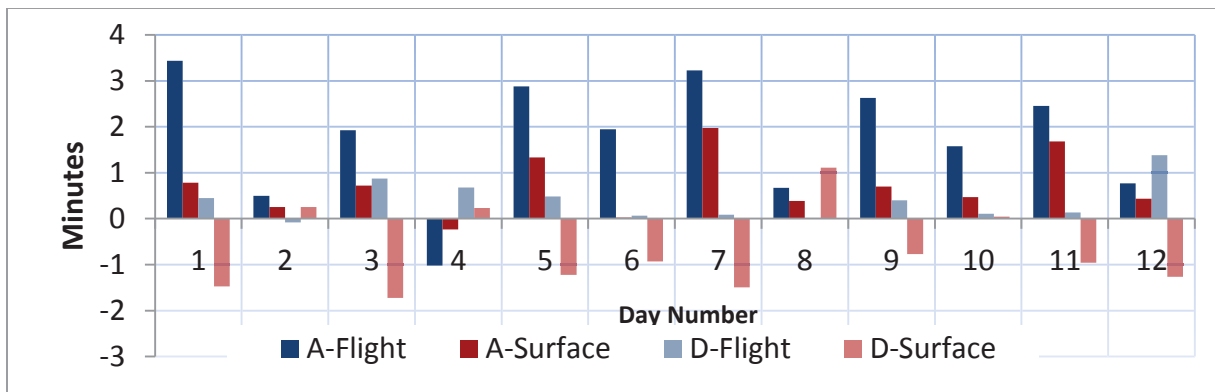
Figure 13. Daily flight and surface time benefit contributions for JFK

Figure 14 shows daily transit times for the baseline and TRCM cases. Daily transit times for the baseline arrivals (rather than departures, as was the case at MEM) fluctuated the most among the four series. Similarly to the results from MEM, the baseline case in each pair of lines on the graphs that follow had more fluctuations than the TRCM case. Also counter to MEM, at JFK flight times of arrivals had more fluctuations than departures (Figure 15); in the case of flight versus surface times, results were similar to MEM for departures (higher variation for surface than flight), but reversed for arrivals (higher variations for flight than surface. Surface times of arrivals had less fluctuation than departures (Figure 16). Thus, the day-to-day fluctuation in transit time of the baseline arrivals is due mainly to the fluctuations in the flight segment. Standard deviations of all daily series are shown in Figure 17.

Figure 14. Daily transit times for the baseline (BL) and TRCM cases at JFK

Figure 15. Daily flight times for the baseline (BL) and TRCM cases at JFK

(a) Arrivals

(b) Departures

Figure 16. Daily surface times for the baseline (BL) and TRCM cases at JFK
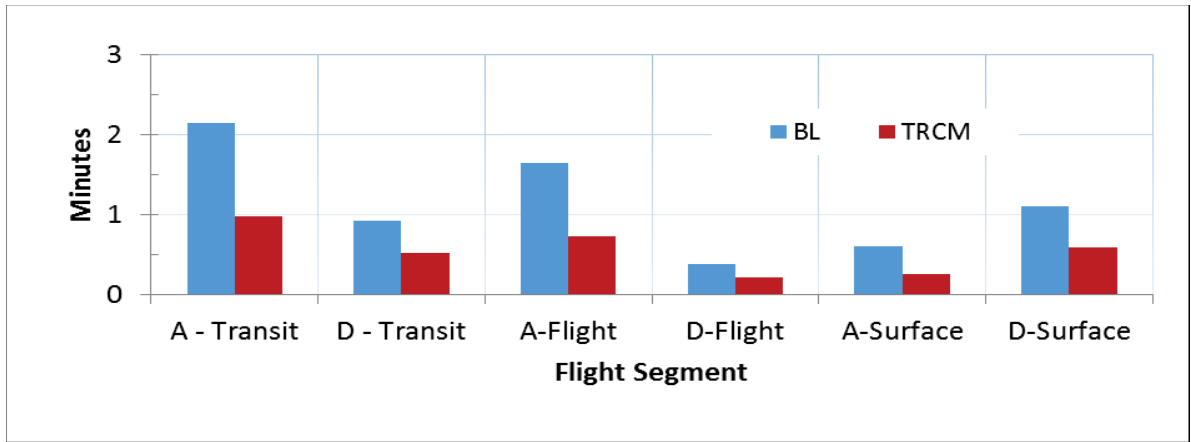
Figure 17. Day-to-day standard deviations at JFK

Similar to the MEM case, the baseline generally had higher day-to-day variations than the TRCM case (i.e., about twice the TRCM standard deviation). Thus, variations in transit time benefits were largely due to the variation from the baseline. For flight times, arrivals had about four times the standard deviation as departures. For surface times, departures had twice standard deviation as arrivals. This is consistent with what was observed in Figure 15 and Figure 16.

Dallas-Ft. Worth International Airport (DFW)

Figure 18 shows the daily transit time benefit broken down into flight and surface segments. Arrivals had higher flight benefits than surface benefits for the first 6 days, while the last 6 days, surface benefits of arrivals were generally higher than their flight benefits. Departure benefits (day #2 and #3) included contributions from both flight and surface benefits. For DFW, there was no clear-cut relationship between how flight or surface benefits (or penalties) contributed to arrival and departure benefits (or penalties).
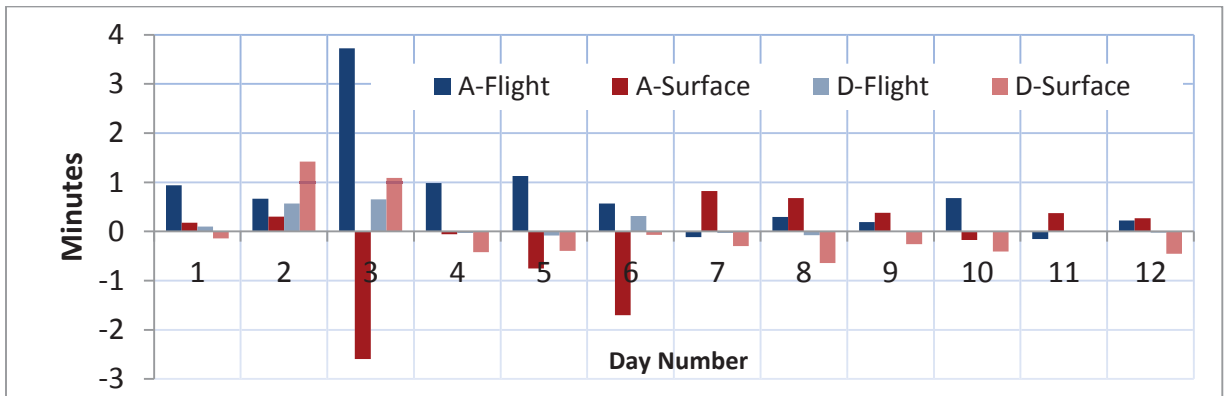
Figure 18. Daily flight and surface time benefit contributions for DFW

Daily transit time fluctuation of arrivals was higher than departures (Figure 19). As with JFK, daily flight times of arrivals had more fluctuations than departures (Figure 20). Daily surface time fluctuations did not show a strong

correlation to either the runway schedules or the operation types (Figure 21). Standard deviations of all daily series (Figure 22) shows that the baseline generally had slightly higher day-to-day transit time variations than the TRCM, as for both MEM and JFK. Therefore, variation in transit time benefits seems to be largely due to the variation in the baseline. For flight times, arrivals had about 1.5 times the standard deviation as departures; for surface times, arrivals had a slightly higher standard deviation than departures.
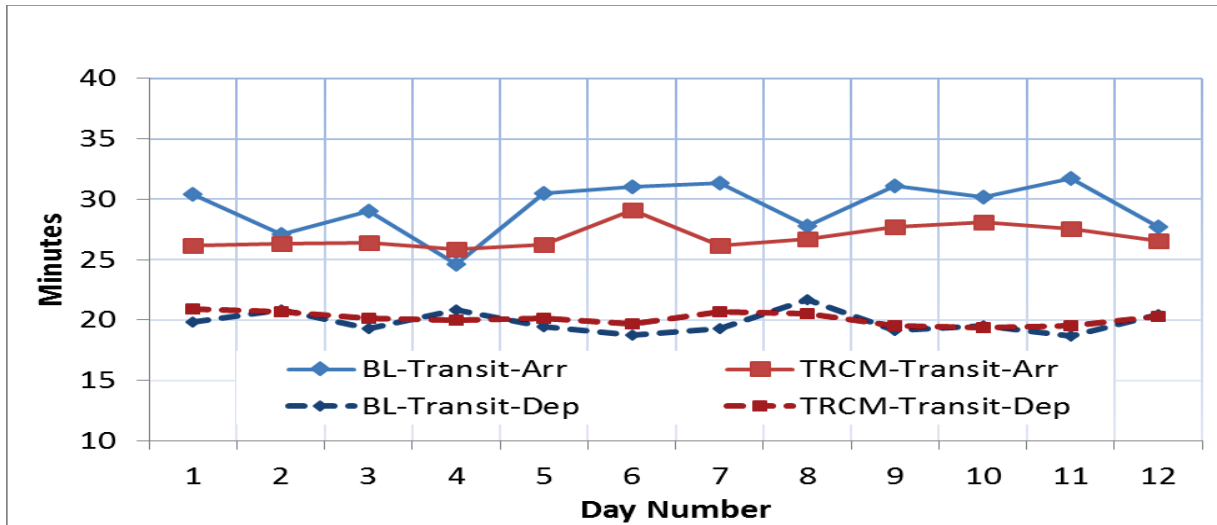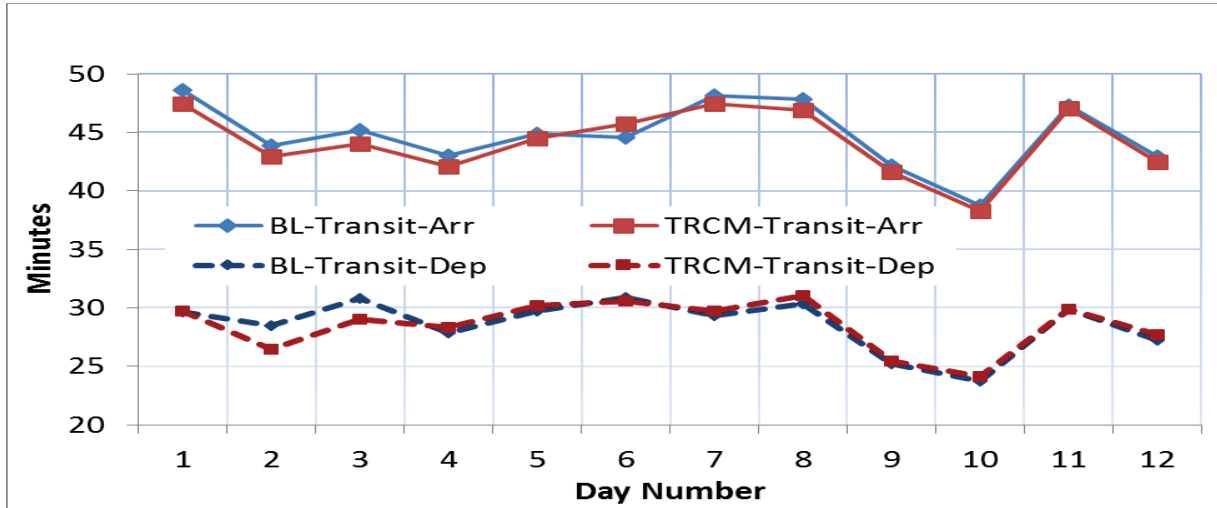

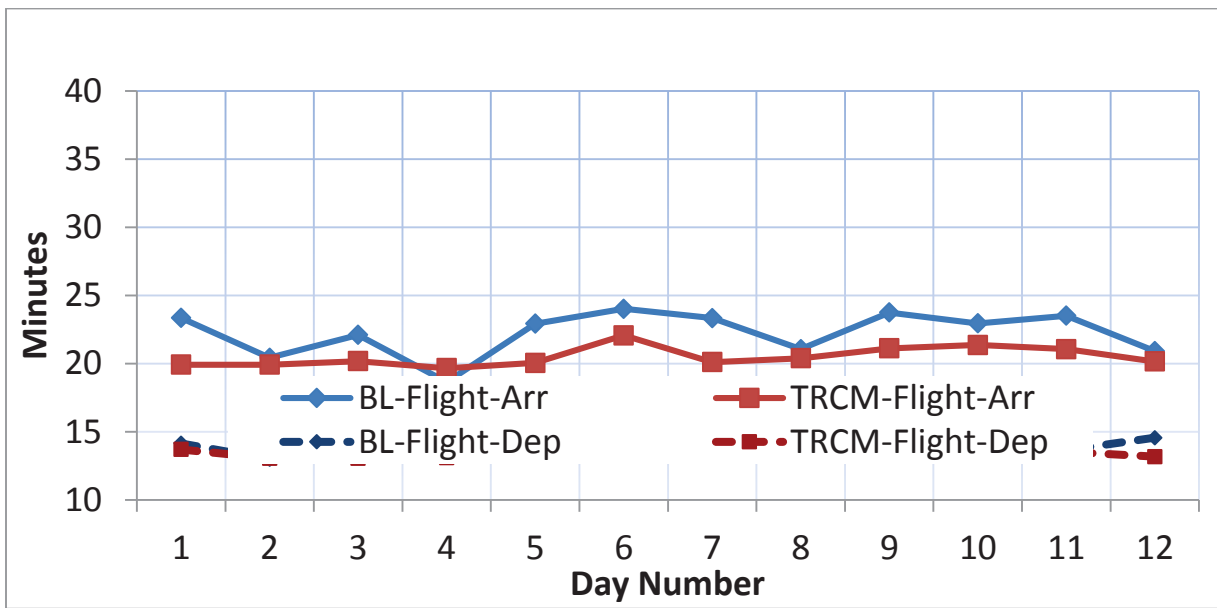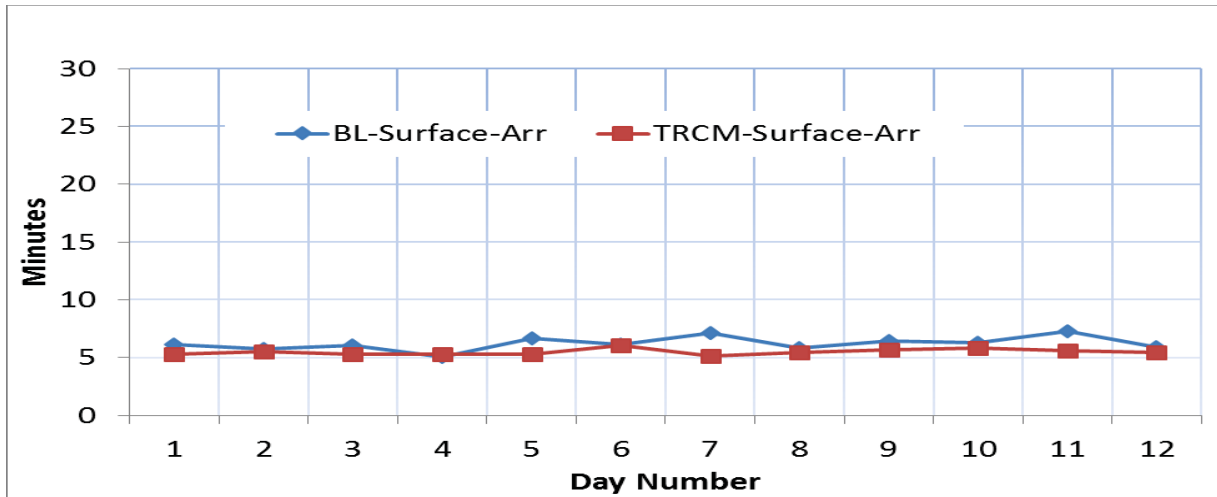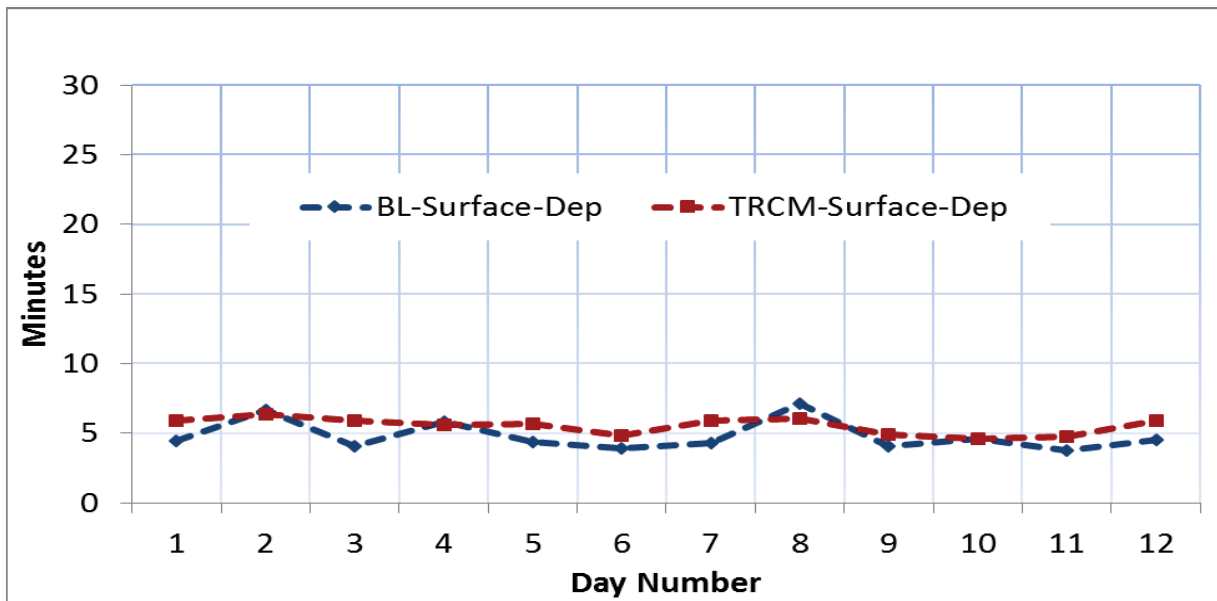Figure 19. Daily flight times for the baseline (BL) and TRCM cases at DFW
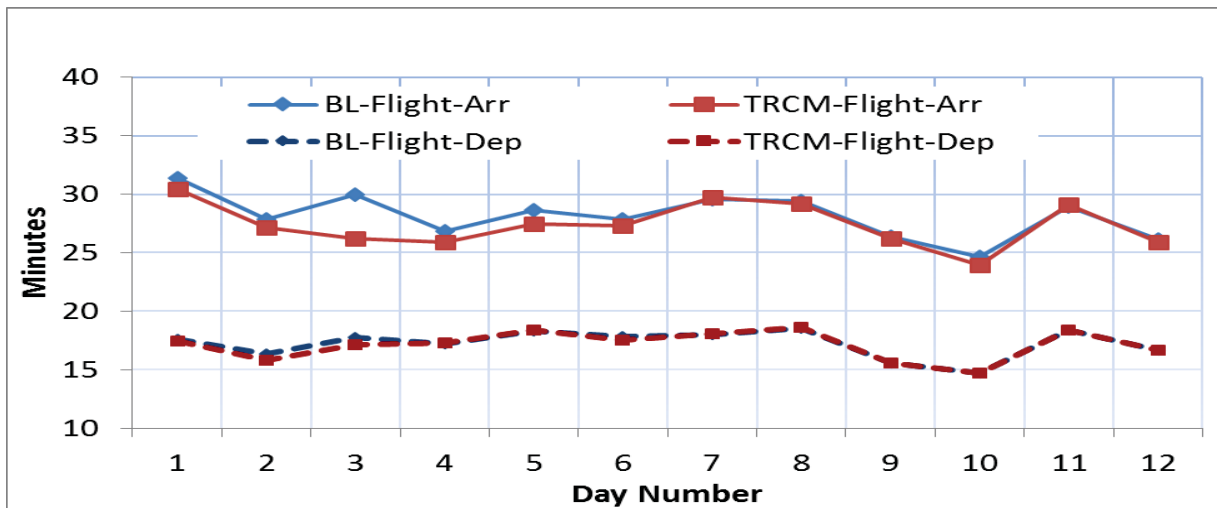
Figure 20. Daily flight times for the baseline (BL) and TRCM cases at DFW
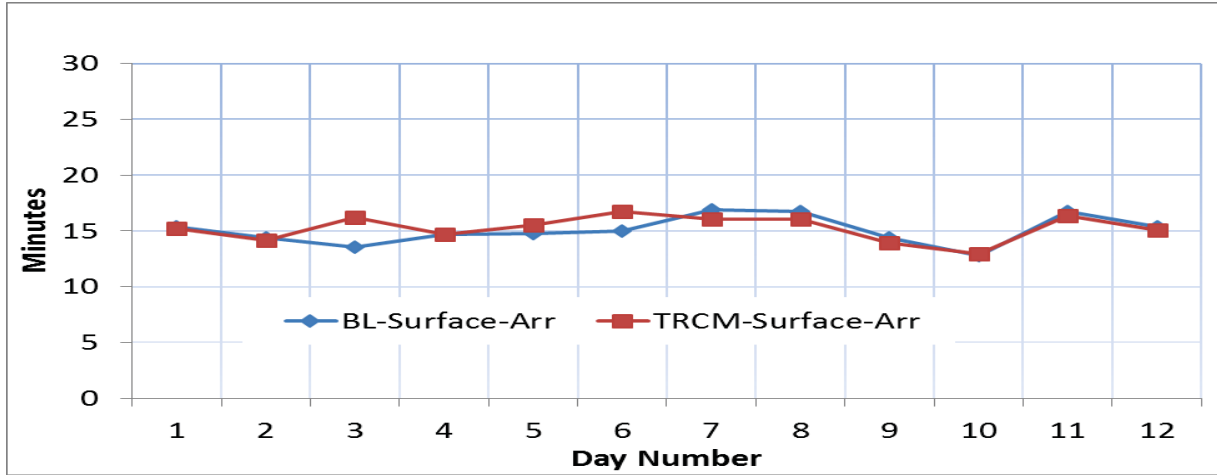
a) Arrivals
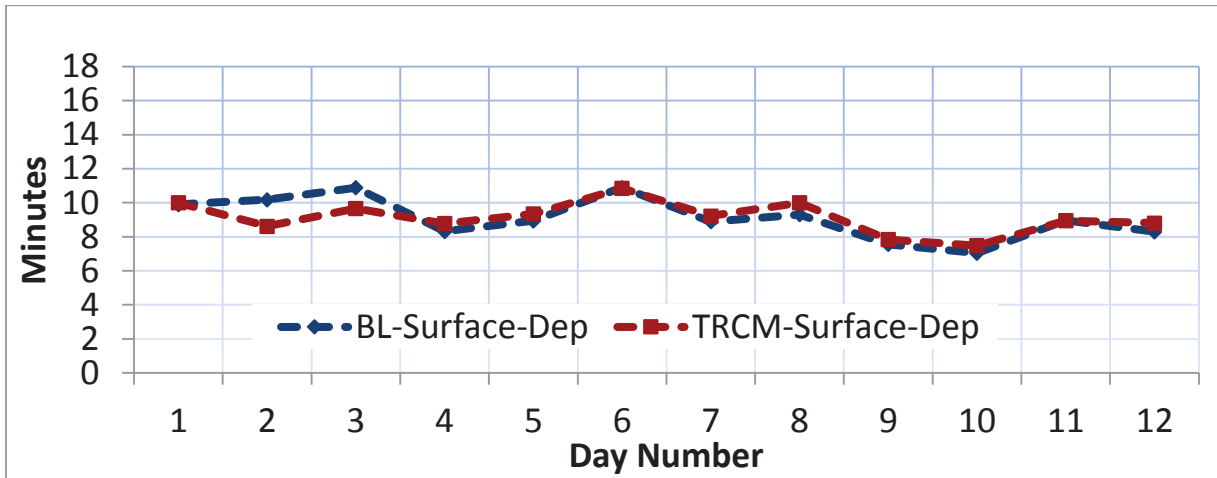
b) Departures

Figure 21. Daily surface times for the baseline (BL) and TRCM cases at DFW
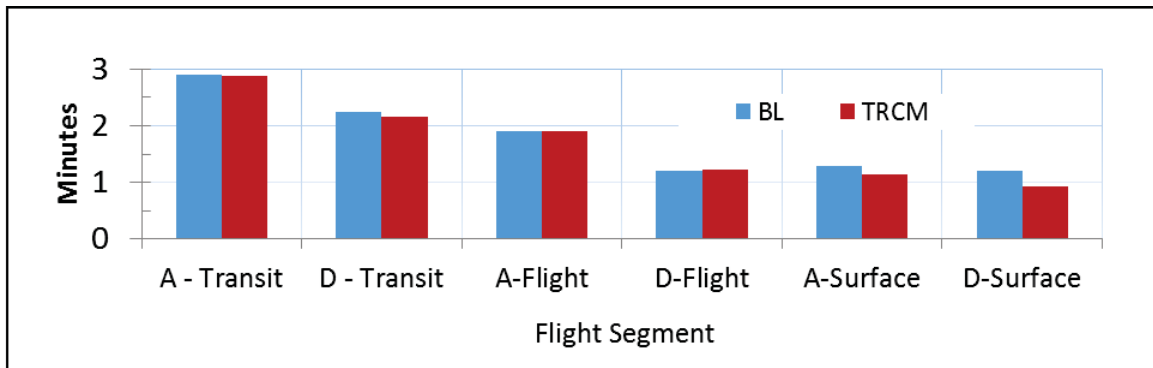
Figure 22. Day-to-day standard deviations at DFW

Departure Queues

The mean number of aircraft ahead in queue (when an aircraft approaches the runway for departure) are shown in Figure 23 for each of the three airports, for the twelve days; each chart shows two bars, for TRCM and Baseline cases. From the figures it can be seen that, for MEM and JFK, in most cases the TRCM tool provided a benefit of fewer aircraft in the departure queue (the TRCM bar is lower than the corresponding Baseline bar). At JFK in particular, there were a few days where the Baseline case had much higher queues than the TRCM case (days number 3,4, and 12). For MEM there were three days (7, 8, and 10) that had much higher queues in the Baseline case than the TRCM case. Because the overall queues at JFK were much lower than at MEM, the percent reduction in queue length is much higher, as seen in Table 4. The lack of any departure queue benefits at DFW could indicate that the simulation is not correctly modeling surface movements at DFW. If this is the case, this would most likely be an artifact of the MSE, not the TRCM algorithm, although the TRCM estimate would need to be checked also to insure that it is not missing any important factors that might have a primary effect. Further investigation is needed to be able to determine whether or not modifications are needed to better reflect surface operations at DFW.

Correctly modeling flight and surface operations is very important in being able to determine benefits. Each airport adaptation has a unique design, in particular the surface operations, chiefly due to the different designs for the terminal buildings, gate locations, companies that operate there, types of aircraft, and any existing local procedures. Thus, the modeling of surface operations at a large airport such as DFW is more complicated and more likely to face problems during its development. A method for detecting problems in surface operations is necessary; a tool to detect anomalies in surface (or flight) operations would be very helpful; a method for visualizing the operations was used, however it would require large amounts of time to detect any anomalies, and is not guaranteed that they could be detected in this way. For this study, this method was used only in a handful of cases where there were very noticeable errors in the output data.

Also, since the schedule resulting from the TRCM planning cycle is based on a low-fidelity estimate of transit times, results from the higher-fidelity simulation using the TRCM schedule could produce results that are very different from the TRCM estimate. In other words, the TRCM estimate may be over-simplified, resulting in little to no benefit when the scenario is fully simulated in the higher-fidelity MSE environment. This could be addressed by improvements to the planning (TRCM) estimate to more accurately reflect effects that are seen in the full simulation. A summary of the overall number in queue for each of the airports, (Table 4) shows a substantial benefit for MEM and JFK (especially high for JFK), and penalty for DFW.
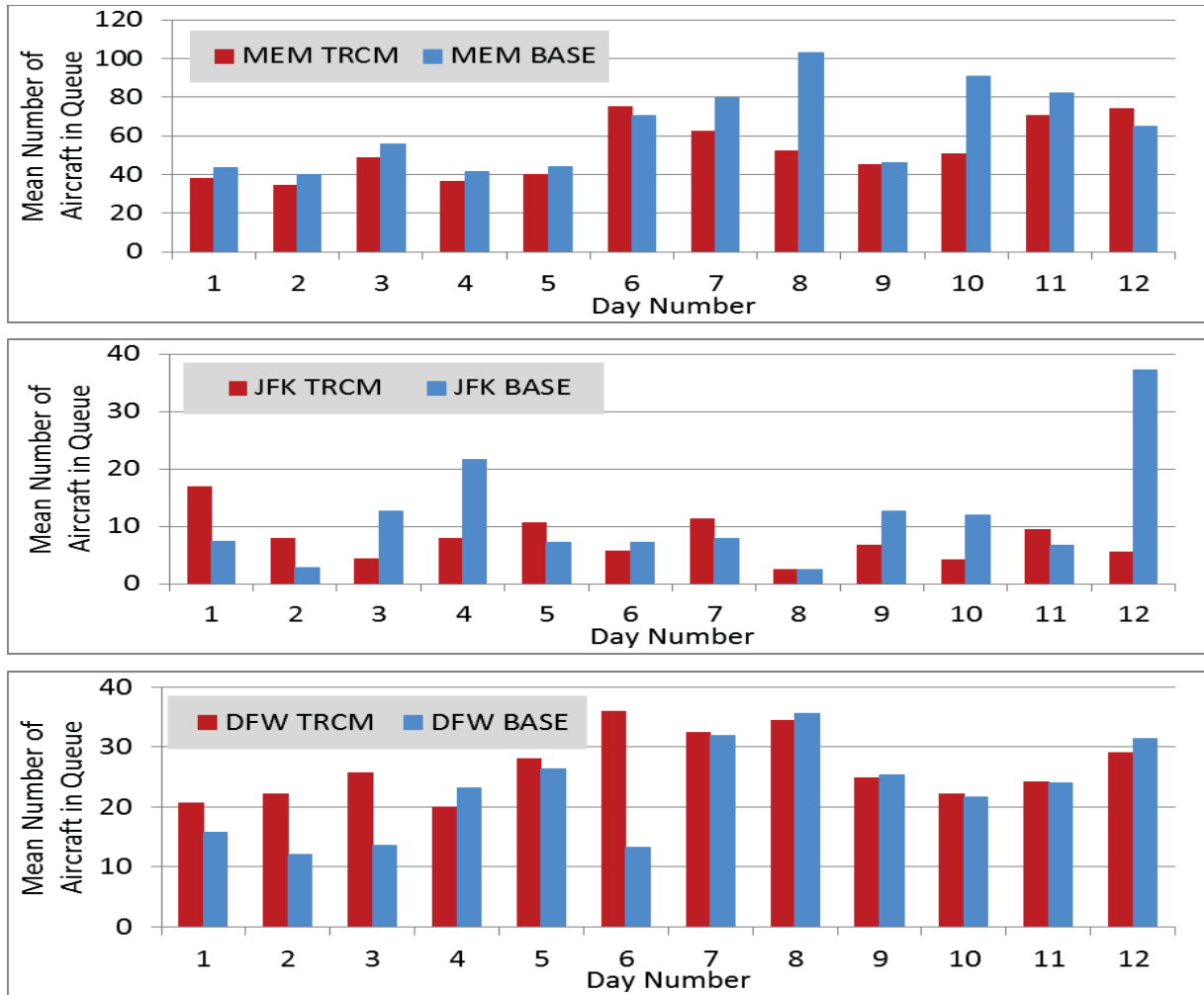
Figure 23. Mean aircraft in queue at the three airports for all test days

Table 4. Total number in queue and percent benefit in departure queue length for all airports, all days

	MEM	JFK	DFW
TRCM	1548	267	1136
BASE	1716	496	982
Percent benefit	9.8%	46.2%	-15.7%

A related parameter that is also of significance is the time spent in queue. Cumulative duration in queue for each of the three airports is shown in Figure 24, for each of the twelve days; this represents the total of queue times for all the aircraft that were reported as being in a departure queue. The same convention is used as in the previous chart: blue bars for MEM, brown for JFK, and green for DFW. From the figure it can be seen that, for MEM the time in queue was higher for baseline than TRCM for nine of the days; the other three days the TRCM queue duration was longer, but generally not by much. At JFK, in half the cases the Baseline queue duration was longer than TRCM; on the other six days, the TRCM duration was higher, but usually not by very much. At DFW the Baseline queue duration were higher than TRCM on only four days, and not by very much; on all but one of the other days, the

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queue durations were substantially higher for TRCM than Baseline, and equal on the remaining day. A summary of the mean overall queue duration for each of the airports, for Baseline and TRCM cases (Table 5) show similar trends as for the queue length, with a substantial benefit for MEM and JFK (especially for JFK), and a penalty for DFW. Also, by comparing the two figures, it is evident that the trends follow closely on a daily basis – that is, on days when Baseline cases had higher queue length than TRCM, they also had a higher cumulative queue duration. Although this is not unexpected, it gives us confidence in the quality of the results.
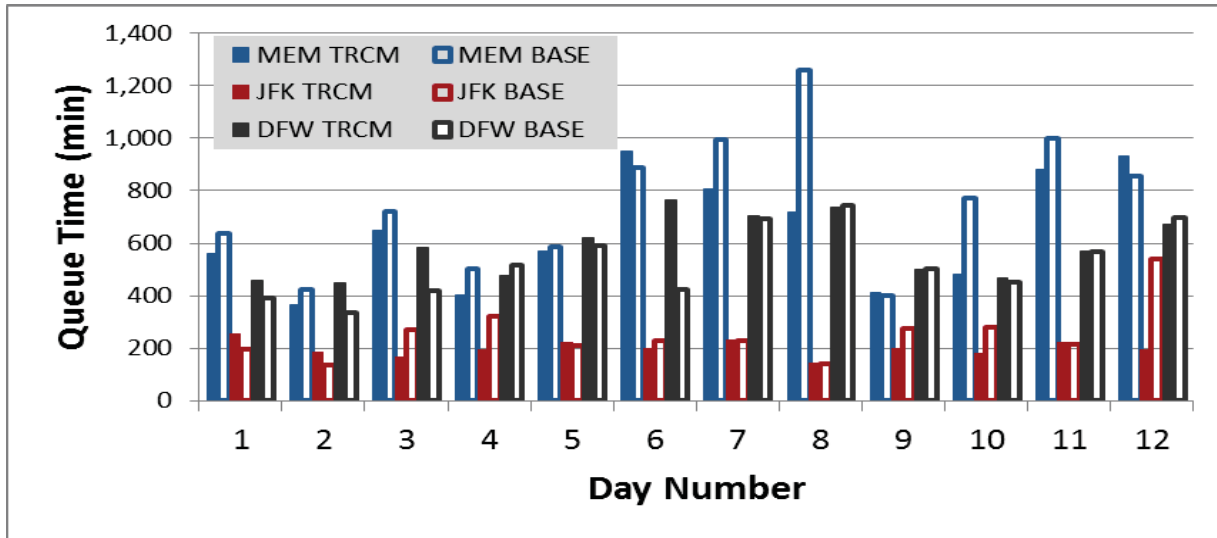
Figure 24. Cumulative queue duration minutes for the three airports, per test day

Table 5. Mean cumulative queue duration and percent benefit for all airports, all days

	MEM	JFK	DFW
TRCM	643.59	198.34	583.95
BASE	753.28	253.13	528.07
Percent benefit	14.56%	21.64%	-10.58%

Fuel Burn

Fuel use benefits were calculated for the in-flight portion and for the following segments on the surface: ramp, airport movement area (AMA), spot queue, departure queue, runway, and runway crossing. Of these surface segments, only the movement area contributed a significant amount to the overall fuel benefit compared to the other segments, except for the case of DFW departures, which had a high departure queue penalty, as can be seen in Table 6 (in this table, percentages are computed relative to positive benefits only – i.e., net negative benefits do not count towards 100%). Since the other five surface segments combined contributed 5% or less of fuel use, they are omitted in the plots for clarity. Figure 25 shows total fuel benefit for the three airports, for all days. Three bars are shown for each day, for AMA, in-flight, and total fuel used. From these plots, it can be seen that the surface fuel benefit is a small part of the total; the in-flight fuel benefit is the primary contributor to the overall total, for all but one or two days at all three airports; however at DFW the fuel benefit for the last six days is very small, thus the in-flight and surface contributions are nearly the same.

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Table 6. Average percent segment contribution to fuel benefit for all airports, all days

Airport	Op Type	Ramp	Spot Queue	Airport Mvmt Area	Runway Crossing	Departure Queue	Runway	In-flight
MEM	Dep	-0.5	0.0	29.6	0.2	3.0	0.5	66.7
	Arr	4.9	0.0	20.3	-0.4	---	-0.5	74.7
JFK	Dep	0.0	0.0	-10.5	-4.6	0.9	0.9	98.2
	Arr	0.0	0.0	4.4	3.3	---	0.0	92.3
DFW	Dep	-0.9	0.0	7.1	-0.4	-6.6	-1.1	92.9
	Arr	0.0	0.0	-5.8	4.7	---	0.1	95.2

Further subdividing the fuel benefit in the AMA segment by different phases of taxiing (stopped, accelerating, and steady taxiing) showed that the time spent in "stopped" mode had a very large negative value for DFW, much more than either of the other two phases; this was not true at the other two airports, which had little or no fuel benefit loss when stopped. This would suggest that the resulting negative values seen for transit time benefits at DFW may be largely due to the time lost during surface operations, possibly while waiting for runway crossings.

Possible ways to alleviate this effect could be to impose a time penalty when the taxi path requires crossing multiple active runways, or in some other way to limit the number of active runway crossings for each flight; this approach to reducing losses of fuel or time benefits during surface operations would need to be examined further prior to drawing definitive conclusions about the effectiveness of TRCM at DFW. Fuel benefit is summarized in Table 7.

Table 7. Mean fuel use (and TRCM percent benefit per flight) for all airports, all days

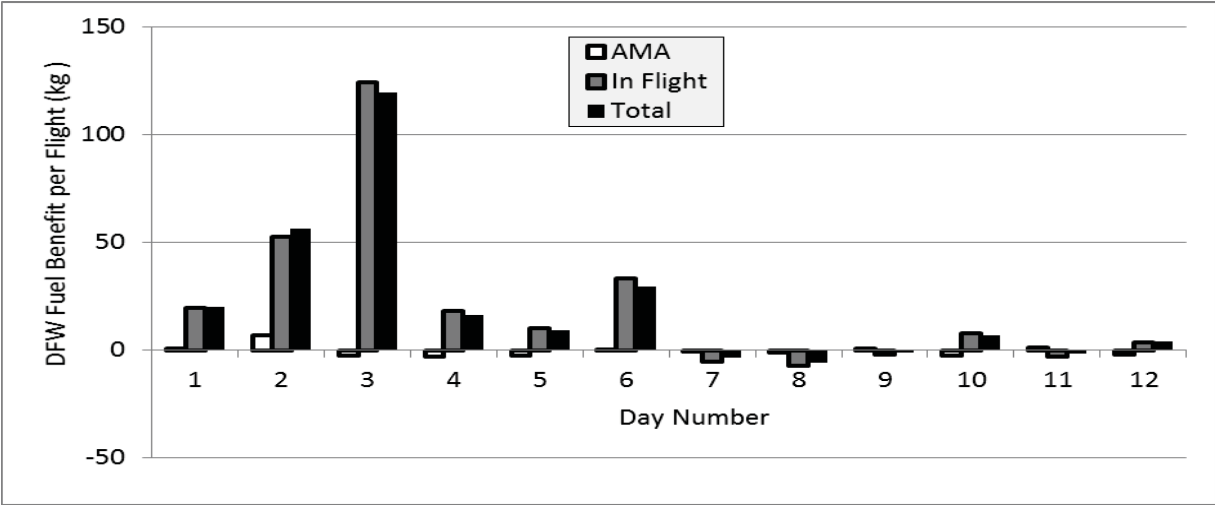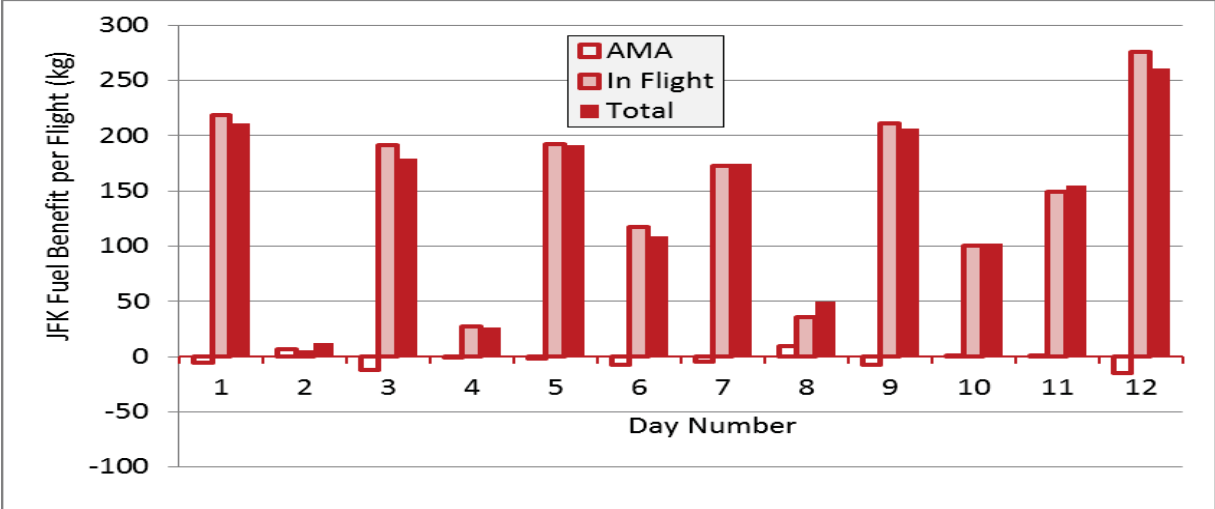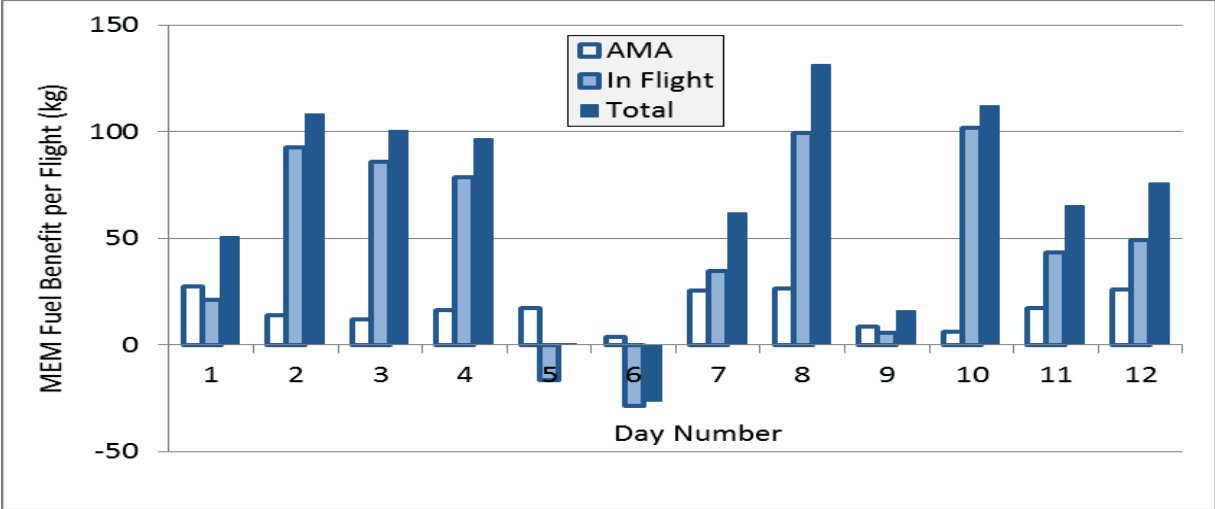|	Type of Operation	Baseline (kg x 1000)	TRCM (% benefit)
MEM	Dep	1575.6	1528.7 (3.0)
	Arr	973.6	954.4 (2.0)
JFK	Dep	2257.6	2203.5 (2.4)
	Arr	1233.6	1148.2 (6.9)
DFW	Dep	1168.8	1163.4 (0.5)
	Arr	673.4	658.1 (2.3)

Figure 25. Fuel use benefit per flight for in-flight and AMA segments, and total

Throughput Efficiency

Throughput efficiency (TE) is the ratio of the actual to the optimum effective throughput of a system, and is dimensionless. The actual effective throughput is defined as the ratio of the number of aircraft that have transited through the system exit point to the total actual travel time of these aircraft. For the arrival operation, the total travel time is the sum (over all arriving aircraft) of the difference between the actual time stamp at spot (where aircraft exit the system) and the earliest time stamp at arrival fix (where aircraft enter the system). For the departure operation, the total travel time is the sum (over all departing aircraft) of the difference between the actual time stamp at departure fix (where aircraft exit the system) and the actual time stamp at spot (where aircraft enter the system). The optimum effective throughput is defined similarly, with the exception of using the total unimpeded times instead of the total actual times. A TE ratio closer to 1 is preferable, indicating that the system is operating at close to an unimpeded level. The TE can be thought of as a throughput metric that has been standardized so that it is insensitive to traffic volume [15].

Hourly throughput efficiencies were computed for both baseline and TRCM cases, and compared for this assessment. Figure 26 shows mean (over all hours) TEs for arrivals and departures at all three airports. TE varies by days, type of operation (arrival vs. departure), and runway configuration schedules (baseline vs. TRCM).

Table 8 summarizes the mean (over all days) and standard error by type of operation, runway configuration schedules, and airports. The standard error can be thought as uncertainty associated with the average TE. Some general observations can be made. The average TEs of departures are higher than arrivals for all airports; this makes sense operationally because departure schedules are more easily adjusted than arrival schedules. The TE uncertainties of the TRCM are smaller for all airports. In other words, the baseline has more variability in their operations than the TRCM. As in the transit time analysis, it is thought that this could be due to the historical operations using different criteria (or objectives) in making runway configuration decision, whereas the TRCM used the same objective across all tested days.

Using the TRCM schedule usually provides better TEs, in terms of averages and uncertainties, over the baseline schedule for arrivals and departures.

Table 8. Summary of the average and standard error for Throughput Efficiency (TE) performances at all airports.

		Baseline	TRCM	Baseline	TRCM
MEM	Arrivals	0.7837	0.8154	0.0051	0.0045
	Departures	0.8093	0.8578	0.0061	0.0056
DFW	Arrivals	0.8103	0.8354	0.0033	0.0029
	Departures	0.9248	0.9324	0.0041	0.0034
JFK	Arrivals	0.7726	0.8618	0.0052	0.0025
	Departures	0.9208	0.9069	0.0031	0.0029

Improvements in the mean TEs are shown in Figure 27 as percent improvement with respect to the baseline. MEM provides 4% TE improvement for arrivals, and 6% improvement for departures. At DFW and JFK, the TRCM provides higher percent improvements for arrivals (between 3 and 12 percent) than departures (between -2 and 1 percent). JFK especially shows a substantial TE improvement for arrivals (12%), but a slight TE reduction for departures (-2%). Overall these results show similar trends as the transit time results.
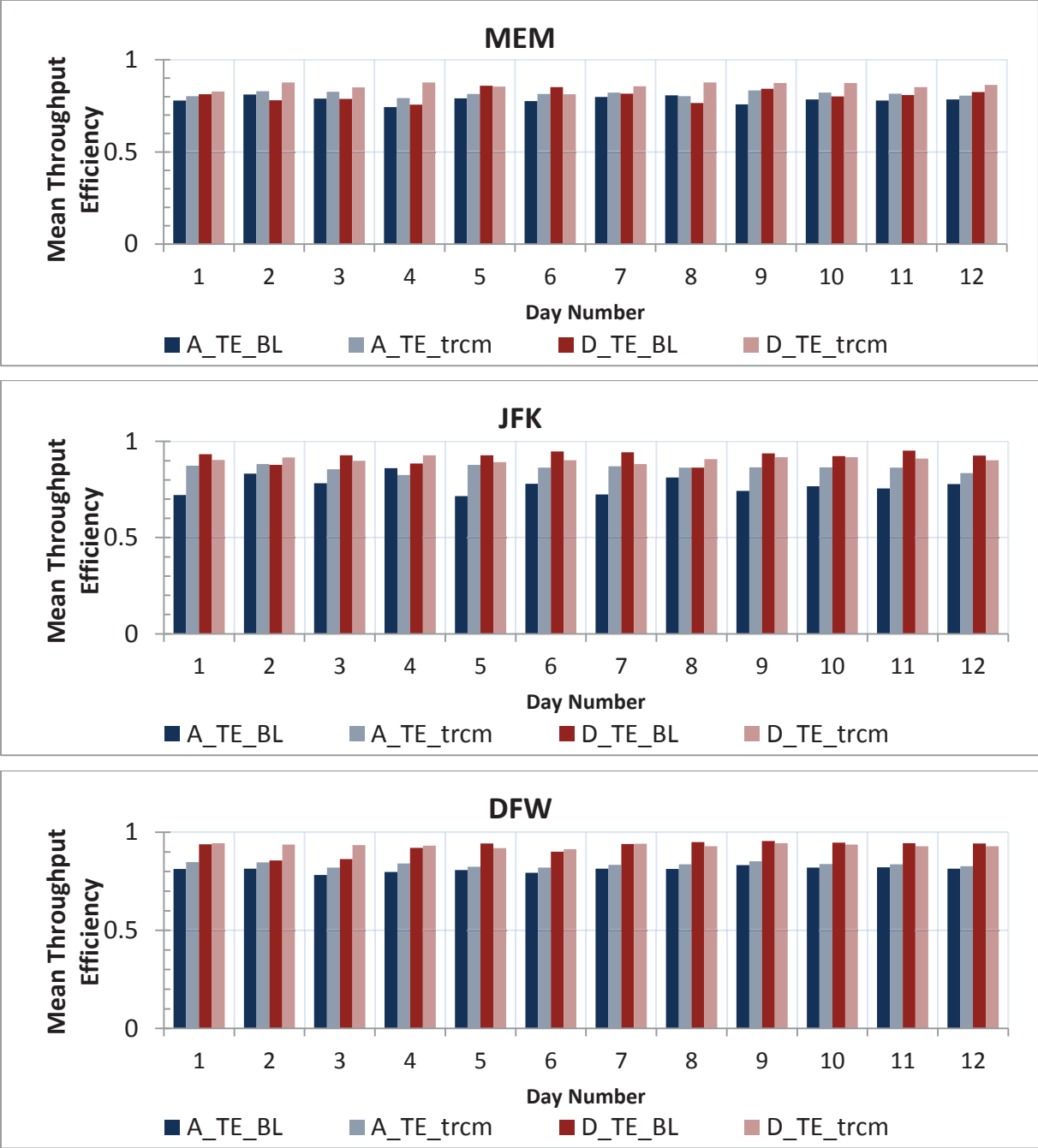
Figure 26. Mean (over all hours) throughput efficiencies (TE) at MEM, DFW, and JFK arrivals and departures.
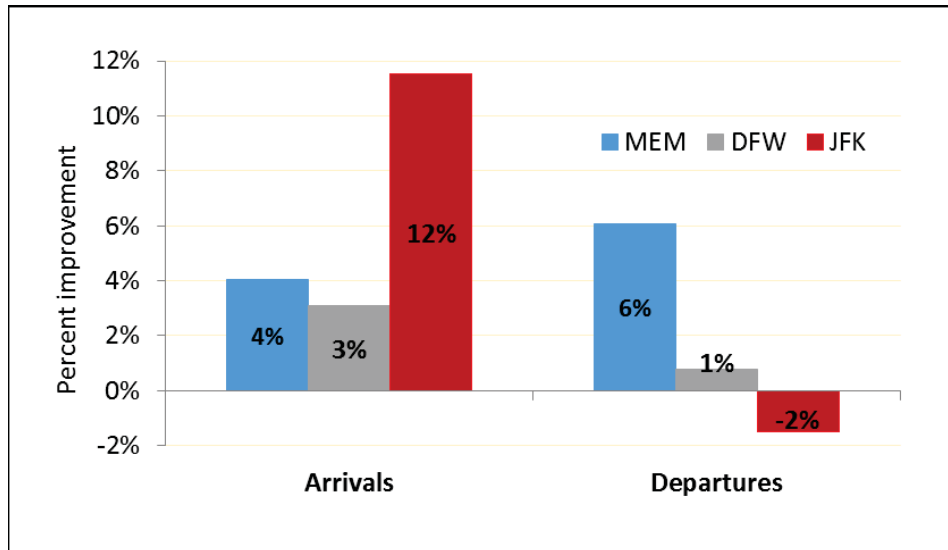
Figure 27. Average (over all days) improvement in throughput efficiency (ratio of TRCM and baseline).

Airport Configuration Changes

Although the workload associated with configuration changes was not addressed in this study, it is known that changes in runway configuration are accompanied by increased workload for controllers and managers. As a way of determining whether or not the workload might be increased with use of the TRCM tool, a comparison can be made of the number of changes recommended by the TRCM tool, and the historical number of changes that occurred on those days. Generally speaking, a change in direction of flow (for example, from North Flow to South Flow at an airport that has North-South runways) can result in a loss of efficiency, increase in workload for controllers, and additional coordination required between the airport and TRACON management, as the flow of traffic in the terminal must change Basically, inbound routes across arrival fixes at the terminal boundary into the initial part of TRACON airspace is static; they remain unchanged regardless of the runway configuration. Airspace used by final controllers to space and sequence arrival traffic does change. During the transition between these configurations, coordination beyond that necessary for normal operations is required. Changes in the way runways are used (for arrivals only, departures only, or mixed-use) without a change in flow direction does not have as high a cost, in terms of coordination, workload, and loss of efficiency.

For this analysis, the number of configuration changes per day were computed, and subdivided by the type of change, whether a change in flow direction (FD) or runway usage (RU). For this study, runway usage changes encompass any other type of change that does not involve changing the direction of flow. Examples of runway usage changes can include: a runway that was being used for arrivals only (or departures only) is changed to mixed-use, changed to the opposite type of operation, or removed as an option; a mixed-use runway is changed to arrivals only, departures only, or removed as an option; a runway is added as either a departure, arrival, or mixed-use runway; more than one runway is added, removed, or changed in the type of operation for which it will be used.

Figure 28 shows the mean number of configuration changes per day for all twelve test days, for each of the airports. As can be seen, the number of flow direction (FD) changes recommended by TRCM (dark blue bars) was much higher than what were historically used at all three airports (dark red bars). The number of runway usage (RU) changes (light blue bars) are also higher than the historical changes (light red) at MEM and JFK, but not at DFW.

Across all days and all airports, the number of changes in flow direction that were recommended by TRCM was much higher than the number of runway usage changes.
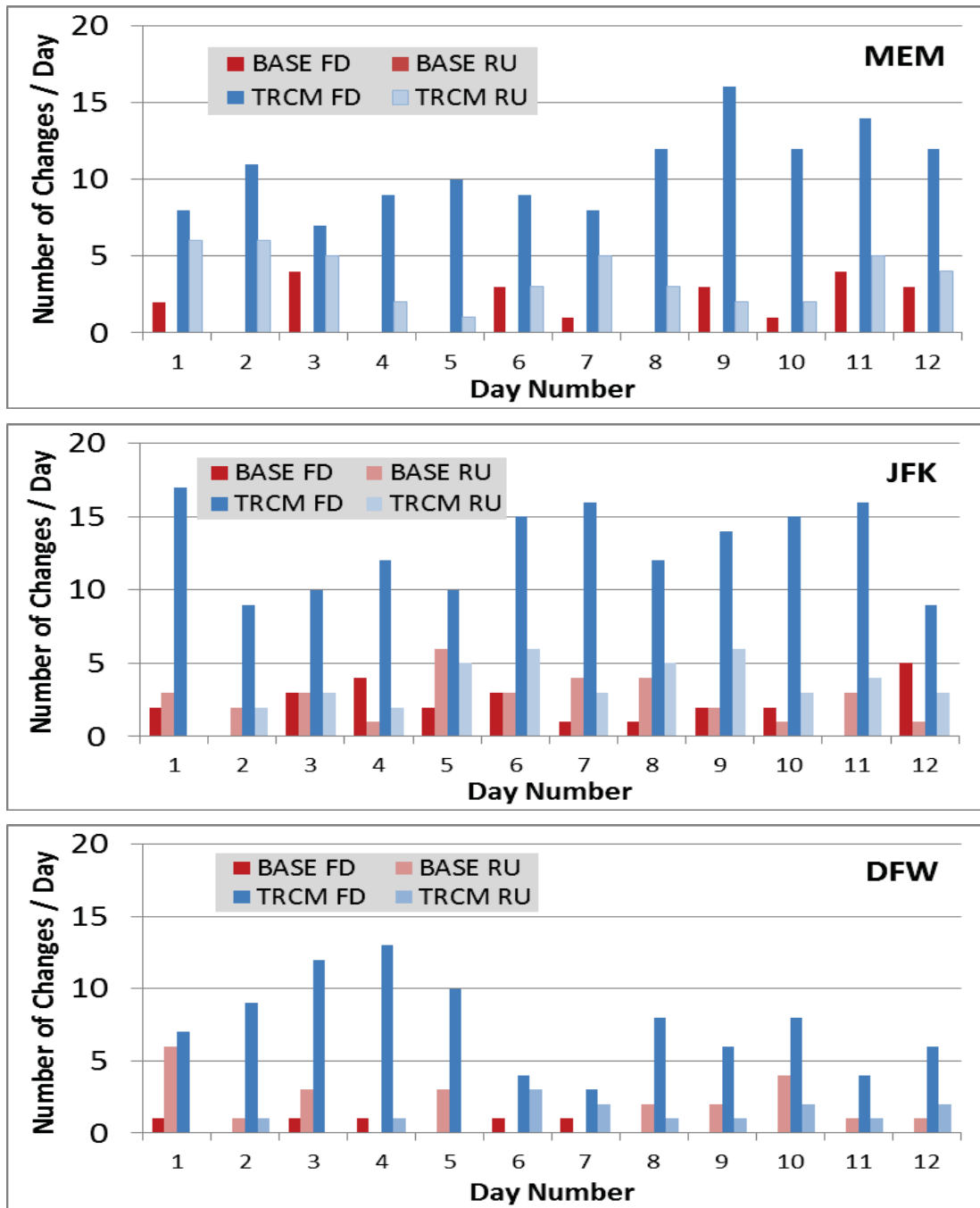
Figure 28. Mean number of recommended configuration changes per day

Table 9 shows the mean number of changes in flow direction across all days for the three airports. For all three airports, the average number of changes in flow direction recommended by TRCM was several times greater than the historical data would suggest. The average number of changes recommended for MEM was 6 times greater than the historical case; for JFK it was 6.4 times, and for DFW almost 19 times the historical average. These values are excessive compared to what is normally found at airports throughout the NAS. Although a benefit of having TRCM

is the ability to better manage the changes in runway configuration, at some point the changes in flow direction become excessive, primarily from the standpoint of controller workload.

Table 9. Mean number of changes per day (flow direction and runway usage) for MEM, JFK, and DFW

	TRCM FD	BASE FD	TRCM RU	BASE RU
MEM	10.8	1.8	3.9	0.0
JFK	13.5	2.1	7.3	1.0
DFW	7.5	0.4	1.2	1.7

In this study, no attempt was made to determine what is the optimal number of configuration changes per day at an airport; however, considering that there are generally 16 hours of the day when the majority of traffic operations occur at most airports, having more than 13 changes in flow direction would mean an average of almost one per hour. Considering the workload and coordination involved in executing this type of change, it is desirable to reduce the number of changes recommended by TRCM. The TRCM algorithm was limited to changing configurations not more than once every 30 minutes; however there was not a limit on how many changes per day were allowed, so clearly more investigation of this issue needs to be done. It is likely that the TRCM tool would need to be adjusted to a particular airport's needs, to limit the number of changes per day to what would be considered acceptable. For example, at JFK it is not uncommon to have five configuration changes per day, whereas at DFW most days operate in South Flow, with very few changes during the average week. Figure 29 shows the amount of time spent in each of the main directions of flow for both Baseline and TRCM cases (RU changes are contained within each of the main categories shown). The vertical axis is the total number (over the 12 test days) of 15-minute epochs spent in each of the configurations listed along the horizontal axis. For MEM it can be seen that in the historical case North flow was predominant over South flow, whereas in the TRCM case the opposite was true. This indicates that historically the airport operates in a North flow configuration more than in South flow, but the transit time benefit shown previously would suggest that there would be a benefit to operating more in South flow. Considering also that TRCM use showed benefits for queue length, queue duration, and fuel use would also support using this type of configuration. Because it is not easy to assess the combination of surface and in-flight benefits simultaneously to optimize the various parameters than contribute to benefits, it is likely that using TRCM could provide a tangible benefit to MEM operations.

JFK historically operated on 22L_22R, and to a lesser degree on 4L_4R, however with TRCM the amount of time spent in each was reversed, as for MEM. Also with TRCM, more time was spent using the 31L_31R and 13L_13R than was historically used. Because the TRCM algorithm did not include provisions for metroplex constraints, it is possible that the TRCM configuration change results would be different when flows are restricted due to its proximity to other airports. A separate metroplex TRCM algorithm was provided as part of the SORM research effort, and results from that analysis are reported separately.

Results for DFW show that TRCM recommended nearly the same amount of time in each of the flow directions as was historically used, with slightly more time spent in North flow. This might suggest that current operations sufficiently capture most of the benefits (in terms of runway flow direction usage), which is most likely why the resulting benefits in transit time, fuel use, queue duration, and queue time were minimal or non-existent. It is likely that the area most likely to provide a benefit would be on the surface; this should be investigated more closely.
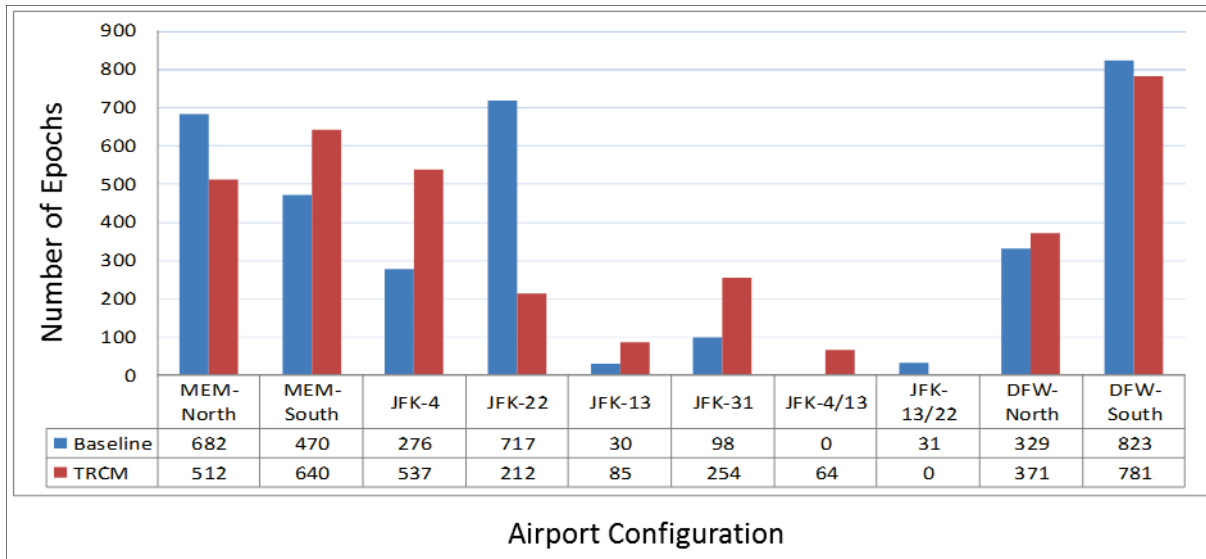
Figure 29.Amount of time spent in configurations.

The following plots give a detailed look at the daily relationship between transit time benefits and demand levels separately for arrivals and departures. In all the figures, the solid lines are the number of flights (departures in blue and arrivals in red); the scatter-plot symbols are the transit time benefit for each flight (transit time from the baseline run minus transit time from the TRCM run), with vertical axis on the right side. Horizontal axes are the same for the two super-imposed plots, and represent time in 15-minute epochs (for a total of 96 per each 24-hour day). Figure 30 shows a typical day at MEM; this particular day was November 20, 2009, which was a Friday, with fairly high demand (535 arrivals and 435 departures). From the solid lines it can be seen that the traffic demand levels are cyclical, with distinct peaks and troughs for both arrivals and departures; most of the time the peaks are in opposite phases (i.e., when there is a departure peak, there are very few arrivals and vice versa). This is partially due to the large number of FedEx flights that arrive as a group early in the morning and depart as a group late at night and mid-afternoon, however some of the peaks are due to the schedules of other airlines as well (there are a large number of Delta Connection flights throughout the day). From the plot, it can be seen that the demand peaks are often associated with transit time benefits for the corresponding flight operation; for instance, between epochs 0-4, there is a peak in arrivals, and corresponding peak in transit time benefits. Similar patterns can be seen for arrivals between epochs 30-36, 50-52, 66-70, and 88-96, although for the middle three peak periods there is also a substantial penalty (negative values); for departures the peaks are during epochs 8-18, 36-40, and 54-62, with a smaller number of flights that were penalized, mostly during the time that the operations were changing from arrivals to departures at epochs 32-34, where departures and arrivals overlapped. Similar patterns can be seen on other days, some more pronounced than others, however the overall resulting benefits for MEM seem to indicate that having opposing peaks and troughs of traffic demand for arrivals and departures results in higher benefits for both types of operations. This particular day resulted in a 2.7% transit time benefit for arrivals and 8% benefit for departures.
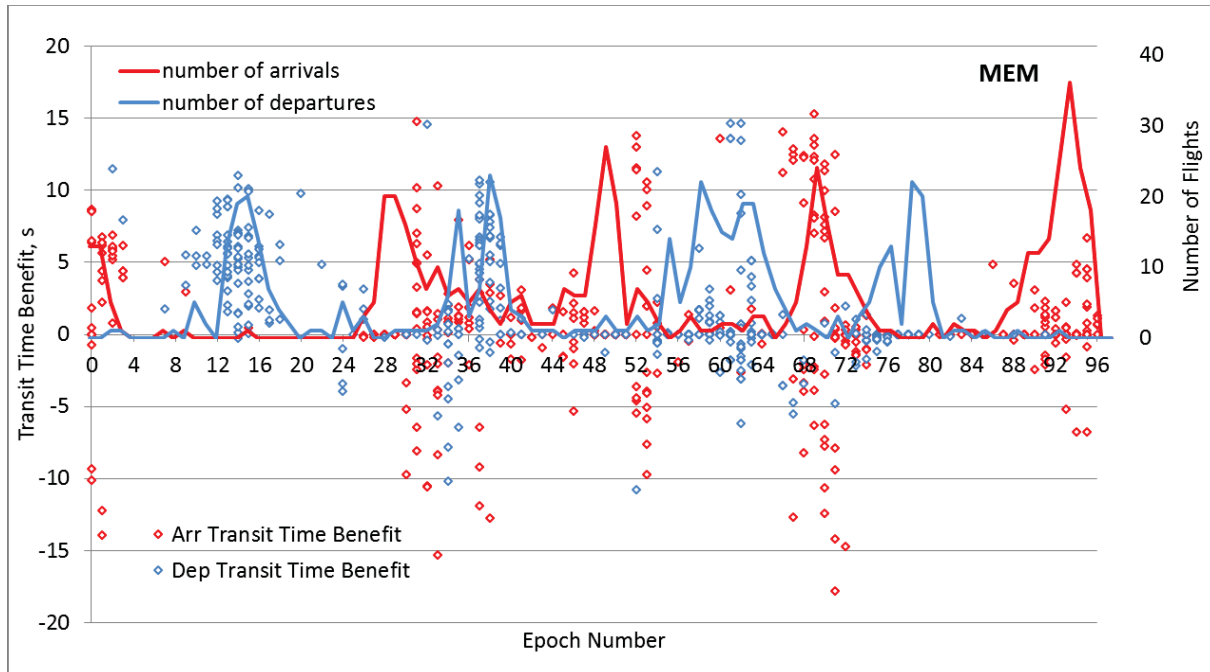
34

Figure 30. Demand and transit time benefits by epoch for MEM Day 3 (20NOV2009).

A much different example can be seen in a case from DFW in Figure 31 (from test day October 17, 2009). The traffic profile for DFW on the test days used in this assessment was very different from that at MEM; rather than distinct peaks and troughs for arrivals and departures, the traffic was more evenly distributed throughout the day. Although there were peak periods, they were much less distinct than at MEM; the more distinct departure peaks were accompanied by a lower level (but still significant number) of arrivals. On the example shown in the figure (a Saturday), there were 721 departures and 738 arrivals, so it was the lowest level of the twelve test days. During most of the day the recommended TRCM configuration was the same as the baseline schedule, except for three intervals, during early-morning, late-morning, and late-evening hours; during these intervals, most of the flights benefited from the different flow direction, although there were also many that were penalized. Overall departures benefited more than arrivals, however the net was positive for both (2.2% for arrivals and 7% for departures).
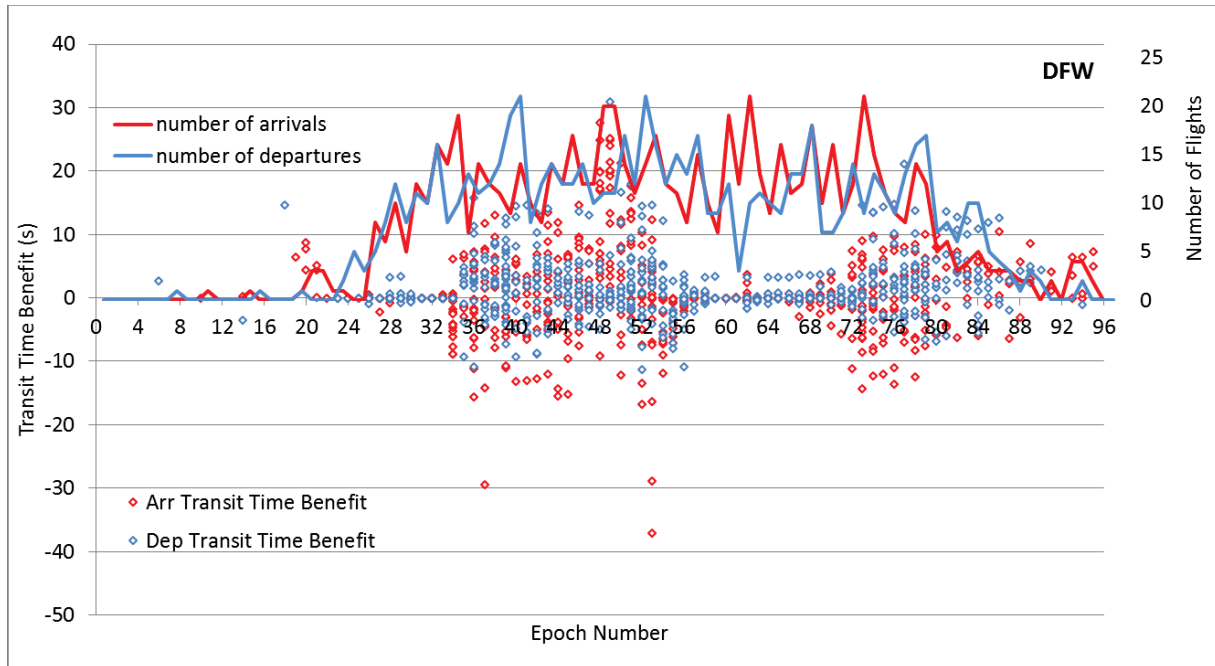
Figure 31. Demand and transit time benefit for DFW Day 2 (17OCT2009).

Most of the test days at JFK showed transit time benefits for arrivals and penalties for departures; the corresponding configuration changes seemed to favor arrivals. The daily traffic profile for JFK is somewhere between MEM and JFK; that is, there are distinct peaks in arrivals and departures with offsets between them, but they are not as distinct as for MEM.

A case where there was benefit for both arrivals and departures is shown in Figure 32. The data is from May 18, 2010 (a Tuesday). There are two distinct peaks towards the beginning of the day, from epochs 26-30 for arrivals, and from epochs 32-38 for departures. During the first of these, the TRCM configuration differs from the Baseline (between epochs 17-28), in fact is opposite to the flow direction of the baseline (22 vs 04); this resulted in benefits for arrivals. Two other intervals that resulted in benefits for arrivals are in 50-53 and 57-60; for portions just before these intervals (epochs 47-50 and 53-57), the flow directions were the same for baseline and TRCM, but still resulted in benefits. This could have been due the change in runway usage (the use of additional runways) that took place during these intervals. It is noted that during most of the day, the baseline configuration included arrivals on 4R and departures on 4L, but the TRCM recommendation had arrivals on 4R and 4L, with departures on 31L and 4L. It is not clear why the baseline configuration did not use similar runway combinations to make more runways available, however it seems that the TRCM combinations may have been what made the difference in benefits seen for this particular day. For departures, the first distinct peak had a large number of flights that benefited, possibly because there were not as many arrivals during that period. However, on this particular day most of the departures benefited, as can be seen by the small number of flights below the zero-line (penalty). During most of the time between epochs 39-70, the main difference for departures between the baseline and TRCM configurations was the additional use of 31L.
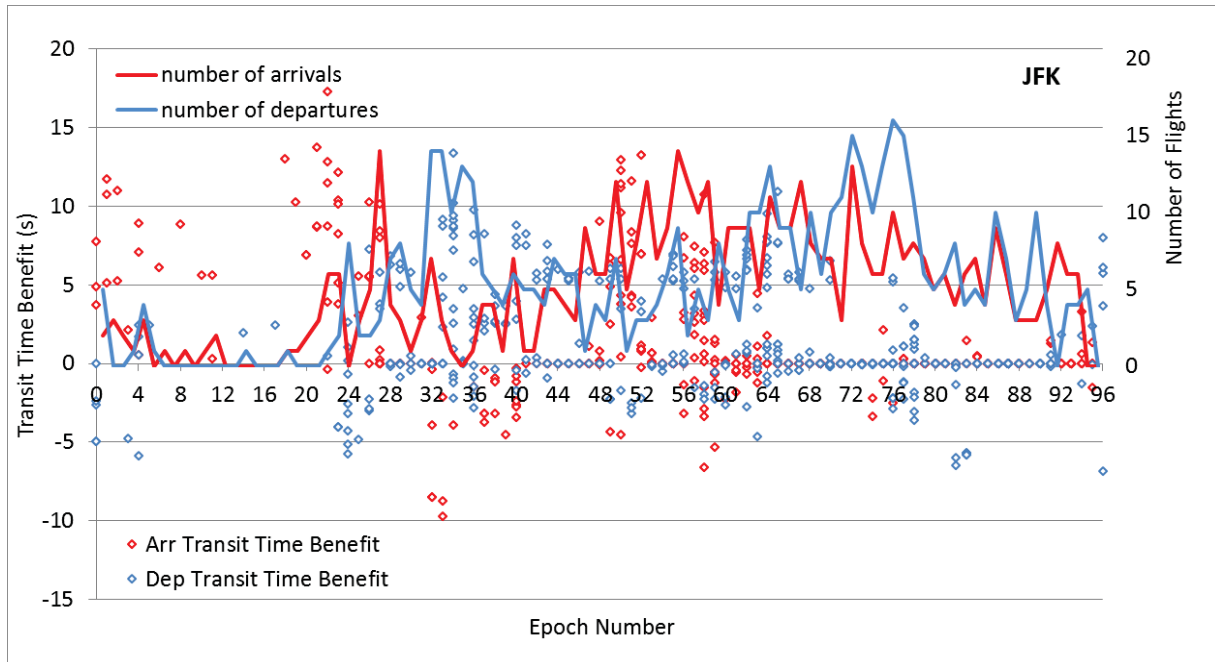
36

Figure 32. Demand and transit time benefit for JFK Day 8 (18MAY2010).

Sensitivity Study

A study was conducted to explore how to reduce the number of configuration changes recommended by the TRCM tool. A number of different methods were considered, including limiting to a specific number of changes per day, changing the time limit between configuration changes, and adding a threshold level to the objective function. The latter of these is the most likely to preserve TRCM benefits, because it directly addresses what the TRCM algorithm seeks to optimize. Setting a limit to the time between changes or to the number of changes allowed per day is arbitrary, since neither of these really addresses the variable nature of traffic demand and weather. On the other hand, the objective function seeks to minimize the transit time for all aircraft within a given time interval, thus it directly depends on the demand. Further, if one considers the number of aircraft within a given planning interval, and not just the total transit time for all aircraft in that interval, a threshold level per flight can be applied, minimizing the possibility of a situation where a single flight has a large transit time benefit, but a configuration change driven by that benefit would affect all the other flights in that same time interval, for whom little benefit might exist.

After examining the values of the objective function that were being computed during the TRCM planning cycle, it was determined that a threshold value of 30 seconds per flight was a reasonable starting point for exploring the effects that application of this threshold would have on the metrics already analyzed. The number of configuration changes is examined first, to ensure that application of the threshold is having the intended effect.

Figure 33 to Figure 38 show the resulting mean number of flow direction and runway usage changes per day for the twelve days at MEM, JFK, and DFW, for three cases: Baseline, TRCM with no threshold, and TRCM with a 30s/flight threshold. Flow direction (FD) and runway usage (RU) changes are shown on separate charts for clarity.

From these charts it can be seen that for five of the test days at MEM, the 30s per flight threshold did not make a difference in number of flow direction changes per day; on the other days the threshold resulted in 17-29% fewer changes in flow direction. For runway usage, the threshold resulted in substantially fewer changes per day for all but one day (#10).

Figure 33. Mean daily changes in flow direction at MEM

Figure 34. Mean daily changes in runway usage at MEM

At JFK, application of the threshold resulted in fewer changes in flow direction for all but one day, with reduction in average changes per day varying between 7-54%. Runway usage changes were reduced for all days, with an average reduction ranging between 14-56% per day.
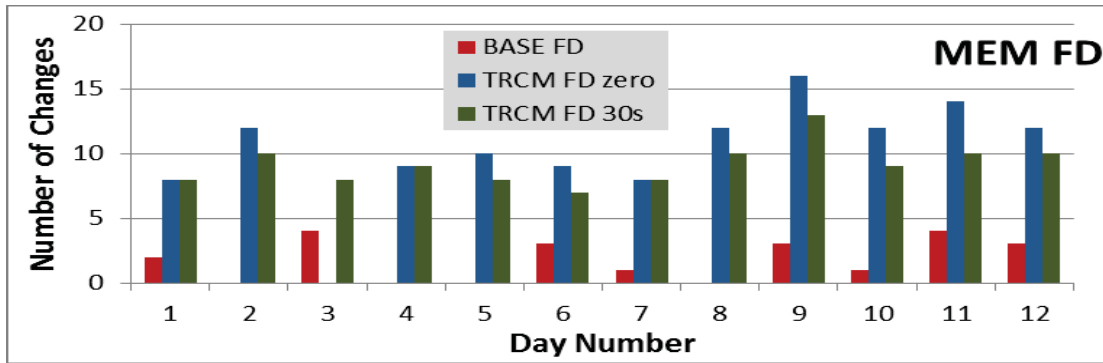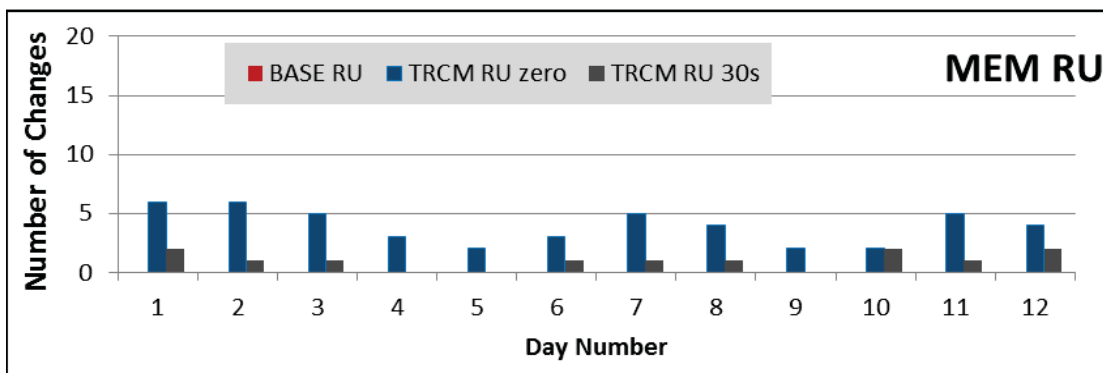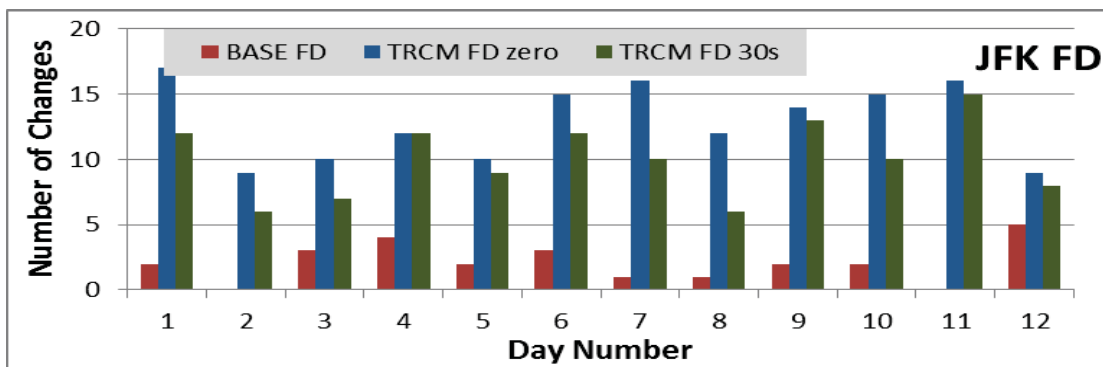

Figure 35. Mean daily changes in flow direction at JFK
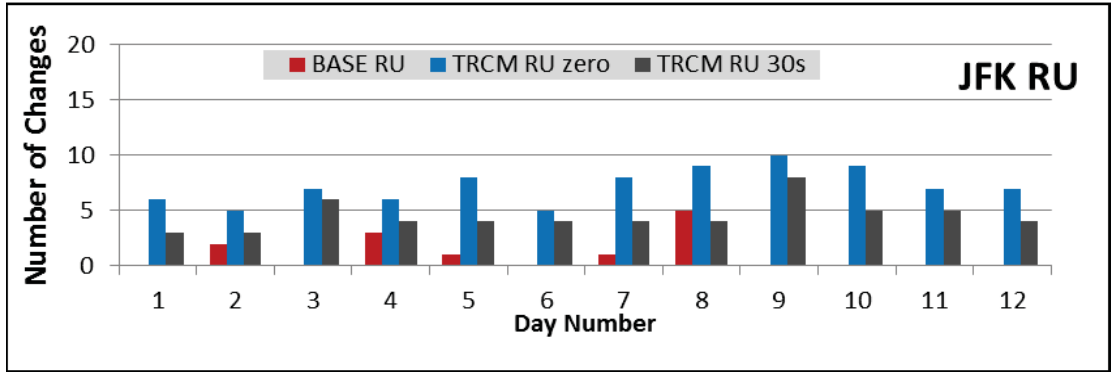
Figure 36. Mean daily changes in runway usage at JFK

At DFW, application of the threshold resulted in fewer changes in flow direction for 10 of the 12 days, with an average of 22-67% fewer changes over all the test days; runway usage changes were reduced to zero for all the test days, however there were not many in the TRCM unconstrained case to begin with (average of just over one per day). Overall mean reduction in number of changes for all airport and days is summarized in Table 10.
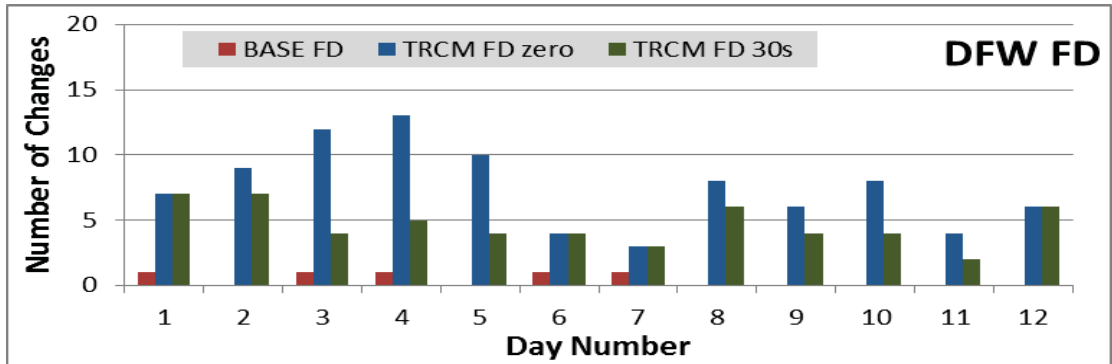
Figure 37. Mean daily changes in flow direction at DFW
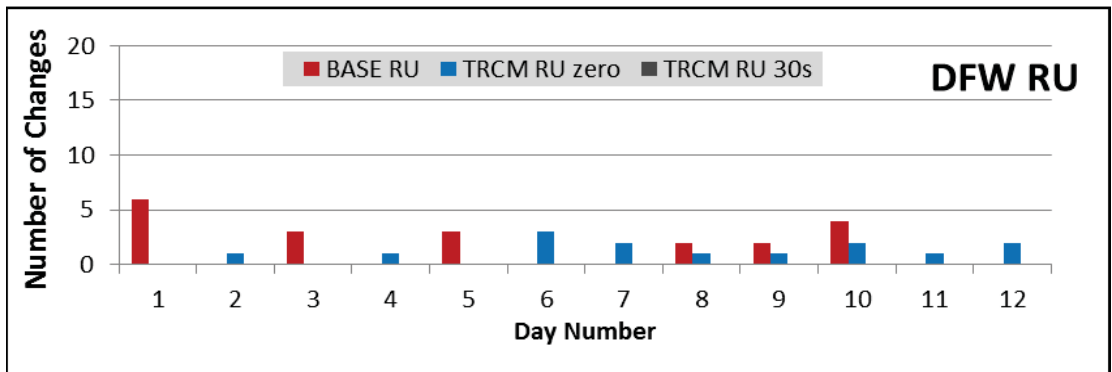
Figure 38. Mean daily changes in runway usage at DFW

Table 10. Overall mean reduction in number of FD and RU changes, averaged over all days

	MEM	JFK	DFW
Flow Direction	13.8%	25.3%	37.8%
Runway Usage	74.5%	37.9%	100.0%

Since some of the configuration changes were significantly reduced, it is necessary to see what effect that reduction had on the benefits, namely on the transit time and fuel use. Figure 39, Figure 40, and Figure 41 show the daily mean transit time for each of the three cases, baseline, TRCM with zero threshold, and TRCM with 30s threshold, for the three airports.
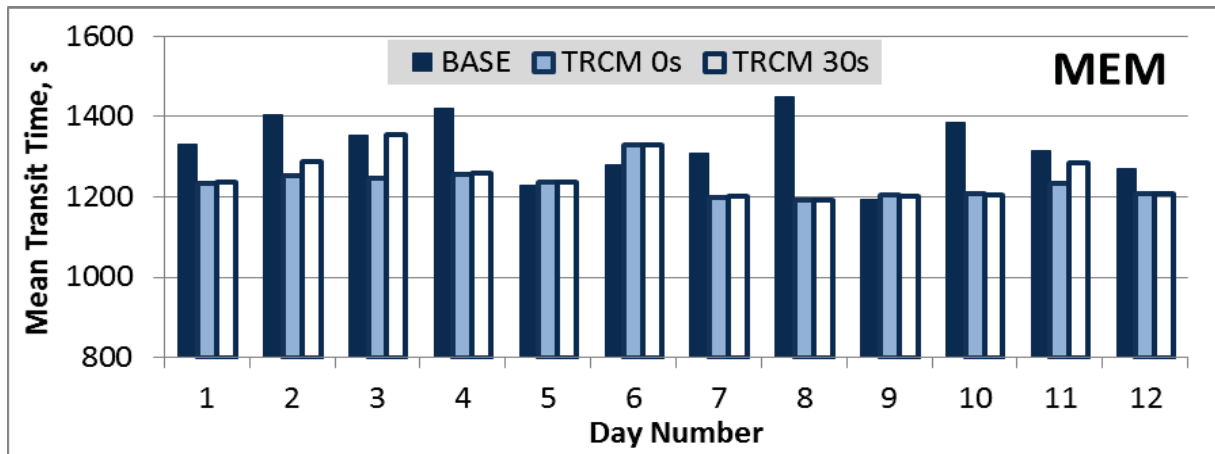
Figure 39. Mean daily changes in transit time at MEM
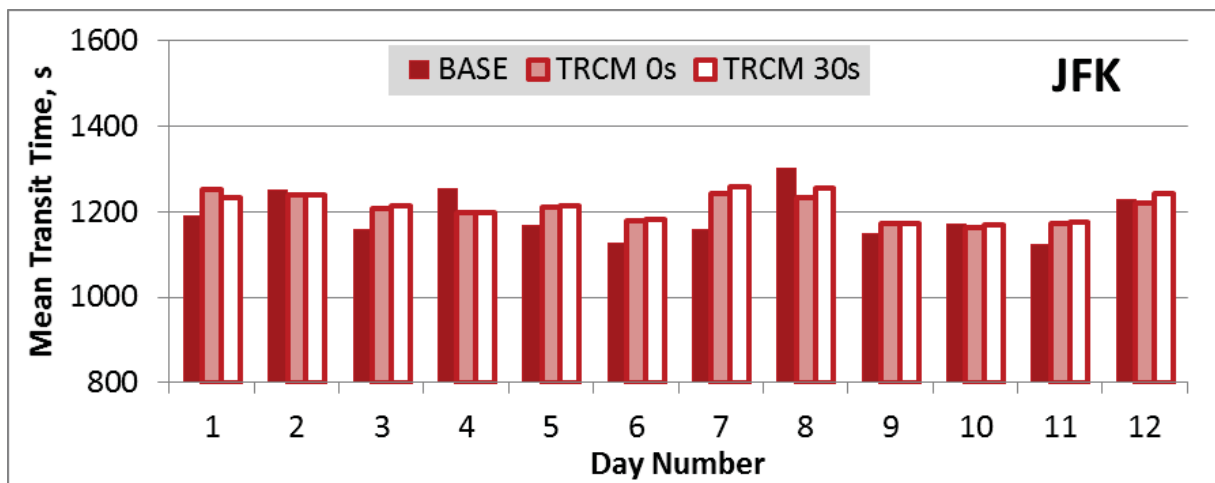
Figure 40. Mean daily transit time at JFK
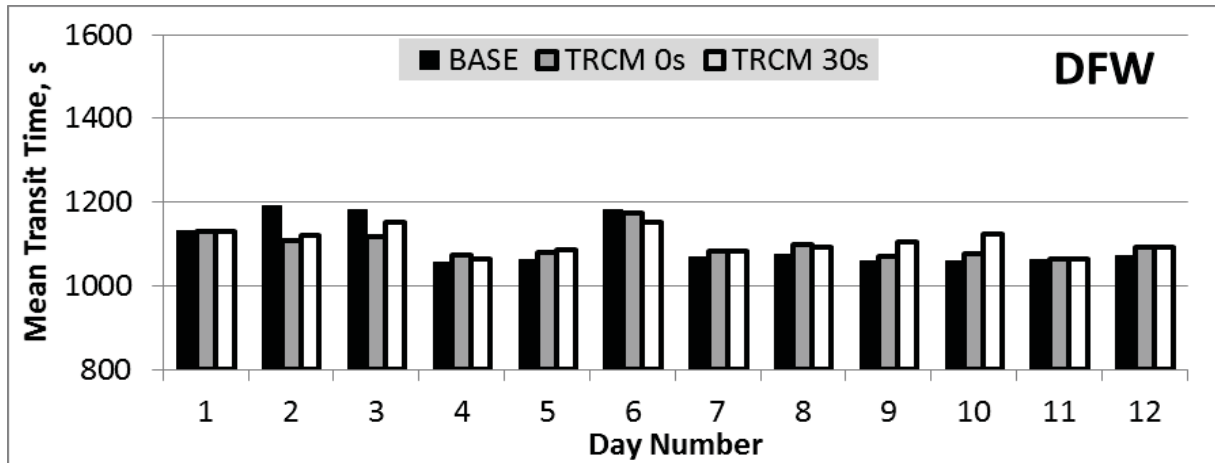
Figure 41. Mean daily transit time at DFW

A summary of the percent difference in transit times is shown in Table 11. For all of the airports, the difference in benefit between the 0s and 30s threshold case was within one percentage point; however, in some cases the benefit was very small to begin with, so a change by less than one percentage point was significant.

Table 11. Mean transit times (and percent benefit) per flight for all airports over all days, with 0s and 30s per flight threshold

|	Type of Operation	Baseline	TRCM 0s (% benefit)	TRCM 30s (% benefit)
MEM	Dep	1328.9	1233.1 (7.2)	1244.3 (6.4)
	Arr	1575.6	1541.8 (2.1)	1544.9 (1.9)
JFK	Dep	1189.2	1207.3 (-1.5)	1213.9 (-2.1)
	Arr	1762.0	1614.6 (8.4)	1608.3 (8.7)
DFW	Dep	1100.0	1096.8 (0.3)	1106.5 (-0.6)
	Arr	1604.8	1584.3 (1.3)	1582.7 (1.4)

A summary of the percent difference in fuel benefit is shown in Table 12. The numbers are the mean fuel used per flight (averaged over all days); for TRCM cases, the numbers in parentheses are the percent over the baseline that this number represents. Comparing these numbers shows that the percent benefit over the baseline was within one point for the 30s cases as for the zero-threshold case. Especially noting that the number of configuration changes at DFW and JFK were substantially reduced, the difference this reduction had in the transit time and fuel benefits is not proportional to the reduction in number of configuration changes. This would indicate that many of the configuration changes (particularly the changes in flow direction) recommended by TRCM were due to estimated benefits that were small in magnitude. Thus, applying a per-flight threshold on the objective function of the TRCM planner seems to result in configuration change numbers that are closer to what is historically used (and presumably more acceptable to air traffic managers), while only affecting the benefits by a small amount.

For completeness, the analysis was expanded to include additional threshold values added and resulting benefits, to further explore the space available for reducing configuration changes. Figure 42 shows the effect on configuration changes of applying threshold values of 0s, 30s, 60s, 90s, and 120s; mean number of flow direction (FD) changes

are shown in black symbols, mean number of runway usage (RU) changes in white symbols. From the chart it can be seen that, for all airports the mean number of FD and RU changes per day diminishes as the threshold increases. It can also be seen that for each airport the number of FD changes is much greater (at least twice as high) than RU changes, but they are also reduced as the threshold level increases. The baseline cases (leftmost cluster of markers) are all at or below a mean of 2 changes per day; it is possible that these are lower than what actually normally takes place, due to one of two factors: 1) this study only used a sample of twelve days, and the days chosen could have resulted in lower than normal average number of changes, or 2) the historical data might not accurately reflect the changes at a facility; it is not known how accurately this information is logged, since it often relies on a manual entry system. A more accurate analysis would require ensuring that these changes are correctly taken into accounted.

Table 12. Mean fuel use (and percent benefit) per flight for all airports over all days, with 0s and 30s per flight threshold

	Type of Operation	Baseline	TRCM 0s (% benefit)	TRCM 30s (% benefit)
	Dep	1575.6	1528.7 (3.0)	1528.0 (3.0)
MEM	Arr	973.6	954.4 (2.0)	959.9 (1.4)
	Dep	2257.6	2203.5 (2.4)	2199.8 (2.6)
JFK	Arr	1233.6	1148.2 (6.9)	1143.5 (7.3)
	Dep	1168.8	1163.4 (0.5)	1166.1 (0.2)
DFW	Arr	673.4	658.1 (2.3)	663.3 (1.5)

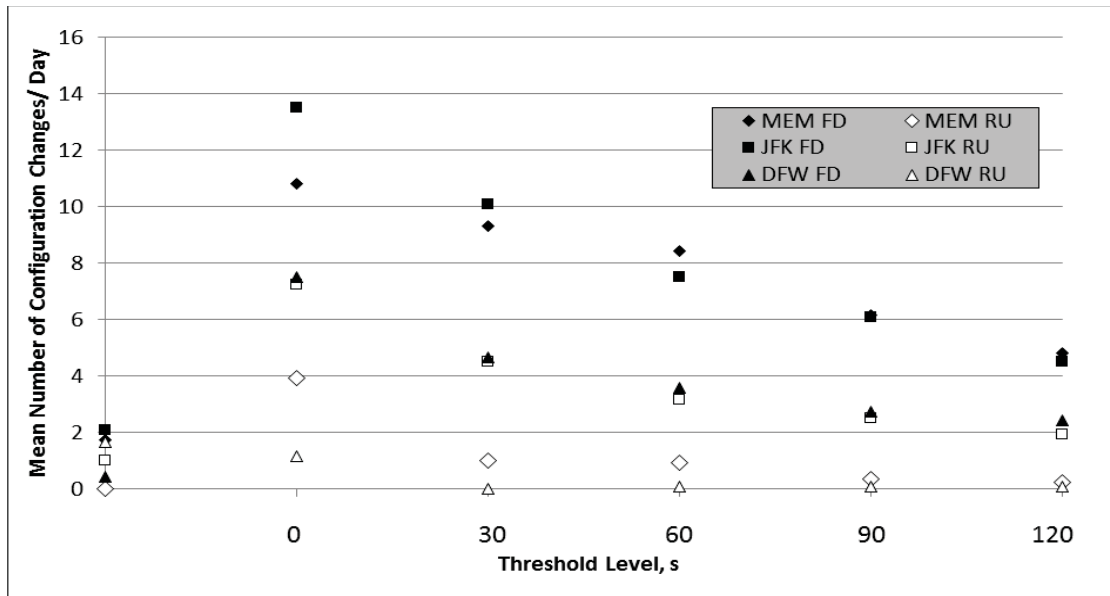Figure 42. Effect of threshold level on number of configuration changes per day

Mean transit time benefit is shown in Figure 43; because the results shown are the benefit, not the actual transit time, no data is shown for the baseline case, since benefit is defined as TRCM minus Baseline, so all the markers for Baseline would be at zero. Comparing the results from 0s and 30s it can be seen that the transit time benefit was

slightly reduced for most cases, except JFK arrivals. Moving on to 60s, there is slightly more reduction, which continues to be reduced as the threshold increases. This is as expected, except that the magnitude of the reduction in benefit is not as steep as had been anticipated. This would suggest that many of the original recommended changes (in the unconstrained TRCM case) are based on estimated benefits that are quite low; when these low-benefit-level recommendations are filtered out by applying a threshold, the overall benefits are not significantly affected.
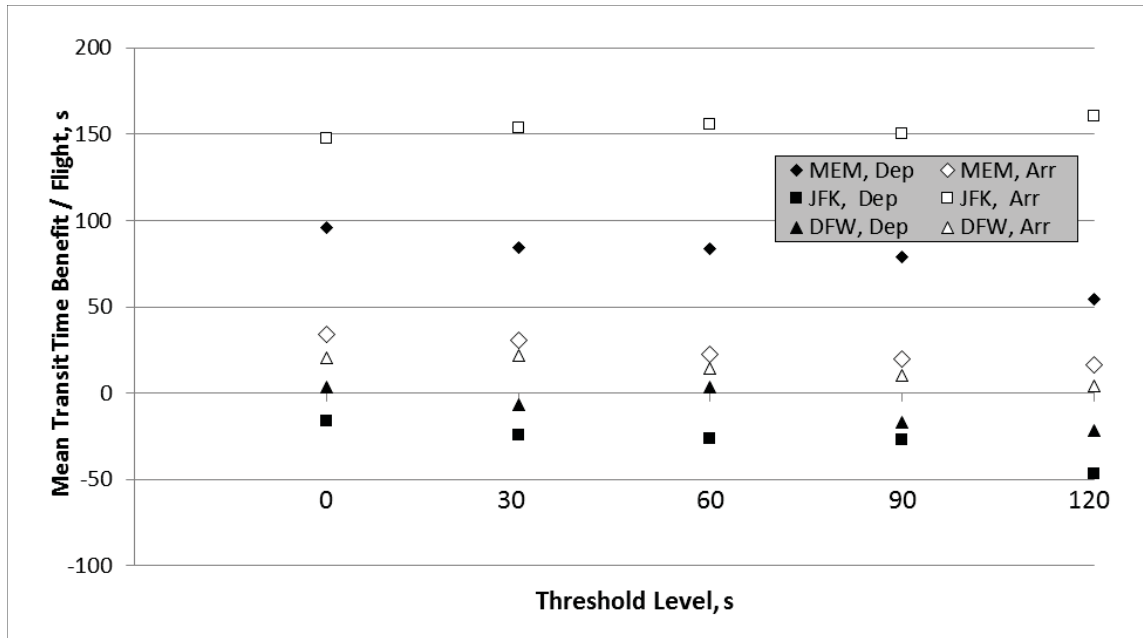
Figure 43. Effect of threshold level on transit time benefit per flight

Fuel benefits (Figure 44) show a similar decline with higher threshold settings, although there are some increases as well, for JFK arrivals at 30s, and 120s, and for JFK departures at 60s; at 90s MEM departures showed an increase over the 60s mean value. It is not clear why these resulted in increased benefits; however it does appear that fuel benefits are more sensitive to variations than are transit time benefits, particularly as related to any resulting changes in surface operations. Figure 45 shows departure queue benefit results in terms of percent change in both time and number in queue. Benefits at MEM remain fairly even regardless of the threshold level, however at JFK there is a slight improvement at 30s, followed by a rapid decline at higher threshold levels, and at DFW there is a slight improvement at 60s, followed by a decline at higher levels. This type of results illustrates how a different threshold level affects each airport differently, and could help to better determine the threshold level that provides the best operational level for a particular airport.

Figure 44. Effect of threshold level on fuel benefit per flight

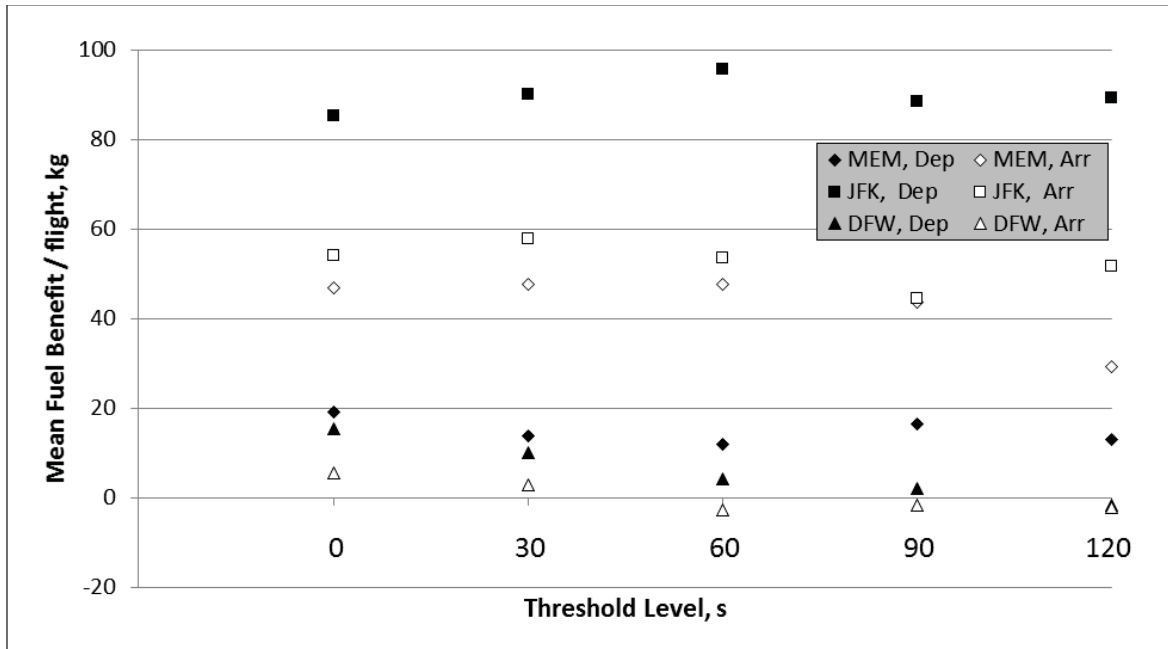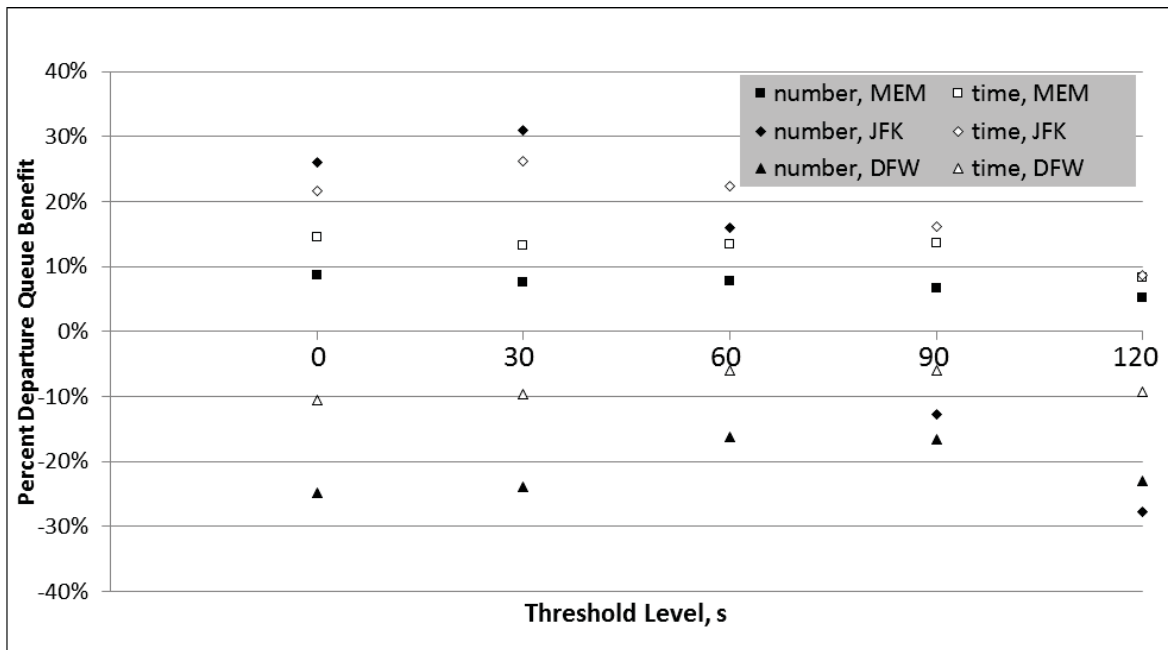Figure 45. Effect of threshold level on percent departure queue benefits (number and duration)

Alternative Method

An alternative form of this method for reducing the number of configuration changes was also studied. This alternative method involved only applying the threshold to changes in flow direction, such that the runway usage option was still available, even if the benefit threshold for flow direction changes was not reached. Figure 46 shows the resulting configuration changes when these thresholds were applied only to the FD changes. The FD changes remain the same as in the previous set of runs, because nothing was changed with respect to how those types of changes would be limited. However, the mean number of RU changes increased as the threshold was applied. In particular for MEM, the RU changes continue to increase as the FD changes decrease. For DFW the RU changes increase and then level off, while at JFK the RU changes increased until the 90s threshold level where they begin to decrease. Although this was a somewhat unexpected result, this effect makes sense, since there are still opportunities to improve the objective function with an RU change, if a FD change is not possible. As the threshold increases and there are fewer opportunities for FD changes, there are more opportunities for RU changes.
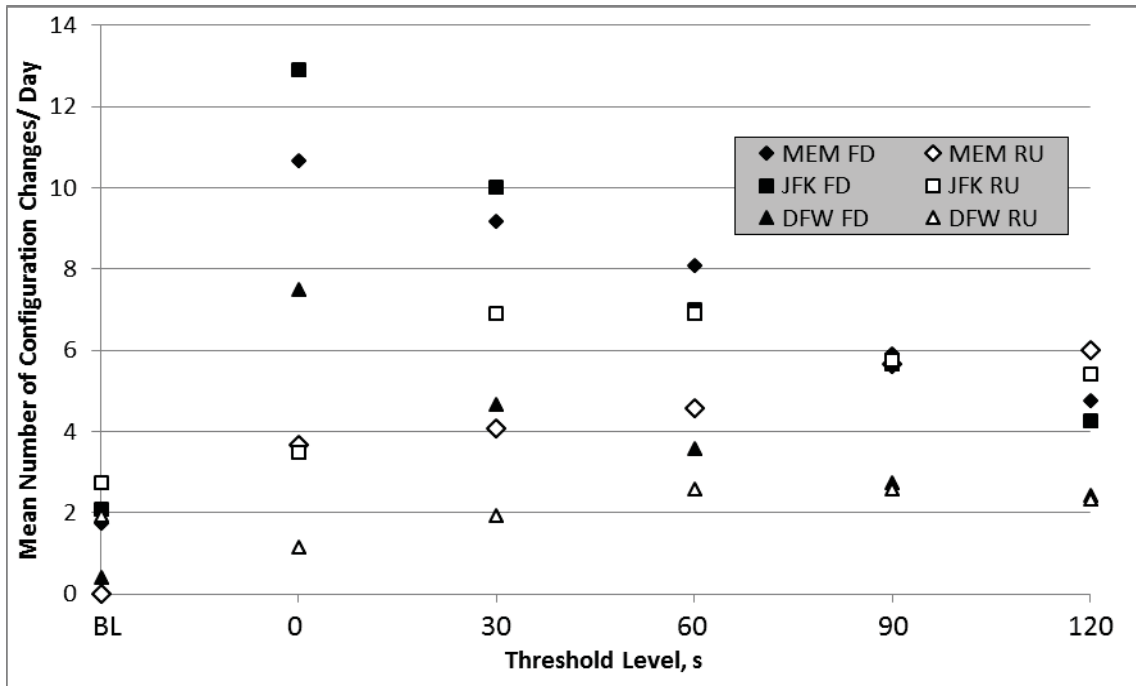
Figure 46. Effect of threshold level (applied only to Flow Direction changes) on number of Flow Direction (FD) and Runway Usage (RU) changes per day

Figure 47 shows the effect of this method for reducing the number of changes on transit time benefits. Comparing with the same chart for the previous set of results (when the threshold was applied to all types of changes), there is not much difference in the results, indicating that any additional gains from the increased number of RU changes is minimal.

Fuel and departure queue benefit results (Figure 48 and Figure 49) are very similar for this method of applying the threshold as for the previous method, also indicating that the additional RU changes did not have a primary effect on the fuel benefits. At the higher threshold levels however, the differences are more noticeable.

Figure 47. Effect of threshold level (applied only to Flow Direction changes) on transit time benefit per flight

Figure 48. Effect of threshold level (applied only to Flow Direction changes) on fuel benefit per flight.

At MEM the percent departure queue benefits remain fairly even regardless of the threshold level; at JFK the benefits are fairly even until 60s, then there is a rapid decline at higher threshold levels; at DFW there is a slight improvement until 60s, and then fairly even beyond that.
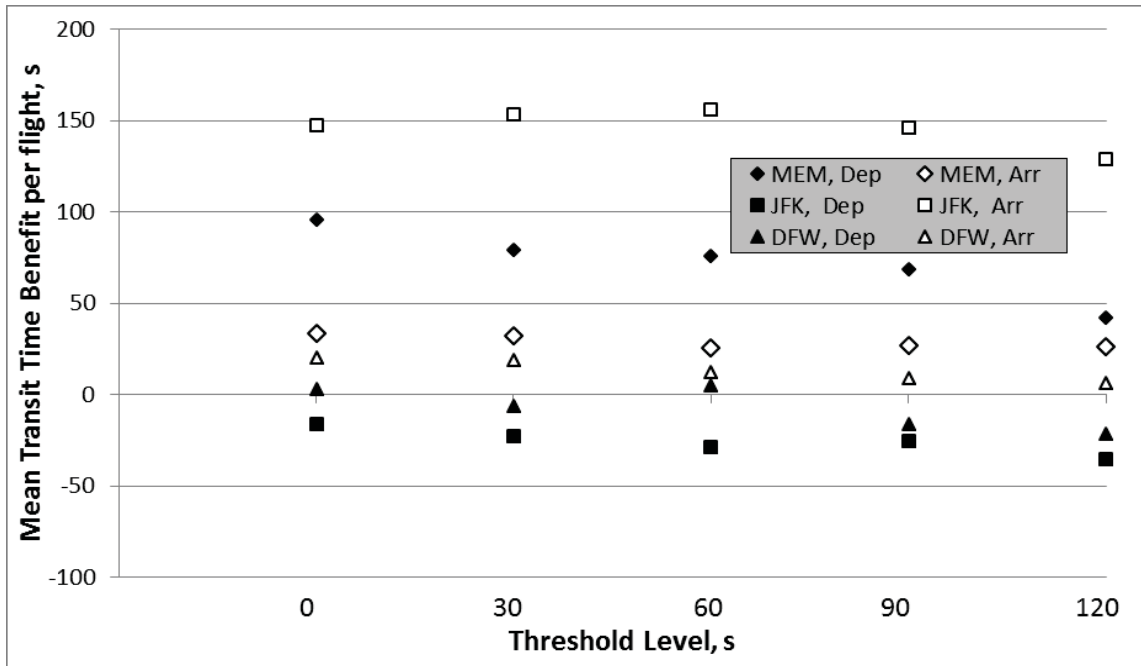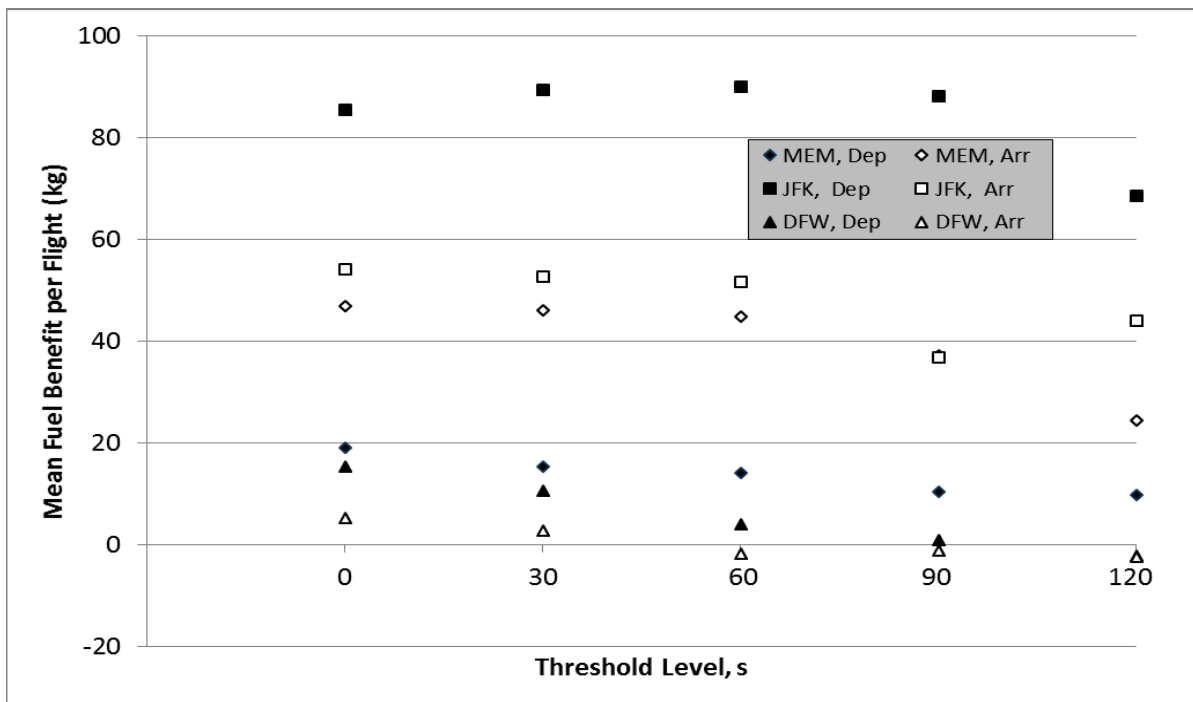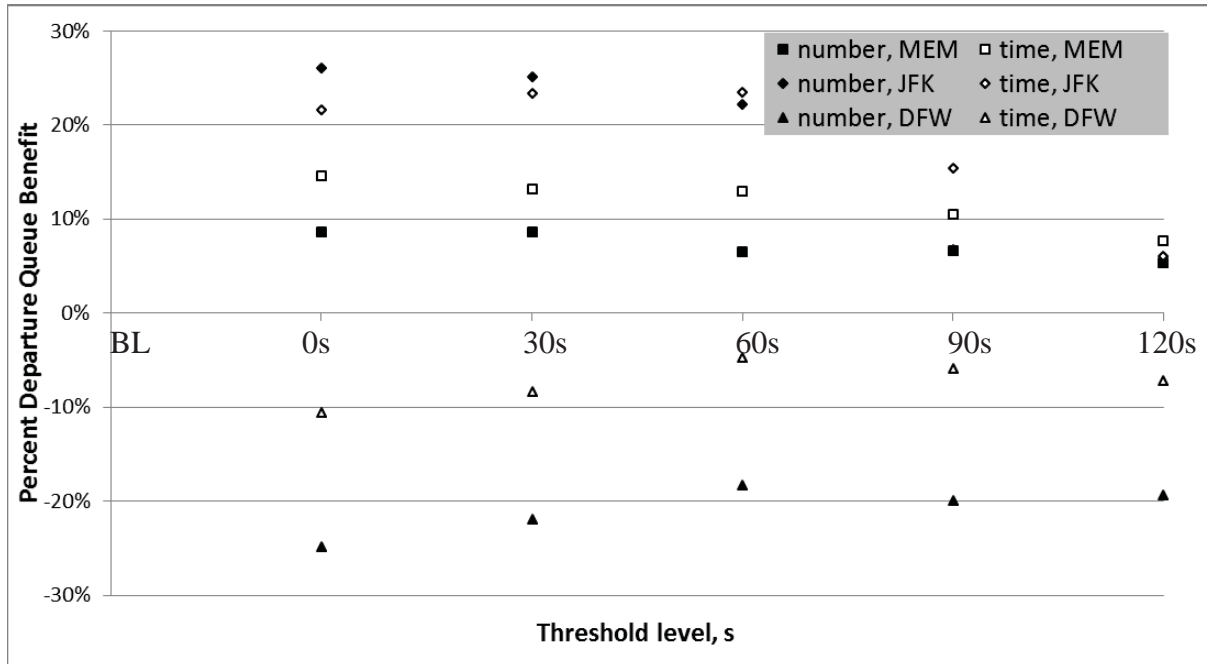

Figure 49. Effect of threshold level (applied only to Flow Direction changes) on percent departure queue benefits (number and duration)

Concluding Remarks

The System-Oriented Runway Management (SORM) is composed of two basic capabilities: Runway Configuration Management and Combined Arrival/Departure Runway Scheduling. The central component in the SORM concept is Tactical Runway Configuration Management, a tool for taking into account all the various factors and producing a recommendation for what would be the optimal runway configuration, runway use strategy, and aircraft sequence (last aircraft in old configuration and first in new configuration.

The benefit mechanisms that were explored in this analysis were lower transit times, shorter departure queues, and lower fuel burn for arrivals and departures. Based on results from this analysis, TRCM provided transit time benefits per flight for arrivals at all three airports (2.1%, 8.4%, and 1.3% for MEM, JFK, and DFW, respectively), and for departures at MEM (7.2%), when averaged over all flights. Benefits in departure queue length (ranging from 9.8-46.2%) and queue duration (14.6 to 21.6%) were observed at MEM and JFK, however at DFW there was a penalty of -15.7% in queue length and -10.6% in queue duration. Fuel use results showed benefits on the order of 2% for most cases except MEM departures (3%), JFK arrivals (6.9%), and DFW arrivals (0.5%). Thus it would appear that TRCM benefits arrivals more than departures; the percent benefit is higher for transit time than for fuel use, but they follow similar trends. Also, many of the departure benefits can be traced back to improvements in surface operations, and arrival benefits to improvements in flight times, particularly for JFK and MEM.

In this study, results showed greater benefits at MEM than at JFK; at JFK, benefits were greater for arrivals than for departures. Results from DFW have shown a smaller benefit than at the other two airports. The DFW results may be due to excessive taxi times, which in turn may be caused by delays due to inefficient surface operations, which would need to be investigated in future studies.

Transit time benefits were decomposed into surface and flight components, to trace back the source of the benefit (or penalty). Some of the key findings were:

- At MEM, departure and arrival benefits were largely the result of shorter surface times;

- At JFK: departure benefits were mostly the result of shorter surface times, while arrival benefits were driven by shorter flight times;

- At DFW: arrival and departure benefits included contributions from both the surface and flight.

A sensitivity study was conducted on the TRCM algorithm, to determine how the benefits varied in response to reductions in the number of recommended configuration changes. Results showed that both methods used provided a marked reduction in number of configuration changes per day at all three airports; in response to the reduced number of changes, transit time and fuel benefits were somewhat reduced, although generally by less than 10%. This suggests that many of the recommended changes in the unfiltered (no threshold applied) case were in response to smaller estimated benefit levels, and could be removed while still maintaining most of the original benefit. Exact values to be used for threshold level would need to be studied more carefully for a particular airport, prior to recommending where it should be set.

Based on the results of this study, some observations can be made regarding characteristics that appear to lend themselves to obtaining greater benefits from using TRCM:

1) Multiple options for runway configuration changes –having more than two options for direction of flow can increase the possibilities for TRCM to offer a benefit.

2) Demand levels that alternate between departures and arrivals; having traffic that alternates between arrivals and departures throughout the day appears to result in greater overall benefits for both types of operations.

3) A flow that is not dominated by one particular pattern. Airports that are limited due to geography, noise operating limits or other similar factors would have more limited options for configuration changes.

4) The ability to apply a weighting function to different intervals in the TRCM planning cycle may be a way to skew the configuration recommendation to favor arrivals or departures, which could be a more beneficial way for TRCM to operate.

A higher fidelity assessment of benefits is required prior to determining suitability of TRCM at any particular airport. This would include more accurate recording of historical configurations used, to ensure an accurate baseline condition for comparison. Also, a carefully modeled adaptation to include all configurations and runway use plans, and accurate modeling of surface operations is recommended.

Follow-on studies to this analysis should include investigation of sensitivity of benefits to demand levels and to suggested TRCM algorithm modifications for estimating surface operations, and improvement of simulation strategies for detecting anomalies in modeling of operations. Conducting this study in a different simulation environment would help to verify results obtained. Assessment of benefits at additional airports would help to better understand how TRCM benefits relate to airport characteristics, and allow extrapolation to estimate NAS-wide benefits.

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REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE *(DD-MM-YYYY)* 01- 03 - 2015	2. REPORT TYPE Technical Memorandum	3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE Benefits Assessment for Single-Airport Tactical Runway Configuration Management Tool (TRCM)	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Oseguera-Lohr, Rosa M.; Phojanamongkokij, Nipa; Lohr, Gary W.	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 305295.02.90.07.03.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199	8. PERFORMING ORGANIZATION REPORT NUMBER L-20475
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	10. SPONSOR/MONITOR'S ACRONYM(S) NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA-TM-2015-218700

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category03
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A benefits assessment was conducted for three simulated airports, for Tactical Runway Configuration Management (TRCM), a tool that considers various factors in producing a recommendation for optimal runway configuration, runway use strategy, and aircraft sequence. Results show benefits in transit time, fuel use, and departure queue; benefits were greater at MEM than at JFK or DFW, which had the least benefits. The magnitude of benefits depends on factors including the number and type of options available for runway configuration and usage, and the traffic demand on a particular airport. Arrivals benefited more than departures; departure benefits resulted from shorter taxi times, arrival benefits from shorter flight times. Throughput benefits followed a similar trend as transit time benefits. A sensitivity study showed that the number of changes in flow direction per day could be reduced with acceptable levels of benefit reductions. A higher fidelity assessment is required to determine suitability of TRCM at any particular airport. Follow-on studies should investigate sensitivity of benefits to demand levels and to improvements in simulation of airborne and surface operations; verification of results with different simulation platforms; studying additional airports to better relate TRCM benefits with airport characteristics, and allow extrapolation to the NAS.

15. SUBJECT TERMS

Benefits; Configuration; Runways

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)
a. REPORT	b. ABSTRACT	c. THIS PAGE			
U	U	U	UU	57	19b. TELEPHONE NUMBER *(Include area code)* (443) 757-5802

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