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Shadow Evaluation of the ATD-2 Phase 3 Trajectory Option Set Reroute Capability in the North Texas Metroplex

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Abstract—**This paper presents results of NASA's Airspace Technology Demonstration 2 Phase 3 Trajectory Option Set reroute capability designed to resolve a demand capacity imbalance along the terminal airspace boundary. We focus on Candidate flights generated during the Stormy 2020 Shadow Evaluation which was the result of using the system to passively collect predictions for each flight at the OUT event. Benefit metrics associated with the predictions are defined for the individual rerouted flight and also the system-wide savings. Candidate flights are grouped into three distinct use cases and the benefit mechanism is explained for each use case along with illustrative data. Analysis of the different use cases shed light on the underlying causes of the reroute opportunites. Lessons learned from the Stormy 2020 Shadow Evaluation including the importance of reroutes during recovery from Severe Weather Avoidance Programs and also reroutes in the absence of terminal airspace restrictions will be incorporated into the Phase 3 Field Evaluation in 2021 to maximize reroute opportunities.**

I. INTRODUCTION

Concepts and technologies to manage arrival, departure, and surface operations have been under development by NASA, the Federal Aviation Administration (FAA), and industry to improve the flow of traffic into and out of the nation's busiest airports. Whereas trajectory-based concepts and technologies have been developed for specific phases of flight, their integration across surface and airspace domains to increase efficiency of the traffic flows remains a considerable challenge [1].

To address this challenge, NASA is conducting the Airspace Technology Demonstration 2 (ATD-2) to evaluate an Integrated Arrival, Departure, and Surface (IADS) traffic management system [2], [3]. The IADS concept builds on and integrates previous NASA research such as the Terminal Sequencing and Spacing (TSAS) [4], the Precision Departure Release Capability (PDRC) [5], and the Spot and Runway Departure Advisor (SARDA) [6], [7] which each focused on individual airspace domains. The IADS concept was initially developed based on the Surface Collaborative Decision Making (S-CDM) Concept of Operations [8] and refined over time [9].

The IADS Phase 1 and Phase 2 system was deployed to Charlotte Douglas International Airport (KCLT) for a three-year field evaluation. The Phase 1 field evaluation began in September 2017 and ended September 2018. During this time the IADS system was evaluated for three key capabilities 1) data exchange and integration, 2) tactical surface metering, and 3) departure scheduling and electronic negotiation of controlled flight release time for insertion into the overhead stream [10]. The Phase 2 field evaluation between September 2018 and September 2019 evaluated 1) Strategic Surface Metering Program (SMP) [11], 2) integration of Elecontronic Flight Strips, and 3) pre-scheduling using airline provided Earliest Off Block Time (EOBT) for electronic negotiation of controlled flight release time into the overhead stream .

The IADS Phase 3 system [12] extends the coordinated scheduling of arrivals, departures, and surface traffic from a single airport to a Metroplex environment in North Texas [13]. The North Texas Metroplex contains two major airports Dallas/Fort Worth International Airport (KDFW), Dallas Love Airport (KDAL), and other satellite airports in the D10 Terminal Radar Approach CONtrol (TRACON). The challenges in the North Texas Metroplex are fundamentally different than the challenges addressed by the IADS Phase 1 and Phase 2 capabilities deployed to KCLT. At KCLT surface congestion and constraints from controlled flights are the main challenges, whereas in the North Texas Metroplex, the main constraint is the departure fix capacity as multiple major airports compete for the same limited resources. The demand capacity imbalance at the terminal airspace boundary can be magnified when inclement weather impacts the Metroplex and reduces the capacity at the departure fixes which can propagate delay to the surface of each airport within the Metroplex.

The IADS Phase 3 system aids Flight Operators in the decision to reroute aircraft over an alternative departure fix by assessing the delay savings on each alternative route defined by a Trajectory Option Set (TOS). The TOS is a set of alternative routes the flight is willing to fly and each route has an associated Relative Trajectory Cost (RTC). The delay savings for each route in the TOS is compared to its RTC to determine when the delay savings on an alternative route rises above the RTC threshold value. The predictions of delay incorporate all known constraints in both the terminal airspace and each airport within the North Texas Metroplex. In addition to predicting the delay savings for individual flights, the IADS Phase 3 system also calculates the overall savings at the system level resulting from a reroute of a single flight. The savings at the system level is important for the Flight Operators as they are able to see how rerouting a single flight can benefit their fleet.

Previous to the IADS Phase 3 system, the majority of TOS research focused on strategic reroutes of flights around airspace constraints such as Flow Constrained Areas or sector capacity restrictions [14]–[16]. Tactical reroutes around airspace constraints using TOS were considered in [17], [18]. These scheduling solutions provide insights into the demand capacity imbalance in the airspace, but might not be feasible in practice due to surface constraints that are not accounted for. Other methods incorporating both surface and airspace constraints were proposed in [19], [20], but did not incorporate TOS options in the formulation or scheduling.

This paper presents results of the IADS Phase 3 TOS reroute capability in the North Texas Metroplex. We focus on Candidate flights generated during the Stormy 2020 Shadow Evaluation. The Stormy 2020 Shadow Evaluation was the result of using the IADS Phase 3 system to passively collect predictions for each flight at the OUT event. Benefit metrics associated with the predictions are defined for the individual rerouted flight and also the system-wide savings related to better use of available capacity.

For analysis, the Candidate flights are grouped into three distinct use cases defined by Traffic Management Iniatives (TMIs), recovery from Severe Weather Avoidance Program (SWAP), and non-TMI. The benefit mechanism is explained for each use case along with illustrative data. Analysis of the TMI and non-TMI use cases shed light on the underlying causes of the TOS reroute opportunites. Lessons learned from the Stormy 2020 Shadow Evaluation will be incorporated into the Phase 3 Field Evaluation in 2021.

This paper is organized as follows. Section II provides background information on the North Texas Metroplex and the IADS Phase 3 TOS reroute capability. Section III defines the benefit metrics used to evaluate the Candidate flights and Section IV defines three distinct use casses that the benefit flights are cagetorized into for analysis. Section V analyzes the Candidate flights to better understand the underlying causes and concluding remarkes are provided in Section VI.

II. BACKGROUD ON IADS PHASE 3 TOS REROUTE CAPABILITY IN NORTH TEXAS METROPLEX

The North Texas Metroplex airspace is centered at or around Dallas/Fort Worth International Airport and extends outward approximately forty miles. It contains two major airports, KDFW and KDAL, which are separated by approximately ten miles, see Fig. 1. Several busy general aviation airports, a regional cargo hub, and a Naval Air Station Joint Reserve Base are also located within the D10 TRACON, contributing to operational complexity [21].

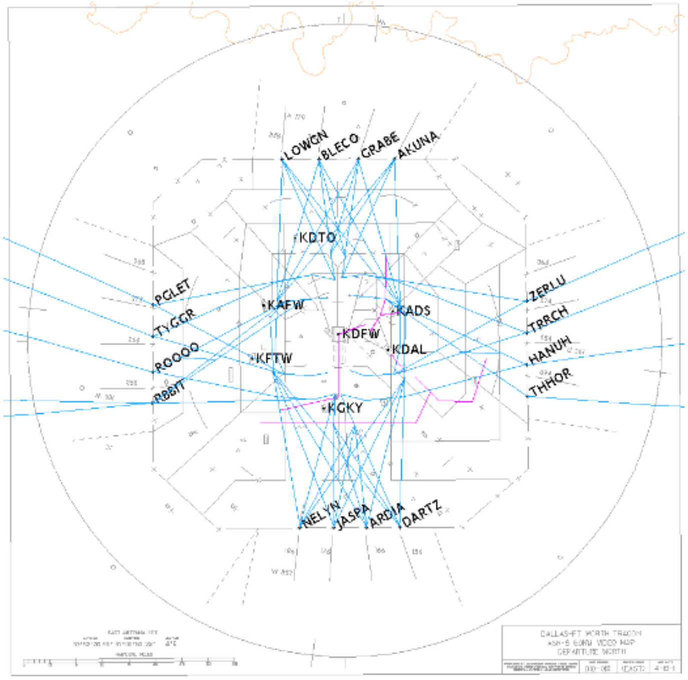

Fig. 1. North Texas Metroplex with multiple airports sharing 16 departure fixes along the terminal boundary.

A. Capacity and Restrictions at the Terminal Boundary

Capacity along the North Texas Metroplex terminal airspace boundary is defined by minimum separation constraints and TMI restrictions that are enforced at the departure fix. TMIs at the terminal boundary are typically triggered by weather events or downstream flow constraints that propagate back to the TRACON environment [21], and ultimately the departure airports.

In response to weather events around or near the terminal boundary the TRACON Traffic Management Unit (TMU) will close departure fixes which result in the departure gate being partially or completely blocked. The departure gate is the collection of four departre fixes along each side of the terminal boundary. Fig. 2(a) illustrates a situation where three of the four East departure fixes have been closed and traffic through these fixes is rerouted to the single remaining fix along the East gate. This compression of the departure fixes reduces the capacity at the terminal boundary and delays can be amplified when Air Traffic Control (ATC) enforces additional departure fix restrictions such as Miles-In-Trail (MIT).

B. Trajectory Option Set Reroute

When TMI restrictions reduce the capacity at the terminal boundary there are often opportunities to route around the

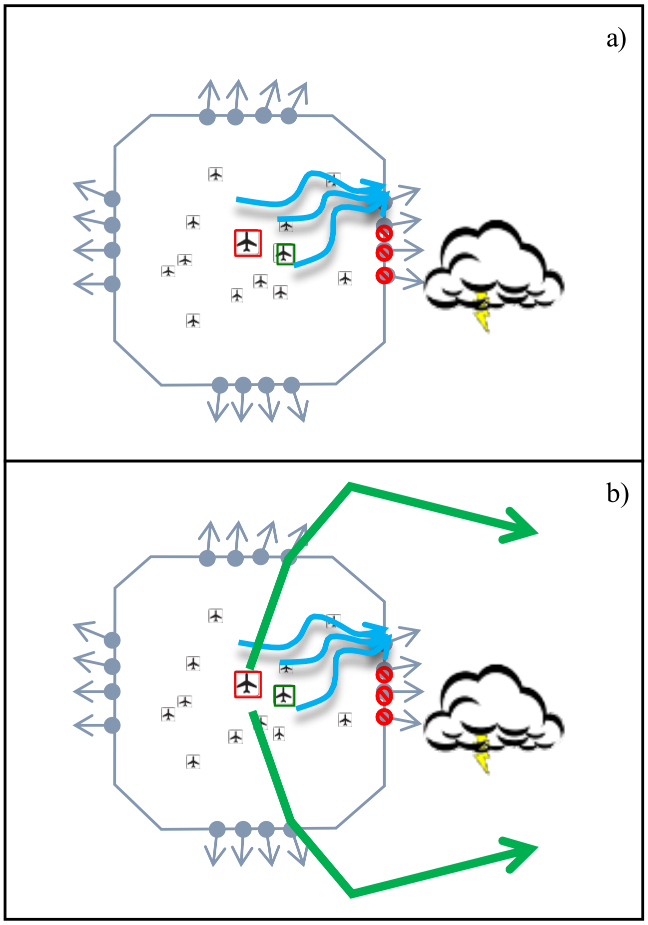

Fig. 2. a) D10 airspace with weather impacting the East gate. b) Available TOS routes not impacted by weather constraints.

restrictions and reduce the delay. Fig. 2(b) shows the situation where the East gate is limited to a single fix with a MIT restriction, while the North gate and South gate have all four fixes available. When the traffic volumes through the North and South gate are relatively light and the green routes are not impacted by a TMI restriction, a flight could reroute through the North or South gate with little to no delay.

A Flight Operator defines the TOS which is the set of feasible routes for a given flight. The filed route is typically the most direct route and is preferred by the Flight Operators under nominal operations. The cost of each route option, often a function of the additional mileage needed to fly the route, is provided by the Flight Operators in the form of a Relative Trajectory Cost (RTC). The RTC is a way for the Flight Operators to express their willingness to fly a more costly route when the delay savings on the surface exceeds the RTC threshold.

C. *Stormy 2020 Shadow Evaluation*

The IADS Phase 3 TOS reroute capability was intended to be evaluated during the IADS Phase 3 Stormy 2020 Field Evaluation between May and September 2020. Prior to the start of the Field Evaluation in March 2020, air traffic demand dropped sharply due to impacts of COVID-19. Fig. 3 shows the count of departure flights in North Texas originating from KDFW and KDAL plotted in blue and orange, respectively. The horizontal axis shows the date and the vertical axis shows the percentage of the average departure demand benchmarked against traffic levels from early 2020.

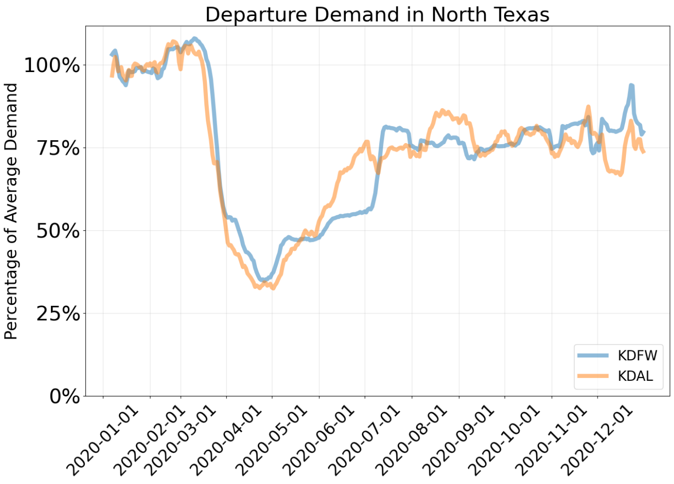

Fig. 3. 2020 departure demand in North Texas.

In April 2020 demand in North Texas dropped to around 35% of average demand. With such low traffic demand it was uncertain if the demand capacity imbalance at the terminal boundary would manifest resulting in enough delay to test the TOS reroute capability. To allow for demand levels to return, the IADS Phase 3 Stormy 2020 Field Evaluation was postponed to 2021.

The Phase 3 system was nonetheless built and deployed to the North Texas Metroplex in March of 2020. This provided the means to passively collect predictions from the Phase 3 system in shadow mode to evaluate the type of TOS reroute opportunities that arise. Lessons learned during the Stormy 2020 Shadow Evaluation will be incorporated into the Phase 3 Field Evaluation during Stormy 2021.

This paper presents the results from the Stormy 2020 Shadow Evaluation. The results should be interpreted with the context of the low traffic demand levels shown in Fig. 3. As demand is expected to grow and return to normal levels, the demand capacity imbalance at the terminal boundary should also grow and result in more TOS reroute opportunities and greater benefits.

III. IADS PHASE 3 METRICS

Here we define the metrics which we use to analyze the benfit to the Candidate flights. We begin with metrics associated with the individual flight that is rerouted and then extend the metrics to incoporate the system-wide savings associated with better use of available capacity.

A. *Metrics for Individual Rerouted Flight*

A core capability of the IADS Phase 3 scheduler [13] is predicting an individual flight's OFF Delay Savings (ODS) for a TOS route. The ODS on a given TOS route is defined as:

$$ODS_T = TT_T - TT_F \tag{1}$$

where TT_T and TT_F represent the predicted Taxi Time (TT) on the TOS alternative route and original filed route, respectively. A negative value represents the TOS route is beneficial as the predicted taxi time on the TOS alternative route is less than the predicted taxi time on the original filed route.

We sample the ODS and all other metrics defined in this paper at the OUT event for each aircraft. For consistency, we identify the last schedule generated by the IADS scheduler prior to the OUT and measure the TT as the diference between the Estimated Take Off Time (ETOT) and the Unimpeded Off Block Time (UOBT). These metrics represent the last predictions Flight Operators would see prior to the pushback event. Predictions on both the filed route and the TOS routes reflect all known TMI constraints within the system. At the OUT event, different TOS routes could show different values of OFF Delay Savings ODS_T reflecting the unique constraints each route is subject to such as predicted runway and terminal restrictions.

The Candidate status for a TOS route is determined by comparing the ODS_T to the TOS route RTC_T to calculate the Net OFF Delay Savings (NDS). The NDS on a given TOS route is defined as:

$$NDS_T = ODS_T + RTC_T \tag{2}$$

where the RTC_T takes a positive sign if the TOS route has an additional cost associated with flying. A negative value for the NDS_T represents that the taxi time savings of the negative value ODS_T exceeds the cost of the positive value RTC_T and the TOS route meets the minimum Flight Operator requirements for a reroute. If a flight pushes back when multiple TOS routes have a negative NDS_T value, the TOS route with the minimum value (i.e., the TOS route with maximum benefit) is chosen by the system as the Candidate route for this analysis.

A flight which pushes back in the Candidate status can sometimes be a poor choice for reroute due to downstream constraints. For example, a flight could push back with -30 minutes of ODS_T and -20 minutes of NDS_T and appear like an attractive candidate, but if rerouted, the flight might get to the downstream destination too early and cause a gate conflict. To inform Flight Operators about downstream predictions we introduce the IN Delay (ID) for the filed route. The ID on the filed route is defined as:

$$ID_F = \Big[ETOT_F + \Big(LIBT_F - LTOT_F\Big)\Big] - SIBT_F \tag{3}$$

where the $ETOT_F$ represents the predicted ETOT on the filed route, $LIBT_F$ represents FAA Traffic Flow Management System (TFMS) airLine IN Block Time on the filed route, $LTOT_F$ represents the TFMS airLine Take OFF Time on the filed route, and $SIBT_F$ represents the Scheduled IN Block Time on the filed route.

The component of the ID_F in the square brackets represents the predicted IN time and is composed of the IADS predicted ETOT plus a component that represents the TFMS airline provided prediction of transit time between OFF and IN events. The predicted IN time is compared to the SIBT to determine the amount of delay on the filed route that is predicted at the downstream airport.

The ID_F can be compared to a TOS route IN Delay Savings (IDS) to determine if the the reroute might be disruptive to downstream operations. The IDS on a given TOS route is defined as:

$$IDS_T = ODS_T + AFT_T \tag{4}$$

where AFT_T represents the Additional Flight Time on the TOS alternative route. A negative value for the IDS_T represents the TOS route would arrive at the destination earlier than the original filed route. The AFT_T is calculated based on the difference between the ground miles of the TOS route and the original filed route divided by the filed flight speed.

Comparing the ID_F with the IDS_T we can estimate the IN Delay on the TOS route. The ID on a given TOS route is defined as:

$$ID_T = ID_F + IDS_T \tag{5}$$

where a negative value represents the TOS route is predicted to get to the downstream destination earlier than scheduled. With the ID_T we can now determine if a flight pushing back with -30 minutes of ODS_T and -20 minutes of NDS_T would be good to reroute in practice. A Flight Operator can determine a constraint that Candidate flights should arrive no earlier than X minutes before SIBT at the destination. If the ID_T is greater than $-X$ minutes then the TOS route would meet their criteria.

B. Metrics for System-wide Aggregate Delay

For each TOS alternative trajectory we calculate an $ETOT_T$ for the rerouted flight and $ETOT_R$ for the rest of the flights in the schedule under the assumption of the TOS reroute. We define the system-wide Aggregate Delay Savings (ADS) associated with a given TOS route as:

$$ADS_T = ODS_T + \sum_{\mathbb{F}} \Big(TT_T^* - TT_F^*\Big) \tag{6}$$

which is the OFF Delay Savings to the rerouted flight plus a sum over the set of flights $\mathbb{F}$ of the difference in taxi time $TT_T^* - TT_F^*$ for other flights under the assumption of the TOS reroute. When a single flight is rerouted and the reroute results in $ETOT_T$ on the TOS route not equal to $ETOT_F$ on the filed route, the change propagates through the schedule and other flights ETOTs can be updated. The result can be that flights that are not rerouted have taxi time TT_T^* (assuming the TOS reroute) not equal to TT_F^* (assuming the original filed route), thus the system-wide ADS_T measure changes.

The set of flights $\mathbb{F}$ that we include in the ADS_T summation can be defined to provide different flavors of the metric. We

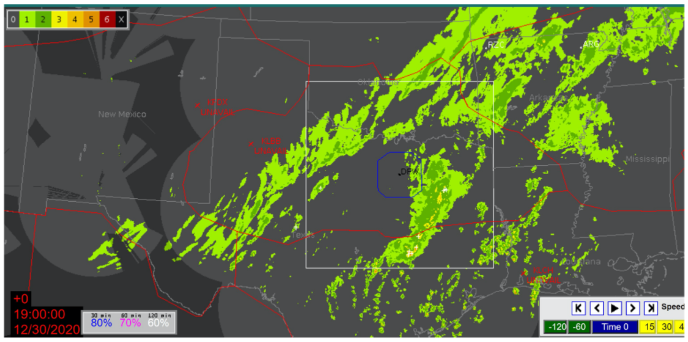

Fig. 4. Weather in North Texas on December 30th 2020 provided by Corridor Integrated Weather System (CIWS).

define ADS_T to be restricted to flights with Unimpeded Take Off Time within sixty minutes of current time. Additional filters focusing on all flights in the North Texas Metroplex, flights only from KDFW, or flights only from KDAL can be added. The different versions of ADS_T could be valuable to different decision makers. ATC might be interested in looking at ADS_T summed over the entire Metroplex to understand the impact of a single reroute to the flow through the terminal whereas Flight Operators might be more interested in the set of flights $\mathbb{F}$ from a specific airport or even a specific Flight Operator to understand the impact of the reroute decision on their fleet.

IV. IADS PHASE 3 TOS REROUTE USE CASES

Here we define three distinct use cases that emerged during the Stormy 2020 Shadow Evaluation. We begin with a use case labeled TMI which is triggered by ATC restrictions along the terminal boundary. Next, we explain how Flight Operators can use the Phase 3 TOS reroute capability to recover from Severe Weather Avoidance Programs (SWAP). Lastly, we describe the non-TMI use case which are often tactical TOS reroute opportunities associated with TOS route runways located near the flight's parking gate.

A. *Traffic Management Initiative (TMI) Use Case*

On December 30^{th}, 2020 the North Texas Metroplex experienced a five hour weather event lasting between 14:00Z and 19:00Z (Fig. 4) during which a weather front along the East departure gate impacted traffic flows. ATC restricted the East departure gate by closing three of the four departure fixes and rerouting the flows to the single open departure fix illustrated in Fig. 2a. ATC also restricted the single flow with 10 MIT which requires additional spacing between subsequent aircraft.

The combination of fix closures and MIT restrictions reduced the capacity along the East gate: however, the other gates were not subject to any restrictions and created an opportunity to reroute around the weather restrictions. During this five hour event, a total of 352 flights departed from KDFW and KDAL and 51 (51/352 = 14%) of these flights were TOS Candidates at the OUT event. The TOS Candidates were concentrated within the East gate departures where 115 flights had a total of 49 (49/115 = 43%) Candidates at the OUT event.

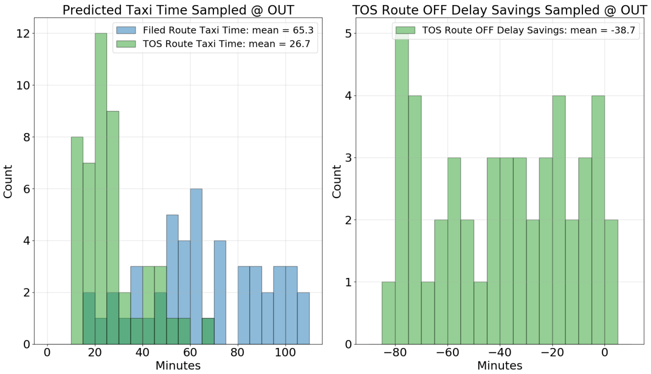

Fig. 5. OFF Delay Savings for Candidate flights.

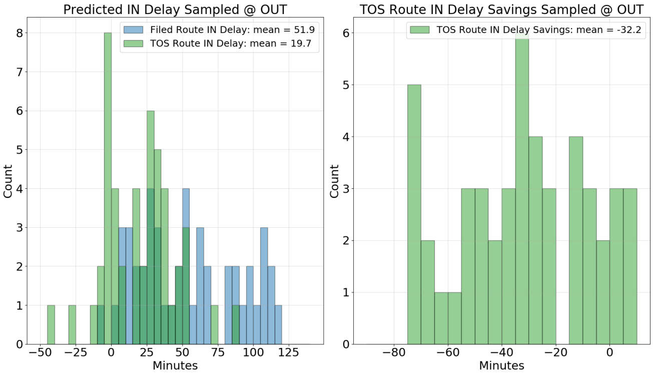

Fig. 6. IN Delay Savings for Candidate flights.

The demand capacity imbalance along the terminal boundary generated the Candidate flights with benefits shown in Fig. 5, Fig. 6, and Fig. 7. Three of the Candidate flights were filtered out due to missing predictions of IN Delay leaving 48 flights for analysis. The Fig. 5 subplot on the left shows the predicted taxi time in minutes on the filed route T_F and on the TOS route T_T, colored in blue and green respectively. The blue taxi time T_F on the filed route shows flights were predicted to experience large values of delay with an average taxi time of 65 minutes. In contrast, the green taxi time T_T on the TOS route shows flights were predicted to experience much less delay with an average taxi time of 27 minutes.

The subplot on the right of Fig. 5 shows the prediction of OFF Delay Savings ODS_T (Eqn. 1) in minutes for the Candidate flights colored in green. The ODS_T is the difference between the predicted taxi time on the filed route TT_F and on the TOS route TT_T (shown in the left subplot). As can be seen in the Fig., these Candidate flights had an opportunity to save significant amount of delay with the average ODS_T of -39 minutes.

Given the OFF Delay Savings, the Candidate flights were predicted to get to the destination much earlier on the TOS routes. The left subplot of Fig. 6 illustrates the predicted IN Delay in minutes on the filed route ID_F (Eqn. 3) and on the TOS route ID_T (Eqn. 5), colored in blue and green respectively. The predicted IN delay follows a similar pattern

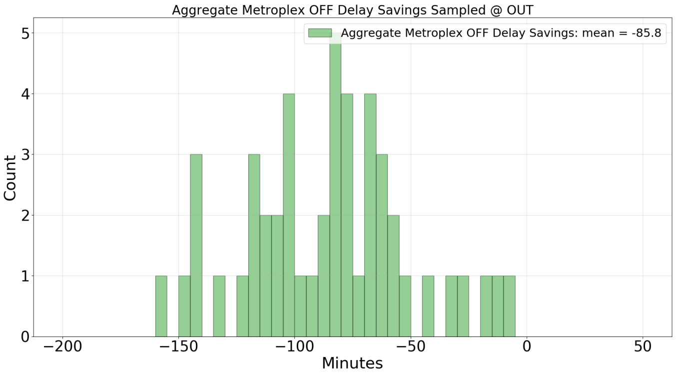

Fig. 7. System-wide Aggregate Delay Savings for Candidate flights.

to the predicted taxi times where the average flight is predicted to get to the destination 52 minutes late on the filed route compared to 20 minutes late on the TOS route.

Predicted IN Delays clustered around zero indicate the TOS route is predicted to arrive at the destination around the SIBT. These flights with ID_T near zero can be attractive TOS candidates as the reroute reduces delay and maintains network schedule integrity.

The right subplot of Fig. 6 shows the predicted IN Delay Savings in minutes on the TOS route IDS_T (Eqn. 4). As can be seen in the Fig., the average flight had a predicted IN Delay Savings of -32 minutes which is slightly less benefit than the -39 minutes of OFF Delay Savings. The difference between the IN Delay Savings and the OFF Delay Savings is the Additional Flight Time on the TOS route AFT_T shown in Eqn. 4.

In addition to the individual benefits to Candidate flights, the weather event on December 30th created TOS reroute opportunities that would have benefited the system as a whole. Fig. 7 shows the system-wide Aggregate Delay Savings associated with each Candidate ADS_T (Eqn. 6). The system level benefits were larger than the individual flight level benefits (Fig. 5). The average Candidate flight pushing back in this weather event could have saved -86 minutes of system-wide Aggregate Delay Savings compared to -39 minutes of OFF Delay Savings at the individual level. Because the ADS_T includes the ODS_T, the average flight would have created an additional -47 minutes of delay savings above and beyond the benefit to the rerouted flight.

The system-wide aggregate benefits materialize when the MIT restricted flights are able to move one slot earlier owing to the rerouted flight giving up its slot. If the MIT restrictions at the terminal boundary are operating as the the main constraint on the system, then there is often available capacity at the runway to accommodate the rerouted flight without delaying other flights. The result is better use of the available capacity and a savings at the system level.

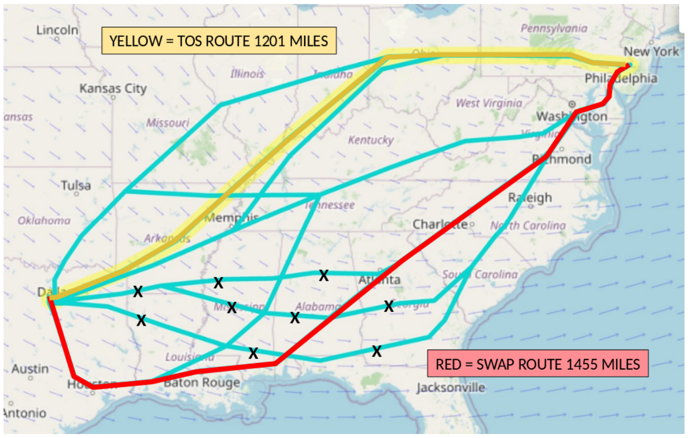

Fig. 8. During SWAP event East departure gate routes assigned to the South route colored red. When the East departure gate restrictions are lifted the yellow TOS route through the East gate becomes a Candidate.

B. Recovery from Severe Weather Avoidance Program Use Case

During a SWAP event ATC will route traffic around weather by closing departure fixes and rerouting the flow through a departure fix along the adjacent departure gate. This type of SWAP event occurred on March 17^{th}, 2021 and generated the TOS candidate route illustrated in Fig. 8 in yellow.

The flight began with a filed route through the East departure gate using the departure fix HANUH. Due to severe weather, ATC completely closed the East departure gate and routed departure fixes HANUH and THHOR to DARTZ (South gate), and rerouted departure fixes TRRCH and ZERLU to AKUNA (North gate), see Fig. 1. Due to the reroute of HANUH to DARTZ, the flight plan was ammended by ATC to the red departure route shown in Fig. 8.

Given the flight's destination is North East of the origin airport, the red route through the South gate is much longer than the original route through HANUH and the East departure gate. In addition, during the SWAP event ATC restricted the flow through the south departure fix DARTZ with a required 20 MIT leading to significant delays along the south route.

Prior to the flight pushing back, ATC removed the SWAP restrictions and opened up all routes through the East departure gate. With all departure fixes open, ATC maintained the 20 MIT applied to DARTZ routes along the South departure gate. Even though ATC opened the departure fixes along the East gate, flights which were near departure already had their flight plan amended by ATC to fly the South route through DARTZ. This created an opportunity to recover from the SWAP event by rerouting flights which were assigned to the South route through DARTZ through more efficient routes across the East departure gate.

Benefit opportunities recovering from a SWAP event are slightly different than the benefits associated with the TMI use case because the TOS route can be significantly shorter than the filed route as shown in Fig. 8. The yellow TOS route was 1201 nautical miles compared to the red SWAP route of 1455 nautical miles, resulting in a savings of 254 nautical miles. This is in contrast to the TMI use case where the filed route was restricted, but still within the same departure gate, which generates TOS routes within the adjacent gate that are longer than the filed route. Flights that are recovering from SWAP events can save from both avoiding terminal restrictions and selecting a more efficient route, which results with the IN Delay Savings IDS_T exceeding the OFF Delay Savings ODS_T.

The large benefits observed with the recovery from SWAP on March 17th was helped out by the complete lifting of restrictions along the East departure gate once the event was over. Not all recovery from SWAP events happen in the same way. For example, if the departure fixes along the East gate were opened but restricted with 20 MIT we would expect the TOS benefits to not be as large.

C. Non-TMI Use Case

Through use of the system during the shadow evaluation a new use case emerged for TOS reroutes in the absence of terminal restrictions. At KDFW the traffic patterns ebb and flow in concentrated time periods of demand known as banks. Often times early in a bank, the traffic demand is not distributed evenly across runways and the banks will begin slightly earlier on one runway than the other as shown in Fig. 9. This Fig. illustrates the West runway timeline and the East runway timeline on the left and right of the image, respectively. Current time (01:10Z) is shown with a horizontal bar near the bottom of the screen. As you move higher on the timeline this represents the runway schedule at later moments in time.

The upcoming banks shown in Fig. 9 start at slightly different times. The East runway has consistent traffic starting at 01:40Z whereas the West runway has sparse traffic between 01:40Z and 02:00Z with consistent traffic after 02:00Z. If flight AAL1274 circled in orange has a TOS route off the West runway, then AAL1274 could reroute to the West runway and experience little to no delay while vacating its runway slot on the East runway and enabling subsequent flights to move up. This reroute is attractive at a system level as it reduces demand to the East runway by utilizing unused capacity on the West runway, but not always attractive at the individual flight level. The reason being that the flight might experience little to no delay on either runway, thus the chance for individual OFF Delay Savings ODS_T may be negligible.

The TOS reroute opportunity for a flight like AAL1274 becomes more attractive when the flight's parking gate is physically closer to the runway with available capacity. In this scenario, the reroute of AAL1274 is beneficial at the system level as discussed previously, but also beneficial at the individual flight level as the TOS route runway is much closer and requires less taxi time to get to the departure queue. Fig. 10 shows AAL1274 transitioning from the ramp to the Airport Movement Area (AMA) circled in orange. The terminal the flight is coming from is physically closer to the West runway which creates an opportunity for delay savings at the individual flight level. The close proximity of the gate and TOS runway combinations create tactical opportunities to reroute flights at the beginning of the bank which result in both shorter taxi times for the rerouted flights and less delay at the system level.

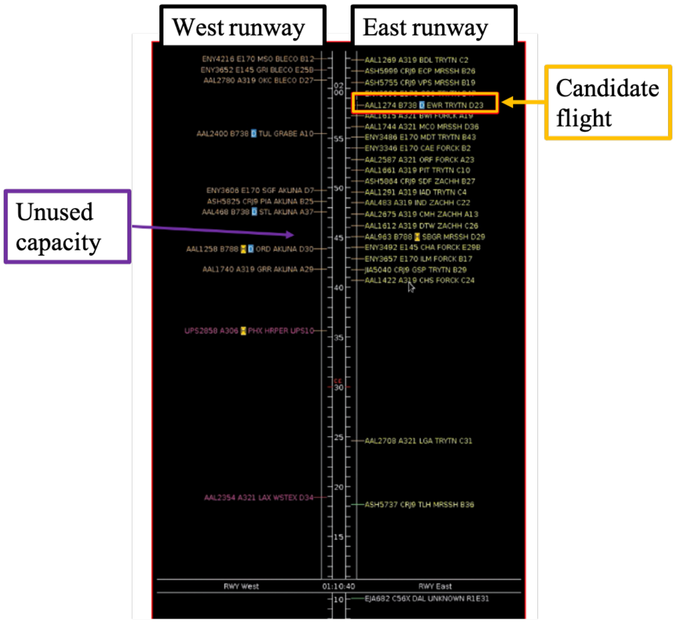

Fig. 9. Unused capacity on the West runway early in the bank.

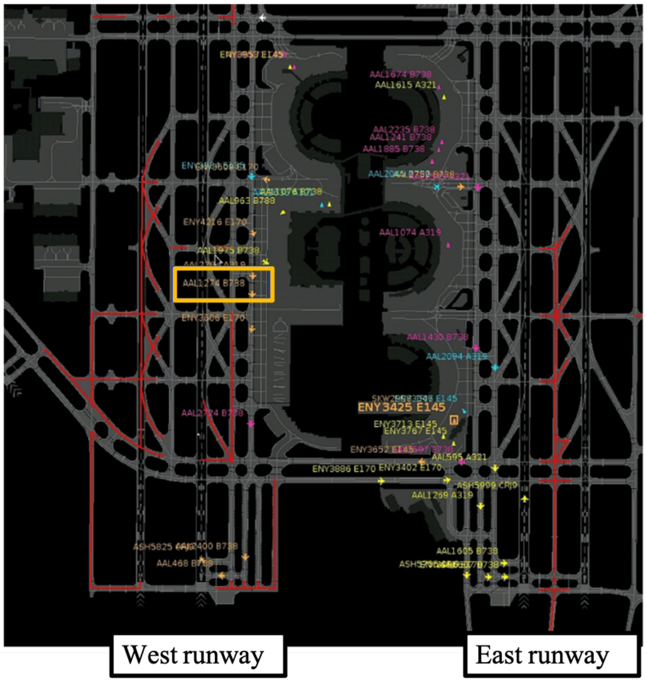

Fig. 10. Parking gate on West side of the airport is closer to the West runway.

These type of tactical reroutes without terminal restrictions early in a bank are sensitive to the exact runway utilization strategy the ATC Tower (ATCT) chooses. Different runway

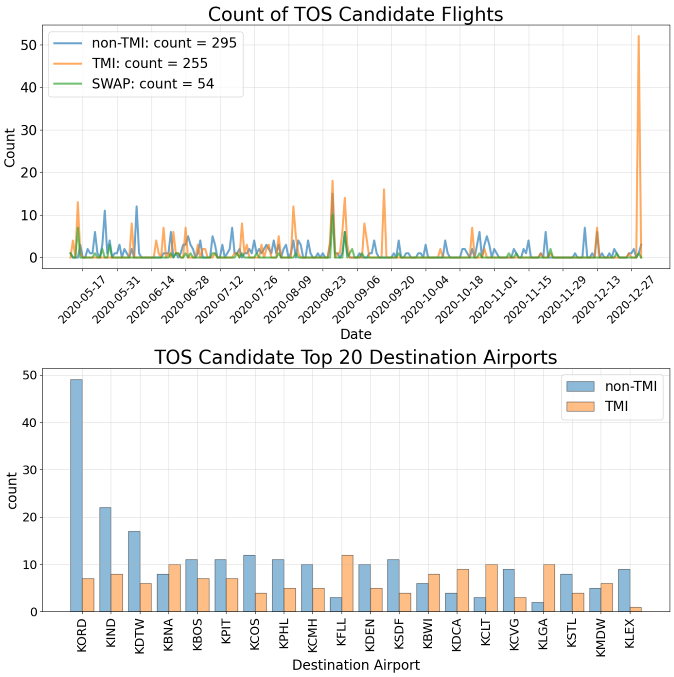

Fig. 11. Top: Count of candidate flights by date. Bottom: Count of candidate flights by destination airport.

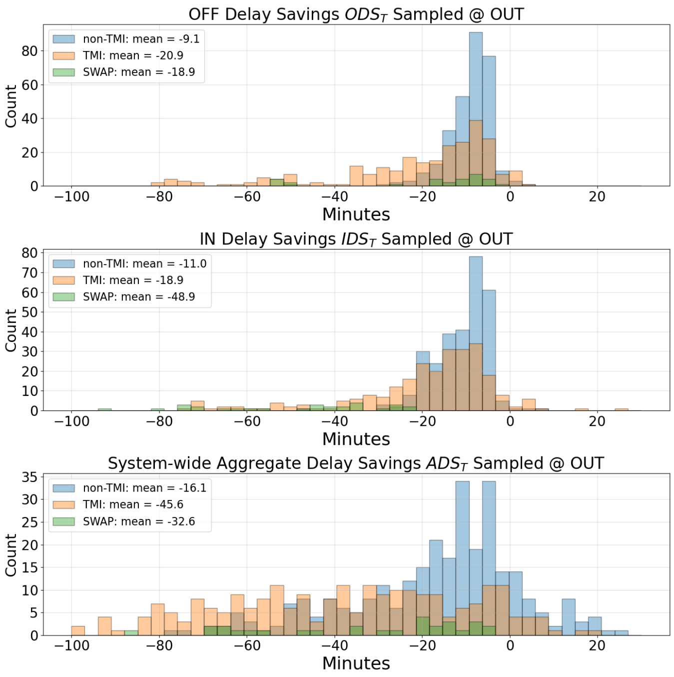

Fig. 12. Top: OFF Delay Savings. Middle: IN Delay Savings. Bottom: System-wide Aggregate Delay Savings

utilization selected by ATCT will result in different load balancing strategies between departure fixes and runways and impacts which runways have available capacity. Because of this, it is difficult to know in advance of the runway utilization strategies the exact TOS opportunities that will be available. If common runway utilization strategies are chosen by ATCT and specific candidates at the beginning of the departure banks show up with high frequency, then this information could be fed back to the airline network schedulers who might take advantage of these opportunities in a more strategic way.

V. ANALYSIS OF CANDIDATE FLIGHTS

We analyzed flights at both KDFW and KDAL between May 1, 2020 and December 31 2020. During this time we had a total of 604 Candidate flights at the OUT event. The Candidate flights were categorized as 295 non-TMI flights, 255 TMI flights, and 54 SWAP flights. The top subplot of Fig. 11 shows the count of Candidate flights per day for non-TMI, TMI, and SWAP colored blue, orange, and green, respectively.

Fig. 11 shows the blue non-TMI and orange TMI Candidates constitute the majority of the opportunities outside of a small number of SWAP events shown with a green spike. The largest SWAP event occured on August 27^{th}, 2020 where in total there were 43 Candidate flights with 18 TMI, 15 non-TMI, and 10 SWAP. Most days have a five or fewer non-TMI or TMI Candidate flights. The blue non-TMI Candidate flights consistently appear throughout the time frame whereas the orange TMI Candidate flights are concentrated during the stormy season between May and the end of September. There are four days which show a spike in the TMI candidate flights above fifteen, and we see that in two of the four days we also have a spike in the green SWAP opportunities.

The bottom subplot of Fig. 11 shows the count of non-TMI and TMI Candidate flights by destination plotted for the top twenty destinations. It is interesting to see different distributions for the non-TMI and TMI Candidate flights. The TMI Candidate flights seem to be close to uniformly distributed across the destinations whereas the non-TMI flights concentrate in a small handful of destinations. The single destination of Chicago O'Hare Internation Airport (KORD) accounts for 49 of the total 295 non-TMI flights (49/295=17%) suggesting that some consistent reroute opportunities are not driven by TMI restrictions. As mentioned in Section IV-C, the repeated TOS Candidate flight opportunities to destinations like KORD can be provided to airline network schedulers to investigate opportunities to reroute these flights in a more strategic way.

The distribution of predicted benefit metrics for the 604 Candidate flights are shown in Fig. 12 with non-TMI, TMI, and SWAP flights colored in blue, orange, and green, respectively. The top, middle, and bottom subplot of Fig. 12 shows the OFF Delay Savings ODS_T, IN Delay Savings IDS_T, and System-wide Aggregate Delay Savings ADS_T, respectively. The TMI and SWAP events have more OFF Delay Savings compared to the non-TMI Candidate flights, because the TMI and SWAP Candidate flights are subject to a demand capacity imbalance along the terminal boundary which increases delay along the filed route.

Fig. 12 shows that TMI and SWAP Candidate flights have similar values of OFF Delay Savings ODS_T with the average

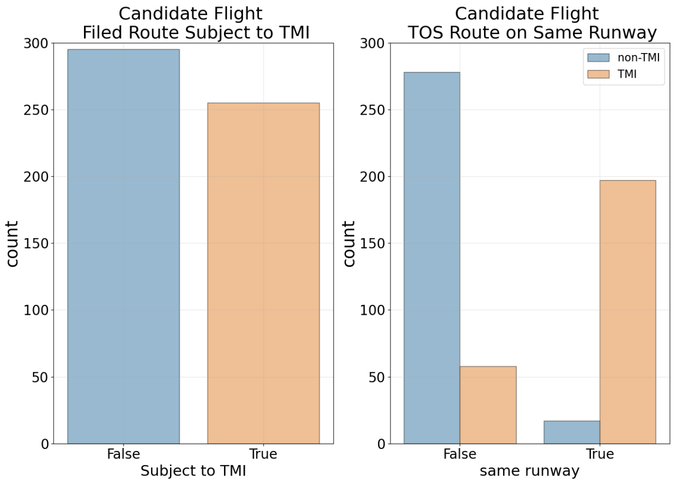

Fig. 13. Left: Count of Candidate flights without TMI (blue) and with TMI (Orange). Right: Count of Candidate flights with TOS route on the same runway (True) and TOS route on a different runway (False).

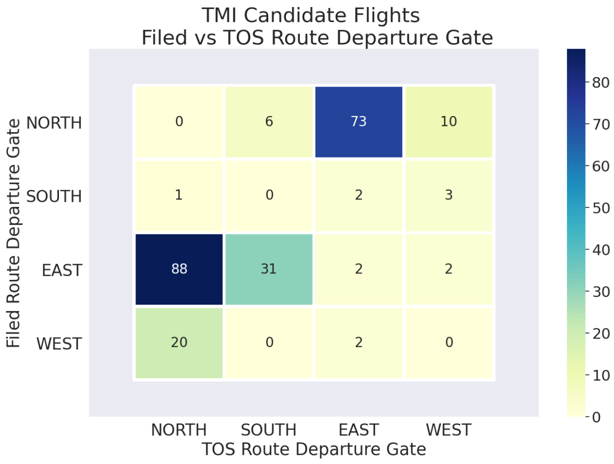

Fig. 14. TMI Candidate flights filed route departure gate vs. TOS route departure gate.

TMI Candidate having -20.9 minutes and the average SWAP Candidate having -18.9 minutes. The SWAP flights, however, have significantly more IN Delay Savings IDS_T with the average TMI Candidate flight having -18.9 minutes and the average SWAP Candidate flight having -48.9 minutes. The SWAP flights IN Delay Savings IDS_T is benefiting from both the OFF Delay Savings ODS_T and the significantly shorter TOS routes which together manifest as the large benefit at the destination.

The System-wide Aggregate Delay Savings ADS_T shows a similar pattern to the OFF Delay Savings ODS_T where the average non-TMI flights show the smallest benefit of -16.1 minutes and the TMI and SWAP events have larger benefits with average Candidate flight values of -46 minutes and -33 minutes, respectively. The similar patterns between the OFF Delay Savings ODS_T and the System-wide Aggregate Delay Savings ADS_T makes sense as the System-Wide Aggregate Delay Savings ADS_T is aggregating the OFF Delay Savings for all flights in the schedule.

A. *Analysis of TMI flights*

Here we focus on analysis of the 255 TMI flights to better understand what is driving the TOS Candidate status. The left subplot of Fig. 13 shows the overall count of non-TMI and TMI flights colored in blue and orange, respectively. The right subplot of Fig. 13 shows 197 (197/255 = 77%) TMI Candidates had a TOS route using the same runway compared to 58 (58/255=23%) Candidates with TOS route using a different runway. When a TOS Candidate uses the same runway, that is an indication that the delay is caused by the terminal boundary as opposed to the runway. The OFF Delay Savings ODS_T can manifest by using the same runway and simply routing through an alternative departure fix which has available capacity.

To better understand how delay propogates from the terminal boundary back to the airports within the North Texas Metroplex we analyze the filed route departure gate vs the TOS route departure gate for the TMI Candidate flights. Fig. 14 shows the filed route departure gate on the vertical axis and the TOS route departure gate on the horizontal axis. The count of TMI Candidate flights which had the given filed route departure gate and TOS route departure gate are provided within each grid cell and colored such that the darker the blue the more Candidate flights within the grid cell.

Fig. 14 shows that the majority of TMI Candidate flights have a filed route either through the East departure gate or the North departure gate. For TMI candidate flights with filed route East, the most frequent TOS route came through the North departure gate. For TMI candidate flights with filed route North, the most frequent TOS route came through the East departure gate.

It is interesting to see the symmetry between the TMI Candidate flights with respect to the East and North departure gates. This symmetry makes sense as the North Texas Metroplex has heavy traffic flows with destinations North East and there are likely TOS routes through both the North and East departure gates with relatively similar distance. When either of the departure gates is subject to terminal restrictions there are attractive candidates through the alternative departure gate that require relatively small OFF Delay Savings ODS_T to become Candidates as the RTC will be quite low.

B. *Analysis of non-TMI flights*

Here we focus on analysis of the 295 non-TMI flights to better understand what is driving the TOS Candidate status. The first thing we notice from the left subplot of Fig. 13 is that there were slightly more blue non-TMI Candidate flights than orange TMI candidate flights. The right subplot of Fig. 13 shows the count of blue non-TMI flights where the TOS route was on the same runway (17/295 = 6%) and the count of non-TMI flights where the TOS route was on a different runway (278/295=94%). The non-TMI flights are concentrated with

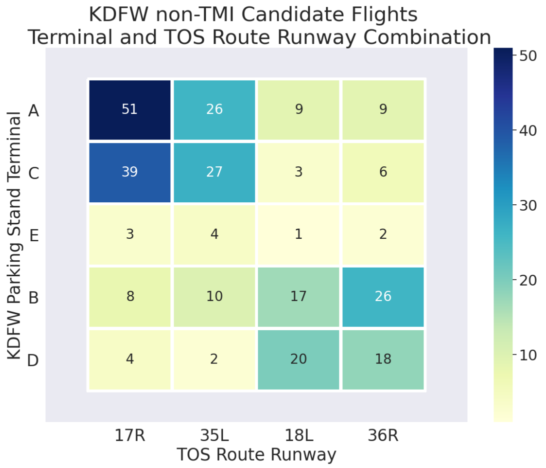

Fig. 15. KDFW non-TMI Candidate flights: combination of parking stand terminal (vertical) and TOS route runway (horizontal).

TOS routes on a different runway which is in contrast to the TMI flights.

From the right subplot of Fig. 13 we conclude that the runway change is an important part of the non-TMI Candidate status. The dependency on the runway change for non-TMI flights was discussed in Section IV-C where we showed a non-TMI Candidate flight where the OFF Delay Savings ODS_T was driven by a runway change to a runway that was physically closer to the parking gate. By rerouting to a TOS route using a runway closer to the parking gate, a flight benefits from a shorter unimpeded taxi time from gate to runway which can manifest as OFF Delay Savings ODS_T.

Fig. 15 shows the relationship between the TOS route runway and the parking gate terminal for KDFW Candidate flights. The vertical axis represents the parking gate terminal where terminals A, C, and E are located on the East side of the airport and terminals B and D are located on the West side of the airport. The horizontal axis represents the TOS route runway with runways 17R and 35L on the East side of the airport and runways 18L and 36R on the West side of the airport. The count of KDFW non-TMI Candidate flights which had the given parking gate terminal and TOS route runway are provided within each grid cell and colored such that the darker the blue the more Candidate flights within the grid cell.

The relationship between parking gate terminals and TOS routes on the same side of the airport is illustrated in Fig. 15. The majority of non-TMI TOS Candidates are coming from flights parked at terminal A or C on the East side of the airport and rerouting to runways 17R and 35L on the East side of the airport. Similarly, flights parked at terminals B and D on the West side of the airport most often reroute to runways 18L and 36R on the West side of the airport. From Fig. 15 we conclude that the main driver of TOS Candidate opportunities for non-TMI flights is not just switching runways, but switching runways to a runway that is physically closer to the flight's parking gate.

VI. CONCLUSION

This paper presented results from the IADS Stormy 2020 Shadow Evaluation of a TOS reroute capability. The TOS reroute capability was designed to resolve a demand capacity imbalance along the terminal boundary of the North Texas Metroplex containing major airports KDFW and KDAL and other satellite airports in the D10 TRACON.

The shadow evaluation was conducted by collecting a set of benefit metrics sampled at the OUT event for each departure flight. The benefit metrics were defined for an individual flight with respect to the OFF Delay Savings, Net Delay Savings, IN Delay, and IN Delay Savings. Metrics were defined at the System-wide level to provide a measure of the Aggregate Delay Savings which accounts for impacts to flights in the schedule beyond the individual rerouted flight.

Examples of three distinct use cases of the TOS reroute capability were provided with the associated benefits metrics. The first use case, labeled as the TMI use case, is triggered by ATC restrictions along the terminal boundary and was shown to exhibit large OFF Delay Savings benefits. A single TMI event during a four hour period in December 2020 created 53 TOS candidates and the average Candidate pushed back with an OFF Delay Savings on the TOS route of -39 minutes. Throughout the Stormy 2020 Shadow Evaluation there were 255 TMI Candidate flights with average OFF Delay Savings -21 minutes. The filed route and TOS route departure gates were evaluated for the TMI flights and we found a relationship between the East and North gates where TMI flights filed through one would often reroute through the other.

The second use case, labeled as SWAP, are triggered by severe terminal restrictions which when lifted present opportunities to reroute flights on to TOS routes that are significantly shorter. Recovering from the SWAP events can result in significant benefits at the destination airport since the flight benefits from the OFF Delay Savings and also from a shorter TOS route. An example was shown for a flight to a North East destination which due to SWAP was rerouted on a South route and when the SWAP restrictions were lifted the TOS route was shorter by 254 nautical miles. The double benefit manifests in the IN Delay Savings where the SWAP flights had an average benefit of -49 minutes compared to -19 minutes for TMI flights.

The third use case, labeled as non-TMI, are triggered when a flight has a filed route assigned to a runway on the opposite side of the airport and a TOS route assigned to use a runway on the same side of the airport as the parking gate. It was shown that 94% of non-TMI Candidate flights had a TOS route on a different runway and the TOS route runway would often be physically closer to the parking gate. During the Stormy 2020 Shadow Evaluation there were 295 non-TMI TOS Candidates which was more than the TMI use case. The average non-TMI candidate flight pushed back with OFF Delay Savings -9 minutes which was less than both the TMI and SWAP candidate flights.

The lessons learned from the Stormy 2020 Shadow Evaluation will be incorporated into the IADS Phase 3 Field Evaluation. In particular, the Stormy 2020 Shadow Evaluation revealed the importance of the SWAP and non-TMI use cases. It was expected that the TOS reroute capability would provide benefits to the TMI flights but seeing the majority of Candidate flights being non-TMI creates attractive reroute opportunities outside the concentrated TMI events. Furthermore, the large benefits at the destination airport for flights recovering from SWAP highlights the potential of the system. These type of SWAP recovery and non-TMI opportunities are being communicated with Flight Operators who are eager to pursue the benefits in Stormy 2021.

The actual benefits from the TOS reroute might not materialize exactly as predicted due to the stochastic nature of surface operations. To address the uncertainty, the IADS Phase 3 system estimates the probability that the OFF Delay Savings will materialize based upon historical accuracy of the scheduler. Validating the predictions of benefits and the associated probability of OFF Delay Savings was not possible during the IADS Stormy 2020 Shadow Evalution since Candidate flights were not actually rerouted. Future work will define the actual benefit metrics and present the results of the IADS Phase 3 Field Evaluation which will include American Airlines, Southwest Airlines, and Envoy Airlines using the system to reroute flights in the real-time operational environment.

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