ATD-2 Field Evaluation of Pre-Departure Trajectory Option Set Reroutes in the North Texas Metroplex

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***Abstract*—The NASA Airspace Technology Demonstration-2 Phase 3 capabilities extend Integrated Arrival, Departure and Surface scheduling to a Metroplex environment where multiple airports are interacting and sharing resources along the terminal boundary. The Phase 3 coordinated scheduling provides pre-departure reroute recommendations to flight operators which reduce delay caused by terminal restrictions. This paper reports results of the Phase 3 Stormy 2021 Field Evaluation conducted between November 2020 and September 2021 in the North Texas Metroplex. During the field evaluation NASA partnered with the FAA, American Airlines, Southwest Airlines, and Envoy Airlines to evaluate Phase 3 capabilities in an operational environment. The benefits results are provided as delay savings metrics measured in time and converted to fuel and emissions savings using detailed fuel flow models provided by flight operators.**

***Index Terms*—Airspace Technology Demonstration-2, metroplex scheduling, trajectory option set**

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 conducted 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 [10] 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 [11]. The Phase 2 field evaluation between September 2018 and September 2019 evaluated 1) Strategic Surface Metering Program (SMP) [12], 2) integration of Electronic 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 [13] extends the coordinated scheduling of arrivals, departures, and surface traffic from a single airport to a Metroplex environment in North Texas [14]. The North Texas Metroplex contains two major airports Dallas/Fort Worth International Airport (KDFW), Dallas Love Field Airport (KDAL), and other satellite airports all within 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) provided by the flight operator. The TOS is a set of alternative routes the flight is willing to fly and each route has an associated Relative Trajectory Cost (RTC) pre-determined by the flight operator. 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

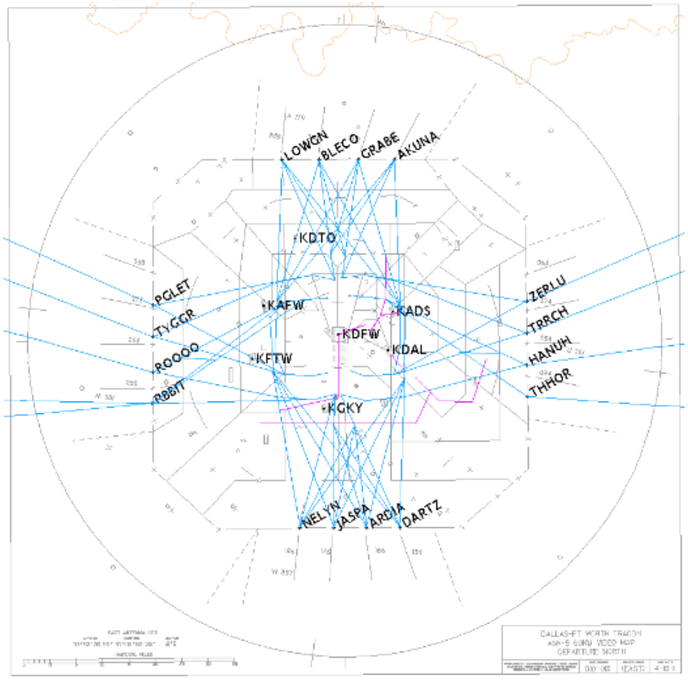

Fig. 1. North Texas Metroplex with multiple airports sharing 16 departure fixes along the terminal boundary.

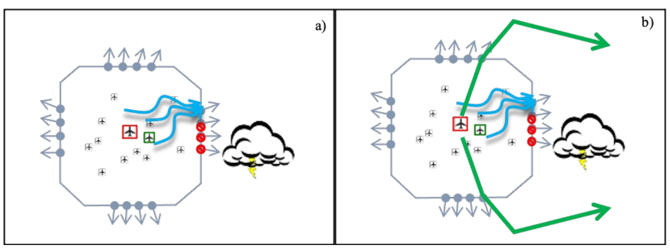

Fig. 2. a) D10 airspace with weather impacting the East gate. b) Available TOS routes not impacted by weather constraints.

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.

This paper reports results of the Phase 3 Stormy 2021 Field Evaluation in the North Texas Metroplex between November 2020 and September 2021. During the field evaluation NASA partnered with the FAA, American Airlines (AAL), Southwest Airlines (SWA), and Envoy Airlines (ENY) to evaluate the IADS Phase 3 system in an operational environment. The tool was used continuously during this time period by flight operators to assess delay savings opportunities and submit pre-departure reroute requests to Air Traffic Control (ATC) who then approved the reroute requests when appropriate. The data captured during the field evaluation enables accurate estimates of delay savings benefits in time which are converted to fuel and emissions sustainable aviation benefits using detailed fuel flow models provided by flight operators.

This paper is organized as follows. Section II provides background information on the pre-departure TOS reroutes in the North Texas Metroplex and the different facilities using

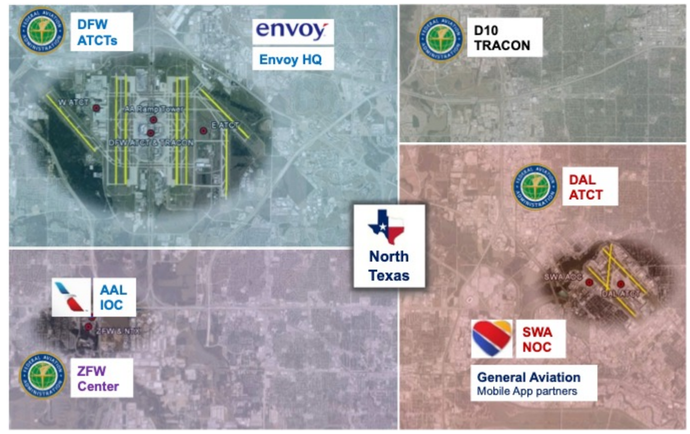

Fig. 3. FAA and flight operator facilities where the Phase 3 User Interface is provided to users. The UI enables coordination between flight operators and Air Traffic Control Traffic Management Unit during the lockout period starting 45 minutes prior to pushback.

the IADS Phase 3 tool. Section III defines three use cases that were identified for pre-departure reroutes. Section IV analyzes the candidate flights, submitted flights, and rerouted flights. Section V analyzes the time savings benefits of the rerouted flights and Section VI converts the time benefits into environmental benefits. Section VII contains a discussion and provides direction for future work.

II. Background Information on Pre-departure TOS Reroutes in North Texas

The North Texas Metroplex airspace is centered around the 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 [15].

A. Terminal Restrictions and Trajectory Option Set Reroutes

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 departure 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 ATC enforces additional departure fix restrictions such as Miles-In-Trail (MIT).

When Traffic Management Initiative (TMI) restrictions reduce the capacity at the terminal boundary there are often opportunities to route around the 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

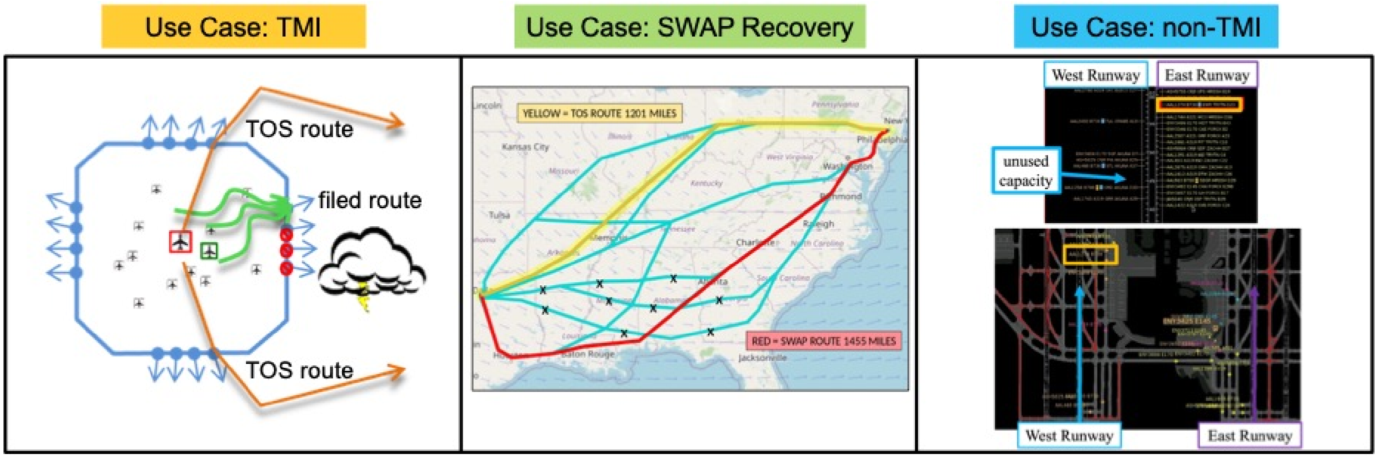

Fig. 4. Pre-departure TOS reroute use cases.

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. During the Stormy 2021 Field Evaluation flight operators and ATC agreed to use vetted Coded Departure Routes (CDR) as the available TOS routes for departures. 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.

B. User Interface and Coordination Between Flight Operator and Air Traffic Control

The predictions generated by the IADS Phase 3 system are delivered to users through a custom User Interface (UI) [13] developed by NASA. The UI is delivered to facilities shown in Fig. 3 including: KDFW and KDAL Air Traffic Control Tower, D10 TRACON, ZFW Center, American Airlines Integrated Operations Center, Southwest Network Operations Center, and Envoy Airlines Headquarters. The UI provides the predicted delay savings on the filed route and each TOS alternative route which is the basis for the reroute recommendations provided by the tool. In addition to the delay savings predictions the UI enables coordination between flight operators and ATC.

Enabling coordination between flight operators and ATC is a critical component in the Phase 3 concept. Without the UI the flight operator would be constrained to changing a flight's route through filing a new flight plan outside of the lockout period. The lockout period starts roughly 45 minutes prior to pushback, and once initiated, eliminates the flight operator from changing the route of flight. Since weather and TMI restrictions in the North Texas Metroplex can be dynamic, flight operators prefer to wait until just prior to the pushback event to determine to reroute a flight.

The NASA UI enables flight operators to directly coordinate with ATC within the lockout period to submit pre-departure reroute requests. Flight operators can submit one or more TOS routes for a flight and these requests are delivered to ATC via the UI to approve the submitted requests. Audio/visual alerts are available to ATC users when a TOS route is submitted and to flight operator users when a TOS route is approved by ATC. After approval by ATC the flight operator dispatch and pilots concur on the new route. The route is then amended by ATC in the FAA's Flight Data Input/Output (FDIO) system and ATC clears the pilots on the new flight route.

III. TOS Reroute Use Cases

Prior to the Stormy 2021 Field Evaluation the system was running in Shadow mode throughout calendar year 2020 and the Candidate flights were analyzed [16]. Shadow mode is the process of using the system to passively collect predictions for each flight at the OUT event. Through this analysis we identified three distinct use cases of the system defined as TMI, recovery from Severe Weather Avoidance Procedures (SWAP), and non-TMI. A brief description of each use case is illustrated in Fig. 4

The TMI use case shown on the left in Fig. 4 is triggered by ATC restrictions along the terminal boundary. In the TMI use case the filed route is the most direct route but is subject to some type of TMI restriction while the TOS alternative route goes through and adjacent departure gate and is not subject to restrictions. Since the TOS route goes through the adjacent departure gate there is often times additional flight time on the TOS route and the reroute decision reduces surface delay in exchange for increased flight time. The reduction in surface delay is achieved by avoiding the TMI restriction enforced at the departure fix of the filed route. The flight operator preference for how much reduction in surface delay triggers the reroute is communicated via the RTC.

The SWAP use case shown in the middle of Fig. 4 occurs when the Metroplex is recovering from Severe Weather Avoidance Procedures. The SWAP event shown in Fig. 4 illustrates an example where due to severe weather ATC closed the East departure gate completely and routed East bound flights through the South departure gate on the red SWAP route. Typically ATC will also put additional MIT restrictions on the red SWAP route increasing the delay passed back to each airport surface.

When the SWAP restrictions are removed from the system flights which already had their flight plans amended by ATC will remain on the red SWAP route even if there are better route options available through the recently re-opened East departure gate. In this situation, the IADS Phase 3 system recommends the yellow TOS route. The yellow TOS route generates a double benefit as the yellow TOS route is much shorter than the red SWAP route and the yellow TOS route is not subject to the MIT restrictions that are often in place on the SWAP route.

The non-TMI use case shown in the right of Fig. 4 is a tactical reroute opportunity that does not require restrictions on the system. The non-TMI use case often occurs when the TOS route runway is physically closer to the parking gate than the filed route runway. The figure illustrates a situation where the flight outlined in orange is pushing back from a parking gate on the West side of the airport and has a TOS route using the West runway. In this situation, the flight can get off the surface quicker by using the closer runway instead of taxing to the other side of the airport. The non-TMI use case also provides opportunities for ATC and flight operators to load balance demand to take advantage of unused capacity on the West runway.

IV. Analysis of Candidates, Submissions, and Approvals

The Stormy 2021 Field Evaluation took place between November 22nd, 2020 and September 17th, 2021 during which there were a total of 363,944 departures from KDFW and KDAL combined. Table I reports the counts and percentages of Departures, Potential, Candidate, Submitted, and Approved flights broken down between NTX, KDFW, and KDAL. In Table I NTX refers to all flights within the Metroplex. The percentages are reported with respect to the count in the above row in Table I. Potential flights are flights operated by AAL, SWA, or ENY and eligible for TOS reroutes.

A Potential flight is any departure with a valid TOS route which can be used for reroute. Candidate flights are flight that push back at the OUT event with delay savings on one of the TOS routes at or above the RTC threshold. The OUT event is the time the departure flight pushes back from the departure gate (or stand). Submitted flights are flights which the flight operator submit to ATC for reroute and Approved flights are flights which ATC approves for reroute.

Table I shows in total from NTX there were 216,391 Potential (59.5% of all departures) flights that were eligible for TOS reroutes. Of the Potential flights, there were 1,569

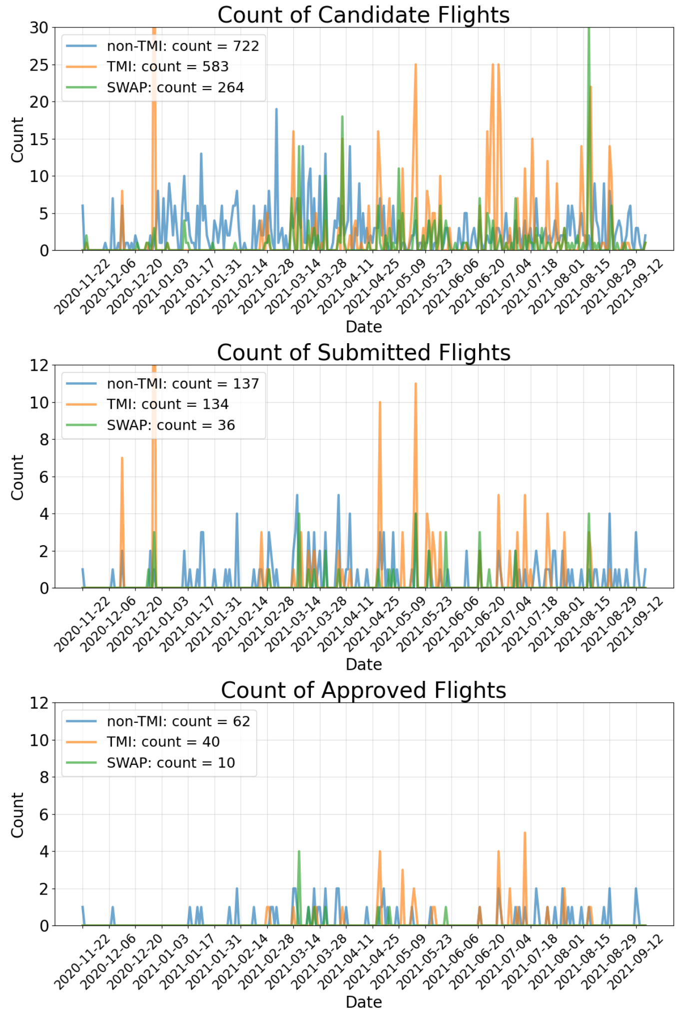

Fig. 5. Top: Daily count of Candidate flights by use case. Middle: Daily count of Submitted flights by use case. Bottom: Daily count of Approved flights by use case.

Candidates (0.7% of all Potential flights) where 307 were Submitted (19.6% of all Candidates) by the flight operator and 112 were Approved (36.5% of all Submitted) for reroute by ATC.

A. Daily Count of Flights by Use Case

Each Candidate flight identified by the system is assigned to one of the TMI, SWAP, or non-TMI use cases defined in Section III. In practice it is possible for a TMI flight to also benefit from the non-TMI benefit mechanism (TOS runway being physically closer to the parking gate), but for the purpose of this paper flights are assigned to non-TMI only if the TMI or SWAP use case did not apply. Throughout the remainder of this paper the results will be broken up by use case to better understand the benefit mechanism of each.

Fig. 5 shows the daily count of Candidate, Submitted, and Approved flights in the top, middle, and bottom subplot, respectively. The Candidate flights illustrate the impact of the Stormy season as the number of orange TMI candidates and the number of green SWAP Candidates increase between April

Type	NTX	KDFW	KDAL
Departure	363,944	258,406	79,692
Potential	216,391 (59.5% Departure)	175,592 (67.9% Departure)	40,799 (51.2% Departure)
Candidate	1,569 (0.7% Potential)	1,409 (0.8% Potential)	160 (0.4% Potential)
Submitted	307 (19.6% Candidate)	296 (21.0% Candidate)	11 (6.9% Candidate)
Approved	112 (36.5% Submitted)	101 (34.1% Submitted)	11 (100% Submitted)

TABLE I
COUNT AND PERCENTAGE OF DEPARTURE, POTENTIAL, CANDIDATE, SUBMITTED, AND APPROVED FLIGHTS.

Type	Submitted/Candidate	Approved/Candidate
All	0.69	0.47
TMI	0.75	0.42
SWAP	0.65	0.53
non-TMI	0.55	0.71

TABLE II
CORRELATION BETWEEN CANDIDATE AND SUBMITTED FLIGHTS AND BETWEEN SUBMITTED AND APPROVED FLIGHTS.

through September. Between November and April prior to the stormy season, the majority of Candidates were blue non-TMI flights. The blue non-TMI Candidate flights that appear outside of the Stormy season are interesting as this indicates the opportunity for TOS reroutes year round independent of terminal restrictions.

The number of Submitted flights shown in Fig. 5 follow a similar pattern to the Candidate flights where inside the Stormy season we see an increase in orange TMI Submitted flights and prior to the Stormy season the majority of Submitted flights were blue non-TMI. The number of green SWAP flights that were both Candidate and Submitted also increase during the Stormy season as the SWAP events are a result of severe weather.

The number of Approved flights shown in Fig. 5 follow a similar pattern to the Submitted flights but the relationship is not as strong as the relationship between Candidates and Submitted flights. The overall correlation between Candidates and Submitted flights is 0.69 whereas the overall correlation between Submitted and Approved flights is 0.47. The correlation between Candidate and Submitted flights and the correlation between Submitted and Approved flights is shown in Table II for each of the use cases.

For the TMI and SWAP use case the correlations shown in Table II follow a similar pattern where the correlation between the Candidate and Submitted flights is higher than the correlation between the Submitted and Approved flights. This makes sense as during TMI and SWAP events ATC workload is high and so not every Submitted flight can be analyzed and approved by ATC. During TMI and SWAP events it is also possible that the adverse weather introduces unaccounted constraints that make the TOS reroute infeasible, which lowers the correlation between the Submitted and Approved flights.

For the non-TMI use case we see a lower correlation between Candidate flights and Submitted flights when compared to TMI and SWAP. This is reasonable as the non-TMI use case occurs more frequently as shown in Fig. 5 and Section V will show the non-TMI use case has lower benefits compared to

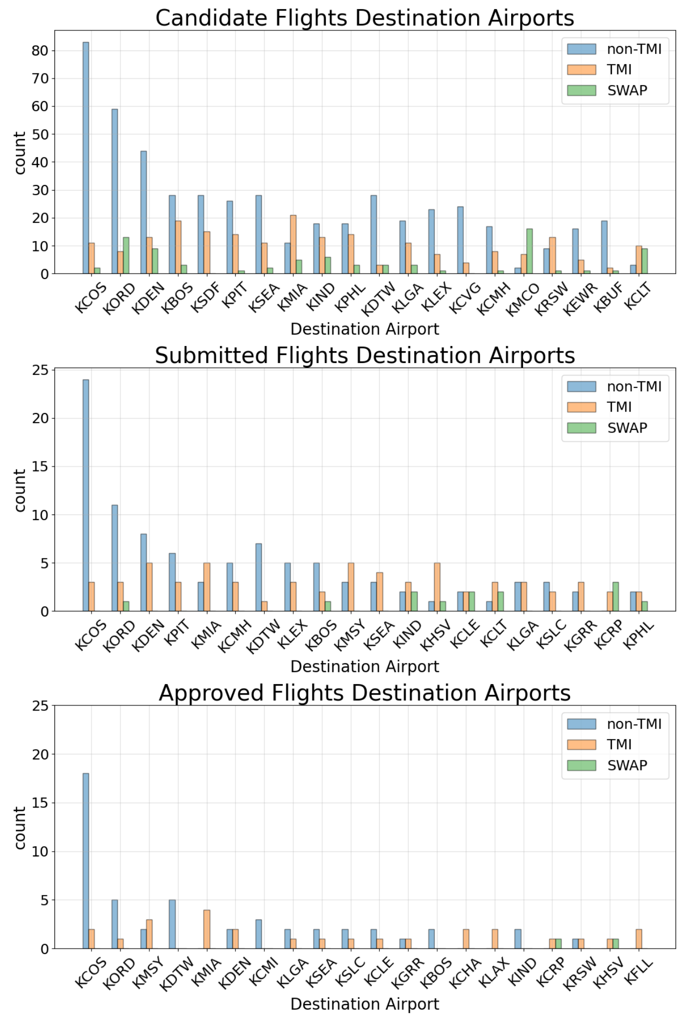

Fig. 6. Top: Count of Candidate flights by destination. Middle: Count of Submitted flights by destination. Bottom: Count of Approved flights by destination.

TMI or SWAP. The data indicates that for flight operators it is not as critical to submit the non-TMI candidates. For the non-TMI candidates that are submitted, however, the correlation between Submitted and Approved is higher than any other use case. This most likely is the result of ATC having more time to analyze and approve these flights outside of TMI or SWAP events.

B. Count of Flights by Destination

Fig. 6 shows the count of Candidate, Submitted, and Approved flights for the top 20 destinations in each category.

For the non-TMI flights Colorado Springs (KCOS), Chicago O'Hare (KORD), and Denver (KDEN) show a high number of Candidates flights and KCOS and KORD show a high number of Submitted flights. By far the highest number of Approved reroutes was for non-TMI flights headed towards KCOS.

Given the high number of Submissions and Approvals for non-TMI KCOS flights, the flight operator might be interested in feeding this information back to the network schedule to consider how this repeatable opportunity could be taken advantage of in a more strategic way. The high number of non-TMI KCOS Approvals also indicates that ATC is comfortable with these flights using the alternative TOS routes when the opportunity arises.

For TMI and SWAP flights there does not appear to be a strong pattern associated with the destination. For the TMI flights, no single destination was Submitted more than five times and there were many destinations with three to five TMI Submitted flights. The most common TMI flight to be Approved by ATC was to destination Miami (KMIA). This makes sense as the KMIA flights from an operational perspective are attractive candidates as the East and South gates provide routes that are similar distance and the adjacent departure gate can be used to avoid the TMI restrictions with minimal impact to additional flight time.

C. CPDLC Equipped Flights

Throughout the field evaluation both flight operators and ATC reported that the workflow associated with relaying the reroute clearance to the pilot could be impacted by the availability of Controller Pilot Data Link Communications (CPDLC). When an aircraft was equipped with CPDLC, then ATC can relay the CDR digitally and the CDR can be directly entered into the Flight Management System (FMS). When the aircraft is not CPDLC equipped, ATC has to read off the full route string for the pilot to enter into the FMS. With CPDLC the reroute clearance takes roughly one minute whereas without CPDLC the reroute clearance could take up to four to five minutes.

The importance of CPDLC equipment on the aircraft is illustrated in Fig. 7 which shows the count of Candidate, Submitted, and Approved flights that were CPDLC equipped. The percentage of Submitted flights CPDLC equipped were 33% and Approved flights were 54% CPDLC equipped. The higher percentage of Approved flights indicates that ATC is more likely to approve the TOS reroute when the aircraft is CPDLC equipped. This is aligned with ATC feedback which reported increased workload associated with relaying the clearance to aircraft not equipped with CPDLC.

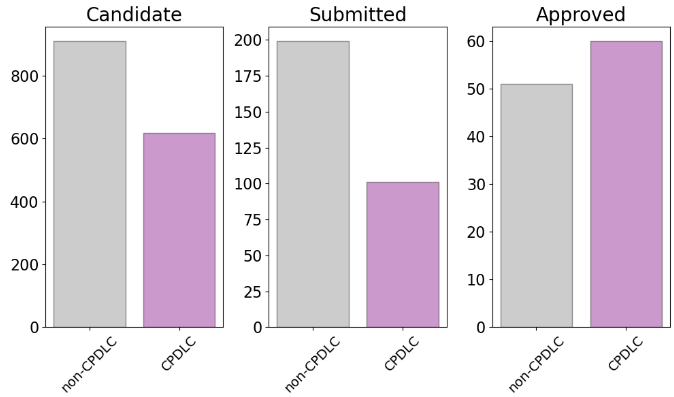

Fig. 7. Count of Candidate, Submitted, and Approved flights that were CPDLC equipped.

V. Analysis of Savings in Time

A. Predicted Delay Savings

A core capability of the IADS Phase 3 scheduler [14] is predicting an individual flight's OFF Delay Savings (ODS) for a TOS route. The IADS scheduler is responsible for generating Estimated Take OFF Time (ETOT) predictions on the filed route and each TOS alternative route which can be used in calculating delay savings predictions. The OFF event is the time the departure takes off from the origin airport. The ODS on a given TOS route is defined as:

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

where TT_F and TT_T represent the predicted Taxi Time (TT) on the original filed route and the TOS alternative route, respectively. A positive 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 predicted 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 difference between the 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 system also provides an IN Delay Savings (IDS) prediction with respect to the benefit of getting to the destination airport on the TOS alternative route. The IN event is the time that the flight arrives at the arrival gate (or stand). The IDS is defined as:

$$IDS_T = ODS_T - AFT_T \tag{2}$$

where AFT_T represents the Additional Flight Time on the TOS alternative route. A positive value for the IDS_T represents the TOS route would arrive at the destination earlier than the original filed route. 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.

In addition to the benefit to the individual rerouted flight, the system provides a prediction of the benefit at the system level. For each TOS alternative trajectory we calculate an Estimated Take Off Time on the TOS route $ETOT_T$ 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:

$$ADS_T = ODS_T + \sum_{\mathbb{F}} \left(TT_F^* - TT_T^* \right) \quad (3)$$

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 $TT_F^* - TT_T^*$ 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 flight's 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.

B. Actual Delay Savings

The actual delay savings is calculated by comparing the predictions of taxi time on the filed route to the actual taxi time on the TOS alternative route. The Actual OFF Delay Savings ($\mathbb{ODS}$) is defined as:

$$\mathbb{ODS}_T = TT_F - \mathbb{TT}_T \quad (4)$$

where TT_F represent the predicted Taxi Time on the filed route, sampled at the OUT event, and $\mathbb{TT}_T$ represents the actual taxi time on the TOS alternative route.

Similarly, the Actual IN Delay Savings ($\mathbb{IDS}$) is defined as:

$$\mathbb{IDS}_T = \mathbb{ODS}_T - AFT_T \quad (5)$$

which is the Actual OFF Delay Savings $\mathbb{ODS}_T$ minus the Additional Flight Time associated with the TOS route AFT_T.

C. Analysis of Delay Savings

For benefits analysis we take the 112 rerouted flights reported in Table I and filter this list down to 86 flights to report benefits. The list of flights included for benefits analysis was agreed upon between NASA, flight operators, and FAA participants. Reasons that flights were removed from benefits analysis include but are not limited to pilots refusing the reroute (5), challenges with non-CPDLC equipped flights changing the route in the FMS (3), ATC not amending the flight plan after approval (2), airport flow change after the approval (2), and general outliers (7). Section VII will provide additional details on the challenges faced which limited the number of reroutes overall.

Figure 8 shows the predicted and actual delay savings metrics defined in Equations (1) through (5). The top subplot shows the predicted OFF Delay Savings ODS_T in green and the Actual OFF Delay Savings $\mathbb{ODS}_T$ in purple. As can be seen in Fig. 8, the average rerouted flight pushed back with predicted OFF Delay Savings ODS_T of 9.6 minutes and the

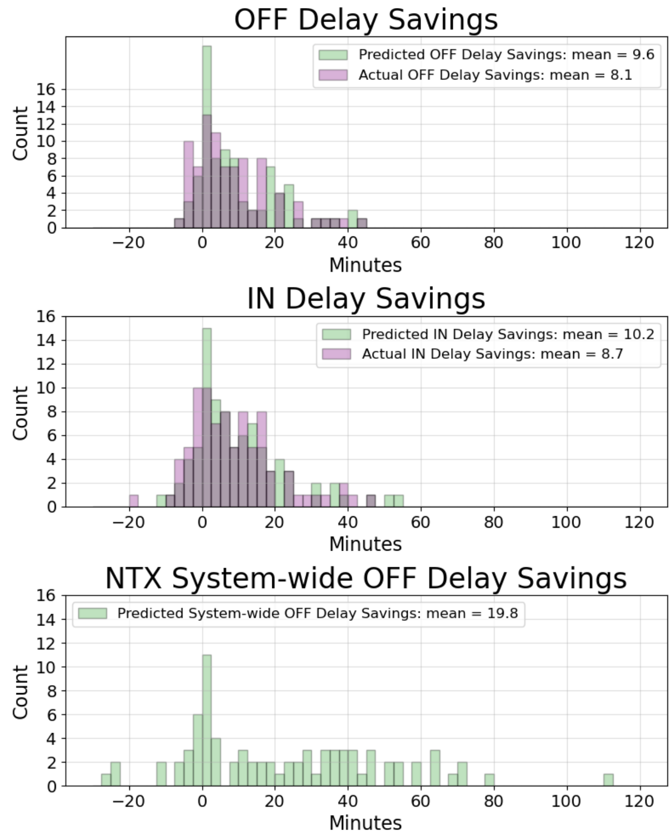

Fig. 8. Predicted and actual time savings for rerouted flights.

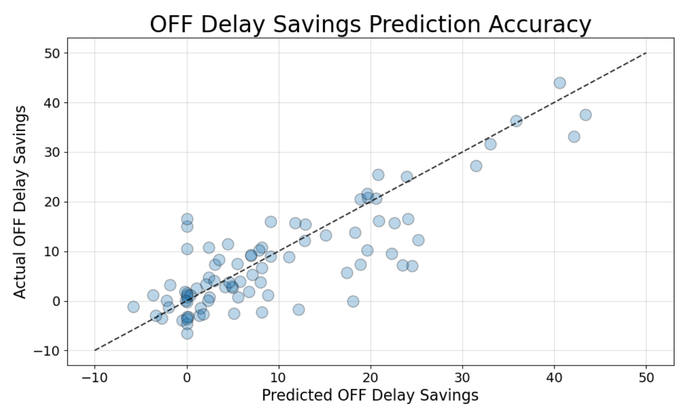

Fig. 9. OFF Delay Savings prediction accuracy per flight.

realized benefit Actual OFF Delay Savings $\mathbb{ODS}_T$ was 8.1 minutes.

The middle subplot of Fig. 8 shows the predicted IN Delay Savings IDS_T in green and the Actual IN Delay Savings $\mathbb{IDS}_T$ in purple. The average rerouted flight pushed back with predicted IN Delay Savings IDS_T of 10.2 minutes and the realized benefit Actual IN Delay Savings $\mathbb{IDS}_T$ was 8.7 minutes.

The bottom subplot of Fig. 8 shows the predicted Aggregate Delay Savings ADS_T in green. The average rerouted flight

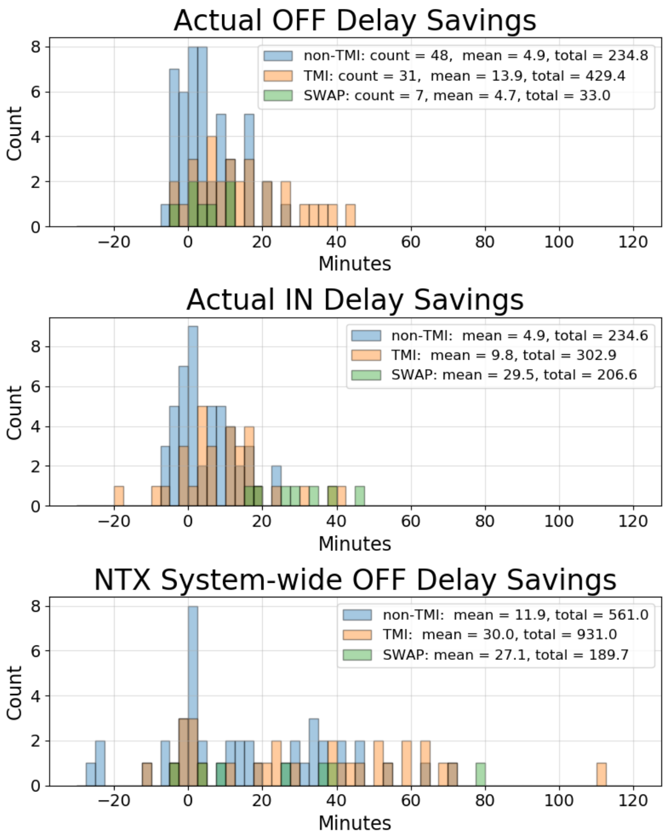

Fig. 10. Time savings broken down for each use case.

pushed back with a predicted system-level savings of 19.8 minutes which is more than double the predicted ODS_T savings to the individual rerouted flight. Being able to measure the system-level savings is important to flight operators as it helps them understand the impact of a single reroute across their fleet.

There is a slight reduction between the average predicted and actual delay savings, but overall the majority of predicted benefit was captured by the rerouted flight. It is also encouraging to see the overall shape of the green (predicted) and purple (actual) benefits distributions look so similar. This is an indication that the system predictions are relatively accurate and the benefits can be realized.

Fig. 9 further illustrates the relationship between the predicted ODS_T and the actual $\mathbb{ODS}_T$ on a flight by flight basis. The horizontal and vertical axis represent the predicted and actual OFF Delay Savings, respectively. Each blue dot represents a rerouted flight and it is encouraging to see the data follow the pattern along the diagonal dashed line which represents the values where the actual values are equal to the predicted values.

It is interesting to see that the Actual IN Delay Savings $\mathbb{IDS}_T$ of 8.7 minutes is greater than the Actual OFF Delay Savings $\mathbb{ODS}_T$ of 8.1 minutes. Given that the filed route is typically the most direct route we expect the Additional Flight Time AFT_T on the TOS route to be greater than zero, thus Equation (5) should be less than Equation (4). For SWAP flights, however, the TOS route is typically much shorter than the SWAP route and the benefit of the shorter route combined with avoiding TMI restrictions results in a significant amount of $\mathbb{IDS}_T$ at the destination.

Consider Fig. 10 which shows the delay savings broken up by each use case. The top subplot shows the OFF Delay Savings where the TMI flights have an average benefit of 13.9 minutes, SWAP flights 4.7 minutes, and non-TMI 4.9 minutes. The middle subplot shows the IN Delay Savings where the SWAP flights have an average savings of 29.5 minutes, TMI flights 9.8 minutes, and non-TMI 4.9 minutes.

Comparing Fig. 10 IN Delay Savings with the OFF Delay savings we see that even though the TMI flights get OFF the surface with more savings (13.9 minutes) than the SWAP flights (4.7 minutes), the SWAP flights get IN to the destination (29.5 minutes) with significantly more savings than either TMI (9.8 minutes) or non-TMI (4.9 minutes). It is this large IN Delay Savings benefits for SWAP flights which skew the overall Actual IN Delay Savings $\mathbb{IDS}_T$ of 8.7 minutes to be greater than the Actual OFF Delay Savings $\mathbb{ODS}_T$ of 8.1 minutes.

The bottom subplot of Fig. 8 shows the system-wide Aggregate Delay Savings ADS_T by use case. The TMI and SWAP flights have average savings of 30 and 27.1 minutes compared to the non-TMI flights which have average savings of 11.9 minutes. This difference in the system-wide benefits indicates that when there are restrictions on the system a single reroute can have large benefits in reducing system level delay. When the individual flight is rerouted off the restricted route, all subsequent flights move up one slot and the system makes better use of the available capacity.

VI. Sustainable Aviation Environmental Benefits

The delay savings benefits reported in Section V are converted into environmental benefits using the methodology described in Fig. 11. For an individual rerouted flight, the fuel savings is calculated as follows. The $\mathbb{ODS}_T$ is used in combination with a NASA developed surface fuel flow model to calculate the surface fuel savings [17]. The AFT_T associated with the TOS route is combined with flight operator provided airborne fuel flow models to calculate the airborne fuel cost. The surface fuel savings plus the airborne fuel cost is combined to calculate the rerouted flight fuel savings associated with the TOS reroute.

The NASA developed surface fuel flow model was used previously by ATD-2 to estimate fuel and emissions benefits for departure surface metering and overhead stream insertion. The model begins by using the tail number of a flight to identify the specific engines on the aircraft. NASA collaborated with flight operators to identify what percentage of flights use single engine vs. double engine taxi during the taxi out phase and encoded this information in decision trees. Knowing the engine type and the single vs. double engine taxi details we

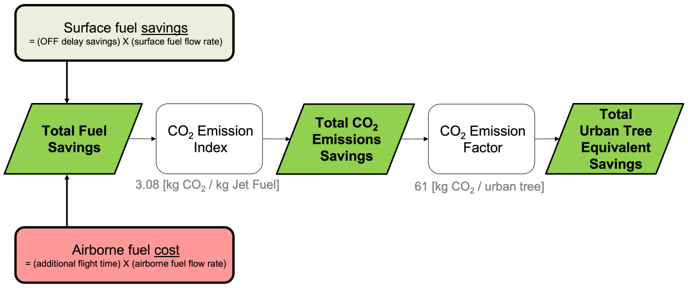

Fig. 11. Method to convert time savings to environmental benefits.

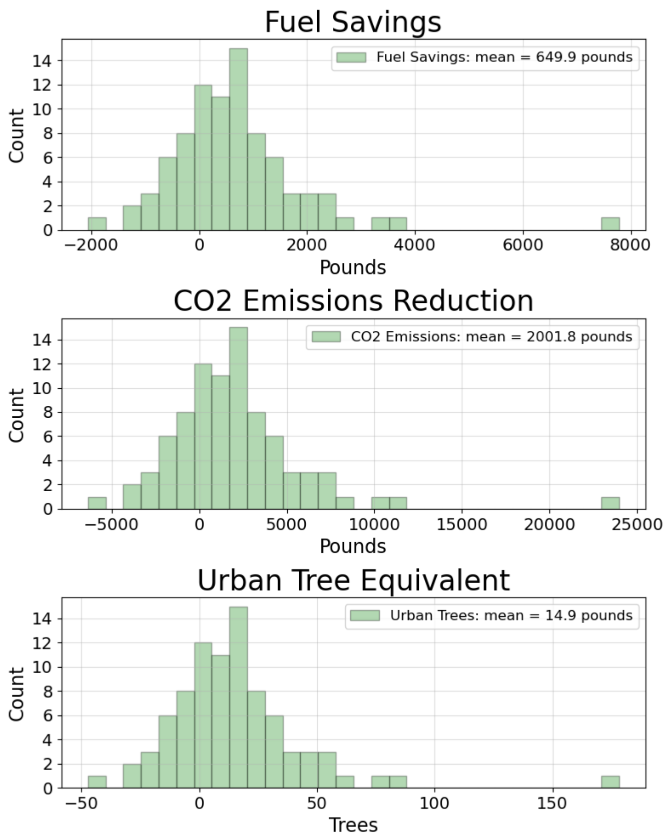

Fig. 12. Environmental benefits including fuel savings, CO2 emissions reduction, and urban tree equivalent.

calculate a fuel flow rate on the surface. This fuel flow rate is then multiplied by the $\mathbb{ODS}_T$ to calculate surface fuel savings.

For the airborne fuel cost NASA collaborated with flight operators which provided detailed airborne fuel burn tables. The airborne fuel burn tables allow for calculations that incorporate a variety of inputs including the flight range, flight time, total payload, load factor, and fuel weight. Each month the flight operators provide estimates of the load factor which we use to estimate the total payload for a specific flight. Given the flight range and the total payload, we use the flight operator provided lookup tables to obtain the airborne fuel burn rate. Multiplying the airborne fuel burn rate by the AFT_T provides the airborne fuel cost.

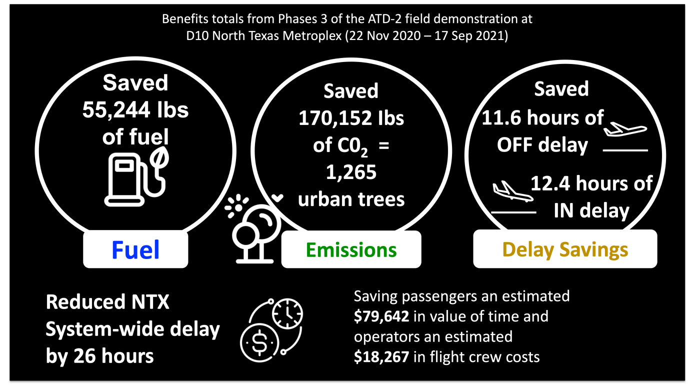

Fig. 13. Summary of total benefits from TOS pre-departure reroutes.

For each flight that is rerouted, we calculate the total fuel savings for the individual rerouted flight and then add the fuel savings at the system level. Since flights that are not rerouted will fly the same route, the fuel savings at the system level is calculated using the summation in Equation (3) which represents the OFF Delay Savings summed over all flights in the system. At the system level we assume each flight is a Boeing 737-800 (the most frequent aircraft type in NTX) and apply the NASA surface fuel flow model to obtain the system level surface fuel savings. The total fuel savings accounts for the fuel savings of both the individual rerouted flight and the system level surface fuel savings.

The total fuel savings is converted to CO_2 emission savings using the conversion that 3.08 pounds of CO_2 is generated for each pound of jet fuel burned. The total CO_2 emissions savings is converted into the equivalent number of urban trees using the conversion 134.48 pounds of CO_2 is equivalent to 1 urban tree grown for ten years.

Figure 12 illustrates the distribution of fuel savings, CO_2 savings, and urban tree equivalent associated with each rerouted flight in the top, middle, and bottom subplot, respectively. As can be seen in the figure, the average rerouted flight saved 649 pounds of jet fuel and 2001 pounds of CO_2 emissions which is equivalent to planting 14.9 urban trees. It is encouraging to see the average reroute had such positive impact on the fuel and emissions, however, we do see some flights had a negative fuel savings (additional fuel cost). This likely is an indication that the flight operators decision to reroute is not purely motivated by fuel and emissions savings. By providing the predictions of OFF Delay Savings, IN Delay Savings, and Additional Flight Time the IADS Phase 3 system enables flight operators to consider multiple factors when determining whether to submit a reroute request or not. In some situations, the flight operators might be willing to burn additional fuel to reduce delay at the destination and maintain schedule integrity.

The total benefits throughout the 300-day long field evaluation are summarized in Fig. 13. In total, the TOS reroutes saved an estimated 55,244 pounds of fuel reducing CO_2 emissions by 170,152 pounds which is equivalent to planting

1,265 urban trees over a 10 year period. The rerouted flights had a total of 11.6 hours of OFF Delay Savings and 12.4 hours of IN Delay Savings and the system level OFF Delay Savings was 26 hours. The rerouted flight IN Delay Savings is converted to passenger value of time savings $79,642 and $18,267 in flight crew cost savings.

VII. Discussion and Future Work

This paper reported results of the IADS Phase 3 Stormy 2021 Field Evaluation conducted between November 2020 and September 2021 in the North Texas Metroplex. During the field evaluation NASA partnered with the FAA, American Airlines (AAL), Southwest Airlines (SWA), and Envoy Airlines (ENY) to evaluate the IADS Phase 3 system in an operational environment. The IADS Phase 3 system aids flight operators in the decision to reroute aircraft over an alternative departure fix by predicting delay on the filed route and each TOS alternative route and recommending a reroute when the delay savings exceeds Flight Operator defined thresholds. The data captured during the field evaluation provided actual delay savings benefits in time which were converted to fuel and emissions benefits using detailed fuel flow models provided by flight operators.

Throughout the field evaluation there was a total of 112 flights rerouted over a 300-day period of which 86 were used for analysis of benefits. The average rerouted flight generated an OFF delay savings of 8.1 minutes with average IN delay savings of 8.7 minutes while the benefit at the system-level was 19.8 minutes, which was more than double the benefit to the individual rerouted flight. The time savings represents an average savings of 649 pounds of fuel savings with CO_2 emissions reduction of 2001 pounds which is equivalent to planting 14.9 urban trees.

The results of the Stormy 2021 Field Evaluation have demonstrated the IADS Phase 3 system as a proof of concept that flight operator requested reroutes can be processed in an operational environment. However, the workflow associated with the reroute approval by ATC is not ideal because it requires ATC to use the IADS Phase 3 system alongside existing FAA systems to analyze, process, and approve the reroute request. This can sometimes prevent the reroute from being approved when ATC is experiencing high workload. An integrated system that incorporates all of the information ATC needs to evaluate, process, and approve the reroute request would help increase the number of Submitted flights that are Approved, and as a result, increase the benefits.

While the IADS Phase 3 system demonstrated operational feasibility of TOS pre-departure reroutes, the design of the system creates challenges to scaling the capability across the NAS. The IADS Phase 3 system relies on detailed adaptation for each airport surface which requires significant time and effort to develop and maintain. Future work will focus on replacing the adaptation based airport surface models with a Machine Learning airport surface model providing a scalable solution that will be evaluated as part of NASA's Sustainable Aviation Demonstration series.

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