NASA ATD-2 Trajectory Option Set Prototype Capability For Rerouting Departures in Metroplex Airspace

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***Abstract*—This paper describes NASA's Airspace Technology Demonstration 2 (ATD-2) Phase 3 prototype capability that is being tested in the North Texas region through summer 2021. For the first time, a shared Decision Support Tool (DST) provides opportunities for participating Flight Operators (FOs) and Air Traffic Controllers (ATCs) to coordinate using a Trajectory Option Set (TOS). When the metroplex airspace is impacted by demand/capacity imbalances, TOS enables departure flights to be rerouted to alternative departure routes with less surface delay.**

Keywords—Trajectory Option Set, TOS, Metroplex, Traffic Management Initiatives, scheduling, delay savings, flight operations, Air Traffic Management

I. Introduction

This paper describes NASA's ATD-2 Phase 3 prototype capability, its initial demonstration in the North Texas, and its expected benefits. The Phase 3 concept expands on Phases 1 and 2 of the Integrated Arrival, Departure, and Surface (IADS) traffic management system and incorporates the use of TOS to identify alternative departure routes when flights are predicted to incur surface delay due to demand/capacity imbalances.

A. Background

The National Aeronautics and Space Administration (NASA) has collaborated with the Federal Aviation Administration (FAA) and industry partners to investigate and test IADS technologies over the last decade [1, 2, 3, 4, 5]. For Phases 1 and 2 of the ATD-2 field demonstration, NASA developed a prototype Surface Metering Program (SMP) for the FAA's Terminal Flight Data Manager (TFDM) [6, 7]. This system has been used since 2018 by the American Airlines ramp and Air Traffic Control (ATC) Tower personnel at Charlotte Douglas International Airport (KCLT) with positive results [8]. From November, 29 2017 to April, 30 2020, 25,748 departures (3.8% of departures) were held at the gate for an average of 5.9 minutes. Gate holds were estimated to have saved about 2,883,410 pounds of fuel and reduced CO_2 emissions by 8,880,901 pounds, the equivalent of 66,038 urban trees [9]. The maturation of the Phase 2 system which enables a strategic SMP [10], was based on a series of human-in-the-loop simulations [11], users' feedback [12, 13], as well as refinements of the scheduler's takeoff, pushback and taxi times [14]. The technologies and lessons learned have been transferred to the FAA. The FAA plans to replace the ATD-2 IADS system in CLT with TFDM by late 2021 and has started the process of developing new requirements for its future implementations.

The goal for Phase 3 was to develop and operationally test a capability to support the management of departure demand/capacity imbalances in a multi-airport airspace. The Dallas-Fort Worth TRACON (D10) metroplex was chosen due to its high traffic demand and frequent delays due to inclement weather. This airspace includes two major hub airports, Dallas Love Field (KDAL) and Dallas-Fort Worth (KDFW), where both Southwest Airlines and American Airlines, NASA's ATD-2 field demonstration partners, have a large presence.

The desire to incorporate TOS operations in the ATD-2 Phase 3 capability and evaluation stemmed from both industry partners' support and early analyses. In recent years, the concept of TOS has gained recognition by the FAA and the airline industry as a potentially useful resource to help ATC manage flow-constrained areas. Use cases of TOS outside of the Collaborative Trajectory Option Program (CTOP) were investigated by The MITRE Corporation, with the FAA and Collaborative Decision Making (CDM) groups [15]. In addition, NASA's early benefit analysis indicated that rerouting departure flights on alternative routes, when deemed beneficial, may result in delay reductions for both rerouted flights and subsequent flights. The initial concept received strong support from field demonstration partners, the airline industry, the CDM Flow Evaluation Team (FET), the Surface CDM Team (SCT) group, and the FAA NextGen organization (FAA/ANG).

B. *Trajectory Option Set (TOS)*

In current-day operations, Flight Operators (FOs) can file only one flight plan per flight. While airline dispatchers may consider various routes before filing a flight plan, ATC assume that pilots will fly the filed route. This assumption is reasonable when flights are not subjected to surface or airborne delay. When demand/capacity imbalances occur, however, both the FOs and the ATCs may be looking for opportunities to offload demand to reduce congestion and flight delay.

A TOS consists of a set of preferred routes, each of which has an associated Relative Trajectory Cost (RTC). The RTC is a weighted time that accounts for the cost of flying additional miles. Adding alternative TOS routes to the filed plans may provide opportunities to compare routes and determine when flights could depart or arrive earlier and benefit from a reroute. This is analogous to when drivers look up alternative routes on a map application to assess if other routes would enable them to arrive at their destination sooner. This determination requires the ability to predict when benefits (delay savings) outweigh the cost (RTC) of flying an alternative versus the filed route (net savings) in real-time. This is, in essence, what the Phase 3 capability attempts to provide for departure flights to both the FOs and ATC in a tactical manner.

The concept of TOS has been integrated in FAA's Traffic Flow Management System (TFMS). It is a key component of the CTOP to help ATC to strategically manage flows in constrained areas. CTOP analyzes demand at a constrained area and determines when flights could be routed outside of constrained areas based on TOS submitted no later than 45 min prior to departure. Flights that cannot be rerouted would receive an Expect Departure Clearance Time (EDCT). TOS has also been integrated in Pre-Departure ReRoute (PDRR) and Airborne ReRoute (ABRR) capabilities. Both PDRR and ABRR would enable Traffic Management Coordinators (TMCs) to amend flight plans, based on submitted TOS, via the Route Amendment Dialog (RAD). However, to this date, CTOP has been mainly used for analysis purposes, and TOS has not been used operationally.

There are three types of potential TOS scenario that we considered for the development of Phase 3:

1) Departure Demand/Capacity Imbalances: Excess demand and/or reduced capacity may result in surface departure delay for the flight's filed route, but not necessarily for alternative routes.

Under normal circumstances, the D10 airspace has enough route capacity to absorb the departure demand from both major airports and the surrounding airports. D10 has four terminal gates (North, East, South, and West), with four departure routes each (for a total of 16 departure routes).

When convective weather occurs in the region, routes may be closed and/or increased space between departures may be required, i.e., Miles-in-Trail (MIT) between departures. The most common restriction compresses the capacity from four routes down to one with 10 MIT. In this situation, both KDFW and KDAL airports are requested to space departures, and as a result, flights frequently incur surface delays. While departures to the East gate may be delayed, departures to the North or South

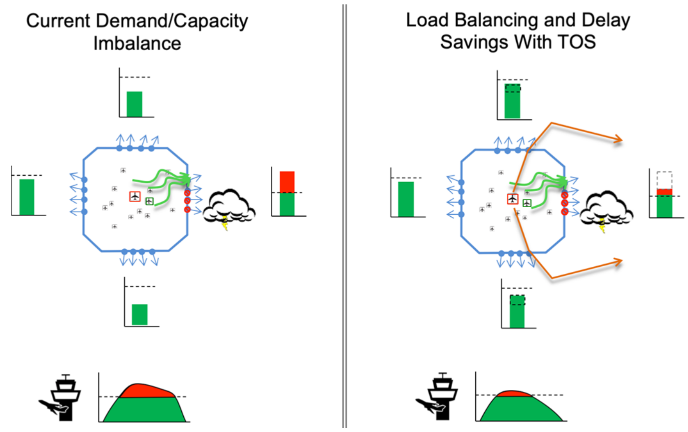


Fig. 1. Alternative TOS departure routes to offload demand and reduce delay.

gates may not be. Therefore, opportunities for flights to depart earlier on a north or south alternative route may provide advantageous delay savings despite the cost of flying a longer route. In this scenario, rerouting flights would effectively off load demand and reduce delay to the East gate as well, as shown in Fig. 1.

In addition to terminal restrictions, different taxi times and demand loads across runways may also provide options for flights to take off earlier and thus may contribute to potential delays savings.

2) Arrival Demand/Capacity Imbalances: Arrival flights may also experience airborne delay due to excess demand or reduced capacity at the arrival metering fixes or runways. Recent HITL simulations, using a research version of CTOP, assessed the potential benefits of using TOS to strategically offload arrivals across routes into Time-Based Flow Management (TBFM)'s arrival metering. Results indicated that delays could be reduced while maintaining throughput at the destination [16]. This scenario was not addressed in Phase 3.

3) En-route Demand/Capacity Imbalances: Special Use Airspace (SUA), Aircraft Hazard Areas (AHA), and weather events may constrain airspace and create demand/capacity imbalances, as well. The Air Traffic Control System Command Center (ATCSCC, or DCC) may issue Traffic Management Initiatives (TMIs), such as Airspace Flow Programs (AFPs), or route advisories to manage flows.

AFPs may be used to reduce the demand near constrained airspaces. Flights that are subject to AFPs receive an EDCT and are usually delayed. The flights that are delayed are those that cross metering arcs set near the constrained airspaces. Under this type of TMI, TOS may be used to look for alternative routes that would not cross metering arcs and would therefore enable flights to depart earlier.

Mandatory route advisories may also be issued to manage the flow of traffic away from constrained areas onto specific protected route segments. In this case, comparing TOS routes to the protected segments may help to identify which TOS routes may be available.

There may be other constraints, such as predicted arrival time, flight duty time limitations, or airport curfews, that may be considered by the FOs. These may act as compounding factors to the demand/capacity imbalance scenario described above.

II. Concept Overview

At a minimum, the tactical identification of beneficial alternative TOS routes depends on the ability to consider constraints on available resources, to predict real-time delay savings benefits, and for the FOs and ATC to coordinate the submission and the approval of flight reroutes.

The Phase 3 concept can be summarized as consisting of four essential processes: 1) creation of a TOS, 2) estimation of delay, 3) determination of candidate TOS routes, and 4) submission and approval of TOS reroutes. These four processes are described at a high-level below.

1) Creation of a TOS: A TOS service generates a TOS, that is a set of alternative routes, for every departure flight. It computes an RTC for each TOS route. In this early prototype and evaluation, Coded Departure Routes (CDRs) were used as pre-defined TOS routes. CDRs are full-route procedures that are published, and therefore accessible to both ATC and the FO. Using CDRs also enables the system to continuously assess the impact of restrictions and delays on these routes.

2) Delay estimation: A scheduling service provides off-times and delay estimates for both the filed route, and each TOS route, every 10 seconds. This is based on demand and capacity predictions at the runways and at the terminal boundaries, and delays that are imposed on the surface. The scheduler then predicts delay savings for each TOS route, as well as aggregate delay saving for subsequent flights that would not need to be rerouted themselves. Lastly, real-time metrics indicate the probability that a delay savings will occur based on the accuracy of the previous system predictions and the expected size of the delay savings.

3) Determination of Candidate TOS Route: A TOS service identifies when and which TOS routes may be beneficial to fly. It compares the TOS route RTC (cost) with predicted delay savings (benefits). When the delay savings exceeds the RTC (net savings), the system identifies the TOS route as a candidate for reroute.

4) Submission and Approval of TOS reroute: A Graphical User Interface (GUI) enables the FO to view and submit one or more TOS routes for a flight, and enables ATC to view and *approve* a reroute of a flight on a TOS route. Audio/visual alerts are available to ATC users when a TOS route is submitted and to FO users when a TOS route is approved by ATC. The scheduler updates the estimated schedule and predicted delays for all flights after each TOS reroute approval. Dispatch and pilots concur on the new flight route. The ATC tower updates the flight plan in the FAA's legacy system and clears the pilots on the new flight route.

In the following sections, the technology, the GUI and how the system is used are described in more depth.

III. Phase-3 Capability

A. ATD-2 Phase 3 Built Upon Phase 1 & 2 Capabilities

The Phase 3 TOS capability was built upon the Phase 1 and 2 single airport IADS traffic management system. The purpose of the single airport system is to provide accurate prediction of future surface demand/capacity imbalances, to propose SMPs, and to provide gate hold advisories to reduce excess taxi time for departures [6, 7, 10]. The scheduling capability used in Phases 1 and 2 is fully compatible with the Phase 3 TOS capability. However, it is worth noting that the Phase 3 prototype is being evaluated on its own in the North Texas metroplex.

Another precursor of the Phase 3 TOS prototype was the Tactical Departure Scheduling – Terminal software that was developed to provide a terminal-wide scheduling system that would support the management of demand/capacity at the terminal boundary [5]. Some of the terminal capability has been integrated in the Phase 3 system described below.

B. Traffic Management Inititiatives (TMI) Service

This service parses TMI restrictions from across the NAS and provides the constraints needed by the scheduler service to schedule takeoff times and predict delays at the runways and crossing times at the terminal boundaries. It also identifies constraints on the CDRs used by the TOS service to determine when CDRs are available in the flight's TOS.

The TMI service parses restrictions that are available in the TFM Flow data via the System Wide Information Management (SWIM). The system accounts for Ground Stops, EDCTs from Ground Delay Programs (GDPs) and AFPs, Approval Request / Call-for-Releases (APREQ/CFRs), as well as terminal fix closures and MITs.

TMCs at the Fort Worth Air Route Traffic Control Center (ZFW) agreed to enter terminal restrictions imposed on the D10 TRACON in the National Traffic Management Log (NTML). These entries were standardized so that the ATD-2 system could parse them reliably. Both fix closures and MITs are entered in the NTML's MIT restriction tab. Alternative fixes to the closed fixes are entered in a qualifier field.

The TMI service assesses whether CDR routes are impacted by the DCC's route advisories that mandate traffic to fly specific protected route segments. The system compares the CDRs with the protected segments and filters out excluded CDR routes from the flight's TOS accordingly.

C. Trajectory Option Set (TOS) Service

For this first TOS prototype and evaluation, field demonstration partners agreed to use CDRs in the flights' TOS. These pre-defined routes provide full procedures from KDFW and KDAL to over 95% of their destinations. Examples of CDRs to La Guardia Airport (KLGA) are shown in Fig. 2. Some CDRs were removed from the database, including, CDRs to international destinations and those that could only be used when arrival traffic demand is light at a specific D10 arrival gate.

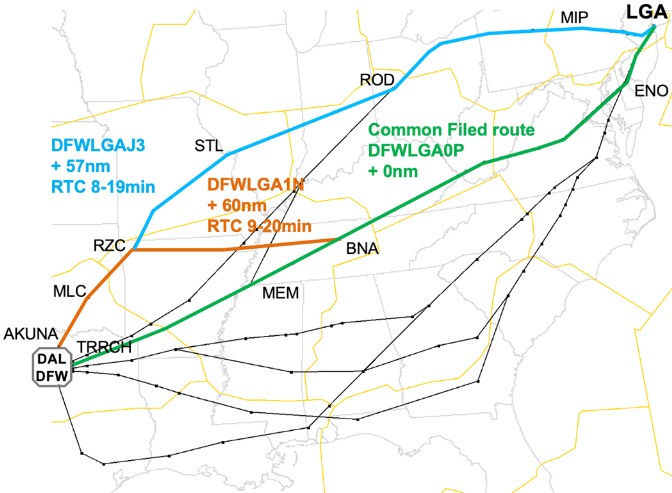


Fig. 2. RTC values and CDRs from KDAL, KDFW to KLGA. The green line is the CDR route via the East gate that is commonly filed, and the blue and orange lines are two CDRs via the North gate.

There are several advantages to using CDRs as static TOS routes. First, they are known by ATCs and FOs, and thus do not require the FO to submit a TOS to ATC via SWIM. This enables the TOS service to compare the CDRs to the filed routes on a constant basis. Second, ATC can use the CDR alphanumerical codes to expeditiously amend the flight plan in the ATC legacy system. Third, the CDR codes may also be used by the ATC Tower to relay the new route to the fight crew without having to go through a full route readout, provided a Letter of Agreement to that effect is in place.

The TOS service determines TOS states. The eligibility state indicates whether a route is available and if it is beneficial for a reroute. The eligibility states are: Potential, Candidate, Excluded, and Expired. The coordination state enables communication between the FO and ATC about the TOS routes. The coordination states are: FO Submitted, ATC Approved, Reroute Filed, ATC Excluded, and FO Excluded.

Before the TOS Service determines if any TOS route is a candidate for a reroute, the service first determines if any CDRs are available. This information is provided by the TMI service. CDRs may be impacted by DCC mandatory reroutes, terminal fix closures, or be excluded due to APREQs, EDCTs or Ground Stops. In these instances, the routes will be labeled “ATC Excluded.” Note that the FOs can also exclude their own flights.

The service then compares the TOS route delay savings to its RTC. Predicted delay savings are provided by the scheduler service. When delay savings rise above the RTC (net savings), the route state is changed from the “Potential” state to “Candidate” (for reroute). Flights’ TOS routes are initially shown as in a “Potential” state until they become a “Candidate.” The TOS states are updated every 10 seconds.

The RTC of a TOS route is a weighted travel time (in minutes). It is computed by multiplying the difference between mileage of the TOS route and the filed route by a cost factor, divided by the filed speed. The cost factor accounts for the FO’s additional cost to operate in the air versus on the surface, or other business priorities. As an example, the FOs’ costs could be based on types of aircraft, destinations, and time of day. The FOs’ cost factors are static and accessed by the TOS service. A configurable minimum RTC is also included. This sets a threshold for the minimum delays savings that is deemed beneficial. A future system may consider cost factor parameters to be dynamic and managed by the FOs.

Fig. 2 shows an example of additional nautical miles and ranges of RTC values for two CDRs via the North terminal gates (in blue and orange) compared to the commonly filed route to KLGA via the East gate (in green). In this example, the routes to the north add about 57 to 60nm, and depending on cost factors, the RTC values could range from a weighted time of about 8 min to 19 min, depending on the variability of FOs’ cost factors.

The concept includes a buffering feature that prevents the eligibility state to change from “Potential” to “Candidate” too frequently when the delay savings value is close to the RTC value. Thresholds can be set under and above the RTC value to allow for some fluctuations. When the thresholds are set, the state doesn’t change unless the delay savings crosses the threshold. So far, the scheduler has proven stable enough to not use these buffers.

The TOS service identifies a “top” route amongst the flight’s TOS. The top route is the route with the highest predicted net savings, that is, the difference between predicted delay savings and the RTC. The top route is displayed in a TOS Table. Users can also view each TOS route for a particular flight in that flight’s TOS Menu.

When the FO determines that a flight would benefit from a reroute, the FO submits the route in the ATD-2 GUI. The route coordination state then changes to “FO Submitted.” When the ATC Tower determines that they can approve the reroute, they approve the route in the GUI. The route coordination state then changes to “ATC Approved.” With this prototype, no data is sent to the TFMS. The ATC Tower enters the CDR code in the FAA legacy system to amend the flight plan. Once the flight plan is updated in SWIM, the ATD-2 system will detect the change and update the coordination state to “Reroute Filed” on the GUI.

Note that the system allows the FO to submit any route at any time, whether the route is in a “Potential” or “Candidate” state. Indeed, there may be circumstances when the FO may want a flight to take off earlier on an alternative route despite the RTC value, for example, to accommodate other time constraints.

Lastly, the prototype includes the option that TOS routes can be set to expire. A Required Minimum Notification Time (RMNT) can be tailored to certain flight events. For example, this type of threshold could be used by ATC or FO personnel to prevent TOS submissions to occur after certain events, such as pushback. This feature has not been used by the field demonstration partners, yet.

D. Scheduling Service

The scheduling service computes predicted delay savings and provides opportunities to use TOS in a tactical manner. It uses multiple algorithms to provide:

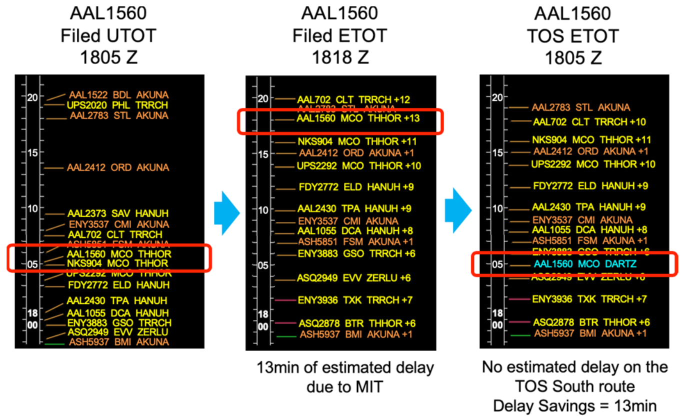


Fig. 3. Example of filed route UTOT and ETOT, and TOS route ETOT and delay savings for AAL1560.

- Time and delay estimates from multiple departure runways and at the departure fixes at the terminal gates
- "What-if" time and delay estimates for each alternate TOS route to compute individual flight delay savings
- Probability of individual flight delay savings for each alternate TOS route
- "What-if" aggregate delay savings for other flights behind a flight using each possible TOS reroute

Below is a high-level description of the Phase 3 scheduler's capability. More details are provided in [14, 17].

The Phase 3 scheduler computes Estimated Takeoff Times (ETOTs) based on various inputs and constraints: 1) the surface scheduler that provides surface transit times, runway predictions, aircraft movement detections and position of traffic on the surface; 2) the tower TMC's runway utilization entered on the ATD-2 GUI; 3) FOs' estimated departure times, such as the Earliest Off-Block Times (EOBTs) that are used to predict the Undelayed Takeoff Times (UTOTs)—the earliest times flights could depart independent of other flights and separation applied at the runway; 4) Terminal restrictions from the TMI service which may require combining departures over certain fixes when other fixes are closed, as well as increased spacing for MIT compliance; and lastly 5) the competing demand between major airports and engine types over certain departure fixes that may result in terminal delay that is passed back to the departure runways.

The best estimate of a flight's takeoff time on the filed route is the ETOT. Predicted total delay on the filed route is computed as the difference between the ETOT and the UTOT. In addition, the scheduler computes what-if ETOTs for all TOS routes for all flights. It assumes the same UTOT on the filed route but then computes a new ETOT for each specific TOS route. Because the restrictions and the demand may vary across the different routes and runways, it is possible that the ETOT for an alternative route may differ from the ETOT for the filed route. The difference between the two ETOTs is then used to compute delay savings.

The following factors may influence delay savings: 1) when a terminal restriction may be in effect on the filed route, but not on the alternative route, 2) when departures on the alternative route depart from a different runway that has a lower demand than the filed route, and 3) when departures on an alternative route have a shorter taxi time.

TABLE I. AGGR. DELAY SAVINGS (IN MIN) IF FLIGHT ABC123 DEPARTED ON TOS ROUTE #1

Aggregate Levels	**Delay Values Added Together (min)**			**Total**
	Flight Delay Savings	***Flights With Reduced Delay***	***Flights With Increased Delay***	***Aggregate Delay Savings***
Air carrier	-10	-4	0	-14
Fleet	-10	-7	2	-15
Airport	-10	-10	2	-18
Metroplex	-10	-15	2	-23

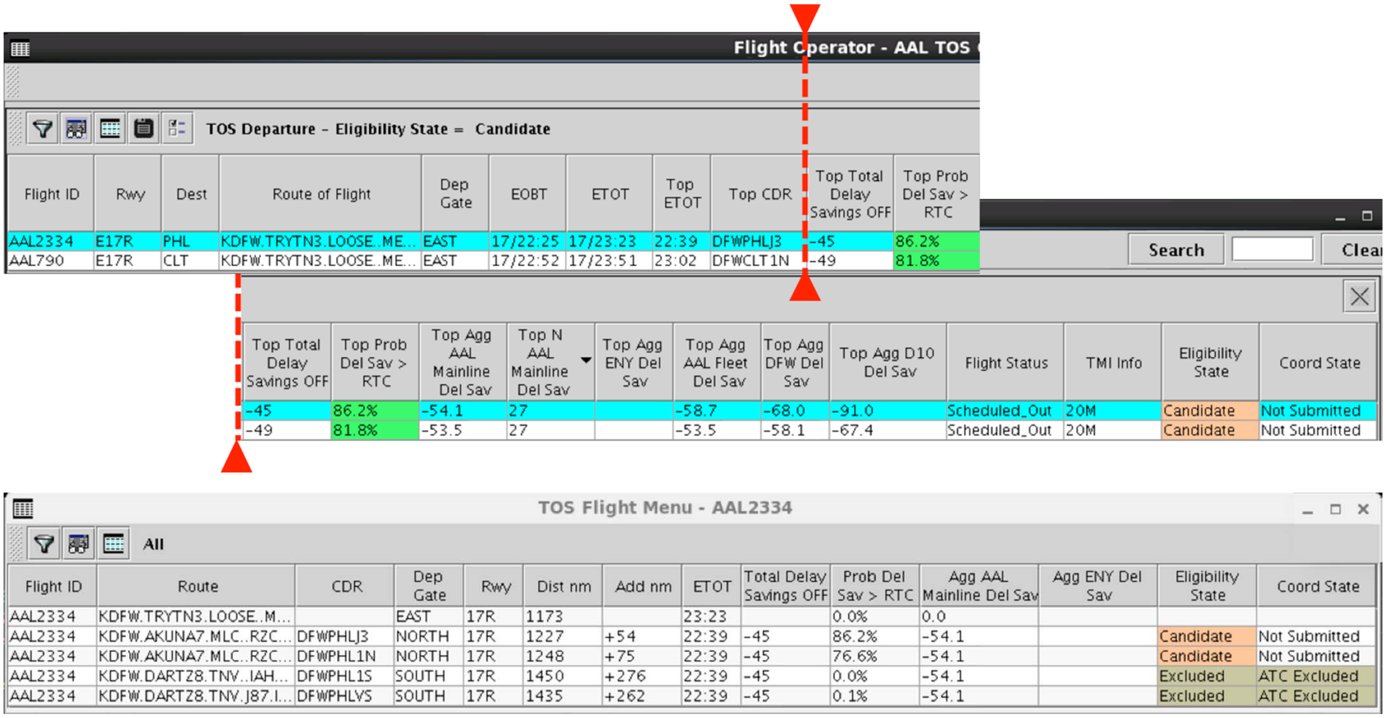
Fig. 3 provides an example of AAL1560's UTOT, filed route ETOT and a TOS route ETOT. In this example, the ETOT of filed route indicates a delay of 13 minutes (middle timeline). However, the ETOT for the southern TOS route (right timeline) is as early at the UTOT (left timeline) thus providing a delay saving of 13 minutes.

Note that the delay savings accounts for different UTOTs at different runways, as well as when flights push from the gate (out events). This helps to account for accrued delays, in case route submissions and reroute decisions are made after pushback. Typically, an increase in accuracy is observed after an aircraft pushes back and gets closer to the runway. However, the closer the flight gets to the runway, the fewer the opportunities there will be for departing earlier on an alternative route, and the higher the workload for the FO and ATC to reroute the flight.

Lastly, the scheduling service provides a probability (%) that the flight's delay savings for the "top" route will occur. Essentially, it compares the likelihood of a flight's ETOT with previous Actual Takeoff Times (ATOTs) from historical data. The difference between the probability of an ETOT and the distribution of ATOTs then yields a probability for various delay values. The method to calculate this probability is described in detail in [17].

The probability can indicate how likely a delay savings is going to be higher than zero, or higher than the RTC value. When compared to the RTC value, the probability typically reaches 50% or higher when a TOS route becomes candidate which is when the delay savings is estimated to be higher than the RTC. The probability is influenced by 1) the accuracy of estimates (the higher the accuracy, the higher the probability), and 2) the size of the delay savings (the larger the size, the higher the probability).

In addition to individual delay savings estimates, the scheduling service also provides what-if estimates of aggregated delay savings for other flights, up to 60 minutes, behind a given flight if the given flight were rerouted on its top TOS route. The aggregated delay savings is a sum of the delay savings for other flights plus the delay savings for the given rerouted flight. The aggregate delay savings is computed at the following levels: for the air carrier (e. g. SWA), for the major's fleet (e. g., the American Airlines Group operates with several sub air carriers), for each airport, and for the metroplex (KDFW and KDAL).


Flight Operator - AAL TOS

TOS Departure – Eligibility State = Candidate

Flight ID	Rwy	Dest	Route of Flight	Dep Gate	EOBT	ETOT	Top ETOT	Top CDR	Top Total Delay Savings OFF	Top Prob Del Sav > RTC
AAL2334	E17R	PHL	KDFW.TRYTN3.LOOSE..ME...	EAST	17/22:25	17/23:23	22:39	DFWPHLJ3	-45	86.2%
AAL790	E17R	CLT	KDFW.TRYTN3.LOOSE..ME...	EAST	17/22:52	17/23:51	23:02	DFWCLT1N	-49	81.8%

Search Clear

Top Total Delay Savings OFF	Top Prob Del Sav > RTC	Top Agg AAL Mainline Del Sav	Top N AAL Mainline Del Sav	Top Agg ENY Del Sav	Top Agg AAL Fleet Del Sav	Top Agg DFW Del Sav	Top Agg D10 Del Sav	Flight Status	TMI Info	Eligibility State	Coord State
-45	86.2%	-54.1	27		-58.7	-68.0	-91.0	Scheduled_Out	20M	Candidate	Not Submitted
-49	81.8%	-53.5	27		-53.5	-58.1	-67.4	Scheduled_Out	20M	Candidate	Not Submitted

TOS Flight Menu - AAL2334

All

Flight ID	Route	CDR	Dep Gate	Rwy	Dist nm	Add nm	ETOT	Total Delay Savings OFF	Prob Del Sav > RTC	Agg AAL Mainline Del Sav	Agg ENY Del Sav	Eligibility State	Coord State
AAL2334	KDFW.TRYTN3.LOOSE..M...		EAST	17R	1173		23:23		0.0%	0.0			
AAL2334	KDFW.AKUNA7.MLC..RZC...	DFWPHLJ3	NORTH	17R	1227	+54	22:39	-45	86.2%	-54.1		Candidate	Not Submitted
AAL2334	KDFW.AKUNA7.MLC..RZC...	DFWPHL1N	NORTH	17R	1248	+75	22:39	-45	76.6%	-54.1		Candidate	Not Submitted
AAL2334	KDFW.DARTZ8.TNV..IAH...	DFWPHL1S	SOUTH	17R	1450	+276	22:39	-45	0.0%	-54.1		Excluded	ATC Excluded
AAL2334	KDFW.DARTZ8.TNV.J87.I...	DFWPHLVS	SOUTH	17R	1435	+262	22:39	-45	0.1%	-54.1		Excluded	ATC Excluded

Fig. 4. Top: Example of a TOS Departure Table (image shown in two parts: left and right halves) which shows two flights with candidate TOS routes. Bottom: Example of a TOS Flight Menu which shows the filed route and each alternative TOS route for AAL2334.

Consider the following example: Flight ABC123's filed route is under a 10 MIT restriction to the terminal East gate. It shows a delay savings of 10 minutes on TOS route #1. There are 10 flights under the same MIT restriction that are predicted to take off behind ABC123 at the same airport. Each of the 10 have an additional one minute of delay, due to the increased spacing to comply with the MIT. Four of those belong to the same air carrier. An additional three of those belong to the same fleet. There are five other flights from another airport that are also impacted by the MIT. In this example, rerouting ABC123 on the TOS route #1 would actually delay two flights from the same fleet by a minute each, because the rerouted flight would be predicted to move in front of these 2 flights. The breakdown of the aggregate delays is shown in Table 1.

IV. Graphical User Interface

The Phase 3 GUI, called Metroplex Planner, provides key display elements such as, Timelines, Maps, and Tables. Many of these elements are part of the Surface Trajectory Based Operations (STBO) GUI that was developed for Phases 1 and 2 - See [6, 7]. Modifications to the GUI for Phase 3 are highlighted in the sections below.

A. *TOS Tables*

Two new tables were created for TOS information as shown in Fig 4. The TOS Departure Table (TDT) lists flights' filed route data, the "top" TOS route data, and the TOS states. Users can set various relevant information to be displayed in the TDT. Fig. 4 shows examples of flight's filed route, equipage, TMI information, ETOT, delay, plus the top route's individual and aggregate delay savings, the probability of delay savings, and the TOS eligibility and coordination states. An editable scratchpad field was added to allow users to make notes for themselves and to communicate with NASA researchers.

Several TDTs can be stacked on top of each other. Using filters, tables can be set up by TOS states, flight events, and time or value thresholds, thus enabling an ad-hoc organization of flights. For example, one table may list flights with candidate routes, and another may list the flights with submitted and approved routes.

The other table is the TOS Flight Menu (FM). It lists all the routes for a specific flight as shown in the bottom of Fig. 4. The filed route is in the first row, and in the following rows are the CDRs that are available. Each of these rows indicates the route procedure, the mileage, additional mileage compared to the filed route, the RTC, as well as the ETOT and estimated delay. In the TOS Flight Menu shown in Fig. 4, the CDRs via the North gate show earlier ETOTs than the filed route and delay savings above the RTC.

In Fig. 4 the FM for AAL2334 lists two candidate routes via the North gate with 45min of delay savings on each route. On the TDT display above, the top route is the CDR DFWPHLJ3. This is due to its lowest additional mileage of 54nm (as seen under "Add nm" in the FM). The ETOT of this route has a probability of 86% of delay savings above the RTC value. The aggregate delay savings are 54min for 27 flights (2min per flight) at the air carrier level, 59min at the fleet level, 68min at the airport level, and 91min for both airports.

Both tables can be used to submit or approve TOS routes. To do so, an FO user right-clicks on a flight route and selects which TOS route to submit. The FO can submit more than one route per flight. Once the FO submits one, or more, routes, the coordination state of the route changes to "FO Submitted." To

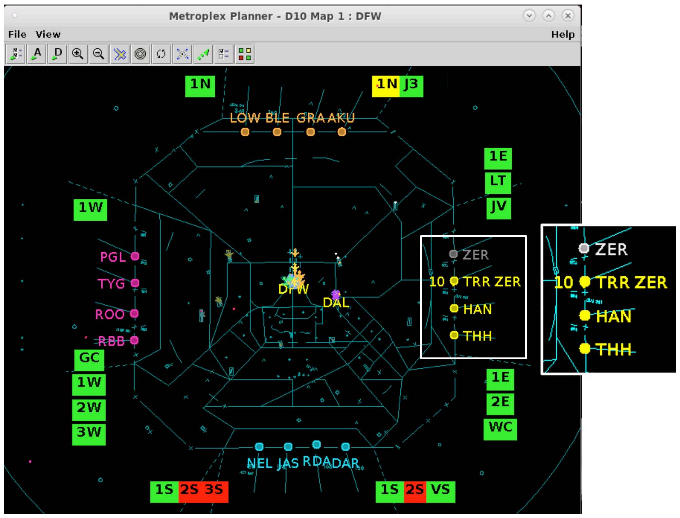


Fig. 5. Map with Departure Fixes, TRACON radar video map, and TOS Route availability labels.

approve a reroute, the ATC user right-clicks on the flight route and approves the route. This will update the Coordination State to "ATC Approved." The FO has the ability to undo a submission until ATC approves a submitted route. ATC can also undo an approval, as needed. Optional pop-up windows can be set to alert ATC users when a route has been submitted or to alert the FO users when a route has been approved.

Measures were taken to protect any sensitive information of the FOs. Each operator had their own criteria to compute the RTC's cost factor and minimum RTC values. Each FO can see only their own flight and TOS information in the TOS tables, but can see all the traffic on the timeline and map on their respective clients. However, ZFW, KDFW and KDAL ATC facilities can see both FOs' flights and TOS information across airports.

B. *Timeline*

The purpose of the Timeline is to present the likely time of departure or arrival to a reference point, such as a runway or a fix. Datablocks provide flight-related information such as delay, restrictions, aircraft type, destinations, origin, runway, and parking gates.

In Phase 3, timelines were upgraded to show the ETOT of the flights' filed route, the predicted delay, as well as two new letter indicators. The letter D indicates that the aircraft is equipped with Controller Pilot Data Link Communications-Departure Clearance (CPDLC-DCL). The letter T, highlighted in white, indicates that a TOS route has been submitted for a flight, and the letter T, highlighted in green, indicates that the TOS route has been approved by ATC.

Both the FO and ATC can submit and approve routes by right-clicking on a flight's datatag. The users can also bring up the Flight's TOS Menu from there.

C. *Map*

The Map provides a planview of D10 arrival and departure traffic, as well as airspace elements, such as airports, fix names

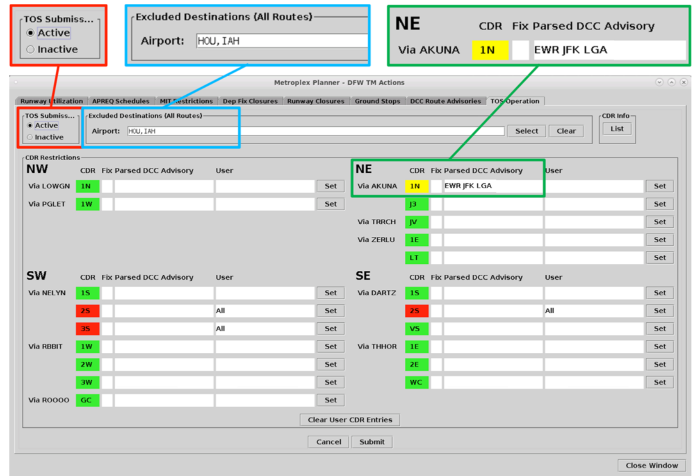


Fig. 6. Metroplex Planner TOS Operation Tab.

and radar video maps. New information about restrictions at the terminal boundary and on the CDRs were added to the Metroplex Planner Map. Terminal restrictions impacting departure fixes, such as fix closures and MITs are now indicated next to the fix name, and restrictions on CDRs are located on the outskirts of the D10 airspace. An example is shown in Fig. 5.

In Fig. 5, Fix ZERLU (ZER) is displayed in gray. This indicates that the fix is closed. "ZER" is however displayed next to the adjacent fix, TRRCH (TRR). This indicates that flights bound to ZERLU are being routed over the alternate fix TRRCH. The number 10 in front of the fix indicates that there is a 10 MIT in place over TRRCH.

In Fig. 5, color-coded indicators of CDR availability in the D10 airspace are shown, grouped by Departure Fix. These indicators are based on the last two alphanumeric characters of each CDR. Many CDRs have the same route name since many use the same Standard Instrument Departure (SID) routes exiting in the D10 airspace into the ZFW airspace. For instance, numerous CDRs ending in 1N fly over the AKUNA (AKU) fix.

The color indicates the level of restriction on the CDRs. When the color is green, the CDRs are available to all possible destinations. The CDR is shown as either "Potential" or "Candidate" state in the flight's TOS. When the color is red, the CDRs are not available to any destination. In this case, the CDR is shown as "ATC Excluded" state in the flight's TOS. When the color is yellow, some CDRs are not available to specific destinations. The CDR is shown as "ATC Excluded" state in the flight's TOS to these destinations only. The user can hover over the indicator to see which destinations are effectively excluded.

D. *Management of TOS Operations*

A TOS Operation tab and a DCC Route Advisory tab were added to the Traffic Management Menu in the GUI. The TOS Operation tab provides ways for the center's TM Unit to turn TOS operation ON or OFF, as well as to manage the exclusions of destinations or CDR routes in the flights' TOS as shown in Fig. 6. The upper left corner of Fig. 6 (highlighted in red) shows where the TM Unit can activate or deactivate TOS operations. When TOS operations are active, the FO can submit TOS routes, and ATC Tower can approve them. When TOS operations are active, a TOS icon (not shown in the document) changes from gray to orange to provide situation awareness.

The top section of Fig. 6 (highlighted in blue) shows where the TM Unit can enter destinations that are restricted from TOS rerouting. That is when none of the CDRs are available to these destinations. The TMI service automatically provides destinations under TMIs such as those with EDCTs under GDPs, and APREQ/CFRs. However, the parsing of the TMIs may not include all destinations that need to be excluded.

The main section in Fig. 6 displays CDR indicators by cardinal direction. The CDRs listed under each direction are the most frequently used for reroutes via adjacent terminal gates. For instance, flights that are filed over the East gate may use the 1N or 1S CDR via the North and South gates respectively as alternate routes.

The TMI Service will determine when certain CDRs are excluded to certain destinations in the DCC mandatory routes. These destinations are then listed next to the given CDR indicators. For example, in Fig. 6, the CDRs ending in 1N are excluded in the flights' TOS to EWR, JFK, and LGA (highlighted in green). The user can manually add or subtract destinations, as needed.

V. ATD-2 Phase 3 Process Flow and Agreements

A. Phase 3 – Process Flow

The Metroplex Planner was designed to be adaptable to various decision processes. It can help either the FOs or ATC to identify flights that would benefit from being rerouted. Below is the approximate process flow developed by the FOs and ATC after a period of shadow evaluation, early tests, and discussion amongst field demonstration partners in 2019.

1) The en route ZFW TM Unit determines terminal restrictions and makes entries in NTML. This unit also decides if TOS operations could be initiated based on the traffic situation and workload involved in the terminal airspace and airports.

2) The FO's ATC coordinator coordinates with dispatch about potential flights that could be rerouted. They discuss whether flights could be rerouted based on fuel and equipment. They may decide to include CDR information in the flight plan release for pilots.

3) The FO's ATC coordinator monitors the TOS Table. As the flight approaches 30min before pushback, a TOS route may be inspected for weather and wind information. If dispatch and the ATC coordinator concur, the TOS route is submitted on the ATD-2 GUI.

4) The ATC Tower verifies that there is an opportunity to reroute the flight on the alternative route. The ATC may approve the reroute and coordinate with Clearance Delivery or Ground Control, depending on which position is controlling the flight at the moment. The flight plan is amended in the Flight Data Input/Output system.

5) The FO's ATC coordinator may alert dispatch when ATC approves the reroute on the ATD-2 interface. Dispatch may see that the flight plan amendment has been updated on the FO's system. Dispatch is then legally required to concur with the pilots on the new route and the amount of fuel on board.

6) The ATC Tower clears the pilots on the new route. The clearance may be carried via CPDLC-DCL or VHF. CPDLC-DCL allows the Tower to send the amendment via datalink to flights that indicated this capability in the flight plan. VHF requires a full route readout. Some airlines may have a Letters Of Agreement with ATCT to use the CDR code to relay the new route, in the absence of CPDLC-DCL equipment.

7) The pilots eventually enter, or select, the new route in the Flight Management System, verify fuel and recompute weight and balances on the new departure procedure.

B. Phase 3 – Procedural Agreements

Agreements were made to facilitate the above process. These may not be applicable to other airspaces.

The ZFW TM Unit agreed to make standardized NMTL entries. Restriction durations are up to two hours, but these may be updated as needed, based on evolving conditions and weather predictions.

The ZFW TM Unit determines if TOS submissions and approval are acceptable, based on workload and constraints in the airspace. However, the ATC Towers approve the reroutes, since they were in control of the flights 45 min prior to departure time.

FO submissions are treated as reroute requests and are approved by the ATC Towers, as able. It was agreed that ATC Towers don't need to approve or reject each of the TOS reroute requests and instead, don't act upon a TOS submission if they are not able to evaluate the request due to higher priority duties. This, however, has not happened yet.

The system allows the FO to submit one or more TOS routes, regardless of its "Potential" or "Candidate" state. If several are submitted, ATC picks the route they deem beneficial and can approve. However, in practice, the FO has submitted only one alternative route per flight, so far.

Both the FO and ATC have preferred to submit and approve a TOS reroute before pushback to reduce workload on the pilots and the controllers. There is a mutual desire to avoid amending the flight plan once the flight is past the spot.

Note that so far in North Texas, the onus has been on the FO to submit TOS routes when reroutes are deemed beneficial for a flight. The Phase 3 system supports that approach which seems to work particularly well when multiple routes are available, and the demand on alternative routes is not saturated. This may not be the case in other circumstances when ATC is constrained to impose reroutes, such as during Severe Weather Avoidance Plan (SWAP) events.

VI. Benefits

A. Individual and Aggregate Delay Savings

The Phase 3 system calculates predicted delay savings for both individual benefits (for the rerouted flights) and aggregate (system-wide) benefits (for multiple subsequent flights). These predicted benefits may weigh differently in the decisions made by the FOs or by ATC. The combination of individual and system-wide benefits can result in the following:

1) High individual delay savings, and high aggregate delay savings: This is the “no-brainer” case when the cost of rerouting the flight provides both individual and system-wide benefits, which may or may not span across air carriers and airports.

2) Low individual delay savings, and low aggregate delay savings: This is the nominal scenario where demand is not exceeding capacity, and no delay savings can be produced.

3) High individual delay savings, and low aggregate delay savings: In this case, rerouting the flight may result in delaying other subsequent flights. An aggregate savings value lower than the individual value indicates that delay may increase for some flights, since the aggregate delay savings includes the individual delay savings as well.

4) Low individual delay savings, and high aggregate delay savings: In this case, rerouting the flight may not result in individual delay savings, but in aggregate delay savings for the air carrier, the fleet, for the airport, or for the metroplex. When the aggregate delay savings benefits the air carrier or the fleet, the FO may consider rerouting ‘low-impact’ flights. ATC may have different criteria for selecting flights to reroute. The aggregate delay savings computation may be used to justify rerouting a particular flight.

The operational use of the system should provide additional insights in how the individual and aggregate delay savings weigh in the decisions to submit and approve reroutes. A future system could leverage both individual and aggregate delay savings, as well as other inherent costs to determine possible outcomes when several flights are considered for a reroute, or to provide recommendations on which flights would provide targeted benefits. Such a capability could be designed to support both FOs or ATC priorities.

B. Stormy 2019 and 2020 Evaluations

An initial TOS prototype was deployed at the end of Spring 2019 to AAL and SWA ATC Coordinators at their respective Operation Centers, to the TMC positions at ZFW, D10, and to KDFW and KDAL ATC Towers (there is no TMC position at KDAL). After a period of training and shadow observations, the system was tested with users for four-hour periods over several days in the summer of 2019. On a few occasions, the weather resulted in restrictions and delay savings and candidate routes were observed. Several TOS routes were submitted, and flights were rerouted on the TOS routes. This provided opportunities to evaluate the system, and identify additional features to be added, such as aggregate delay savings and the probability of delay savings.

A field test was initially planned during the stormy season of 2020, which usually takes place from late May to early September. However, the health-related measures implemented to contain the COVID-19 pandemic resulted in a significant reduction of air traffic. By May 2020, the combined average daily departures at KDFW and KDAL had dropped to 47% of January 2020’s average (1226/day average in January to 572/day in May). Departure demand was reduced from eight to three banks at KDFW. In addition to traffic, both FO and ATC staffing was reduced. By the end of June, neither the FO nor the ATC had effectively used the system.

However, inclement weather developed as expected. Severe weather took place on several days which resulted in fix closures, MITs, and some departure delays, despite reduced demand. The TOS system indicated candidate TOS routes on several occasions. Below is one example to illustrate possible benefits in the absence of actual reroutes.

On May 15th, fix closures restricted the East gates. Traffic from two departure routes were combined over one, with one other departure route remaining unimpacted. That level of restriction lasted for 90min (21:30 to 01:00 UTC) and coincided with the evening departure bank at KDFW (the first OUT occurred at 23:25 and the last OFF occurred at 01:30). During that period of time, the TOS system indicated that seven flights had candidate TOS routes.

No flights were actually rerouted during this period. Therefore, realized aggregate delay savings are not reported here. Because rerouting flights impact the ETOTs and delay savings of subsequent flights, and without knowing how many flights could be effectively rerouted, we opted to show the potential benefits for only one flight in that period of time. In the example below, the flight was the first in a bank that met the criterion of having a candidate TOS route at pushback (OUT).

The example flight was AAL1446 from KDFW to KTUL. Normally, flights to KTUL are filed over the North gate. However, due to weather, this flight was filed on the FORCK route via the East gate and was expected to depart from the East runway. When it pushed from the gate at 23:25, its ETOT was 23:44 with a predicted delay of three minutes at Runway 17R. At the same time, an alternate route to the West gate from Runway 18L had an earlier ETOT of 23:35 with no predicted delay at the runway. Due to differences in taxi times and delay at the runway, the system indicated a delay savings of about nine minutes and a positive net time savings on the TOS route. The flight’s probability of delay savings above its RTC was about 60%. The aggregate delay savings was projected to be about 32min at the air carrier level (AAL), 60min at the fleet level (AAL plus ENY, ASH, and SKW), 63min at the airport level (all airlines at KDFW), and 63min at the metroplex level (both KDFW and KDAL).

It is worth noting that in this example, the predicted delay savings on the TOS route was based upon an advantageous taxi time and the absence of delay at a different departure runway. Also, our decision to pick the first flight in the bank with delay savings greater than the RTC may result in larger aggregate delay savings than if the flight was later in the bank. The delay savings in this example may, or may not, reflect the FO’s own criteria to make a TOS submission. Lastly, the FOs may have additional considerations and metrics that are not yet being accounted for in the ATD-2 system.

C. Operational Benefits

The integration of TOS in FO and ATC operations has been shown to provide many advantages. Below are identified operational benefits from the use of the Phase 3 capability.

These may be worth considering for the development of future systems:

1) Real-time predictions: Estimates of demand, off-time, delay, delay savings, and likelihood of delay savings could support traffic flow management decisions such as load balancing. These estimates could also help identify other sources of delay.

2) Integration of TMIs: It is critical to account for the impact of TMI restrictions when calculating predicted delay, alternative routes, and destinations. Considering TMIs helps to determine when flights are eligible to submit a TOS.

3) Information on which flights are eligible for viable alternative TOS routes: This information helps ATC to identify whether flights are able to fly alternative routes, based on criteria such as equipment and fuel.

4) Information on when alternative TOS routes are beneficial for reroute: This helps to inform FOs and ATC rerouting decisions, based on agreed-upon benefit criteria.

5) More efficient workflow: TOS information helps to increase ATC and FO's awareness of reroute opportunities and decisions. It also reduces the coordination effort between them.

6) Reduction of risks/costs: Avoiding departure delay could help to minimize costs related to flights returning to the parking gate to refuel, to offload passengers to avoid tarmac rules, or to avoid crew Flight Duty Time limitations. Reducing delay may help FOs with passenger, crew, and aircraft connectivity at destinations, as well as help ATC with maintaining throughput.

VII. Conclusion

TOS has been identified as a resource to meet NextGen objectives by the Industry and FAA. Among those objectives are better communications via data exchange across the airspace system and its users, fuel savings, a reduction in emissions and reduced congestion. The ATD-2 Phase 3 system enables both the FOs and ATC to tactically identify reroute opportunities for departure flights impacted for departure fights impacted by demand/capacity imbalances. The Phase 3 field evaluation has helped to identify uses cases and operational benefits. The remainder of the field evaluation will provide opportunities to analyze benefits, identify new areas of development as well document lessons learned. In the future, evaluating TOS opportunities in other airspace configurations and traffic demands, as well as efforts to integrate TOS information and predictive engines into the FO's own flight planning system and into the FAA's TFMS and TFDM systems may be considered.

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