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Publications of the ATD-2 Subproject

# ATD-2 Phase 3 Benefits Mechanism

ATD-2 Team

## Abstract

NASA has been developing and demonstrating a suite of decision support capabilities for integrated arrival, departure, and surface (IADS) operations in a metroplex environment. The effort is being made in three phases, under NASA's Airspace Technology Demonstration 2 (ATD-2) sub-project, through a close partnership with the Federal Aviation Administration (FAA), air carriers, airport, and general aviation community. ATD-2 Phase 1 & 2 have successfully demonstrated new technologies developed to manage the IADS capabilities at a single airport. The Phase 3 builds upon Phases 1 and 2 by extending the capabilities to a Metroplex environment where multiple airports are interacting and competing for resources at the terminal boundary.

This document describes the metrics used to inform the flight operators, Air Traffic Control (ATC) tower, FAA, and even broader aviation community about opportunities to reroute aircraft and the metrics used to assess the performance of the ATD-2 Phase 3 system including benefits. This document provides definitions and detailed calculation methods of identified Phase 3 benefit metrics such as OFF Delay Savings, IN Delay Savings, and Aggregate System-Wide Savings. This document also describes the mechanism to translate delay savings metrics into fuel and emissions savings.

## Revision History

| Rev | Date | Sections Affected | Description of Change | Who |
|---|---|---|---|---|
| v1 | 12 May 2021 | All | First release of document | Divya Bhadoria |
| v2 | 30 Jun 2021 | Section 4 | Added description of fuel burn tables, explained environmental benefits calculations, and included examples for fuel/$CO_2$/Urban tree savings computation. | Divya Bhadoria |
| v3 | 30 Jun 2021 | Sections 3 and 4 | Added description of baseline for benefits calculation (Section 3) and explained assumption about predicted system level environmental benefits being converted into actual benefits (Section 4). | Jeremy Coupe |
| v4 | 17 Aug 2021 | All | Updated convention to indicate positive savings are beneficial. | Divya Bhadoria |
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# 1 Introduction

Under the Airspace Technology Demonstration 2 (ATD-2) sub-project, NASA has been developing and demonstrating a suite of decision support capabilities for integrated arrival, departure, and surface (IADS) in three phases. The Phase 1 Baseline IADS capabilities include data exchange and integration, tactical surface metering, and electronic negotiation of release time of controlled flights for overhead stream insertion. The Phase 2 Fused IADS capabilities include the fusion of strategic and tactical surface metering, Atlanta Center airspace tactical scheduling, Electronic Flight Data (EFD) integration, Terminal Flight Data Manager (TFDM) Terminal Publication (TTP) prototype, and Mobile App for General Aviation (GA) community. The users of the IADS system in Phases 1 and 2 include the personnel at Charlotte Douglas International Airport (CLT) air traffic control tower, American Airlines ramp tower, CLT terminal radar approach control (TRACON), and Washington and Atlanta Air Route Traffic Control Center (ARTCC or Center). [Ref. 1-4].

The Phase 3 IADS system extends the coordinated scheduling of arrivals and departures times at the runways, from a single airport operation at CLT to a multi-airport operation in the North Texas Metroplex environment, containing Dallas Love International Airport (DAL), Dallas Fort Worth International Airport (DFW), and other small satellite airports within the D10 Terminal Radar Approach CONtrol (TRACON). The demand/capacity imbalances in the D10 Metroplex that are addressed by the Phase 3 capability are different than those addressed by the Phase 1 and Phase 2 IADS capabilities in CLT. In CLT, surface congestion and constraints from controlled flights are the main challenges, whereas in the D10 Metroplex the main constraint is the departure fix capacity as multiple major airports compete for the same limited resources.

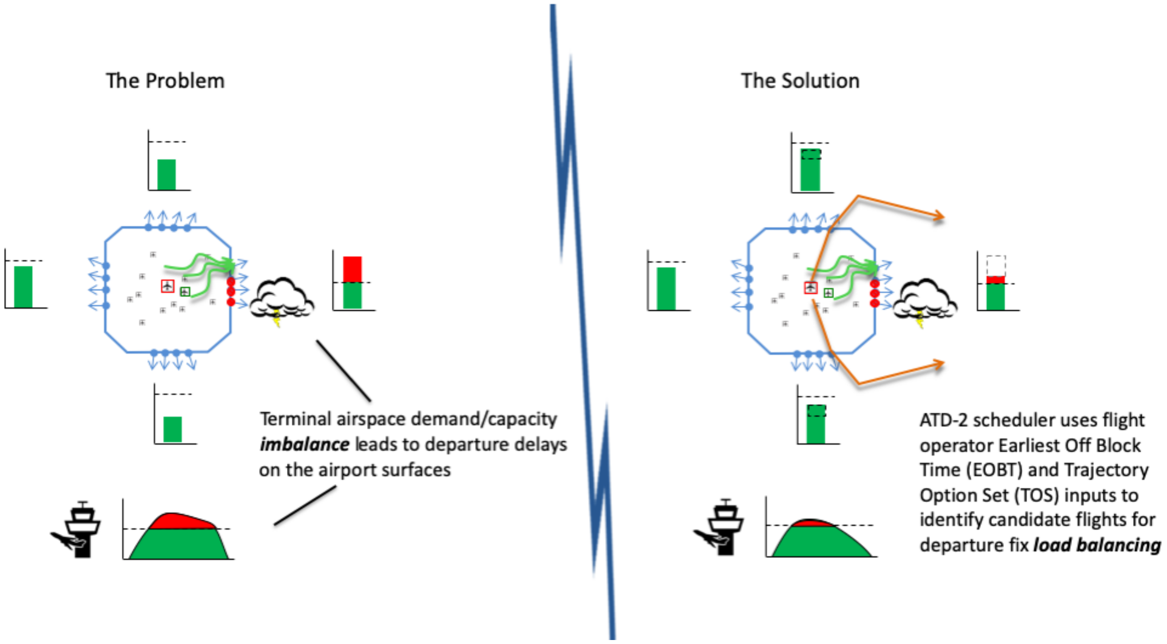


Figure 1: Improving demand and capacity imbalance at the terminal boundary with TOS

This problem can be magnified when inclement weather impacts D10 and reduces the capacity at the terminal fixes which can propagate delay to the surface of each airport in the D10 Metroplex, as shown in Figure 1. While inclement weather may constrain the capacity at a terminal departure gate and increase delay of the flight on restricted routes, there may be available alternative routes that might be free of restriction and subject to less delay. When this situation occurs, a flight that is originally routed through a constrained departure route may be rerouted through an alternative departure route with less surface delay, thus resulting in delay savings. The tradeoff for the flight to reroute onto an alternative route is often, but not always, a longer flight distance which may require additional fuel. By comparing the additional mileage of the alternative route to the delay savings, the airline operators can make an informed decision whether it might be advantageous to fly an alternative route.

The IADS Phase 3 system in the D10 Metroplex aids the decision to reroute aircraft over an alternative route by assessing the delay savings on each alternative route defined in a Trajectory Option Set (TOS). More information on ATD-2 Phase 3 TOS capability can be found in [Ref. 5-7].

The TOS is a set of alternative routes that each have an associated Relative Trajectory Cost (RTC) specified by the Flight Operators' (FO) own cost factors. 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.

In addition to computing the delay savings for individual flights, the IADS Phase 3 system also calculates the overall savings at a system level resulting from a reroute of a single flight. The savings at the system level is important for the FOs as they may be able to see how rerouting a single flight can benefit the air carrier, the larger fleet, as well as the airport or the metroplex. For an in-depth understanding of different benefits use cases see [Ref. 8].

## 1.1 Document Purpose and Scope

The purpose of this document is to describe the foundational mechanisms of ATD-2 benefits and explain the calculation methodology for the reported benefit metrics. The benefits discussed in this document are for Phase 3 benefits at North Texas metroplex terminal airspace. Benefits from Phases 1 and 2 capabilities at CLT are not covered here but can be found in [Ref. 9].

The intended audience for this document includes:

- ATD-2 internal researchers, who will use this document to review, maintain, and update ATD-2 benefits metrics, to improve the benefit calculation methods, and to perform the relevant data analyses using actual flight operations data.
- External field users, who are receiving the updated ATD-2 benefits reports. This document is expected to help them understand how the reported benefit metrics are calculated.
- Broader aviation community interested in understanding ATD-2 TOS rerouting benefits mechanism.

## 1.2 Document Organization

This document is organized as follows:

Section 1 provides introduction and purpose for this document.

Section 2 explains background information on concepts and terminology used in TOS benefits calculation.

Section 3 explains the important TOS benefits metrics along with examples.

Section 4 explains how TOS delay savings benefits can be translated into environmental benefits such and fuel and emissions savings and urban tree equivalent saving.

# 2 Background Information

## 2.1 Relative Trajectory Cost (RTC)

The cost of each alternative route relative to the nominal route for a flight's origin/destination pair is called Relative Trajectory Cost (RTC). It is a function of the mileage difference needed to fly an alternative route than the nominal route and it includes a cost factor to account for the additional airtime. The cost factor is defined by the FO. The RTC is a way for the FOs to express their willingness to fly a more costly route when the benefits exceed the RTC threshold.

## 2.2 Trajectory Option Set (TOS)

For TOS reroute capability for Phase 3 demonstration, ATC and FO have identified feasible Coded Departure Routes (CDRs) for each flight's origin/destination pair that are used as Trajectory Option Set (TOS). The original flight plan route filed by the flight operator, called "original filed route" hereafter, is typically the preferred route filed by the flight operators under the current NAS conditions.

Each of the routes included in a TOS may be classified in three ways:

- **Candidate** - When predicted Delay Savings (in minutes) for a TOS route is greater than or equal to the RTC value (in minutes), the route's Eligibility Status is "Candidate."

- **Potential** - When predicted Delay Savings (in minutes) for a TOS route is less than the RTC value, the route's Eligibility Status is "Potential".

- **TOP route** - The "top" route is the TOS option that has the largest predicted Delay Savings relative to the route's RTC. That is, it is the TOS route that is predicted to be the most advantageous option.

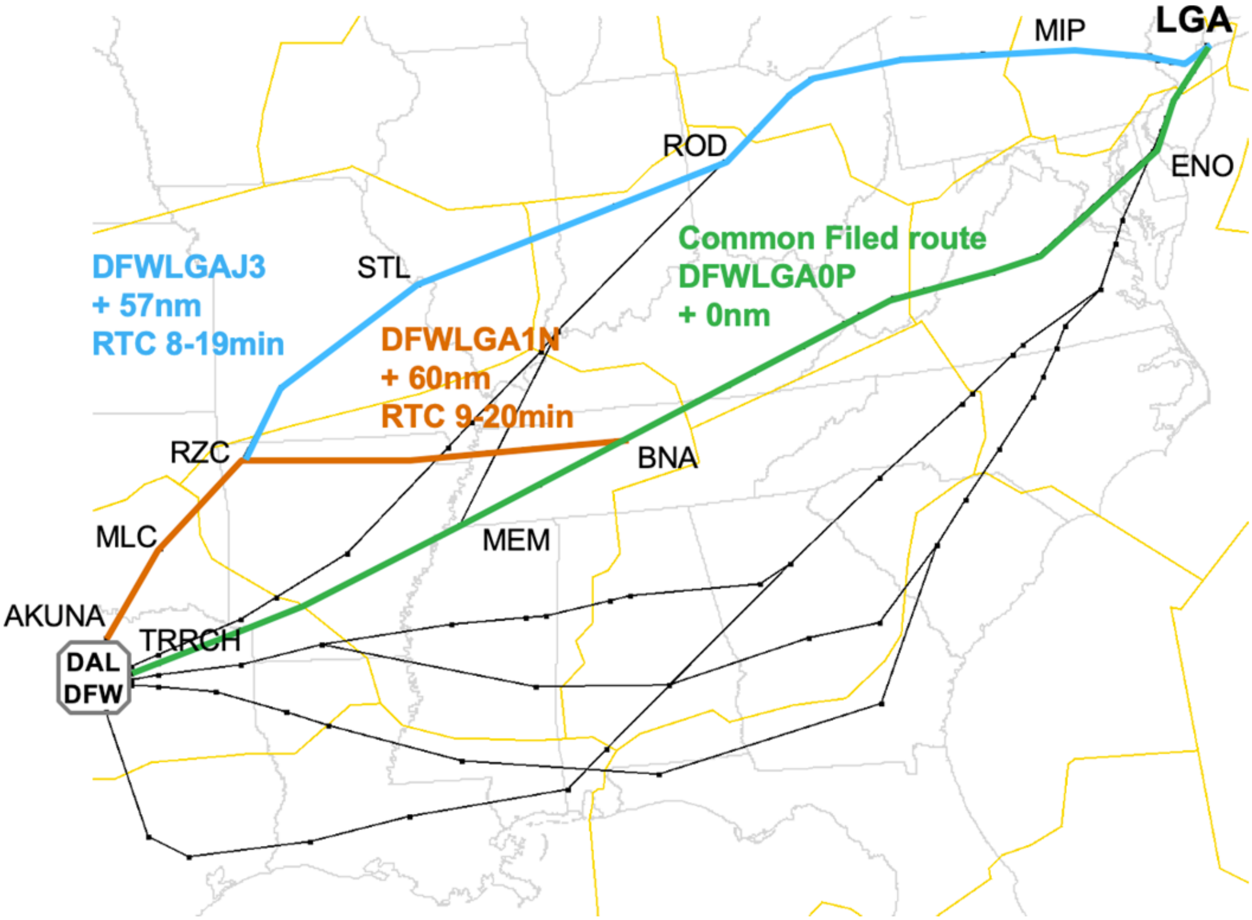


Figure 2: Relative Trajectory Cost (RTC) for alternate TOS CDRs

Figure 2 gives an example of possible RTC values and CDRs from DAL, DFW to LGA. The green line is the CDR route via the East gate that is commonly filed, and the blue and orange lines are two static TOS CDRs via the North gate.

## 2.3 Reference Filed Route

TOS candidate routes are always evaluated against the route the flight is currently filed to fly on. In other words, the current filed route is the reference for deciding when a TOS route becomes more beneficial. In this document the reference route is called the Reference Filed Route. Please note that the Reference Filed Route may or may not be the same as the original filed route defined in the previous section.

## 2.4 Delay

The difference in predicted time for an event under unimpeded conditions and under operational conditions represents the delay for that event. For the purpose of this document, we use the term 'event' to refer to distinct points in the timeline of a departure flight, such as pushback (OUT), spot crossing (SPOT), take off (OFF) etc.

## 2.5 Delay Savings

The difference in delay between a TOS route and a reference route is called the delay savings for the TOS route. When evaluating a TOS route, we look at delay on that TOS route and compare it with the delay on the currently filed route (which serves as the Reference Filed Route). This difference in delay between the TOS route and the Reference Filed Route is compared to the RTC threshold to determine if, and when, a TOS route may be a candidate for the rerouting the flight.

## 2.6 Delay and Delay Savings Convention

We have chosen the convention that a negative delay value indicates the flight is predicted to be earlier than the schedule and a positive value indicates a flight is predicted to be later than the schedule. A positive delay savings value indicates an actual saving for the TOS route compared to the Reference Filed Route, i.e., less delay than the Reference Filed Route, and a negative delay savings value means more delay for the TOS route than for the Reference Filed Route.

## 2.7 Sampling Metrics at OUT

The prediction of the delay on the Reference Filed Route evolves over time and might be different at various events, such as when a TOS route first becomes a candidate, when a TOS route is submitted to ATC for a reroute, or when the flight pushes back from the parking gate (OUT) as shown in Figure 3.

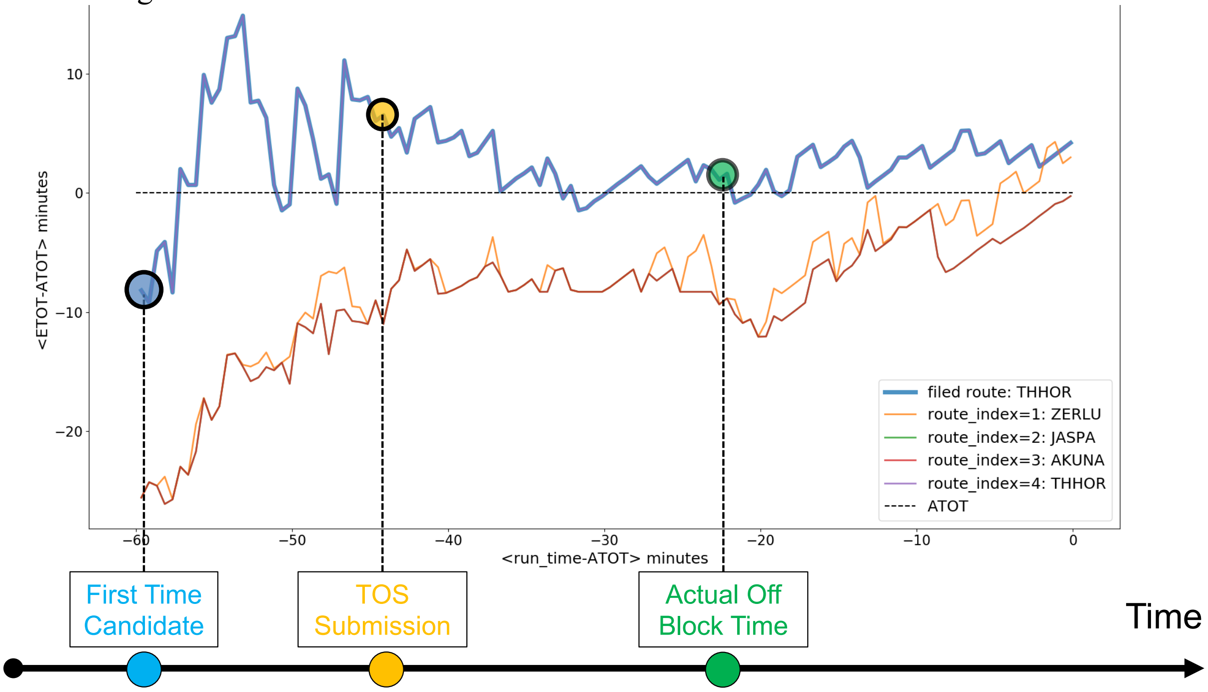


Figure 3: Evolution of benefits over time

In this figure, the horizontal axis is the time before take-off and the vertical axis is the difference between the Estimated Take Off Time (ETOT) and the Actual Take Off Time (ATOT) in minutes. The horizontal dashed line at $y = 0$ represents ATOT. In general, ETOT gets close to ATOT as flight nears the runway threshold, so the difference becomes close to zero. The thick blue line on top is the Reference Filed Route and the TOS alternative routes are shown in thin lines of different colors. The spread between the Reference Filed Route and any of the TOS routes is the predicted

OFF delay savings at that moment. As can be seen, the value of this spread changes over time. Since the predicted delay on the Reference Filed Route will impact the predicted delay savings, we need to define the event which we use to sample the value. The benefits metrics could be sampled at the time of submission, push back (OUT) or spot crossing and all of these samples will provide valuable information to help understand how the system is changing during the course of time and what delay savings may be possible. We chose to hone in on at the OUT event for all of our benefits estimations. This event represents the beginning of the flight's movement and the lapsed time transitioning to the runway for takeoff. This also helps to benchmark various metrics to a consistent event.

# 3 ATD-2 Phase 3 Benefits Metrics

The goal of rerouting a flight on a TOS alternative route (TOS route) is to reduce the delay the flight will experience as compared to the currently filed route (Reference Filed Route). This directly translates into operational cost savings for the airline. Furthermore, reducing departure delay for a flight can help reduce the delay for subsequent flights scheduled to depart after that flight on the same runway at the airport resulting in possible fleet and airport-wide savings. Analogously, in a metroplex environment, such as D10, where flights from multiple airports use the same limited resources (departure fixes) delay savings on one flight in a queue to cross the departure fix can help subsequent flights in the queue for that fix resulting in system-wide delay savings.

When inclement weather constrains the capacity at a given fix in the D10 Metroplex, there are often alternative fixes that are not impacted by the weather that have available capacity. When this situation occurs, a flight that is originally routed through the constrained fix can reroute through the alternative fix with little to no delay. The tradeoff for the flight to reroute to the alternative fix is often, but not always, a longer route in terms of air miles and requires additional fuel. By comparing the additional mileage of the alternative route to the delay savings, the airline operators can make an informed decision about when it is advantageous to fly the alternative route. The IADS Phase 3 system in the D10 Metroplex aids the decision to reroute aircraft over an alternative fix by assessing the delay savings on each alternative route defined by each flight operator's Trajectory Option Set (TOS).

While there may exist one or more beneficial TOS alternative routes for a flight that is experiencing delay, the flight operators may opt to keep this flight on its current filed route. In this document we explain how to calculate the actual benefits for flights that were rerouted on a TOS route, as well as predicted benefits for flights that had a TOS candidate route which was never acted upon. While actual benefits are calculated using actually observed data and tell us how the carrier, airport, or entire metroplex system benefited from rerouting a flight, the documentation of potential benefits is also helpful in understanding what opportunities existed on any given day and for later analysis. An in-depth study of different benefits use cases can be found in [Ref. 8].

In the following sections we define the ATD-2 Phase 3 TOS benefits metrics. As described earlier, all the metrics are sampled at the OUT event and negative benefit values are considered favorable.

### 3.1 OFF Delay Savings

Often times a flight can reduce delay at take-off by departing from a different runway with shorter taxi time which could be a result of less surface congestion between parking gate and the newly assigned runway. The amount of time by which the take-off delay is reduced is called OFF Delay Saving. The OFF Delay Saving is the result of the difference in taxi time between two routes (the Reference Filed Route and the TOS route).

A flight's Unimpeded Off Block Time (UOBT) is defined using its Earliest Off Block Time (EOBT) and Actual Off Block time (AOBT) as follows:

$$\text{Before pushback, } UOBT = \begin{cases} EOBT, & \text{if current time} \leq \text{EOBT} \\ Current\ Time, & \text{if current time} > \text{EOBT} \end{cases}$$

After pushback, $UOBT = AOBT$

Predicted taxi time is defined as the difference between the Estimated Take Off Time (ETOT) and Unimpeded Off Block Time (UOBT).

$$Predicted\ taxi\ time = ETOT - UOBT$$

Once the flight has taken off, the actual taxi time can be calculated as the difference between actual push back time, represented by AOBT, and Actual Take Off Time (ATOT):

$$Actual\ taxi\ time = ATOT - AOBT$$

#### 3.1.1 Predicted OFF Delay Saving

Before pushback, the difference between predicted taxi time at OUT for TOS route and Reference Filed Route gives the predicted OFF delay savings.

$$\begin{aligned} &Predicted\ OFF\ Delay\ Saving \\ &\quad = (Predicted\ taxi\ time\ @\ OUT\ on\ Ref\ filed\ route) \\ &\quad - (Predicted\ taxi\ time\ @\ OUT\ on\ TOS\ route) \end{aligned}$$

##### 3.1.1.1 Example

Flight ABC123 has an EOBT of 12:00Z. The Reference Filed Route is CDR0P via runway 10L with an ETOT of 12:20Z predicted at OUT. The TOS candidate route for this flight is CDR1N via runway 10R with an ETOT of 12:10Z predicted at OUT. Therefore, the predicted taxi time on Reference Filed Route is 20 mins, and that on TOS route is 10 mins if sampled before 12:00Z (EOBT). The predicted OFF delay saving at OUT on TOS route CDR1N for this flight is:

Predicted OFF delay savings at OUT = 20 mins – 10 mins = 10 mins

#### 3.1.2 Actual OFF Delay Saving

Once the flight takes off on a TOS route, we have actual data about the taxi time the flight took on the TOS route. The difference between actual taxi time on the TOS route and the predicted taxi time on the Reference Filed Route is the best approximation of the actual OFF delay savings. Note that we use the actual taxi time for TOS route and the predicted taxi time for the reference route because we cannot have actual values for both routes – the flight will depart either on the TOS route or Reference Filed Route, but not both. The formula for the actual OFF Delay Savings is given by:

$$\begin{aligned} &Actual\ OFF\ Delay\ Saving \\ &\qquad = (Predicted\ taxi\ time\ @\ OUT\ on\ Ref\ filed\ route) \\ &\qquad - (Actual\ taxi\ time\ on\ TOS\ route) \end{aligned}$$

Where we measure the actual taxi time on the TOS route post operations, and we sample the predicted taxi time on the Ref file route at the OUT event. The predicted taxi time on the Ref filed routed is generated by the Scheduler and is the most accurate estimate we have for the duration of taxi time if the TOS reroute did not occur (Scheduler accuracy estimates as a function of lookahead time are available in DASC paper [5]).

We sample at the OUT event because this is the last moment in time before the flight starts operating. Once the flight pushes back and starts moving towards the TOS route runway, there is the potential that the Ref filed route taxi time predictions can be skewed after pushback.

We use the Scheduler prediction of taxi time on the Ref filed route as the baseline for comparison because Fight Operators have communicated that in the absence of ATD-2 Phase 3 system they have no insights into delay or delay savings opportunities along TOS routes. In the absence of this information, Flight Operators routinely stay on the Ref filed route which is our baseline comparison for actual delay savings.

#### 3.1.2.1 Example

The same flight ABC123 is rerouted on TOS route CDR1N. It pushes back at 12:01Z and takes off at 12:10Z. Therefore, the actual taxi time for this flight is 12:10Z – 12:01Z = 9 mins. Since the flight pushed back after EOBT, the predicted taxi time at OUT on Reference Filed Route is 12:20Z – 12:01Z = 19 mins. The actual OFF delay savings for this flight is:

Actual OFF delay saving = 19 mins – 9 mins = 10 mins

## 3.2 IN Delay Savings

This metric is the predicted delay savings for the IN event, that is when the flight pulls in at the parking gate at the destination airport, on the TOS route. This does not take into account wind miles. This metric is calculated as

$$IN\ Delay\ Savings = (OFF\ Delay\ Savings) - (TOS\ route\ additional\ flight\ time)$$

The first term in this calculation is the OFF Delay Savings explained in section 3.1. The second term in the above equation is the difference in en-route flight time between the reference route and the TOS route. If the TOS route is longer than the reference route this value will be a positive number and if the TOS route is shorter than the reference route, this will be a negative number. The additional flight time is computed by dividing the extra nautical miles on TOS route by the flight's filed speed.

### 3.2.1 Predicted IN Delay Saving

Before a flight is rerouted, the predicted OFF Delay Savings is used to calculate the predicted IN Delay Savings as follows:

$$\begin{aligned}\mathit{Predicted\ IN\ Delay\ Savings} &= (\mathit{Predicted\ OFF\ Delay\ Savings\ at\ OUT}) \\ &\quad - (\mathit{TOS\ route\ additional\ flight\ time})\end{aligned}$$

#### 3.2.1.1 Example

Flight ABC123 from example in section 3.1 with Predicted OFF Delay Savings of 10 mins has an additional 3 mins of flight time on the TOS route. Therefore, the Predicted IN Delay Savings at OUT for this flight would be:

Predicted IN Delay Savings = 10 minutes – 3 minutes = 7 minutes

So, if the flight is rerouted on this TOS route, it is predicted that it will arrive at the arrival parking gate 7 minutes earlier than on the filed route.

### 3.2.2 Actual IN Delay Savings

When a flight takes off on a TOS route, we can build upon the Actual OFF Delay Savings to estimate Actual IN Delay Savings:

$$\begin{aligned}\mathit{Actual\ IN\ Delay\ Savings} &= (\mathit{Actual\ OFF\ Delay\ Savings\ at\ OUT}) \\ &\quad - (\mathit{TOS\ route\ additional\ flight\ time})\end{aligned}$$

#### 3.2.2.1 Example

Flight ABC123 from example in section 3.1 experiences an Actual OFF Delay Saving of 11 mins on the TOS route. Since the extra flight time on this TOS route is estimated to be 3 mins, the Actual IN Delay Savings for this flight would be:

Actual IN Delay Savings = 11 minutes – 3 minutes = 8 minutes

## 3.3 System-Wide Aggregate Delay Savings

This metric gives the sum of estimated savings for rerouting one flight plus other flights in the system staying on their filed routes that may benefit from the rerouted flight's new route and new take-off time [Ref. 5].

There are often additional system-wide benefits from a single flight reroute in addition to the net savings to the individual flight that is rerouted. When the terminal boundary is operating as a significant constraint to the flow of traffic, in contrast to situations where the runway is acting as the main constraint, there exists benefits to the set of flights that are not rerouted and subject to the terminal constraints. The system-wide aggregate benefits materialize if MIT restricted flights are able to move one slot earlier owing to the rerouted flight giving up its slot. If the MIT restrictions at the terminal boundary are operating as the main constraint on the system, then there is often available capacity at the runway to accommodate the rerouted flight without delaying other flights.

Aggregate savings may also occur when a flight is departing on the TOS route from a different runway than its filed route. In this case, flights that were behind the rerouted flight would be able to depart earlier given that the flight has given up its slot in the runway queue and joined another runway queue instead, where some subsequent flights may or may not depart later. Depending on the demand between the two runways and the predicted off time difference between the Reference Filed Route and the TOS route, there may be aggregate savings.

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

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

which is the OFF Delay Savings to the rerouted flight ($ODS_T$) plus a sum over the set of flights 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 flights ETOTs can be updated. The result can be that flights that are not rerouted have taxi time $TT_T^*$ (assuming the TOS reroute) not equal to $TT_F^*$ (assuming the original filed route), thus the system-wide $ADS_T$ measure changes.

The set of flights $\mathbb{F}$ that we include in the $ADS$ summation can be defined to provide different flavors of the metric. We can include all flights in D10, flights only from DFW, flights only from DAL, or any other constraints. The different versions of $ADS$ could be valuable to different decision makers. ATC might be interested in looking at $ADS$ summed over the D10 TRACON to understand the impact of a single reroute to the flow through the terminal whereas flight operators might be more interested in the set of flights $\mathbb{F}$ from a specific airport or even a specific flight operator to understand the impact of the reroute decision on their fleet. An additional constraint enforced on the set of flights $\mathbb{F}$ is that the flight must provide an EOBT and the Unimpeded take Off Time (UTOT) must be within 60 minutes of current time. This constrains the calculation to only include flights with high quality trajectories driven by the EOBT predictions and within a reasonable lookahead time.

#### 3.3.1.1 Example

The following table lists the UTOT and current ETOTs of all flights with UTOT within 60 mins after flight ABC123 as well as the what-if ETOTs for all flights if flight ABC123 was rerouted

| Flights | UTOT | Current ETOT ($ETOT_F$) | What-if ETOT after reroute ($ETOT_R$) | $ETOT_F - ETOT_R$ (minutes) |
|---|---|---|---|---|
| BCD123 | 12:15 | 12:25 | 12:19 | 6 |
| CDE234 | 12:30 | 12:35 | 12:33 | 2 |
| DEF345 | 12:35 | 12:40 | 12:38 | 2 |
| EFG456 | 12:38 | 12:48 | 12:35 | 13 |
| FGH567 | 12:45 | 12:55 | 12:38 | 17 |
| HIJ678 | 12:55 | 13:05 | 12:45 | 20 |

ADS for flight ABC123 = 11 minutes + (6 + 2 + 2 + 13 + 17 + 20) minutes
= 11 minutes + 60 minutes
= 71 minutes

# 4 Environmental Benefits

The delay saving that materializes from rerouting a departure flight on a TOS route helps the flight operators to meet not only their operation performance goals but also results in a reduction in fuel burn and $CO_2$ emissions. All the delay saving metrics described in this document can be translated into savings for the environment.

The fuel savings for the TOS rerouted flight is the sum of surface fuel savings that materialize from reduced take-off delay and the airborne cost of flying extra nautical miles on the TOS route. Note that a shorter TOS route than the Reference Filed Route will result in airborne savings instead of airborne cost, thereby resulting in higher total savings for the flight.

$$Individual\ flight\ fuel\ savings = Surface\ fuel\ savings + \ Airborne\ fuel\ cost$$

In addition to individual flight savings, each TOS rerouted flight also results in deep network savings for the flight operators. To capture some of this benefit, we need to capture the environment benefits of systemwide savings resulting from each reroute.
Once we have the individual flight level savings, the total savings form reach TOS reroute can be calculated as:

$$Total\ fuel\ savings = Individual\ flight\ fuel\ savings + \ Aggregated\ fuel\ savings$$

Once the total fuel saving is known, total $CO_2$ emissions savings and urban tree savings can be computed as shown in Figure 4.

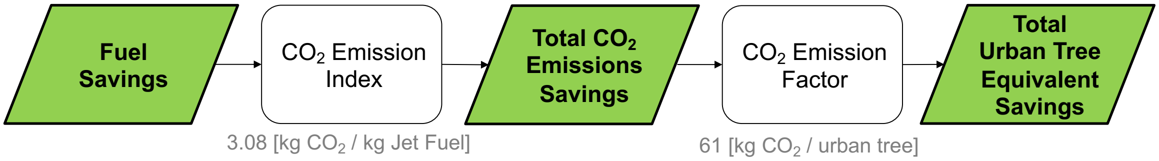


Figure 4: Delay savings from TOS can be translated into fuel savings, $CO_2$ emissions savings, and urban tree equivalent savings.

The total fuel saving can be converted into $CO_2$ emission savings. According to the U.S. Energy Information Administration, the carbon dioxide ($CO_2$) emissions coefficient for Jet Fuel is 9.57 kg $CO_2$ / gallon [Ref. 10]. The density of Jet Fuel (Jet A type for US) is 6.84 [lb/gallon] (= 3.103 [kg/gallon]) at 59°F. Therefore, the amount of $CO_2$ emissions when the aircraft consumes 1 kg of Jet Fuel is EICO2 = 9.57 [kg $CO_2$/gallon] / 3.103 [kg Jet Fuel/gallon] = 3.08 [kg $CO_2$ / kg Jet Fuel]. Thus, once we know the total fuel saved from, $CO_2$ emissions saving can be calculated as:

$$CO_2\ Emission\ Saving\ [kg] = Total\ fuel\ saving\ [kg\ Jet\ Fuel] \times EICO_2\ \ [kg\ CO_2\ /\ kg\ Jet\ Fuel]$$

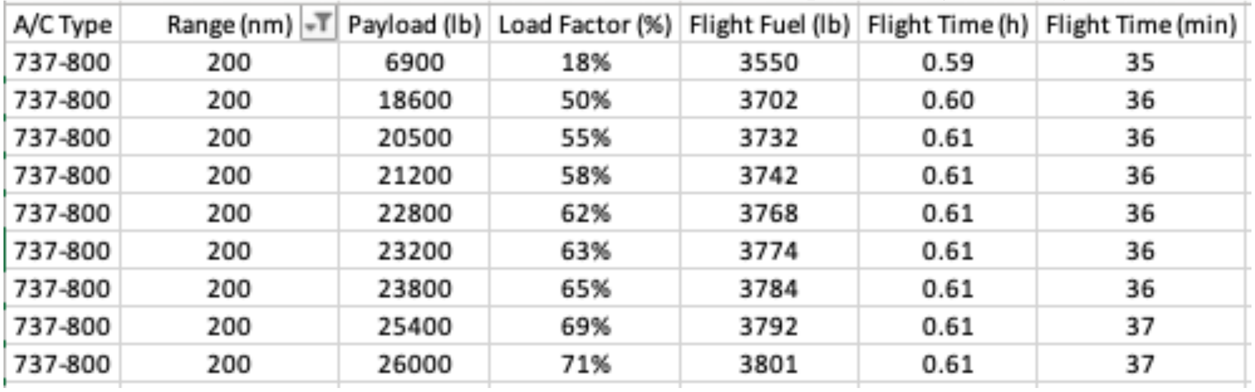
The total amount of $CO_2$ savings can be transformed to the equivalent number of planted urban trees. According to US Environmental Protection Agency (EPA), the emission factor is 0.0605 metric tons $CO_2$ per planted urban tree. That is, one medium growth tree planted in an urban environment and grown for 10 years can sequester 60.5 kg of $CO_2$ [Ref. 11]. Note that on December 17, 2018, the EPA updated this emission factor from 0.039 metric tons $CO_2$ per urban tree planted, which only had captured coniferous trees, to 0.060 based on a weighted average of coniferous and deciduous trees in an urban area. Due to the rounding while performing the calculations given in the equations, the computation results may have a tolerance. In the urban tree benefit calculations, the emission factor of 0.061, instead of 0.060, is used as a conservative approach.

$$\begin{aligned} Urban\ Tree\ Equivalent\ [urban\ trees] \\ = CO_2\ Emission\ Saving\ [kg] \\ \div\ CO_2\ Emission\ Factor\ [kg\ CO_2\ /\ urban\ tree] \end{aligned}$$

ATD-2 worked with its Phase 3 field demonstration partners to develop airborne fuel burn tables for different aircraft models to calculate the environmental benefits of TOS reroute capability. In the following subsections we describe the airborne fuel burn tables, explain environmental benefits calculations, present an example of environmental benefits, and finally present results from ATD-2 Phase 3 field demonstration.

## 4.1 Airborne Fuel Burn Tables

Airborne Fuel Burn Tables give the amount of fuel burned for each aircraft type as a function of the flight range and total payload. For our purposes, we use flight time to measure the flight range and flight load factor to measure the total payload. So, for a given aircraft type and load factor we can use this table to estimate the amount of fuel that will be required to fly it on any route.



| A/C Type | Range (nm) | Payload (lb) | Load Factor (%) | Flight Fuel (lb) | Flight Time (h) | Flight Time (min) |
|---|---|---|---|---|---|---|
| 737-800 | 200 | 6900 | 18% | 3550 | 0.59 | 35 |
| 737-800 | 200 | 18600 | 50% | 3702 | 0.60 | 36 |
| 737-800 | 200 | 20500 | 55% | 3732 | 0.61 | 36 |
| 737-800 | 200 | 21200 | 58% | 3742 | 0.61 | 36 |
| 737-800 | 200 | 22800 | 62% | 3768 | 0.61 | 36 |
| 737-800 | 200 | 23200 | 63% | 3774 | 0.61 | 36 |
| 737-800 | 200 | 23800 | 65% | 3784 | 0.61 | 36 |
| 737-800 | 200 | 25400 | 69% | 3792 | 0.61 | 37 |
| 737-800 | 200 | 26000 | 71% | 3801 | 0.61 | 37 |

Figure 5: Example airborne fuel burn table for Boeing 737-800 aircraft.

## 4.2 Benefits Calculations

As mentioned previously, the total environmental benefits realized from each TOS reroute consist of benefits from the individual rerouted flight as well as systemwide aggregated benefits realized by all other flight which were themselves not rerouted but still benefitted from the reroute. For a detailed explanation of systemwide aggregated benefits see section 3.3.

### 4.2.1 Individual Flight Fuel Savings

Individual fuel saving is calculated for TOS rerouted flight only. It is the net of surface fuel savings and airborne fuel cost.

$$Individual\ flight\ fuel\ savings = Surface\ fuel\ savings + \ Airborne\ fuel\ cost$$

#### 4.2.1.1 Surface Fuel Savings

While a flight is taxiing its engine are tuned on and it is burning fuel. A reduced taxi time, as measured by OFF Delay Savings, results in a reduction in fuel burn and gas emissions on the airport surface. ATD-2 developed surface fuel and emission savings calculation methods as part of its Phase 1 & 2 field demonstration at CLT. These methods can be applied here to calculate surface fuel and emission savings resulting from OFF Delay Savings. For details of calculations see [Ref. 9]

#### 4.2.1.2 Airborne Fuel Cost

The airborne fuel cost of a TOS reroute is the extra fuel burned by flying on a TOS route. For every rerouted fight, ATD-2 captures the aircraft type information, TOS route distance, and Reference Filed Route distance. ATD-2 has worked with FOs to create historic as well as projected load factor database. With all this data and using Airborne Fuel Burn Tables described in section 4.1 we can determine the amount of fuel burned (fuel cost) on TOS route and Reference Filed Route. Then airborne fuel cost would be:

$$Airborne\ Fuel\ Cost = Reference\ Filed\ Route\ fuel\ cost - \ TOS\ route\ fuel\ cost$$

### 4.2.2 Aggregated Fuel Savings

In addition to individual flight savings, each TOS rerouted has the potential to reduce delay for other flights within D10 TRACON. To capture some of this benefit, we need to capture the experienced by other flights in the system which were affected by the TOS reroute. Aggregate System-Wide Savings benefit metric (section 3.3) includes the benefits for the TOS rerouted flight and other flights, therefore:

$$OFF\ Delay\ Savings\ for\ other\ flights = Predicted\ Aggregated\ OFF\ Delay\ Savings \\ - Predicted\ OFF\ Delay\ Savings\ for\ TOS\ flight$$

It is important to recognize that the OFF Delay Savings for other flights is defined as the predicted system level ADS minus the Predicted ODS of the individual rerouted flight. Since we are comparing two predictions, the OFF Delay Savings for other flights is also a prediction. At the individual flight level, we take great care to calculate an actual delay savings for the rerouted flight but at the system level we have no reliable mechanism to calculate the actual delay savings. At the request of Flight Operators, we applied the assumption that the actual system level savings for other flights that are not rerouted is equivalent to the predicted savings for these flights. This assumption was applied to our benefits calculations as shown in the 4.3 example.

Note that the aggregated benefits only come from reduced surface delays. All these flights will still fly on the same route, just that they will experience shorter surface delays because some flight ahead of them on the departure queue was rerouted on a TOS route which resulted in all these flights moving a slot ahead in queue. For this reason, aggregated benefits only have a surface fuel savings. Once again, we use surface fuel and emission savings calculations methods from ATD-2 Phase 1 & 2 [Ref. 9] to translate systemwide aggregated savings to fuel savings.

Whereas for individual benefits the ATD-2 system captures the aircraft type information for the rerouted flight, it does not have that level of information for the aircrafts included in the aggregated benefits measurement. We do know the most popular aircraft type at both DFW (Boeing 737-800) and DAL (Boeing 737-700) so we assume all the aircrafts contributing to aggregated benefits to be one of these types based on the airport.

### 4.2.3 Total Fuel Savings

The total fuel saved from each TOS reroute is the total of individual fuel saved and aggregated fuel saved.

$$Total\ fuel\ savings = Individual\ flight\ fuel\ savings + \ Aggregated\ fuel\ savings$$

## 4.3 Example

In this section we will walk through an example of a TOS rerouted flight and calculate the environmental benefits associated with this reroute. Let us consider a flight XYZ789 with the following data:

| | |
|---|---:|
| A/C type | B737-800 |
| Load Factor | 84% |
| Predicted OFF Delay Savings | 8.2 mins |
| Actual OFF Delay Savings | 10.8 mins |
| Ref filed route flight time | 176.9 mins |
| TOS route additional flight time | -1.6 mins |
| Agg. OFF Delay Savings | 70.9 mins |

Step 1: Individual Flight Fuel Savings

*Surface Fuel Savings*
Using Phase 1 & 2 surface calculation methods, we get surface fuel savings of **131.03 kg**

*Airborne Fuel Cost*
Based on the data, we know that the TOS route flight time = 176.9 mins + -1.6 mins = 175.3 mins

Reference Filed Route fuel cost using Boeing 737-800 airborne fuel burn table, load factor 84% and flight time 176.9 mins = 16,271 lbs

TOS Route fuel cost using Boeing 737-800 airborne fuel burn table, load factor 84% and flight time 175.3 mins = 16,152 lbs

Airborne fuel cost = Reference Filed Route fuel cost – TOS Route fuel cost
= 16,271 lbs – 16,152 lbs
= 119 lbs = **53.98 kg**

**Individual flight fuel saving** = Surface Fuel Savings + Airborne Fuel Cost
= 131.03 kg + 53.98 kg
= **185 kg**

Step 2: Aggregated Fuel Savings

$$\begin{aligned}\text{OFF Delay Savings for other flights} &= \text{Aggregated OFF Delay Savings} \\ &\quad - \text{Predicted OFF Delay Savings for TOS flight} \\ &= 70.9 \text{ mins} - (8.2 \text{ mins}) \\ &= 62.7 \text{ mins}\end{aligned}$$

Assuming the most popular aircraft type at this airport is Boeing 737-800, we use ATD-2 Phase 1 & 2 surface fuel and emissions calculations methods to get fuel savings got 62.7 mins of delay savings. This value comes out to **760.67 kg**

Step 2: Total Fuel Savings

$$\begin{aligned}\text{Total fuel savings} &= \text{Individual flight fuel savings} + \text{Aggregated fuel savings} \\ &= 185 \text{ kg} + 760.67 \text{ kg} \\ &= \mathbf{945.67\ kg}\end{aligned}$$

Now that we have the total fuel savings from this TOS reroute, we can convert it to $CO_2$ savings and urban tree equivalent savings.

$$\begin{aligned}CO_2 \text{ Emission Saving [kg]} &= \text{Total fuel saving [kg Jet Fuel]} \times EICO_2 \text{ [kg } CO_2 \text{ / kg Jet Fuel]} \\ &= 945.96 \text{ kg Jet Fuel} \times 3.08 \text{ kg } CO_2 \text{ / kg Jet Fuel} \\ &= \mathbf{2912.68\ kg\ CO_2}\end{aligned}$$

$$\begin{aligned}&\text{Urban Tree Equivalent} \\ &\quad = CO_2 \text{ Emission Saving [kg } CO_2\text{]} \div CO_2 \text{ Emission Factor [kg } CO_2 \text{ / urban tree]} \\ &\quad = 2912.68 \text{ kg } CO_2 \div 61 \text{ kg } CO_2 \text{ / urban tree} \\ &\quad = \mathbf{47.75\ urban\ trees}\end{aligned}$$

Note, as explained in section 2.6, the negative sign in the above results indicates savings. So, based on the above calculations we can say that the reroute of our example flight XYZ789 resulted in 945.67 kg of jet fuel savings, which is equivalent to 2912.68 kg of $CO_2$ saved, which in turn is equivalent of saving 47.75 medium growth trees planted in an urban environment and grown for 10 years.

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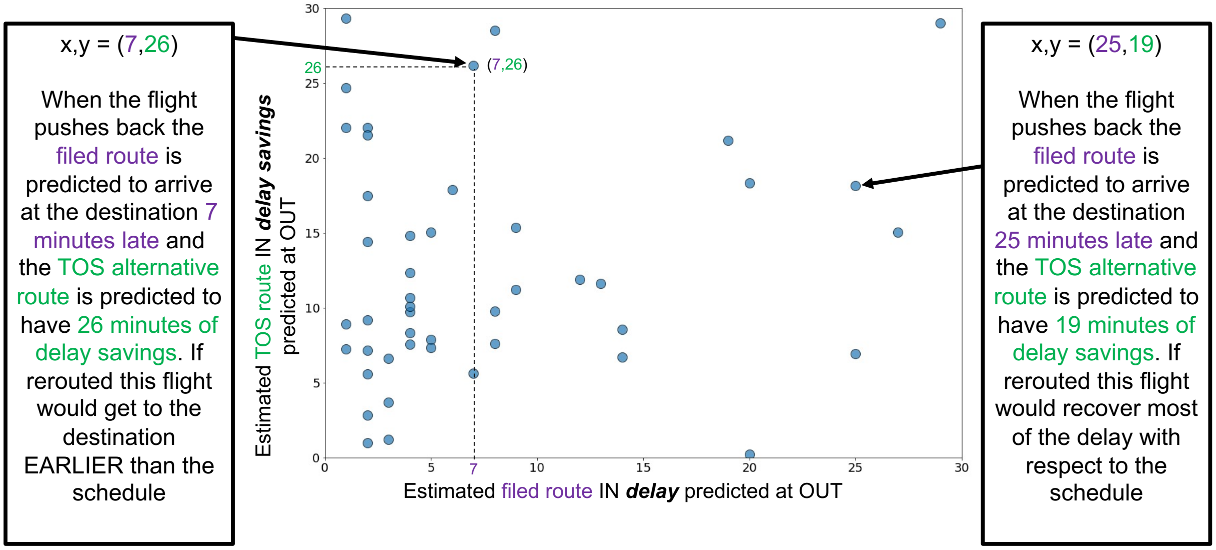
## Appendix A: Using Benefits Metrics for Reroute Decision Making

FOs may want to consider the IN delay on the filed route and the IN delay savings on the TOS route together and see if the tradeoff may be acceptable if the flight was submitted for a reroute on a TOS route.

Figure 5 shows a scatter plot with filed route IN Delay along the horizontal axis and TOS route IN Delay Savings along the vertical axis. Our convention is that positive delay saving values are good, so the chart uses the positive Y-axis of the coordinate plane and hence the origin, or (0,0) point, is on the bottom left corner.



x,y = (7,26)

When the flight pushes back the filed route is predicted to arrive at the destination 7 minutes late and the TOS alternative route is predicted to have 26 minutes of delay savings. If rerouted this flight would get to the destination EARLIER than the schedule

x,y = (25,19)

When the flight pushes back the filed route is predicted to arrive at the destination 25 minutes late and the TOS alternative route is predicted to have 19 minutes of delay savings. If rerouted this flight would recover most of the delay with respect to the schedule

Figure 6: Using Delay and Delay Savings to make reroute decision

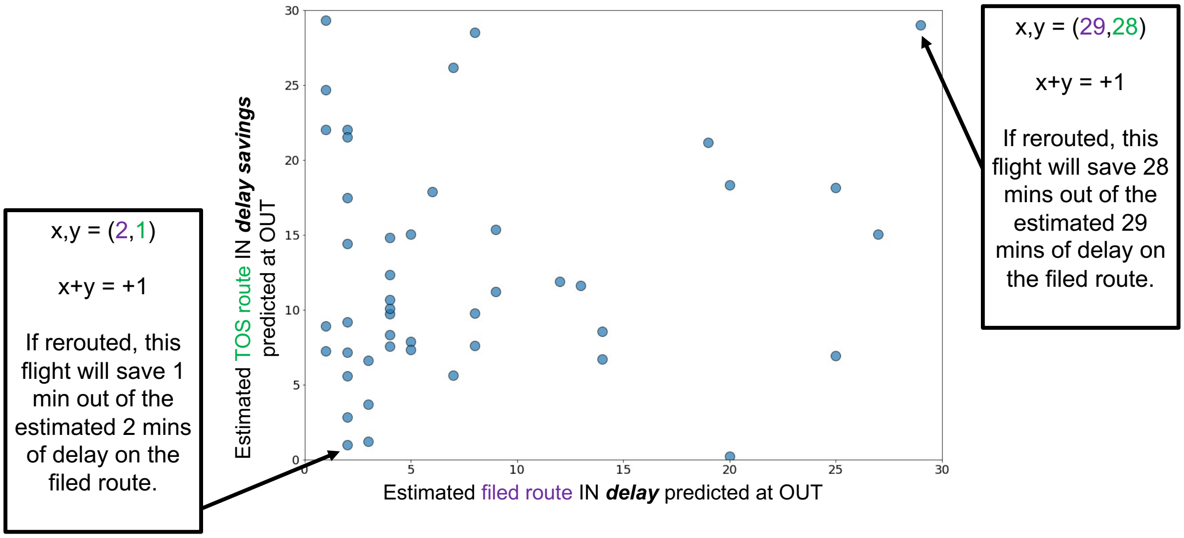
Each blue dot on this chart is a TOS candidate and for each of these candidates you can get delay on its filed route by looking at its X-axis value. Similarly, you can get the delay savings on the TOS route by looking at its Y-axis value.

Consider the point at (7, 26). Here, we have a TOS candidate with an estimated delay of 7 mins on its filed route and a delay savings of 26 mins on its TOS route. This means that when this flight pushes back the filed route is predicted to arrive at the destination 7 minutes late and the TOS alternative route is predicted to have 26 minutes of delay savings. So, if this flight is rerouted, it might get to the destination about 19 mins earlier than the schedule.

Consider another point at (25, 19). In this case, the delay on the filed route is 25 mins and delay savings on the TOS route is 19 mins. So, when this flight pushes back the filed route is predicted to arrive at the destination 25 minutes late and the TOS alternative route is predicted to have 19 minutes of delay savings. If this flight is rerouted it would recover most of the delay and arrive about 6 mins later than the schedule, as opposed to 25 mins later than the schedule on the filed route.

These examples illustrate that each of these TOS candidates have delay savings compared to the filed route and it will reduce delay compared to the filed route

It may appear that instead of looking at both filed route delay and TOS router delay savings, it may be sufficient to look at a single element which would be the IN delay savings (i.e., the sum of X and Y axis in this chart). Given the relative value of the delay savings to the IN schedule, both Filed route IN Delay and TOS route IN Delay Savings are needed to make reroute decisions. This is illustrated in Fig 7.



x,y = (2,1)

x+y = +1

If rerouted, this flight will save 1 min out of the estimated 2 mins of delay on the filed route.

x,y = (29,28)

x+y = +1

If rerouted, this flight will save 28 mins out of the estimated 29 mins of delay on the filed route.

Figure 7: Two very different cases with same x+y value.

Consider point (29, 28) in Fig 7. If rerouted, the TOS route may reduce 28 mins out of 29 mins of delay that was on the filed route and will arrive only 1 min later than the schedule. This may be a great candidate flight to reroute. Now consider point (2, 1) where the flight will also arrive only 1 min later than the schedule after rerouting, just like the point (29, 28) we discussed. In this case, delay on the filed route was only 2 mins to begin with and the TOS route wipes out 1 min of this delay resulting in a net delay of 1 min on arrival for this flight. While both of these candidates look equally good when you look at the $x + y$ value, the first example appears to be a better candidate for rerouting compared to the second one.

Figure 8 shows how this $x + y$ sum can be used to identify disruptive TOS candidates, i.e., routes that would make the flight to arrive too early at the destination and possibly causing gate conflicts and holding patterns due to gate unavailability. This example uses a threshold of 10 mins to illustrate disruptive arrivals, but in practice the flight operators may choose to define this threshold however they see fit or ignore it when gate conflict is not a factor.

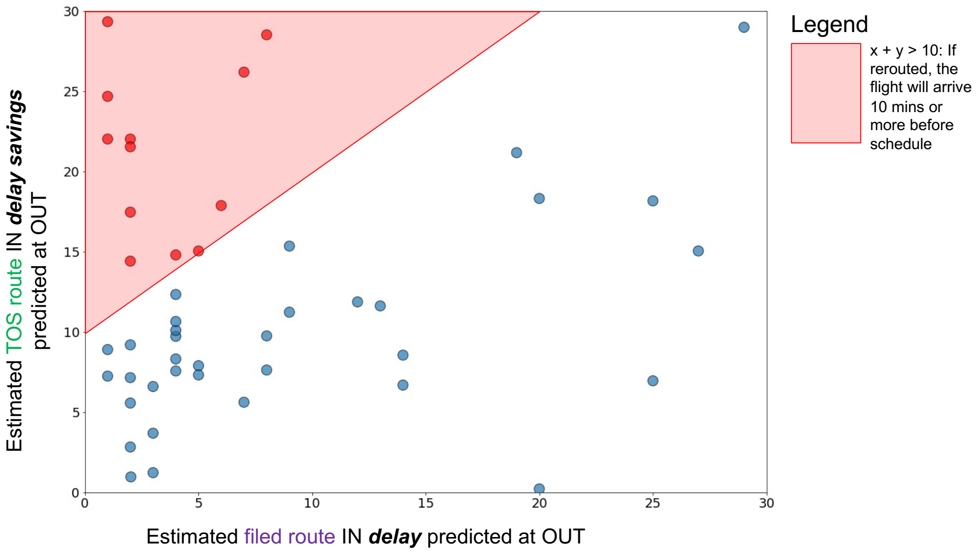


Figure 8: Identifying disruptive flights.

The red dots on this chart are all the TOS candidates that would arrive 10 mins earlier than the schedule at the parking gate. In fact, any candidate that falls within the red highlighted area will arrive earlier than the hypothetical threshold if rerouted. This mechanism provides the FOs a way to identify and possibly avoid disruptive reroutes.

## Appendix B: Acronyms

This appendix contains acronyms that are used repeatedly throughout this document.

| Acronym | Term |
|---|---|
| AOBT | Actual Off-Block Time |
| ARTCC, or Center | Air Route Traffic Control Center |
| ATC | Air Traffic Control |
| ATD-1 | ATM Technology Demonstration 1 |
| ATD-2 | Airspace Technology Demonstration 2 |
| ATM | Air Traffic Management |
| ATOT | Actual Takeoff Time |
| CLT | Charlotte-Douglas International Airport |
| $CO_2$ | Carbon dioxide |
| ConOps | Concept of Operations |
| ConUse | Concept of Use |
| DAL | Dallas Love International Airport |
| DFW | Dallas / Fort-Worth International Airport |
| EDCT | Expect Departure Clearance Time |
| EOBT | Earliest Off-Block Time |
| ETA | Estimated Time of Arrival |
| ETOT | Estimated Takeoff Time |
| FAA | Federal Aviation Administration |
| FO | Flight Operator |
| IADS | Integrated Arrival, Departure, Surface |
| IN | IN parking gate Time |
| LGA | LaGuardia International Airport |
| MIT | Miles-in-Trail |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| OFF | Takeoff Time |
| OUT | Pushback Time |
| RTC | Relative Trajectory Cost |
| SOBT | Scheduled Off-Block Time |
| TOS | Trajectory Option Set |
| TRACON | Terminal RADAR Approach Control |
| UTOT | Undelayed Take Off Time |