Modeling Relative Trajectory Costs for Airborne Trajectory Reroutes using Trajectory Option Sets

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Abstract— **This paper proposes a novel approach to calculating Relative Trajectory Costs (RTC) as part of a new third-party tool to enable advanced airborne reroute operations. A selection of cost and delay factors, such as Crew, Fuel, Airspace Cost and Downstream Congestion, have been modeled to rank reroute options within the NextGen capability called the Trajectory Options Set (TOS). Feedback from airline operations subject matter experts suggested potential limitations of generalized cost modeling due to the divergence in cost estimation between different airlines based on their proprietary business models. Suggestions were made to allow a future RTC tool to allow the airlines to tune the models based on requirements. Nevertheless, we successfully demonstrated the ability of using automation to rank trajectories in airborne reroute scenarios which was well received by the participants. The automated ranking helps to alleviate the additional workload in this airline-centric concept in which responsibilities once held by air traffic service providers are then shifted towards the airline industry.**

Keywords—Relative Trajectory Cost, Automation, Airborne-Reroute

I. INTRODUCTION

In recent years in the U.S. National Airspace System (NAS), a suite of NextGen capabilities have been implemented to enable trajectory-based operation (TBO) and to allow flexible reroute options in response to dynamic changes in the air traffic environment. One such capability, called Airborne Reroute (ABRR), links the Traffic Flow Management System (TFMS), used by the traffic management coordinators (TMCs), with the En-Route Automation Modernization (ERAM) system, used by air traffic controllers (ATCs), to develop trajectory-based reroutes in TFMS and digitally send complex, aircraft-specific reroutes to the controllers' ERAM station for air traffic controllers (ATCs) to review and send to the flight deck as amended route clearances [1].

Originally, ABRR was designed to allow TMCs to develop airborne reroutes across multiple sectors for flow purposes. Additionally, ABRR also has the ability to ingest Trajectory Options Sets (TOS) that airline operators can use to develop multiple alternate trajectories which can be sent to TMCs, one of which could be selected and sent to ATCs via the ABRR mechanism to be issued as amended route clearances.

The TOS concept was initially developed as part of the Collaborative Trajectory Options Program (CTOP) [2]. CTOP strategically controls the air traffic flow rates at multiple specified Flow Constrained Areas (FCAs) by allowing flight operators to submit the desired TOS for each affected flight prior to departure and then assess the multiple trajectories for each flight to select the route options that comply with capacity constraints while minimizing the "RTC- relative trajectory costs" for each flight.

The CTOP algorithm makes use of the TOS by using RTCs to establish selection criteria for a set of trajectories submitted by airline operators, thereby allowing the operators to communicate their trajectory preferences to CTOP. TOS was originally designed to work within CTOP during a pre-departure phase of flight, and not used while an aircraft is airborne. In this paper, we propose to enable TOS usage during the airborne phase of flight by developing new types of RTCs that are tailored for the airborne flights. These new RTCs can weigh multiple factors for the airborne flights and provide metrics that can be used to rank the preference of multiple trajectories and expressed in TOS. The rank ordered TOS can then be sent to the TMCs, who can review and select one of them to be relayed to ATCs to issue as clearances.

II. RELATIVE TRAJECTORY COST FOR AIRBORNE FLIGHTS

In the current adaptation of CTOP, the RTC value represents the ground delay that an aircraft can take before considering one of the alternate trajectories. Table 1 shows the RTC values for each alternate trajectory.

RTC	Route
0	KDEN./.ZIRKL..MCK..LNK.J60.DJB..YNG..ETG.MIP4.KLGA
15	KDEN./.PER..RZC..ARG.J46.BNA.J42.BKW.J42.GVE.KORRY4.KLGA
35	KDEN./.BRYCC..TAYOT..DAYYY..RUBKI..SIKBO..TULEG..RKA.HAARP3.KLGA

Table 1: Trajectory Options Set (TOS)

As shown in Table 1, the original route has an RTC of zero, indicating to the system this is the operators preferred default trajectory. For the second trajectory, an RTC of 15 means that the operator is willing to take up to 15 minutes of ground delay on the default trajectory before considering the second route as the new preferred trajectory. Similarly, for ground delays beyond 35 minutes, the third trajectory is considered as the preferred trajectory. This procedure represents a trade-off calculation between ground and airborne delay depending on how much ground delay has been incurred. If an unfavorable amount of ground delay has been assigned to an aircraft, say 35min, the RTC with 1:1 ratio between ground to airborne delay tradeoff would allow the aircraft to take off right away on the third trajectory in Table 1, even if the new route takes close to 35 minutes of additional flight time compared to the original route.

Past research on RTC has focused on calculating the RTC value as a fixed number and determining the amount of ground versus air delay to be taken. Finding appropriate RTC values has been explored in different ways, such as maximizing a utility function as developed by Tereshenko, et al. [3] The common ground-to-air delay ratio explored has been a double or triple increase in air delay compared to ground delay. Another approach in generating RTCs for airlines has been presented by Hoffman et al [4] by introducing two-piece linear cost functions at which the inflection point for cost increase describes a lost connecting flight.

For airborne flights, the RTC as expressed in its original form in terms of ground delays is no longer useful. Therefore, a new set of cost calculations is needed to compare the airline costs for multiple reroute trajectories. For these new RTC calculations, we propose to model the airline costs with a following set of parameters:

1. RTC calculations should account for multiple airline cost factors instead of a single one.
2. RTC should reflect the costs to the airline business case instead of output metrics such as throughput or delay.
3. RTC should reflect non-linear, “step-function” nature of airline’s decision on when to switch from the current to an alternate trajectory.

In this paper, we present a set of models for multiple factors that impact an airlines’ decision-making process. These models were developed with inputs from subject matter experts (SMEs) from two different airlines, as well as inputs from air traffic control SMEs. The costs in the RTC calculations were expressed as a monetary value (i.e. dollars) which was an easy, tangible metric for airline operators to understand.

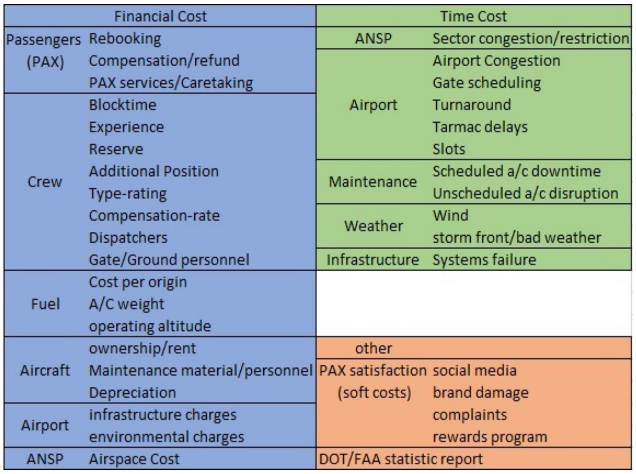
III. AIRLINE COSTS – AN OVERVIEW

Operating an airline can be an unforgiving business as they depend on the global economy as much as they are also the drivers of it. When identifying to serve a new route, an airline may look at potential customers. Depending on the city-pair these can either be tourists or businesses requiring employees to be present at different corporate offices. These business travels are very profitable to airlines as larger corporations usually have contracts with airlines regularly transporting employees. As such these corporations can sometimes be the only reason an airline operates a certain route or serves it much more frequently. In an economic recession where demand by either tourists or business-travelers is low, airlines are the ones hit first and are also the last to recover from it. This is exemplified by the current Covid-19 pandemic with major carriers not expecting travel demand to be back at pre-pandemic levels before the year 2024. Withstanding major crises in the industry while trying to predict demand and making adjustments can be a hard task. Before 2020, airlines were suffering a pilot-shortage and could barely keep up with recruitment whereas in other crises, such as 9/11 or the global financial crisis in 2008 have resulted in a steep decline in passengers forcing airlines to ground aircraft, lay off employees and cut back service overall. [5]

Similarly in everyday operations, predicting demand and making adjustments can also be difficult. Various factors, such as weather or equipment failure, can cause substantial delays. These delays have cascading effects on secondary flights due to passenger connections, in which delays in one flight impact the connections to other subsequent flights. Similarly, other resources such as cargo, mail, crew, maintenance parts and equipment or even the aircraft itself affect other flights.

.Airlines for America (A4A) lists 17 different factors as part of their U.S. Passenger Airline Cost Index trend monitoring. [6] These factors however, are not independent of one-another and may hide a complex structure that may be unique for each airlines’ business model, as well as their schedules, restrictions (national and international) and regulations.

Table 2 was generated in collaboration with airline dispatch SMEs and displays one of many ways of representing these factors. In this paper, they are divided mainly into financial-related costs that incur a direct financial impact and time-related costs that cause operational delays which in turn also incur financial costs.



Financial Cost		Time Cost	
Passengers (PAX)	Rebooking	ANSP	Sector congestion/restriction
	Compensation/refund	Airport	Airport Congestion
	PAX services/Caretaking		Gate scheduling
Crew	Blocktime		Turnaround
	Experience		Tarmac delays
	Reserve		Slots
	Additional Position	Maintenance	Scheduled a/c downtime
	Type-rating		Unscheduled a/c disruption
	Compensation-rate	Weather	Wind
	Dispatchers		storm front/bad weather
	Gate/Ground personnel	Infrastructure	Systems failure
Fuel	Cost per origin		
	A/C weight		
	operating altitude		
Aircraft	ownership/rent	other	
	Maintenance material/personnel	PAX satisfaction (soft costs)	social media
	Depreciation		brand damage
Airport	infrastructure charges		complaints
	environmental charges		rewards program
ANSP	Airspace Cost	DOT/FAA statistic report	

Table 2: Airline operating costs

This table provides a straightforward way of representing cost parameters in general terms. When computing costs, an understanding of each of the parameters as well as their operational impact and dependencies on one another is crucial. Another way to look at these cost parameters is to regard certain situations that may lead to a delay and thus increased cost, compared to nominal/planned operation while also distinguishing between controllable and uncontrollable events.

While this distinction of events is useful when an airline decides whether or not it should compensate passengers for a delay, it was difficult to subdivide parameters mentioned in the table into controllable or uncontrollable. For example, when assessing passenger compensation due to a missed connection, the extent that these costs can be categorized as a controllable or uncontrollable event, depends on airlines' definitions of the events and the individual contracts of carriages that specify how an event is compensated.

In general, convective weather events are considered to be uncontrollable factors in aviation travel. While some of these meteorological/geological events are predictable, others are less or not at all which leads to classifying them as "sudden", "near-term" and "long-term"events according to a dispatcher SME. A sudden event may be an earthquake which locally impacts an area but can damage infrastructure such that aircraft planning to fly to the area may not be able to do so. Developing thunderstorms classified as "near-term" may be categorized as controllable or uncontrollable, depending on the availability of the forecast. While an airline may try to prepare and cancel and rebook passengers in advance, some thunderstorms may sit longer than anticipated affecting flights that may not have been predicted . In this case, the airline may argue that this is an uncontrollable event for those passengers not being rebooked in advance.

A long-term event may be a hurricane which can be predicted and give time for an airline to adjust operations on that day and rebook passengers accordingly. Even though the hurricane itself may be predictable, the extent of damage resulting from it is unclear. If for example the instrument landing system is damaged, it may take days to bring it back online again, which means airlines having flights planned to that airport might have to cancel these as well in the subsequent days, depending on how fast the damage can be repaired. If damage is expected but the initial cause was weather, most airline contracts classify this event as "force majeure" and thus uncontrollable.

Direct passenger compensation such as an extra meal, a hotel voucher or rebooking are considered hard costs. Soft costs on the other hand are much more troublesome to measure. These deal with customer satisfaction and in the US are commonly represented in the Net Promoter Score (NPS). If a flight is delayed or cancelled a passenger may file an air travel service complaint or comment form with the Department of Transportation (DOT) as long as the reason for delay is not related with airline safety or security. This complaint may drive down NPS scores which together with social media have become a new source of attention for airlines. While on paper airlines may draw a hard line, depending on a particular delay, reality drives operators to react differently in order to stay competitive. As a delay involves more than one passenger this type of cost may be substantial, although difficult to measure. This example gives insight into an airlines' complex operation and also the not negligible uncertainties that go with it.

For our cost modelling purposes we will focus on fuel and crew parameters (Table 2), as each account for between 30-35% of total costs according to dispatcher SMEs.

Another important cost to consider is an airspace usage cost. Flights that fly through Canadian airspace to avoid convective weather in the NAS are required to pay Canada for the Air Navigation Service Provider (ANSP) costs in their airspace. Finally, any reroutes that fly through congested downstream airspace may incur additional airborne delays for flow management purposes. Therefore the downstream congestion is also calculated to be included in the airborne RTC cost modeling.

IV. COST MODELING

A. Fuel

Fuel consumption is tied directly to the time the engines are running, thus, if the aircraft is delayed either in flight or on the tarmac, the airline has to account for extra fuel burn and the cost. High volatility in oil prices, in conjunction with uncertainty of unavoidable airborne and ground delays, can significantly impact the daily cost to an airline. In order to gain stability in fuel prices, airlines use a method called "fuel-hedging" in which an airline agrees on a secured price with a provider for a given amount of time, which can turn out to their advantage when the airline secures a price lower than the fuel price in the future or adversely if the fuel prices drop and the airline ends up paying a higher fuel price than necessary.

A more short-term method for cost saving is called "fuel-tankering", in which an aircraft brings more fuel on a particular flight than required for the trip due to knowing in advance that the destination airport has higher fuel prices. There is a trade-off in that the more fuel an aircraft carries, the higher the fuel consumption will be and thus will not always have a net benefit.

Over time the FAA and regulators have established protocol into how much fuel an aircraft must carry. Comprising of five blocks, the amount of fuel is not only a function of distance between city pairs, as can be seen in Table 3:

Fuel Block	Reason
En-route Fuel Burn	Planned fuel between city-pair
Alternate Airport Fuel Burn	Distance to alternate airport
FAR Reserve Fuel	Federal mandated reserve fuel for additional 45minutes of flight
Contingency Fuel	Additional fuel planned for arrival and approach contingencies
Dispatcher Add Fuel	Designated by dispatcher for any possible delaying conditions

Table 3: Fuel requirements

Each block fuel in Table 3, however, vastly simplified parameters than the fuel consideration due to all of the possible scenarios, such as emergencies, weather and other constraints in the NAS have been considered which may require an aircraft to stay in air longer. Modern flight planning systems consider wind, operating altitude and aircraft data such as weight and engine configuration for the corresponding aircraft type in order to calculate fuel burn.

In order to model fuel cost, we use fuel burn information in our simulation environment, called NASA's Multi Aircraft Control System (MACS) [7], which computes a fuel burn value in pound per hour. These values are then converted to fuel cost in dollars by estimating the fuel price at each departure airport that we model. According to dispatcher SMEs, airlines negotiate fuel prices with providers at the airports they serve.

In the case of one of the airlines, new fuel tables get released once a week with a dollar per gallon value per airport as depicted in Table 4:

Airport [ICAO Code]	Week	Price [$/gal]
KABQ	Jun 23 2020 - Jun 30 2020	2.7528
KABE	Jun 23 2020 - Jun 30 2020	2.4018
KALB	Jun 23 2020 - Jun 30 2020	2.6478
KAMA	Jun 23 2020 - Jun 30 2020	2.6026
KATL	Jun 23 2020 - Jun 30 2020	2.3346
KAUS	Jun 23 2020 - Jun 30 2020	2.3814
KBDL	Jun 23 2020 - Jun 30 2020	2.8066

Table 4: Fuel price table (excerpt from original)

Table 4 lists actual values corrected for 2020 fuel prices. As the number of airports used in the study was greater than the list received, missing airport prices have been interpolated depending on their distance to surrounding airports covered by the initial listing. From the examination of the fuel prices across multiple airports, it has been found that fuel prices can vary substantially between airports across the NAS.

Once the fuel price for a given aircraft has been identified, the extra time spent in air due to taking an airborne reroute for that aircraft is used to generate the fuel-burn value in MACS, which in turn is converted to fuel cost in dollars using the fuel price. The fuel cost is calculated using the following formula:

$$Cost_{Fuel}[\$] = Fuel_{burn}\left[\frac{lb}{hr}\right] x \frac{1}{\rho_{Fuel_{ISA}}[\frac{lb}{gal}]} x\, T_{Flight}[h]\, x\, Fuel_{price}[\frac{\$}{gal}]$$

Looking at the units from a pure mathematical perspective, the dollar value can be isolated by simply multiplying by a density. Fuel Jet-A1, which is mostly used throughout commercial aviation has a density of 800 kg/m^3 at 15deg Celsius [8], corresponding to International Standard Atmosphere (ISA) conditions. Converting from the metric to imperial system yields 6.6664 lb/gal. Consultation with a dispatcher SME reveals that airlines in fact do use kerosene density values at airports. For most US airports the density of 6.7 lb/gal is used which confirms aforementioned calculation and assumption referencing to ISA conditions. For airports Albuquerque and Denver, a density of 6.3 lb/gal is used as the elevation compared to main sea level is significantly higher.

B. *Crew*

One key motivation in modeling airline delay costs in this paper was to capture the non-linear factors in cost determination. For example, arrival delay to an airport may not incur much cost to the airline until that delay results in large number of missed connections by the passengers. An airline may accept a delay for a specific amount of time, say 15 minutes, because the corresponding costs then may be reasonable. Yet, if the aircraft is delayed by another five minutes, costs can potentially soar very quickly. In this scenario, very few passengers may miss a domestic connecting flight in the first 15 minutes, but after another five minutes, an international connection may be affected, for which delaying such a flight results in a substantial cost to the airline.

Inside a given time window an airline may or may not have considerable costs, due to either losing a connecting flight for which either crew, passengers or the aircraft itself are needed or it perturbs another schedule such as maintenance. Other factors such as the gate schedule at the arrival airport may lead to the delayed flight sitting on the tarmac upon arrival. Hoffman et al explore this phenomenon on a theoretical basis with two-piece linear functions, however, to the authors' knowledge, all previous work on RTC has been conducted in the paradigm of the pre-departure phase around CTOP.

Based on multiple conversations with the dispatcher SMEs, the crew cost, more than the passenger connection cost, was identified as the largest component of these non-linear factors that were associated with delays. In order to model the non-linear nature of the crew cost, MACS simulation environment was used to model over 2,000 flights for a given traffic day in the NAS. Spanning over several hours, with flights departing and arriving in between, this allows for modeling of an airlines' operating day with typical airline schedules. Using these schedules, the crew costs were generated using the following three parameters:

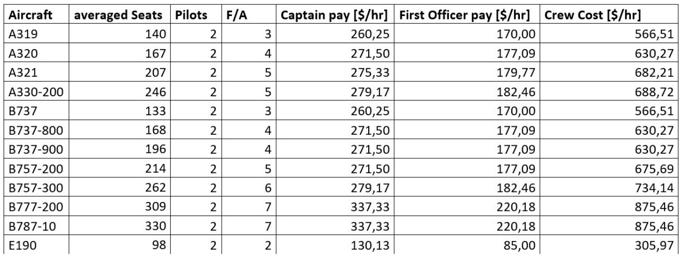
- Additional block-time flown
- Reserve Crew
- Schedule disruption

From the three parameters above, the additional block-time flown increases cost as a linear function, but the other two sub-parameters modeled as non-linear functions.

Crew in a modern-day aircraft is made up of flight attendants and pilots. Among both, there are different positions and ranks that incur various costs to an airline besides their base-salary, such as the cost of training to obtain a certain rank position. Pilots are sub-divided into first officer and captain with the latter having more experience. Similarly, among flight attendants different positions are present. So-called "pursers" or "Maitre de Cabine" are a higher position and responsible for the entire cabin or a section of it in the aircraft. On larger aircraft an airline may also employ a chief-purser being responsible for the entire cabin and assistant purser overseeing a section of the aircraft. These higher positions are compensated higher and can also incur extra cost due to additional training to the airline. For example, United Airlines 2016 tentative agreement with the Association of Flight Attendants (AFA-CWA) is publicly available, listing base salaries, incentive rates and white flag pay days. According to a dispatcher SME, if a flightcrew member surpasses a specific amount of hours worked in a calendar quarter, these higher rates will apply. [9] Flightcrew members however, are legally only allowed to work a certain amount of hours. Airlines per regulations 14 CFR Part 117 and Part 121 have to comply with limitations, certifications, operation as well as airman and crewmember requirements. While Part 117 describes the maximum amount of hours a certain crew member is allowed to work, Part 121 defines the minimum amount of crew members to ensure passenger safety and service during flight.

Specifically, Part 121.391 states an aircraft with more than 50 passengers requires two flight attendants plus an additional flight attendant per every 50 seats. An aircraft with 150 seats would require at least 3 flight attendants to operate. Operating under those minimal conditions translates to “unaugmented” operations while “augmented” operations are those with more flight attendants on board than mandated by Part 121. Airlines may have several reasons to operate under augmented operations. Two main reasons are flying a long-haul international flight and operating more than one service class. For business and first class passengers, airlines seek to provide additional attention through a more sophisticated service.

Part 117 describes flight and duty limitations which regulate crew rest requirements. The maximum number of hours a crew member is allowed to work varies on the time of day the shift starts but also if the operation is conducted augmented or unaugmented and for pilots the type of rest facility impacts the maximum legal working time as well. For long flights more than two pilots are required. Our scenario focuses only on rerouting flights originating and arriving inside the NAS, thus this can be disregarded and we can assume two pilots per aircraft. According to dispatchers, flights inside the NAS, with the exception of east-coast to Hawaii flights, are operated with an unaugmented crew which establishes a first basis for this modeling exercise. Furthermore, to comply with Part 117, and for simplification purposes, pilots and flight attendants, are assigned a maximum flight time of 9 hours. As stated in Table A of Part 117, this translates to the maximum flight time limit of unaugmented operations for a shift between 0500 and 1959.



Aircraft	averaged Seats	Pilots	F/A	Captain pay [$/hr]	First Officer pay [$/hr]	Crew Cost [$/hr]
A319	140	2	3	260,25	170,00	566,51
A320	167	2	4	271,50	177,09	630,27
A321	207	2	5	275,33	179,77	682,21
A330-200	246	2	5	279,17	182,46	688,72
B737	133	2	3	260,25	170,00	566,51
B737-800	168	2	4	271,50	177,09	630,27
B737-900	196	2	4	271,50	177,09	630,27
B757-200	214	2	5	271,50	177,09	675,69
B757-300	262	2	6	279,17	182,46	734,14
B777-200	309	2	7	337,33	220,18	875,46
B787-10	330	2	7	337,33	220,18	875,46
E190	98	2	2	130,13	85,00	305,97

Table 5: Crew Cost per Aircraft-type

Crew cost in Table 5 is the total cost per aircraft and hour for the entire crew in unaugmented operations i.e. having the minimum number of flight-attendants and pilots on board as required by regulation for a specific aircraft-type.

1) Additional block-time flown: When the aircraft is delayed, the first factor to consider is the extra time each crew member must work. For this model, MACS considered the extra flight-time the aircraft spent in the air due to flying a certain TOS Route which is expressed in the following equation as Δt_{TOS}. This variable is the difference between actual and scheduled flight-time. While in this study this variable will be greater than zero, in theory a flight can result on a shorter route saving time and cost subsequently. Multiplying with the Crew Cost Rate for a given aircraft type yields the following:

$$\Delta Cost_{Blocktime}[\$] = CrewRate_{A/CType} * \Delta t_{TOS}$$

2) Reserve Crew: With the uncertainties in everyday operations as described in section III, airlines try to anticipate and plan for scenarios of weather or other system-induced delays. Aside from crew, these measures can range from adding more fuel or increase scheduled block-time as a buffer to catch certain amount of delays and lessen the overall impact.

Increased staffing may be another consequence. By looking at a variety of data, events forecasted, lessons learned and the operational environment itself, an airline determines the appropriate staffing of the crew on-board. However, on the ground, airlines staff additional crew members on reserve to be ready to replace another crew member if he or she cannot make it to their next flight. This is usually but not limited to hub airports in which an airline condenses its operation. For flag-carriers this is a popular model as all flights come to the hub and then fly out again to other destinations. In the US, flag carriers such as United, Delta or American Airlines each focus operations on a variety of airports operating a multi-hub concept which allows them to better react to lost connections by offering additional flights later in the day to the same destination by using reserve crew staff as a contingency for any of those flights out of the hub.

Typically, an airline may be confronted with all sorts of issues throughout the day with incoming and departing flights. An incoming flight may arrive later, a crew member might not be feeling well or have trouble coming to work, or a flight scheduled to push-back is delayed even more which threatens a crew members schedule to exceed maximum legal work hours during the duration of the flight. These are just a few examples of why an airline may fall back to reserve crew members at hand. Mainly, there are two different types of reserve crew: airport standby reserve and on-call reserve. The first type of reserve is for very short-term but anticipated scenarios, such as when a crew member exceeds legal work time or a desire to increase the number of crew members on a flight. Airport standby reserve crew members are placed in an internal waiting area at the airport for that purpose to station them close-by. On-call reserve members are crew members outside the airport at or in the vicinity of their residency in reasonable distance from the airport. Scenarios in which the airline has greater lookahead-time of needing a replacement, these crew members are required to be at the airport and ready to work, usually a few hours after they receive a call.

While on reserve, whether at home or at an airport, a crew members’ actual rate of pay does not change. Instead, their guaranteed number of hours per month becomes lower. Crew members are under contract with a so-called minimum line-guarantee which usually is around 75 hours. This guarantees a crew member a minimum amount of time paid per calendar month, regardless of the actual duty time. According to regulation 14CFR Part 121, pilots cannot exceed 100 hours per calendar month. In the context of reserve or standby, this means if a pilot is placed on reserve, his or her guaranteed number of hours per month is lower. The crew member will get paid 75 hours only, compared to having a line of flying assigned may result in more total hours up to the legal limit of

100 hours. Of course, if a crew member is on reserve duty exceeding 75 hours, the crew member gets paid for those additional hours. This form of equal compensation but less guaranteed hours may be handled differently between airlines creating a disparity but shows that alternate business models can exist.

To simplify our modeling effort, we have assumed an equal pay of crew members, regardless of whether they are in duty or reserve. For the airlines, placing an appropriate number of reserve crew members is a challenging balance of either having too little or too many staffed to meet the demand. Too many can cost the airline more money but having to little and not being able to operate a flight (or delaying it) can be much more expensive. Reserve crew placement is partly a function of the anticipated events, their extent and their predicted impact but for example also which flights and airports may be affected.

In order to downscale this problem, Figure 1 shows our scenario with a weather/storm cell in Cleveland Center (ZOB) blocking entry to flights toward the east coast, requiring airborne reroute. As these weather cells are blocking sectors in ZOB Center, they have a high impact on arriving traffic from the west coast to the airports in New York (ZNY) and Washington (ZDC) Center. With this in mind, the scenario can be refined to look at specific airports like Boston (KBWI), Baltimore (KBWI), Ronald Reagan Washington (KDCA), Newark (KEWR), Washington Dulles (KIAD), New York (KJFK), La Guardia (KLGA) and Philadelphia (KPHL).

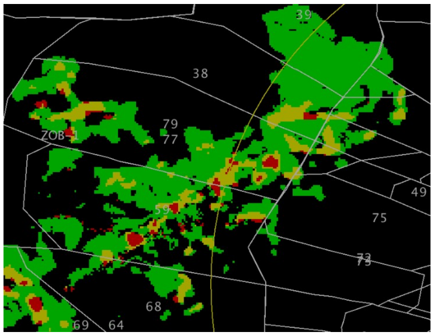
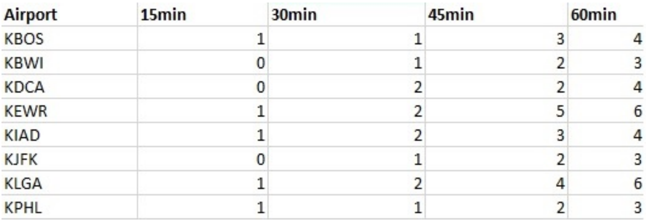


Figure 1: Weather/Storm cells in ZOB

According to a dispatcher SME, an airline would place an amount of reserve crew members equal to about 20% of its incoming flights to those airports in a scenario similar to the one presented here, so we used that number for the modeling of this scenario. Furthermore, only pilot-pairs have been considered as reserve placement in order to model this cost. This simplification is justified by the fact that the cost for all the flight attendants on board is significantly smaller than the two pilots. When comparing our total crew cost (pilots and flight attendants) with total cockpit cost (only the two pilots), the two pilots combined salary, i.e. the total cockpit cost, is between 60-75% of the total crew cost, depending on aircraft type and seat configuration for unaugmented crew operations.

One further simplification is made in expressing these costs. As ATC at the FCAs works with 15min bins to allocate flights, delay costs were associated with these timeframe segmentations as well. Table 6 shows numbers per 15min bins.



Airport	15min	30min	45min	60min
KBOS	1	1	3	4
KBWI	0	1	2	3
KDCA	0	2	2	4
KEWR	1	2	5	6
KIAD	1	2	3	4
KJFK	0	1	2	3
KLGA	1	2	4	6
KPHL	1	1	2	3

Table 6: Reserve-Crew allocation per Airport

Each count represents a pilot-pair. For example, at KEWR, if the flight is between 45 and 60 minutes late, 5 pilot-pairs would be needed equaling 10 individuals that would have to be replaced of the crew onboard the aircraft. The expression of pilot-pairs in this context serves to model the entire crew, pilots and flight attendants. In real-life a delay in that order would force the airline to replace the entire crew. For simplification purposes, aircraft-type specific crew counts where not considered.

A crew reserve member would need to be paid the full shift which in this case is nine hours as mandated by Part 117. The cost calculations are shown in the following equation:

$$Cost_{Reserve} = Number_{Pilot-pairs} * 9\,[h] * Hourly\ Cost_{CockpitCrew}\left[\frac{\$}{h}\right]$$

3) Schedule disruption: This third and last sub-factor in the crew cost calculation represents the cost that is incurred to the airline by having its crew schedule disrupted. Each crew member, especially on short-haul flights may have several of those scheduled to work on that day. While reserve crews may cover the affected flight causing the primary-delay, the original crew member may have been scheduled to work on two or more flights afterwards, potentially leading to more cost if the reserve crew member has been waiting most of its shift in reserve and can only cover the first flight in the chain of flights succeeding the flight with the primary delay.

With long-haul shifts, crew members work close to their legal limit and are then required to use rest facilities on the flight and then have a layover afterwards stretching two or three days before taking on the return flight. Crew members are stationed at specific cities and whenever they are away from their station due to having to work on a specific flight, the airline needs to pay a hotel suite to each member. Therefore, the airlines aim to bring each crew member back to its home-base whenever possible, while trying to max out their legal work time as much as possible. A delay in any of the flights along the day may lead to a carefully planned schedule to be disrupted and a crew member may not being able to work on their last flight of the day or not being brought back to their station. The uncertainties involved in flight planning and the corresponding crew-schedules can be difficult to predict. A schedule disruption apart from crew, such as aircraft-utilization schedule, gate schedule at an airport or maintenance schedule adds more cost to an airline. With the need to react, airlines buy replacement parts, deploy extra flight crew members or even have spare aircraft sitting on standby for the case that one is not able to fly due to mechanical issues for example.

In our scenario with over 2,200 flights, flights to the following destination airports, namely KBOS, KBWI, KDCA, KEWR, KIAD, KJFK, KLGA and KPHL, were identified as "flights-of-interest" and only flights to this destination were identified as potential reroute candidates. Setting the maximum legal work time to nine hours, the first step in allocating crews to flights was, to determine the amount of time a crew or crew member needs to work on the flight-of-interest. To simplify the calculation, the crew was treated as one entity working throughout all the flights, which is not always the case in real-life operations. Figure 2 illustrates an example schedule:

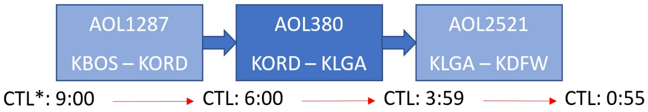


Figure 2: Example of Crew-Schedule

In Figure 2, flight AOL380 in dark blue from Chicago O'Hare to La Guardia in New York is hereby the flight of interest. An underlying algorithm was developed leveraging the simulation entry times of each flight composing of a little more than 2,200 flights mainly focused on the east-coast region.

The Crew Scheduling algorithm assigns the crew to flight AOL380 subtracting the flight-time of this flight with the CrewTimeLeft (CTL) which is originally nine hours. After this, the algorithm first in a forward-loop assigns the crew to flights succeeding the flight-of-interest until either CTL is used up and no other flights may be assigned, or no other flight is available in the simulation. If the latter is the case, the algorithm runs in a backward-loop assigning the crew to flights preceding the flight-of-interest until CTL is used up. The spare time left at the end, is the maximum time the flight-of-interest may be delayed. In Figure 2, the crew starts its shift flying from Boston to Chicago, then Chicago to La Guardia on the flight-of-interest which may get rerouted, then from La Guardia to Dallas. The CTL of 55 minutes at the end is the maximum amount of time the Crew may get delayed on flight AOL380 in order not to disrupt the schedule. In accordance with a dispatcher SME, if the schedule gets disrupted, the penalizing cost can be approximated as the entire Crew and the remaining scheduled block-time this crew would need to fly, in the case of Figure 2, the block-time from La Guardia to Dallas would be regarded.

$$Cost_{ScheduleDisruption}[\$] = Cost_{Crew}\left[\frac{\$}{min}\right] * scheduled\ Blocktime_{remaining}\ [min]$$

Adding all three sub-parameters yields the entire Crew Cost.

C. Airspace Cost

ANSPs of other countries charge ATC handling costs of aircraft flying over their respective airspace. While airlines try to avoid certain countries due to their high fees on international flights, national flights inside the US do not incur ATC handling costs by the FAA. However, if a route leads over foreign territory, this cost may become relevant. The International Civil Aviation Organization (ICAO) recommends a country to charge by a unit rate, the distance flown within a defined area and the aircraft weight, although it states that if a distance flown and/or aircraft types are somewhat homogeneous, the weight elements and/or distance may be neglected and a single overflight charge can be applied. [10] In our scenario, some TOS routes to the north may lead through the portion of Canadian airspace highlighted in Figure 3:

Figure 3: Relevant portion of Canadian Airspace

Unit rates may change once a year. The rates for sectors next to US territory may be lower and charges may increase the further a flight gets into Canadian airspace. According to a dispatcher SME, the cost as of March 6th 2020, can be approximated as a uniform 56 cent/mile value for the airspace highlighted in Figure 3, which was the value used in the airspace cost calculations.

D. Downstream Congestion

Downstream congestion impact was modeled to capture the costs associated with downstream sector congestions for a given aircraft. The northeast part of the NAS especially the Centers Cleveland (ZOB), New York (ZNY), Indianapolis (ZID) and Washington (ZDC) are notoriously plagued by delays due to an excess of traffic in the airspace. ATCs as far back as in Minneapolis Center (ZMP) or Chicago Center (ZAU) establish a choreographically balanced stream of traffic for flights headed to the airports in ZNY and ZDC. Given that the excessive demand can lead to certain delayed flights even in nominal traffic situations, ATCs may reroute, hold or issue Miles-in-Trails (MIT) in convective weather scenarios. Actions of ATC are of very dynamic in nature and depend mainly on three factors:

- Timeframe: How far in advance can a possible problem be predicted and impact of the response to the situation
- Level of predicted congestion: How much workload would be generated due to excess congestion within a specific sector
- Capacity impact on sector: Presence of an event impacting capacity besides a system-induced overload

In addition to the three congestion factors listed above, two types of delays can influence ATC response in different ways: system-induced and event-induced delays. System-induced delays are due to an excess of traffic demand across multiple sectors over normal capacity, causing delays in other parts of the NAS as a result. Event-induced delays are due to capacity reduction at a given sector / airspace, mainly originating from weather but can also be other external factors.

For the system-induced delays, timeframe is a key factor. According to an ATC SME, ATCs can handle the increased workload for a short period of time by staffing additional controllers to help immediately and institute ground stops to limit further traffic in the near future. ATC looks at demand data and has a prediction of capacity for a full shift, being eight hours. If the demand above capacity situation is not steady, extended or long lasting, ATC will withhold action for flights being further away (around 2-3 hours) from the impacted sector and wait to see how the traffic situation develops.

Excess traffic over a long period of time changes the response of ATC to use Miles-in-Trails. Usually 10-20 MIT will be established on incoming flows of traffic before they enter the impacted area. Additionally, departures into the impacted airspace may be delayed, capped or re-routed. Usually weather, more specifically thunderstorms, make a regular appearance and are thus the most common source of event-induced delays, due to the unpredictability of the weather occurrence and its predicted impact. Also, the impact-time plays a role, as ATC response can vary during heavy demand. Lastly, the severity of the weather plays a crucial role in the type of ATC actions taken:

- Lines of heavy thunderstorm will usually drive ATC to make use of published playbook routes combining them with MIT.
- Short lines of thunderstorms with breaks in between may drive ATC to issue playbook routes. In such a scenario ATC is going to be very vigilant about the thunderstorm development. Due to uncertainty, ATC rather prefers to wait longer before initiating any major action. In case the thunderstorms increase in severity, ATC will either issue large playbook routes if the flight is still far away or issue MIT for incoming traffic that got to the impacted area without action taken earlier as well as initiate ground-stops.
- In case of pop-up thunderstorms that only cover a small percentage of a centers geographical area, other routes within that facility are still open to use. ATC will have a plan to respond, mainly vectoring around thunderstorms if necessary.

For the purpose of monitoring demand and capacity in a sector, ATC uses the Monitor Alert Parameter (MAP). The MAP is the normal capacity in sector and if it is exceeded by projected demand, an alert is triggered. ATC can then manually enter a lower MAP capacity but manual adjustments are rarely employed. [11] If the MAP is exceeded, it does not necessarily mean ATC is going to implement MIT restrictions. Since s/he can work with a certain number of aircraft above capacity for a short period of time. A sector spike where demand is only slightly above the MAP value for a short duration usually requires no further action.

In order to model the delays due to downstream congestion we added a time delay that each aircraft above sector MAP capacity receives that would result from thinning out the traffic flow through a sector, which is being achieved through local vectoring of the aircraft. For simplification, a time-delay per aircraft was set at 7 MIT, which in turn equals 1 Minute of delay. 7 MIT spacing created a proper separation between aircraft within a common traffic flow. Consequently, if two aircraft would be over capacity this would equal 7 MIT or 1 minute of delay for the first aircraft and 14 MIT or 2 minutes for the second aircraft. Since we don't know the exact order of aircraft arriving to a sector ahead of time, the average delay will be assigned for all aircraft entering the impacted sector for the modeled delay calculations. In our model, we disregard the ATCs' ability to work over certain capacity values. The following three-step calculation scheme can now be derived:

1. $MCV_i = |Demand_i - Capacity_i| \qquad i \ldots Sector$
2. $Avg.Delay\ Sector_i = \frac{\sum_{j=1}^{MCV} j}{MCV_i}$
3. $DCD_{Route} = \sum_{i=1}^{\#Sectors}(Avg.Delay_i) + (CTA - ETA)$

Equations 1 and 2 calculate the capacity-demand mismatch and the average delay per sector while equation 3 adds up each average sector delay and takes into account potential delay due to another traffic management initiative in place which is attributed by the Calculated Time of Arrival (CTA) vs. Estimated Time of Arrival (ETA) at a FCA leading to the total Downstream Congestion Delay (DCD) for a specific flight.

Figure 4 illustates this with sectors ZOB26 and ZOB38 having a MACS Capacity Value (MCV) Value (i.e. capacity-demand mismatch) of 2 and 4 respectively. The average delay for ZOB26 and ZOB38 is determined as 1.5 minutes and 2.5 minutes with no FCA in place for this deviation adding to a total of 4 minutes of downstream congestion delay.

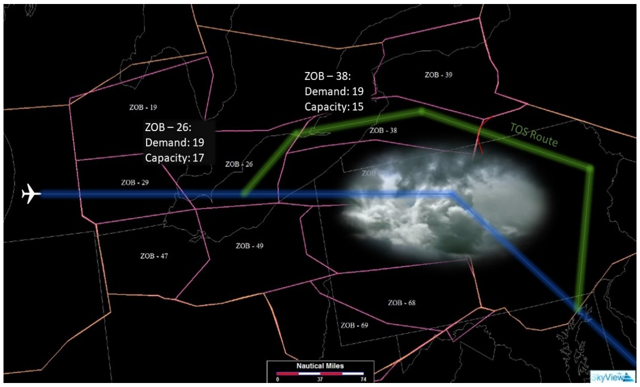


Figure 4: Example of Downstream Congestion Delay

Referring back to Table 2 in section III, it is important to notice that Fuel, Crew and Airspace Cost in these models directly translate to a dollar value and are thus found under the financial cost column. Downstream Congestion is a time cost which in turn influences those financial costs that are a function of time. This is the case for Fuel and Crew for which both costs will increase if Downstream Congestion is a factor when choosing a specific TOS route.

V. RESULTS

The proposed calculation models were developed and used to calculate the cost values for our scenario. Modeling RTC to include multiple cost factors instead of a single metric was implemented and shown to the SMEs. By reflecting the costs of an airline business case with a selection of parameters, we expanded beyond throughput and delay metrics.

According to our dispatcher SMEs, the costs calculated were within reasonable expectations for the TOS routes with extra flight-time calculated to fly the alternate reroute trajectories. We successfully demonstrated to the SMEs that depending on the amount of delay induced by choosing a different trajectory, the overall cost could increase significantly and push a potential trajectory option within TOS down in ranking. This "step-function", non-linear behavior is depicted in the Trajectory Options Window as shown in Figure 5.

TOS ROUTE	ALTITUDE	SPEED	FL COST	DELAY COS...	AIRSPACE ...	TOTAL COST
..SGF..PXV..IIU..BKW..OTT..SIE..BOTON..HOGGS..PANZE..KARRS..CAMRN..KJFK	370	0.8	370	171	0	540
..RWF..BAE..CRL..ROC..IGN..LOLLY..DOORE..LENDY..KJFK	370	0.8	747	3982	124	4853

Figure 5: Trajectory Options Window in MACS

In this example the trajectory in pink is almost ten times more expensive to fly compared to the trajectory in blue, as indicated in the Total Cost column. The significant difference in cost observed is due to the delay cost which comprises of Crew Cost and fueled by the Downstream Congestion Delay. This sudden jump in delay cost within our model can be explained due to a lost connection at the destination airport of the flight of interest resulting in the trajectory being ranked second when the source of the costs are traced.

VI. DISCUSSION

The TOS generation tool that used these RTC calculations to generate ranked ordered weather reroutes were presented to three dispatcher participants as a part of a tool evaluation study. Their feedback and critique are summarized in this section.

The participants liked the weather reroute generation capability and the automated ranking of the trajectories based on the revised RTC calculations. However, they expressed some concerns and skepticism that a cost modeling that does not have access to the detailed business case and the flight planning system may be limited use and produce results that are far off from the actual costs incurred due to rerouting and thus delaying a flight. In general, feedback concluded, since airlines have their own cost calculations implemented within their flight planning systems, separate cost calculations generated by the TOS tool could create confusion. Primarily, the reason for concern is that each airline operates on their own respective business model as mentioned in section III. These business cases will not only differ between a flag carrier and a low-cost carrier but also within those two groups. Airline specific costs such as Crew or Fuel depend highly on individual contracts. Calculating crew costs is highly dependent on how the airline compensates crew members. Some airlines may use as reference to pay by scheduled block-time, the moment from which an aircraft pushes back until it pulls back into the gate at its destination, other airlines may only pay by actual flight time and others will start calculating earlier taking into account preparation time such as briefing and boarding. Another differentiation to consider is each airline's individual crew-pairing philosophy. Depending on their needs and the network, an entire crew may stay together throughout the day, or also split up to different flights which increases complications in calculating financial impacts.

Fuel costs may also depend on the individual contracts between an airline and each fuel provider. Furthermore, if a flight is delayed a common solution to avoid or reduce delay cost is to increase fuel burn. This trade-off, however, depends largely on connecting flights, other schedules and for example the time of day as well as this, depending on the contract of carriage, can affect if a passenger is entitled to certain compensation or not. According to a dispatcher participant, US airlines collectively have billions of dollars tied up in spare parts stored in hangars and warehouses. The amount actually utilized i.e. mounted on an aircraft is in the mere 5-10%. As maintenance components are time-based components this may be another factor worthy of attention.

Overall, all three participants mentioned that rather than calculating the cost values within the RTC calculation tool, it might be better to model the extra delays for the alternate routes, expressed in minutes, and pass the delay values, along with the alternate trajectories to the airlines' flight planning system, which incorporate the airline-specific business cases and have the ability to calculate the cost estimate. An RTC calculation tool, connected to proprietary airline systems such as flight planning tools, can give an airline operator the ability to enter specific values such as the number of connecting passengers, number of crews going to different flights, the timeframe paid according to contract and if a flight is international. Airlines for America captured direct operating cost impacts in general terms per minute. [12] According to a dispatcher SME, it might be better to use this generalization up until the point airlines may be willing to share proprieratary information.

Essentially, we followed inputs based on research and AOCs with basic calculation methods to model fuel, crew, airspace and downstream congestion using fairly generic and non-proprietary data. The main purpose of developing this mechanism is to rank TOS trajectories while not intending to replace airline specific cost estimation methods. AOC dispatch personnel usually has, based on experience and their familiarity with the specific airline business case, an estimate on their own on how they would rank a trajectory, hence the reason the proposed methodology is viewed critically. While having in mind the limitations of a generic model as the one developed here compared to airline-specific calculations, our main objective was to show that automation has the potential to calculate these costs to rank the reroute trajectories that could match different airlines' rankings, independent of their specific business cases. The goodness of the rankings based on the costs could have been better demonstrated in a real-time simulation environment with participants on-site which was not possible due to the limitations imposed by the Covid-19 pandemic.

Lastly, while a cost calculation tool as the one prototyped in this paper may not necessarily serve a flag carrier with its in-house cost prediction tools, smaller, regional carriers without access to sophisticated programs may benefit greatly from access to a general cost modeling tool.

VII. CONCLUSION

To summarize, we prototyped a tool to model a selection of parameters out of the entirety of airline cost factors being considered in a delay case in an attempt to automate the TOS ranking process. In accordance with dispatcher SMEs we chose to model Fuel, Crew, Airspace Cost and Downstream Congestion. While the costs being generated by the models where within reasonable assumptions, AOC participants warned in their feedback of the disparity in each cost factor relating to different airline business models. The errors introduced by a generic model may be considerable depending on each airlines' business case. Thus, a proposed tool in the future should comprise of generic underlying cost calculation functions for each parameter with the ability for an airline to adjust these via inputs to align with their distinct business model. However, a generic cost modeling that differs from airline-specific cost estimations may still be sufficient to provide accurate preference ranking of alternate trajectories for weather reroutes, which was the original purpose of the RTC cost modeling. The initial feedback from the participants was inconclusive on that question and follow-up studies in which the participants could directly interact with the tools, will be needed.

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