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Analysis of Impact of RTC Errors on CTOP Performance

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I. Motivation

Recently, the Air Traffic Management community has made important progress in collaborative trajectory management through the introduction of an FAA traffic management initiative called a Collaborative Trajectory Options Program (CTOP) (Smith, 2014). CTOP allocates delay and reroutes around multiple FCA (Flow Constrained Area) -based airspace constraints in order to balance demand with available capacity. Similar to what is done with Airspace Flow Programs (AFPs), air traffic managers can create an FCA in a CTOP and control any air traffic that crosses that boundary by setting a flow rate for it. However, CTOP has the ability to manage multiple FCAs within a single program, permitting different parts of the program to be changed as conditions evolve. It also assigns delays or reroutes to flights in order to dynamically manage the capacity-demand imbalance as conditions change. For example, as conditions get better, CTOP can reroute traffic off of lengthy reroutes and back onto shorter routes, thereby decreasing their delays in the system.

A CTOP is also collaborative in that it permits airlines to provide a set of preferred reroute options (called a Trajectory Options Set or TOS) around an FCA. Whereas a traditional flight plan contains a single route, altitude and speed, a TOS contains multiple trajectory options [Figure 1] with each option containing a different route, altitude or speed. Furthermore, each trajectory option may contain the “start” and “end” times in which they are willing to accept for that particular option. These are described in the TVST and TVET columns in Figure 1. Airlines also specify a Relative Trajectory Cost (RTC) for each trajectory option that specifies cost of each route relative to the most preferred option. RTC is in terms of equivalent ground delay minutes. For example, Figure 1 lists five different routes and associated RTC costs. Second route option would be preferred over the first route option if ground delay assigned to it is less than 25 minutes as compared to the ground delay assigned to the first route. CTOP assignment algorithm would add RTC to assigned ground delay to calculate total cost for each route and then assign the route with the lowest cost to an aircraft.

Thus, CTOP permits better management of the overall trajectory of flights by considering both routing and departure delay options simultaneously. To benefit from CTOP, an airline will need to do some advance

RTC	RMNT	TVST	TVET	Route	ALT	SPEED
0				GLD SLN J24 MCI J24 STL J134 FLM J24 HVQ SHNON2	350	435
25				GLD SLN J24 MCI J80 VHP APE AIR J162 MGW VERNI ESL SHNON2	350	435
35				PLAIN4 HCT J128 OBH J10 IOW BDF J64 WHETT J30 APE AIR MGW MGW121 VERNI ESL ROYIL2	310	430
50		1945	2145	YELLO6 HANKI OBH J10 IOW BDF J64 WHETT J30 APE AIR MGW MGW121 VERNI ESL ROYIL2	350	425
65		2030	2200	YELLO6 HANKI ONL J148 MCW J16 BAE J34 AIR MGW MGW121 VERNI ESL ROYIL2	310	430

Figure 1.Trajectory Option Set

planning, on days when constraints are anticipated. Airlines do have the option to not participate in CTOP by just filing only their flight plan. In that case, filed plan will serve as a "single-option" TOS. Airlines will have to accept whatever the ground delay is assigned for this option and thus their chances of being assigned ground delay are higher. To participate with CTOP, airlines need to submit a set of route options their TOS, in advance of the flight.

Adoption of CTOPs in airspace has been hampered by a lack of willingness of a majority of airlines to participate in CTOP as there is significant cost in changing workflows and upgrading technology. No commercial vendors are currently offering TOS generation capability. Simpler, cheaper TOS generators may have more errors in RTC specification as compared to sophisticated TOS generators. In this paper, we will investigate the impact of RTC errors on CTOP performance. This work builds on previous work [Kulkarni, 2018] on models of CTOP performance.

II. Errors in Relative Trajectory Costs

Factors influencing RTC costs

A large number of factors including the following influence trajectory costs [MOSAIC, 2018]:

- Aircraft takeoff, landing, climb, descent, and cruise performance.
- Fuel burn/consumption/capability.
- Flight time
- Available routes, NAVAIDs, terminal infrastructure (runways, etc.)
- Weather, both terminal and en-route.
- Decrements to performance such as icing, contaminated runways, deferred system components, etc.
- Payload.
- Ingestion of NOTAM data for closed or unavailable facilities such as runways, NAVAIDs, or Special
- Activity Airspace (SAA).
- Automatic application of decrement data for failed aircraft components, runway contaminants, etc.
- Basic strategic TFM data such as published routes (preferred, playbook, etc.) or European RAD.
- Consideration of international ANSP costs (nav/comm charges).
- Crew availability. crew legalities.

- Connecting passengers and cargo, premium passengers and cargo.
- Overfly charges.
- Gate/tarmac/surface management and turn time.
- priority for wide body aircraft that are a small sub-fleet, or are later assigned to an international flight.

Errors in Estimating Relative Trajectory Costs

RTC is defined as a fixed cost that is the difference in the costs of two trajectories expressed as the number of ground delay minutes. A very significant factor introducing errors in RTC costs is that many flight operators may opt for a simple and cheap TOS generator that would have errors in specified RTC costs as it would ignore many factors that impact RTC costs. However, even for a sophisticated RTC cost computation software, exact computation of RTC at a time when a TOS is filed is not possible for multiple reasons. Status of many contributing factors may not be known with certainty. For example, one may only know average gate turn time and have a rough idea of impact on surface management of fleet. Given uncertainties in these factors, trajectory costs as well as relative trajectory costs can't be estimated exactly. Business models relating these factors to relative trajectory cost may also have uncertainties associated with these. For example, ratio of flight time cost and ground delay cost is generally assumed to be between 2 and 3. If we estimated the ratio as 3, but it is actually 2, there would be an error of 50%. Thus, RTC will have errors associated with it even when sophisticated TOS generators are used. These errors are likely to be even higher for operators with less sophisticated TOS generators. Some of the less sophisticated flight operators may choose not to have a TOS generator at all and use a single flight plan TOS. This amounts to specifying a large RTC value with alternative trajectories.

III. Theoretical Analysis

The analysis done here is based on the following scenario. A CTOP has a constrained FCA *C* and an unconstrained FCA *UC*. When flights that have their most preferred route going through *C* have large enough ground delay assigned, these would prefer to take an alternate route through *UC*. Thus, UC allows flights in constrained FCA *C* to route out. Each aircraft files a two trajectory TOS – one through FCA *C* and one through FCA *UC*. The RTC for route-out trajectory has real RTC cost of *r-rtc* and specified rtc cost of *s-rtc*. Difference between *s-rtc* and *r-rtc* values represents error in specifying rtc values. To simplify our analysis, we assume that *s-rtc* values are uniformly distributed. Let *max-rtc* is the maximum *s-rtc* that has been specified with any of the route-out trajectories. Furthermore, capacity for the FCA *C* is *c* aircraft per hour and demand for *C* is *d* aircraft per hour with evenly spaced flows. Of these, there are *tf* aircraft every hour filing TOSs. We also define *dtf* as demand of aircraft per hour when all TOS filing aircraft choose an alternate route. Therefore, $dtf = d - tf$. Thus, for example if demand d is 100 and there are 20 tos filers, then demand remaining after all 20 tos filers route out would be 80.

As *s-rtc* is different than *r-rtc*, decisions about routing based on these specified RTC values would be correct for some flights and incorrect for others. If a flight's routing is not affected by incorrect specification of RTC, it does not incur an additional cost assuming delay assigned to its preferred route through congested FCA does not get changed. In contrast, if specifying incorrect RTC alters routing decisions, flights would incur some unnecessary cost. In the worst case, this additional cost would correspond to the difference between *s-rtc* and *r-rtc*. For example, if a flight has assigned delay of 20 minutes, actual rtc 40 minutes and specified rtc 15 minutes, then the flight will get routed out because specified cost of alternate trajectory (15 minutes) is less than assigned delay of 20 minutes. Cost for this alternative route is 40 minutes. However, this would not have been routed out if cost of alternative trajectory was specified correctly to be 40 minutes. In that case, its cost would have been that of assigned delay of 20 minutes. Thus, it incurred additional cost of 20 minutes as a result of incorrect specification of rtc. if *s-rtc* is less than *r-rtc* and a flight that is assigned delay *d* to its most preferred trajectory such that *r-rtc* > *d* > *s-rtc*, it will get routed out incurring *r-rtc* cost when it should not and it would incur (*r-rtc* - *d*) additional unnecessary cost. In the worst case, *d* = *s-rtc* and unnecessary cost is (*r-rtc* – *s-rtc*). Similarly, if *s-rtc* is greater than *r-rtc* and a flight that is assigned delay d to its most preferred trajectory such that *r-rtc* < *d* < *s-rtc*, it will not get routed out when it should have been. In the process, it will incur cost d and it would incur (*d- r-rtc*) additional unnecessary cost. In the worst case, *d = s-rtc* and unnecessary cost is (*s-rtc – r-rtc*).

We will now examine impact of RTC errors on system performance by analyzing two different cases (1) *dtf > c* Capacity demand imbalance remain even after TOS filing aircraft reroute An example would be a scenario where demand is 100 acft per hour, number of tos filers are 20 acft per hour and capacity is 70 acft per hour. In this case, even if all 20 tos filing aircraft route out, there would be 80 aircraft who would like to go through the constrained FCA and capacity is only 70 aircraft per hour. (2) *dtf <= c* Capacity demand imbalance is resolved after some aircraft reroute. An example would be a scenario where demand is 100 acft per hour, number of tos filers are 20 acft per hour and capacity is 90 acft per hour. In this case, if 10 tos filing aircraft route out, there would be 90 aircraft who would like to go through the constrained FCA and capacity is 90 aircraft per hour.

Case 1: *Capacity demand imbalance not resolved by CTOP*

We divide our analysis of this case into two periods: (1) initial low delay period when assigned ground delays are < *max-rtc* and not all TOS filers are routing out (2) high delay period when assigned ground delays are >= *max-rtc* and all TOS filing flights are routing out

Initial low delay period: As *dtf > c* , there will be demand capacity imbalance even if all TOS filers route out. Therefore, ground delays assigned to aircraft would keep increasing over time with increase in aircraft queue. The increase would be at a fixed rate as demand is evenly spaced and capacity is constant. During the initial period when assigned ground delays are less than *max-rtc*, not all TOS filers would route out as some do not have an alternative TOS option with *s-rtc* < assigned ground delay. As *s-rtc* values are uniformly distributed, the fraction of aircraft that are getting routed out would increase at a steady rate from 0 to *tf* as assigned delay increases at a steady rate. Thus, average rate of TOS-filing aircraft routing out during this initial period would be *tf/2*. Let *qi* be the queue formed in this period. As capacity is *c* aircraft per hour, time period allowed between successive aircraft would be 1/*c* hours if the scheduling policy is to space aircraft evenly. Therefore, qi/c = *max-rtc*/60 and initial period would last for *qi/(d-c)* hours.Thus, if incorrect *s-rtc* values causes *max-rtc* to increase, queue formed in initial period would be longer and initial time period will be longer.

High delay Period: After assigned ground delays are >= *max-rtc*, all TOS filing flights (*tf* per hour) route out and demand for FCA *C* would reduce to *dtf* = (*d – tf*) per hour. As this demand is higher than capacity c, aircraft queue length would increase at the rate of (*dtf - c*) aircraft/hour. Therefore, queue length after n hours in post-initial period would be *q = (dtf – c) * n + qi =(dtf – c) * n + max-rtc * c/60.*

Maximum assigned delay would be that assigned to the last aircraft in the queue. Thus, maximum delay would be *((dtf - c) * n + max-rtc * c/60) /* c hours. If we ignore the initial period as insignificant, maximum delay is approximately *((dtf - c) * n) /* c hours. Average delay for aircraft going through constrained area would be *a = ((dtf – c) * n) / 2 c* hours. We will refer to this as equation (1).

As capacity is c aircraft per hour, number of aircraft going through the constrained area would be c aircraft per hour and *tf* flights would be re-routed per hour. Thus, throughput of flights that were originally planning to go through FCA *C* is *(c + tf)* aircraft per hour during this high delay period.

Flights routing out incur cost corresponding to their r rtc. Average *rtc* cost for these aircraft would correspond to *b* = $av_{\text{tos filing flights}}$ (*r-rtc*) As this cost as well as cost of aircraft going through FCA *C* is not dependent on *s-rtc* values, delay cost during high delay period is not affected by *s-rtc* and the effect of incorrectly specifying rtc values is limited to the initial low delay period. This is to be expected as all TOS filing flights get routed out in this case and routing decisions are not affected by incorrect specification of rtc values. In contrast, length of initial low delay period is longer when *s-rtc* values are higher. As throughput during this initial period is lower than that in high delay period, overall throughput is lower when *s-rtc* values are higher. Similarly, throughput would be higher when *s-rtc* values are lower.

Case 2: *Demand capacity imbalance resolved with re-routing flights*

Case: $d = c + k * tf$ ($0 <= k <= 1$)

Like the previous case, we will have an initial period when assigned ground delays increase and percent of tos filers routing out increase as well. We have already analyzed this in the previous section. This will be followed by a period when delays assigned will be stable. We will now analyze this stable delay period.

Let *k*-th percentile of *s-rtc* values be *rtc-k*. This does not mean that exactly k% of flights for each time period have rtc less than *rtc-k*. However, to simplify analysis, we assume that *k*% of aircraft during the time period of interest have *s-rtc* values less than *rtc-k*.

If all aircraft are assumed to be assigned ground delay of *rtc-k*, we will have *k*tf* aircraft routing out. As $d - k * tf = c$, there will be capacity demand balance and ground delays would remain stable and would equal *rtc-k*.

Delay assigned to aircraft that are in the constrained FCA would be k-th percentile of *s-rtc*. Ideally, if *s-rtc* did correspond to *r-rtc*, *rtc-k* would have also been k^{th} percentile of *r-rtc*. However, if specified rtc values are such that the k^{th} percentile of *s-rtc* is lower or higher than k^{th} percentile of *r-rtc*, the average delays assigned to aircraft going through the FCA would also be correspondingly lower or higher. Thus, if incorrectly specified rtc values are such that *rtc-k* gets changed, there is an impact on delays assigned to all flights going through the FCA. This may not necessarily be the case in all CTOP scenarios. In particular, flights with RTC values significantly higher or lower than *rtc-k* would not influence system performance with small errors that do not alter *rtc-k* and routing decision.

For example, operators that have most flights with RTC values that are significantly higher than *rtc-k* would have few flights getting routed out. Small errors in these RTC values would not change this situation. Thus, small RTC errors would not have much impact on performance of these operators. Similarly, operators that have most flights with RTC values that are significantly lower than *rtc-k* would have most flights getting routed out. Small errors in these RTC values would not change this situation. Thus, small RTC errors would not have much impact on performance of these operators either. In contrast, flights that have RTC values close to *rtc-k* could alter *rtc-k* value because of errors in specified rtc. In some situations, specifying a lower RTC than the actual RTC can potentially create a situation where competitor airlines may get a significant benefit.

In the next section, we would discuss how errors in RTC would impact CTOP performance in the context of a concrete example.

IV. Specific Example Scenario

We will now illustrate the impact of RTC errors with a specific scenario.

Table 1: Scenario with RTC values

Aircraft	Routed out	RTC (minutes)	Cost Incurred
A	Yes	2	2
B	Yes	6	6
C	Yes	14	14
D	Yes	14	14
E	Yes	27	27
F	Yes	29	29
G	No	41	29
H	No	42	29
I	No	44	29
J	No	60	29
K	No	62	29

Table 1 shows 11 aircraft with their RTC values. If capacity is 6 aircraft, aircraft with RTC of 29 and below would get routed out and others would continue through the FCA with assigned delay of 29 minutes. The extent to which RTC errors would change routing and system performance is different for different aircraft. For example, flights A, B, C and D could have 50% error in RTC and would still get routed out if the median RTC remains 29. Similarly, flights J and K can have 50% error in RTC and would still not get routed out. These changes in RTC values will also not affect the median RTC value. Thus, these would not impact routing decisions or delay assignments to other aircraft. A significant error in RTC specification in these flights would not affect the delay cost incurred by the flight or by the system.

In contrast, changes in RTC values of E and F can potentially impact on median of all RTC values thereby impacting delays assigned to all aircraft that are routing through the constrained FCA. If RTC for flight F was incorrectly specified to be 42, that would change the median to 41 and thus increase assigned delays for all flights that are not getting routed out. It would also result in flight F not getting routed out and incurring a delay of 41 instead of a delay of 29. Thus flight F would incur additional delay of 12 minutes. Also, if RTC values of flights E and F were specified to be 14, it would change the median to 14 and decrease assigned delays for all flights that are not getting routed out. Thus, incorrectly specifying lower RTC values can have impact in reducing system wide delays. It is possible that RTC values of E and F are changed in such a way that median of all RTC values does not change much.

V. Conclusion

In this report, we extended our theoretical analysis to include effect of errors in specifying RTC values. Individual flights with incorrect RTC values incur additional cost only in the cases where errors have impact on routing decision. Incorrect values in these RTC values can potentially impact overall system delays significantly and can also impact throughput. On the other hand, for some flight operators whose flights typically have very low or very high RTC values may not be affected significantly by errors in RTC.

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