Impact of Slot Substitution 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.

After CTOP allocation algorithm has assigned an airline a set of slots for its aircraft in constrained FCAs after processing submitted TOSs, it can choose to change which aircraft uses which slot. Thus, FAA has the responsibility of determining what slots are given to a flight operator and making an initial allocation of flights to slots. An operator can then change which flights use which slots. The substitutions do not alter the demand in FCAs with respect to the capacity. Substitutions allow the flight operators to change its assignments of aircraft to slots. Slot assignment algorithm would consider all operator flights and all available slots and attempts to make optimal assignments. Thus, a trajectory that is initially assigned to a particular flight is a slot that is potentially available to any flight. In the context of slot substitution problem, the value of getting a slot can be very different than it is for a single flight that submitted an original Trajectory Option set. In this paper, we discuss how subbing can help reduce delays significantly and how airlines would benefit by specifying relative slot cost as RTC. We would discuss this using a simple scenario.

II.Operations in the Absence of Subbing

Consider a scenario where a CTOP consists of capacity constrained FCA C and another unconstrained FCA UC. Flow restriction lasts for 120 minutes. Demand for FCA C is 60 aircraft per hour. All aircraft file two trajectory options: one through FCA C and one through UC. The best route through UC has RTC cost of 15 minutes. FCA C capacity is reduced from 60 to 30/hr and FCA UC capacity is high enough not to have capacity-demand imbalance and thus aircraft going through UC do not have any ground delays.

Aircraft are scheduled to arrive at FCA C every minute, However, with capacity reduced to 30 per hour, only one aircraft can be allowed every two minutes. For the purpose of this discussion, each slot is regarded as one minute slot.

During the first 15 minutes, all aircraft go through FCA C and assigned delays increase steadily. After that, half the aircraft go through FCA C and half route out. Aircraft arriving during the last 15 minutes would be scheduled during a period after the CTOP is over. After initial 15 minutes, all aircraft, those going through FCA and those routing out, incur delay cost of 15 minutes.

Table 1. Aircraft Slot Assignments and Delays

Planned arrival minute	Assigned slot arrival minute	Assigned Delay in FCA C	Route out	Delay/ RTC cost
1	2	1	No	1
...				
14	28	14	No	14
15	30	15	No	15
16	32	16	Yes	15
17	32	15	No	15
18	34	16	Yes	15
19	34	15	No	15
...				
45	60	15	No	15
46	62	16	Yes	15
...				
105	120	15	No	15

III. Operations with Subbing

In the above scenario, assigned slots are at arrival times corresponding to even number of minutes. However, aircraft using these slots are incurring a certain amount of delay. If airline operator does subbing such that aircraft that are scheduled to arrive at the slots times are the ones assigned to these slots, these aircraft would not have any delays when slots are used. Rest of the aircraft that were scheduled to go through this FCA would be routed out to alternate FCA and would incur RTC cost in the process. After using subbing, there are no delay costs associated with aircraft that go through FCA C. Thus, overall delay costs are reduced significantly in above scenario. In a more general scenario, so long as an airline has aircraft scheduled to enter FCA at times that are better match for ts slot times, it can assign these aircraft to the slots reducing the delays for aircraft that the airline chooses for utilizing the slots in the congested FCA. It will still incur routing cost for the number of aircraft that are in excess of assigned number of slots. Table 2 shows how subbing will reduce delays in the scenario we discussed in the previous section.

Table 2. Impact of Subbing on Delays

Planned arrival minute	Assigned arrival minute	Assigned Delay in FCA C	Route out	Delay/ RTC cost
1	2	1	Yes	15
2	2	0	No	0
3	4	1	Yes	15
4	4	0	No	0
29	30	1	Yes	15
30	30	0	No	0

31	32	1	Yes	15
32	32	0	No	0

IV.Specifying relative slot cost at RTC

In scenario described above, if an airline gets k slots through a constrained FCA, then it can assign k aircraft to these slots such that there are no delays associated with these aircraft. It can then choose to route out remaining (60 -k) aircraft through the alternative FCA incurring RTC cost for each of these. Therefore, an airline would want to maximize the number of aircraft slots it can get in the constrained FCA C. Thus, relative slot cost of an alternative slot to slot through FCA C is very high and an airline would reduce its delays by specifying a very high RTC in order to get maximum number of slots through a constrained FCA. In a more general scenario, determining relative slot costs would involve a complex stochastic optimization that would depend on expected demand and TOSs of other aircraft operators in addition to availability of aircraft that can utilize different slots.

Table 3. UAL Flights at PENNS on 7/15/2015

Aircraft ACID	Flight Plan Arrival Time UTC	Assigned slots
UAL1492	21:12:51	2230-2245
UAL994	21:21:32	2300-2315
UAL1489	21:24:48	2330-2345
UAL1289	21:48:34	2345-0000
UAL526	23:05:26	2345-0000
UAL1415	23:11:21	0030-0045
UAL1748	23:11:32	0045-0100
UAL277	23:16:32	0100-0115
UAL255	23:22:20	0130-0145
UAL1120	23:35:02	0145-0200
UAL585	23:42:15	0145-0200

V. Open Research Issues

Table 4. UAL Flights at PENNS on 7/15/2015

Aircraft ACID	Flight Plan Arrival Time UTC	Substituted Slots
UAL1492	21:12:51	
UAL994	21:21:32	
UAL1489	21:24:48	
UAL1289	21:48:34	
UAL526	23:05:26	2230-2245
UAL1415	23:11:21	
UAL1748	23:11:32	2300-2315
UAL277	23:16:32	
UAL255	23:22:20	
UAL1120	23:35:02	2330-2345
UAL585	23:42:15	2345-0000

To make the analysis simple, scenario we discussed above makes a number of assumptions that may not be valid in realistic situations. For example, we have assumed that aircraft are evenly spaced in our analysis. In reality, this is usually not so. Table 3 shows expected arrival times for flights according to originally filed flight plans on 7/15/2015 arriving at PENNS Fix. It also shows assigned slots by simulation of a CTOP allocation algorithm where there are three FCAs at three EWR fixes: PENNS, SCHAFF and DYLIN. Table 4 shows that slot substitution can generally find a better flight matching each slot in this scenario shown that has significant delays assigned to flights. In general, the ease of finding suitable flights for slot substitution will vary among different flight operators and different CTOP scenarios. Smaller flight operators with a few aircraft arriving at FCA would find it harder to use slot substitution. Also, it is easier to use slot substitution in large FCAs of the type used in AFPs as compared to small airport fix FCAs (e. g. airport fix FCAs). Also, we assumed that all flights have the same RTC value. In reality, different aircraft are likely to have different RTC values with alternate routes. This would also be factored in slot substitution decisions. It is also possible that there is demand capacity imbalance at more than one FCA. All these variations would make figuring out optimal relative slot costs a challenging problem. The point we would like to make is that an airline is not evaluating just two choices: a specific aircraft going through a FCA and it taking an alternative route. It also has another choice: subbing the slot assigned to an aircraft to one of the many other aircraft it can fly through the FCA. When subbing is allowed, airline should be evaluating value of alternative slots through different FCAs and not just relative costs of two trajectories of a specific aircraft. Evaluation of impact of subbing in CTOP context in realistic scenarios is an open research problem that needs to be addressed by future research.

VI. Conclusion

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). 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. Airlines also specify a Relative Trajectory Cost (RTC) for each trajectory option that specifies cost of each route relative to the most preferred option. CTOP also airlines to do slot substitution. In the paper, we discussed a specific scenario where airlines can reduce their delays by specifying relative slot cost as RTC and using subbing aggressively.

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