Imposing Speed Constraints on Arrival Flights: Case Study for Changi Airport

S. Aneeka, S.M. Phyoe, R. Guo, Z.W. Zhong

Abstract**—**Arrival flights tend to spend long waiting times at holding stacks if the arrival airport is congested. However, the waiting time spent in the air in the vicinity of the arrival airport may be reduced if the delays are distributed to the cruising phase of the arrival flights by means of speed control. Here, a case study was conducted for the flights arriving at Changi Airport. The flights that were assigned holdings were simulated to fly at a reduced speed during the cruising phase. As the study involves a single airport and is limited to imposing speed constraints to arrivals within 200 NM from its location, the simulation setup in this study could be considered as an application of the Extended Arrival Management (E-AMAN) technique, which is proven to result in considerable fuel savings and more efficient management of delays. The objective of this experiment was to quantify the benefits of imposing cruise speed constraints to arrivals at Changi Airport and to assess the effects on controllers' workload. The simulation results indicated considerable fuel savings, reduced aircraft emissions and reduced controller workload.

Keywords**—**Aircraft emissions, air traffic flow management, controller workload, fuel consumption.

I. Introduction

FLIGHT delays often cause dissatisfaction among passengers and incur huge monetary losses for airlines. Also, the additional fuel consumption results in increased environmental emissions such as CO_2 and NO_X [1]. Delays can occur in the ground or airborne. Airborne delay refers to the delay that is assigned in the air either during en-route or during descent i.e. holding, while ground delay refers to the delay that is assigned to the aircraft on the ground, either at the gate or on the taxiway [2]. The fuel consumption due to airborne delays is estimated to be 6 times higher than that of ground delays [3]. Thus, the aircraft emissions due to airborne delays should also be much higher compared to ground delays. Conventionally, airports have Ground Delay Programs (GDP) in place as part of Traffic Management Initiative (TMI). Under GDP, aircraft is delayed on the ground of departure airport, if the arrival airport is congested. While GDP is favorably applied to short-haul flights, it can be also extended to long-haul flights under severe traffic congestion [4]. Aircraft that were assigned airborne delays will have longer cruises. Those aircraft can later speed up to their optimal speed to recover the assigned delay [5], [6].

The speed reduction can also be done in such a way that the delay during the cruising phase does not consume extra fuel as compared to the original flight plan. This implies that the cruise speed control should be such that the specific range is the same as that at nominal speed [5]. However, the issues of maintaining separation minima and the interaction of these slow flights with other air traffic have not been addressed much in literature.

Such speed reduction strategies can help to recover ground delays and also help to reduce the waiting times spent within the vicinity of arrival airports. E-AMAN is a solution by SESAR in which the current Arrival Management (AMAN) is extended to en-route airspace up to 200 nautical miles from the arrival airport. The arrival sequencing occurs during the en-route phase, thus allowing advance preparation for the optimal sequencing of arrival traffic [7]. In this study, a simulation experiment was carried out to quantify the benefits of assigning cruise speed control to arrival flights at Changi Airport that were originally assigned airborne delay. The simulations were carried out using EUROCONTROL's System for Traffic Assignment and Analysis at Macroscopic Level (SAAM) tool and commercial ADS-B flight data. The simulation results showed that there can be considerable potential savings in terms of fuel consumption and reduction in controller workload.

II. Concept & Assumptions

A. Concept

A comparison of the speed reduction strategy with current GDP strategies was represented schematically by Delgado et al. [5]. However, this study focuses on a scenario that is affected by unpredictable factors. The scenario is developed based on the conditions that, even with queue, capacity and slot management techniques in place at departure and arrival airports, traffic operations could still be affected by unpredictable factors such as [4]:

- Interference of unscheduled traffic
- Weather deviations
- Winds aloft that are different from initial forecasts
- Tactical ATC intervention

Fig. 1 depicts the complete profile of a flight from origin to destination. Here, it is assumed that the arrival airport i.e. Changi airport, has been affected by one or more unpredictable factors, thus constraining its available capacity at that time. In such a case, airborne delays in the form of low-

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level vectoring or holdings may be assigned to some of the incoming traffic as part of air traffic flow management measure. Fig. 2 shows this illustration, where the flight path in dashed line indicates the stage during which the flight was assigned to be in holding during approach. In the scenario depicted in Fig. 3, the same flight arrives at the destination airport executing adjustments in cruise speed before the Top of Descent (TOD), as shown by the dotted line. It is expected that such an action will result in reduced waiting time at the TMA, as indicated by the dashed flight path.

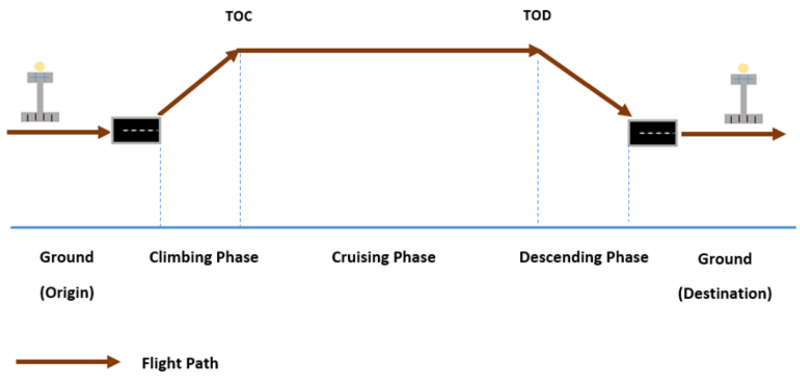

Fig. 1 Complete Flight Profile

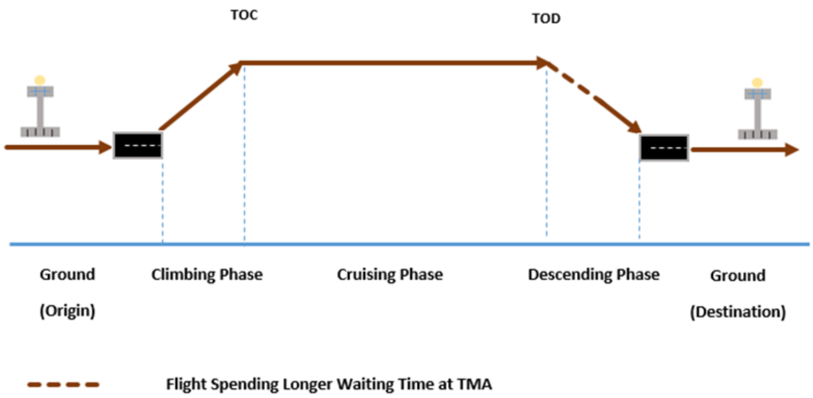

Fig. 2 Flight Assigned Airborne Delay during Approach

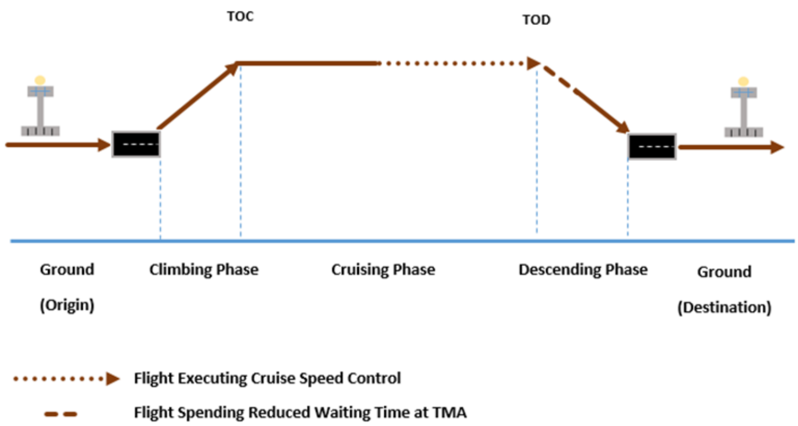

Fig. 3 Flight Assigned Speed Control before TOD

Based on the schematic representation by Louis et al. [5], Figs. 4 and 5 have been furnished to compare the baseline scenario with the cruise speed control scenario respectively. Here, the controlled flight takes T_{V_0} minutes to reach the arrival airport, with D minutes of airborne delay assigned due to unexpected congestion of arrival airport. Thus, the Controlled Time of Arrival (CTA) at the runway is the Estimated Time of Arrival (ETA) over the arrival metering FIX plus D minutes. Fig. 5 shows the scenario in which the flight was assigned to fly at the adjusted speed Vred during the cruising phase. Thus, the new ETA over the arrival metering FIX will be shifted such that the flight only has to spend d minutes in the TMA to arrive at the new CTA.

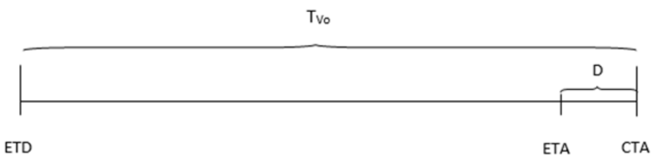

Fig. 4 Baseline Scenario with Conventional Airborne Delay

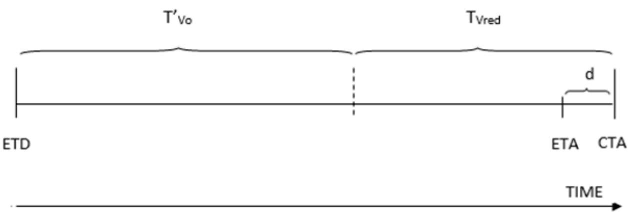

Fig. 5 Cruise Speed Control Scenario

B. Assumptions

Recent reports show that many cruising aircraft tend to make unannounced speed changes of Mach 0.04 or greater, thus posing great risks on separation minima and compromising the safety of the flight. It was observed that a speed change of Mach 0.04 in an FIR applying RNP4 may cause a 20% erosion in separation minima. Thus, pilots are required to notify ATC of subsequent speed changes equal to or greater than Mach 0.02 [14]. Owing to this, the speed change was restricted to Mach 0.02 in this experimental study. The following assumptions were then made to define the scope of the simulation setup on Changi Airport Arrivals.

1) Arrival airport has capacity constraints during the simulation hour.
2) A speed reduction of Mach 0.02 is allowed, owing to operational requirements.
3) Speed changes are announced.
4) Variations are done in controlled airspace
5) The leading aircraft ahead of the selected flights do not exhibit speed changes.
6) Separation Minima is ensured.
7) At constant cursing flight level, Vred is greater than Minimum Stall Speed and ATC has received clearance from Pilot at FL 390.
8) Cruise speed control is done within 200 NM from Changi aerodrome
9) The cruise speed is adjusted within Singapore En-route sectors before TOD and does not involve neighbouring FIRs.

III. Experimental Setup

A. Modelling & Simulation of Baseline and Cruise Speed Control Scenarios

An area extending 200NM in radius from Changi Aerodrome was modelled using EUROCONTROL's SAAM tool. This area will be referred to as "Arrival Sector" throughout this paper. Commercial ADS-B flight data were used to identify flights that were assigned airborne delays in the form of holdings. Table I lists the different aircraft types of the flights that were then simulated to compare the before and after scenarios of cruise speed control.

TABLE I
Simulated Flights

Flight ID	Aircraft Type
Flight A	A333
Flight B	B772
Flight C	A388
Flight D	A333

The basic simulation setup can be thus, simplified as:

- F_X (T_X) = Flight subjected to airborne holding at time T_X
- F_Y (T_Y) = Flight subjected to cruise speed control at time T_Y
- d_X = distance flown during airborne holding
- d_Y = distance flown during cruise speed control
- t_X = Total Time spent by F_X at arrival sector
- t_Y = Total Time spent by F_Y at arrival sector
- V_X = Speed of F_X over distance d_X
- V_Y = Speed of F_Y over distance d_Y

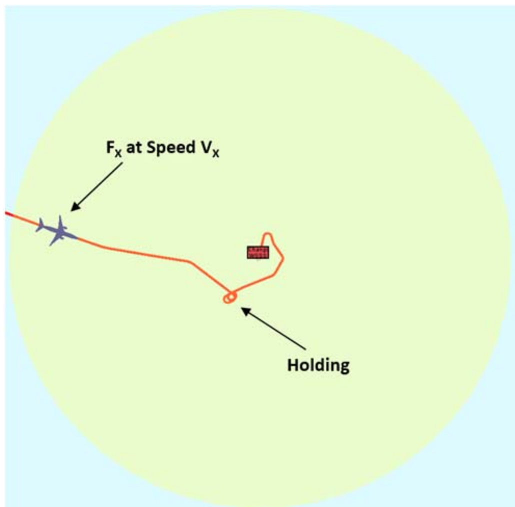

Fig. 6 Baseline Scenario

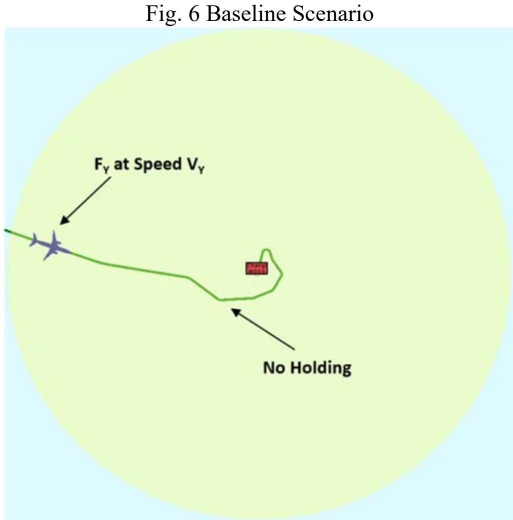

Fig. 7 After Cruise Speed Control Scenario

The simulations of the before and after cruise speed control scenarios for Flight D are depicted in Figs. 6 and 7, respectively.

The cost of assigned airborne holding and assigned speed control depend on the aircraft type of the flight and the total time spent at the arrival sector. Thus, the cost function can be defined here as

$$f1(t_X,F_X) = \text{Cost of assigned airborne holding} \quad (1)$$

$$f2(t_Y,F_Y) = \text{Cost of assigned cruise speed control} \quad (2)$$

B. Model for Estimating Aircraft NO_X and CO_2 Emissions

The approach used for estimating fuel consumption and NO_X & CO_2 emissions by the model we have adopted is summarized in Table II [8], [15].

TABLE II
APPROACH FOR ESTIMATING FUEL CONSUMPTION AND GAS EMISSIONS [8]

	Fuel Burn	NO_X	CO_2
Above 3000 ft Non-Landing Take-Off phases	BADA Data	Boeing Method 2	Proportional to Fuel Burn

Fuel consumption is estimated based on the aircraft-engine characteristics provided in the Base of Aircraft Data (BADA) for different aircraft [8]. The formula for estimating total gas emissions based on EUROCONTROL's Advanced Emission Model, which is an improvisation to the original Boeing Method 2 model, is provided as [9]:

$$\text{Total (HC, CO, NOx)} = N \times \Sigma_i(\text{EIHC, EICO, EINOX})_i \times Wf_i \times t_i \times 10^{-3} \quad (3)$$

where N = Number of Engines; EIHC= Emission Index of HC; EICO= Emission Index of CO; $EINO_X$ = Emission Index of NOx; Wf = Fuel Flow; t= Time [9]. Thus, the model for calculating total NO_X emissions could be simplified from (3) as [9]:

$$\text{Total (NOx)} = N \times \Sigma_i(\text{EINOx}) \times Wf_i \times t_i \times 10^{-3} \quad (4)$$

The emission index for CO_2 is 3,149 kg/kg fuel [10]. This emission index will be constant for all flight phases, as CO_2 is proportional to fuel burn [10].

C. Macroscopic Model for Estimating Workload

The macroscopic workload model adopted for the experiment is determined by an analytical formula that comprises of three main components. These three components are the aircraft entry rate, conflicting tasks and de-conflicting tasks [11]-[13]:

$$Wkl = C*p1+SHER*p2+Avg*p3 \quad (5)$$

where C denotes number of conflicts, SHER is Sliding Hourly Entry Rate, Avg is the average time in the sector in minutes, p1, p2 and p3 are constants.

SHER is the Sliding Hourly entry rate. It calculates the number of aircraft per minute slid across every one hour period [11]. The entry time centering value was set as 0, so that aircraft will be counted only at its entry time.

IV. Results & Discussion

A. Comparison of Time Spent at Arrival Sector

Table III provides the results on the total flight time observed at the arrival sector for baseline and after cruise speed control scenarios. It can be noted that, with cruise speed control assigned, an average reduction of 4 minutes in total flight time at the arrival sector was seen for the simulated flights. Thus, from the simulations, ty < t_X. Hence, from (1) and (2) the cost of assigned cruise speed control delay can be considered lower than the cost of assigned airborne delay in the form of holding i.e. f2 < f1.

TABLE III
COMPARISON OF TOTAL TIME AT ARRIVAL SECTOR

Flight ID	Baseline Scenario	New Scenario
Flight A	25	24
Flight B	37	32
Flight C	41	37
Flight D	50	45

B. Comparison of Fuel Consumption and Aircraft Emissions

Tables IV, V & VI show that the total fuel burn, total CO_2 emissions and total NO_X emissions within the arrival sector indicate a reduction in values due to cruise speed control in comparison with the baseline scenario.

TABLE IV
COMPARISON OF TOTAL FUEL BURN

Flight ID	Baseline Scenario	New Scenario
Flight A	800	579
Flight B	2015	1553
Flight C	5053	4080
Flight D	2599	2298

TABLE V
COMPARISON OF TOTAL CO_2 EMISSION

Flight ID	Baseline Scenario	New Scenario
Flight A	2527	1829
Flight B	6369	4909
Flight C	15968	12894
Flight D	8213	7262

TABLE VI
COMPARISON OF TOTAL NO_X EMISSION

Flight ID	Baseline Scenario	New Scenario
Flight A	7	4
Flight B	34	24
Flight C	76	58
Flight D	30	27

Aircraft waiting at the holding stacks not only cause increased emissions, but also increased level of perceived noise on the ground due to its proximity to the airport, all of which are highly undesirable. The results support the statement that implementing cruise speed control reduces the amount of fuel consumed and the resulting aircraft emissions considerably in comparison with conventional airborne delay

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methods.

C. Effects on Controller Workload

The macroscopic model yielded the workload values for the baseline and after cruise speed control scenarios as indicated in Fig. 8. The results were obtained by simulating the interaction of other arrivals to Changi airport with the selected flights in Table I. It can be seen that assigning cruise speed control gave reduced controller workload values. However, it should be noted that the workload values provided are only representative of the simulated arrival sector. In reality, the flights at this simulated arrival sector are controlled by the TMA controllers during approach phase and by ACC Controllers during the en-route phase. While the cruise speed control strategy can reduce the TMA controllers' workload by reducing flight time at TMA or at the holding stacks, the speed change may slightly increase the workload of ACC controllers since they now have to keep track of separation minima between leading and trailing aircraft.

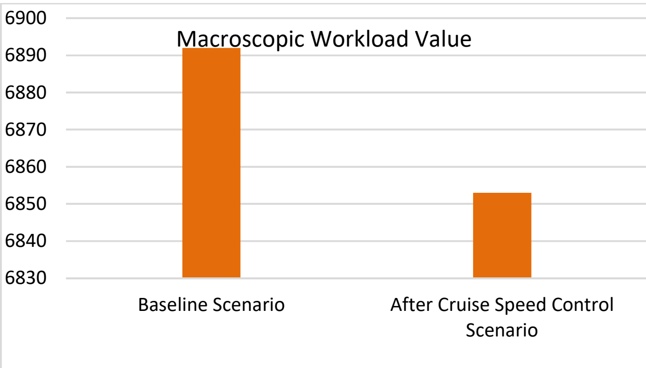

Fig. 8 Workload Comparison between Baseline and After Cruise Speed Control Scenarios

V. Conclusion

This paper presented a case study conducted for Changi Airport arrivals, to quantify the benefits of assigning cruise speed control strategy before the top of descent in place of conventional airborne delay strategies such as holdings and vectoring. The cruise speed control experiment was done based on the extended-AMAN (e-AMAN) concept implemented under SESAR and the speed reduction values were assigned according to operational requirements. The results suggested that an average of 4 mins in flight time could be saved for each flight at the arrival sector by assigning cruise speed control. An average reduction of 21% in fuel burn and CO_2 emissions and 33% in total NO_X emissions were seen. The arrival sector in this paper refers to the simulated area spanning 200NM in radius from the location of Changi Aerodrome. A macroscopic estimation of controller workload also indicated reduction in the arrival sector. However, it should be noted that while the TMA controllers' workload could be reduced, speed reduction by aircraft caters the need for careful monitoring of separation minima, which could slightly increase the workload of ACC controllers.

This case study quantified the potential benefits of implementing the e-AMAN strategy in Changi Airport. Given the necessary equipment and technology management, such solutions can help to improve the traffic operations in many of the congested airports in the Asian region. Regional collaboration could also pave the way for potential implementation of long range-ATFM techniques by extending the AMAN horizon to neighboring FIRs.

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