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Human-in-the-Loop Simulation of Trajectory Based Operation Concept for Remotely Piloted Aircraft System Integration

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Trajectory Based Operations (TBO) is one of the concepts of the next generation air traffic management (ATM) system to maximize throughput by planning and sharing 4-D trajectories between pilots and controllers. Given the current circumstances where many countries put efforts to establish rules and regulations for Remotely Piloted Aircraft System (RPAS) integration, it is essential to analyze the impact of RPAS on the next generation ATM environment. In this research, a Human-in-The-Loop (HiTL) simulation system capable of TBO is developed. HiTL simulations were performed by a licensed air traffic controller assuming integrated operation with Remotely Piloted Aircraft (RPA) with communication delays. The results were analyzed using three evaluation metrics, which are efficiency, safety, and controller workload. It shows that, compared to the conventional radar vectoring, TBO reduced both the arrival delay and the controller workload. However, in terms of the two safety metrics employed for this research, TBO showed slightly reduced level of safety.

I. Introduction

TBO is an operational method where a 4-D trajectory is scheduled and shared between air traffic personnel such as pilots, air traffic controllers, and airline dispatchers. It leads to more accurate control of airborne aircraft by predicting routes and arrival times at designated waypoints. International Civil Aviation Organization is building up the trajectory management procedures and data link infrastructures for constructing TBO environment.[1] In the United States, Federal Aviation Administration is making a framework for trajectory management and separation standard related to TBO through NextGen project.[2] For the establishment of ATM system based on trajectories, agencies in Europe already performed flight tests and fulfilled an initial 4-D trajectory management concept evaluation.[3]

It is necessary to assess the impacts of RPAS, given that many countries are establishing rules and regulations for the integration of RPAs in their civil airspace.[4,5] For realistic simulations of the integrated operations of manned aircraft and RPAS, it is important to understand how the unique characteristics of RPAS such as performances, communications, separations assurance methods, and human factors such as controller workload affect the ATM system. A fundamental difference between RPAS and manned aircraft is that the pilot is not physically positioned inside the aircraft. Instead, a wireless communication link that is reliable and secure is required to control the RPA. In addition, voice and possibly data communication is necessary between the remote pilot and the Air Traffic Control (ATC) system. In the previous research,

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HiTL simulations were performed with conventional radar vectoring approach for the integrated operations between manned aircraft and RPAS with scenarios based on the recorded flight trajectories around the Incheon International Airport (RKSI). To evaluate the impact of RPAS, RPAS was modeled by introducing artificial communication delays or temporary loss of communication in the simulation system. The results showed that the total flight time was increased and the workload was significantly increased.[6] In addition, an attempt was made to analyze safety; however, due to errors in the projection of flight data and time synchronization, meaningful quantitative results were not derived.[6]

In this research, Human-in-the-Loop (HiTL) simulations were performed with the same scenarios and by the same trainee air traffic controller as the previous study.[6] Simulation results of conventional radar vectoring approach and TBO are compared using three metrics, which are efficiency, safety, and controller workload. To assess the integrated operation of RPAS in the TBO environment, an existing ATC simulation system was enhanced to include trajectory estimation and data communication capability.

The rest of the paper is organized as follows. Section 2 describes the concept of TBO, and Section 3 explains the ATC simulation system for the integrated operations using TBO environment. Section 4 introduces three types of metrics for evaluating the impacts. Section 5 describes the scenario where RPAS are integrated into the arrival stream. Section 6 shows the results and comparative analysis between the two ATM concepts. Finally, Section 7 concludes the paper.

II. Trajectory Based Operations

TBO is one of the next generation ATM concepts for accommodating more aircraft in the congested airspace. All aircraft's 4-D trajectories are scheduled and shared with air traffic personnel such as airline dispatchers, pilots, air traffic controllers, and other air navigation service providers. Each waypoint in the flight path has its own position and estimated time of arrival (ETA). ETA for each waypoint is calculated by Flight Management System (FMS) in the form of maximum and minimum times. The 4-D trajectory can be altered by controllers whenever necessary. TBO concept is summarized in Fig. 1.

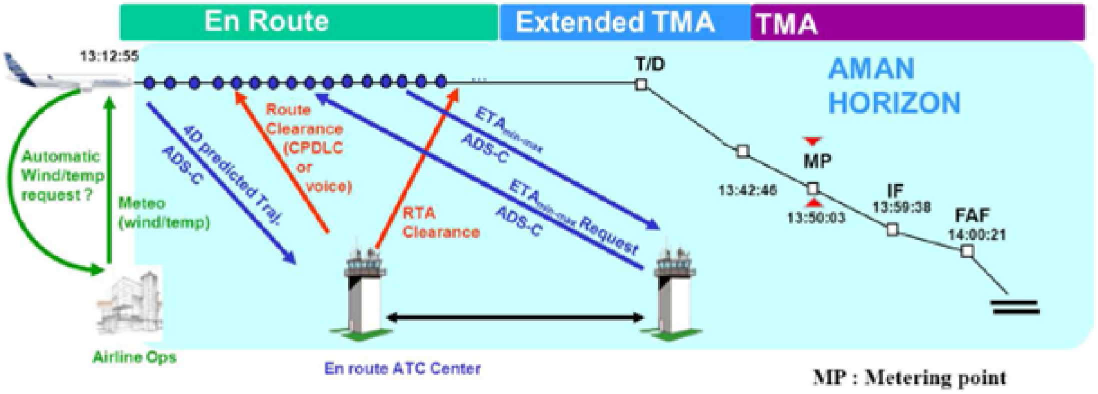

Figure 1. Summary of TBO procedure.[7]

TBO operation procedures are as follows. The expected 4-D trajectory calculated through the aircraft's FMS is downlinked to the corresponding airspace ATC Center on the ground using Automatic Dependent Surveillance - Contract (ADS-C). And then, the ATC center uplinks permission to follow the trajectory using the Controller Pilot Data Link Communication (CPDLC) or voice communication. Then, the ATC center provides the aircraft with the maximum and minimum time of arrivals at the Metering Points (MPs). Through the received ETAs from the aircraft, the ATC performs arrival sequencing and scheduling. As a result, Controlled Time of Arrivals or Required Time of Arrivals (RTAs) at MPs are uplinked and followed by the FMS. TBO provides fuel savings and carbon dioxide emission reduction by providing optimal flight path. Besides, efficient and accurate trajectory management will increase the capacity of the airspace while enhancing safety.

The key technologies for TBO are advanced FMS, data link communication, Automatic Dependent Surveillance - Broadcast (ADS-B), and decision support tool for controllers to determine RTAs. An advanced FMS determines the accuracy of the ETA calculations and RTA tracking performances. Data links can be used to exchange 4-D trajectory information and for pilot-controller communications. ADS-B is an essential technology because it can receive air surveillance information even in areas without conventional radar coverage. Lastly, the decision support tool provides the controller with a user interface to determine arrival sequence scheduling and RTAs at MPs.

III. Simulation System

A. Air Traffic Control Simulator applied to TBO

Figure. 2 indicates the structure of the Inha University ATC simulator. It consists of four parts: a server, multiple pilot stations, multiple controller stations, and a radar and surveillance data processing system.[6]

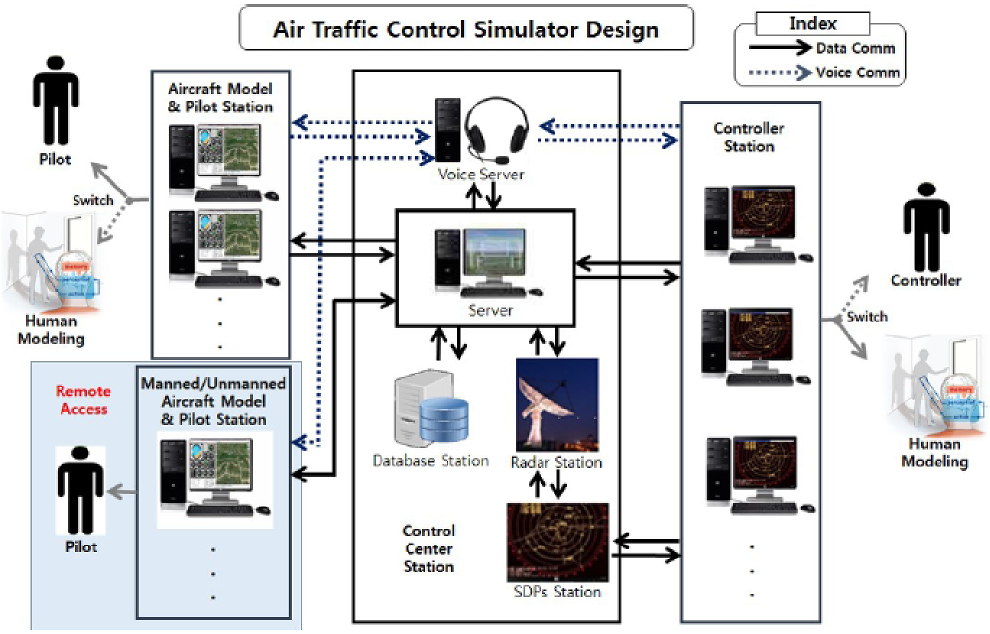

Figure 2. Air Traffic Control Simulator Structure.

1. *Server*

The server manages the simulation scenarios and controls the data flow between the clients. Especially, ADS-B data are collected and processed from the flight dynamics models in the pilot stations. For the current study, CPDLC capability was added so that text messages can be exchanged between pilots and controllers as well as 4-D trajectory information.

2. *Pilot Station*

Multiple pilot stations can be connected to the server, and each pilot station can control multiple aircraft. The flight dynamics model based on a five degree-of-freedom (DOF) model was enhanced using standardized performance data and operational specifications from Base of Aircraft Data (BADA) with improved control and guidance routines.[8] The 5-DOF model is suitable for ATC simulation because it can model basic pitch and roll dynamic but does not require complex stability derivatives, which leads to improved computational efficiency for large scale simulations. In order to properly simulate the scenarios in TBO environment, the flight dynamics model should be able to control aircraft speed to satisfy the RTA at each waypoint. Additionally, one point navigation is included so that aircraft can be operated to a specific fix in the airspace to secure the separation interval according to the controller command. Figure. 3 shows the pilot station display.

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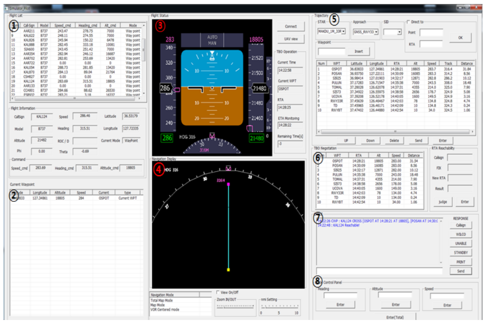

Figure 3. Pilot Station UI.

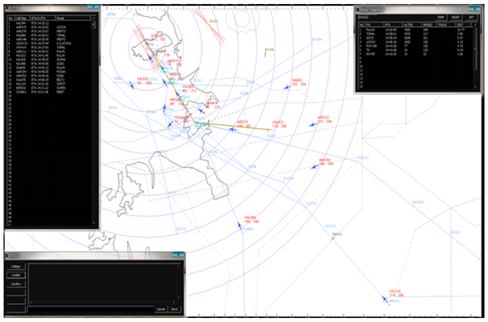

Figure 4. Controller Station UI.

3. *Controller Station*

Controller station display shows the current position of aircraft on the map with airspace boundaries and other essential flight information. Display and functionalities related CPDLC communication of TBO parameters were added. It displays the RTA and ETA at each designated waypoint for each aircraft, which is used as a decision support screen for the scheduling of the arrival aircraft. Depending on the traffic flow and separation between aircraft, controller can issue new RTA in addition to altitude, speed, or heading commands.

IV. Evaluation metrics

In order to assess the impacts of RPAS integration in the airspace system, several metrics are introduced. Arrival time is chosen for the efficiency metric. For safety, two metrics are evaluated that are Conflict Intrusion Parameter (CIP) and Well Clear Score (WCS). Two metrics, NASA Task Load Index (TLX) and Instantaneous Self-Assessment (ISA) are used to evaluate controller workload.

A. Efficiency - Arrival Delay

In general, when an aircraft performs additional maneuvers from the schedule flight, flight time is increased, which results in arrival delays and extra fuel consumption. In this study, the arrival time is selected as an efficiency index. Arrival time includes arrival delay caused by RPAS.

B. Safety metrics

1. *Conflict Intrusion Parameter (CIP)*

CIP is defined in Eq. (1), which is based only on horizontal and vertical separation distances.[9] Horizontal and vertical separation standards, S_{std} and h_{std}, are set to 5 nmi and 1,000 ft (or 2,000 ft if both aircraft are above FL290) respectively. The maximum value of CIP is one and the minimum is zero. CIP value of one means collision.

$$CIP = 1 - 0.5 \times \left\{ min \left(\frac{\triangle s(t)}{S_{std}} + \frac{\triangle h(t)}{h_{std}} \right) \right\}, \ (t_{sec} \leq t \leq t_{eoc}) \tag{1}$$

The original CIP equation is modified for evaluating a conflict risk as a function of time. This will limit the value of CIP to stay between zero and one. CIP of zero means the instant separation exceeds the standard separation criteria.

$$CIP(t) = \max \left\{ 1 - 0.5 \times \left\{ \left(\frac{\triangle s(t)}{S_{std}} + \frac{\triangle h(t)}{h_{std}} \right) \right\}, 0 \right\} \tag{2}$$

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2. *Well Clear Score (WCS)*

Well clear is suggested by the Unmanned Aircraft System (UAS) Executive Committee Science and Research Panel (SarP) and Radio Technical Commission for Aeronautics (RTCA), to be the standard of separation for the Detect and Avoid System of RPAS.[10] Well clear consists of the three parameters given in Eqs. (3), (4), and (5)

$$0 \leq \tau_{mod} \leq \tau^{*}_{mod} \tag{3}$$

$$HMD \leq HMD^{*} \tag{4}$$

$$-h^{*} \leq d_h \leq h^{*} \tag{5}$$

where,

$$\tau_{mod} = \begin{cases} \frac{DMOD^2 - r^2}{r\dot{r}} & (r > DMOD) \\ 0 \quad (r \leq DMOD) \end{cases}$$

$$HMD = \begin{cases} \sqrt{\left(d_x + v_{rx}t_{cpa}\right)^2 + \left(d_y + v_{ry}t_{cpa}\right)^2} & (r \geq t_{cpa}) \\ -inf & (r < t_{cpa}) \end{cases}$$

$$d_h = h_2 - h_1$$

Table. 1 shows the proposed five levels of safety with different threshold values. Loss of Well Clear (LOWC) is the most dangerous situation that should be avoided. To quantify the level of safety in terms of the alert level, a metric called Well Clear Score (WCS) is proposed in this study. Scores of one to five are given to each level from proximate traffic to LOWC.

Table 1. Well Clear self separation alert level

Self Separation		Proximate Traffic	Preventative Alert	Corrective Alert	Warning Alert	LOWC
Alert Level		Advisory	Caution	Caution	Warning	Danger
MustAlert Threshold	Within Time	60 seconds	55 seconds	55 seconds	40 seconds	-
	τ^{*}_{mod}	35 seconds	35 seconds	35 seconds	35 seconds	35 seconds
	DMOD, HMD	2.0 nmi	0.66 nmi	0.66 nmi	0.66 nmi	4000 ft
	h^{*}	1,200 ft	700 ft	450 ft	450 ft	450 ft
MustNot Alert Threshold	Within Time	85 seconds	75 seconds	75 seconds	55 seconds	-
	HMD_p	$>$ 5.0 nmi	$>$ 2.0 nmi	$>$ 1.5 nmi	$>$ 1.0 nmi	-
	D_{h_p}	$>$ 1,300 ft	$>$ 800 ft	$>$ 450 ft	$>$ 450 ft	-

C. Controller Workload

1. *NASA Task Load Index*

NASA TLX is a tool to allow users to perform subjective workload assessments on operators working with various human-machine interface systems.[11] By incorporating a multi-dimensional rating procedure, NASA TLX derives an overall workload score based on a weighted average of ratings on six evaluation indices: mental demand, physical demand, temporal demand, performance, effort, and frustration.

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2. Instantaneous self-assessment

ISA is a method to measure the mental workload of an operator performing work in the real-time simulation environment at five levels, which was developed by Air Traffic Management Development Centre.[12] Participants will assess the level of work from one (under-utilised) to five (Excessively busy) every two minutes.

Table 2. ISA score description

Level	Workload	Capacity	Description
5	Excessive	None	Behind on task; losing track of the full picture.
4	High	Very Little	Non-essential tasks suffering. Could not work at this level very long.
3	Comfortable	Some	All task well in hand. Busy but stim ulating pace. Could keep going continuously at this level.
2	Relaxed	Ample	More than enough time for all tasks. Active on ATC task less than 50 of the time.
1	Under-Utilised	Very Much	Nothing to do. Rather boring.

V. Simulation

A. Scenario

The simulation scenario is generated using the same conditions from the previous study.[6] The scenario used recorded flight data of thirteen departing aircraft and 26 arriving aircraft around RKSI on October 10th, 2015 from 8:00 am to 08:30 am. Among the arriving aircraft, three aircraft (KAL870, KAL622, and KAL124) are selected as RPAs by artificially adding designated communication delays in the simulation system. As shown in Table. 3, case 1 is the reference case without RPAs. Cases 2 and 3 are the cases where the three RPAs that have one, two, and ten seconds of communication delays. Ten seconds of communication delay is considered to be a Loss of Control (LOC) situation.

Table 3. Simulation Scenario

	Communication Delay [s]		
	RPA870	RPA622	RPA124
case 1	0	0	0
case 2	1	2	10
case 3	2	10	1

B. Task

The controller task is to perform the approach control of the aircraft in the Seoul Terminal Maneuvering Area (TMA) in each case. After simulation starts, pilot creates initial 4-D trajectories considering Standard Terminal Arrival Route and Global Navigation Satellite System procedure at each waypoint calculated from FMS for arriving flights. The trajectory is sent to air traffic controller and negotiated. Considering flow of traffic and separation, the controller can direct the pilot to change flight paths or speeds.

C. Participant and Setting

Participants in the HiTL simulation consist of one licensed controller and two pseudo pilots. Pseudo pilots were not licensed but have prior experiences participating in other HiTL simulations as pseudo pilots. The experimental procedure was briefed to the controller prior to the simulation. The controller and the pilots were separated so that they could not see each other‘s screens. The list of callsigns for designated RPAs were given to the controller. However, the controller was not informed about the communication delays of those RPAs. Only the arrival aircraft were controlled by the controller and the pseudo pilots.

VI. Simulation Results

For the computation of the proposed metrics, trajectories were collected in a form of log files. The controller wrote ISA every two minutes according to the established measurement procedure. NASA-TLX was surveyed at the end of each case. The results are presented and compared to the previous study using radar vectoring.

A. Arrival Delay

Figures. 5 and 6 show the number of arrived aircraft with respect to time comparing radar vectoring and TBO environment. Figure 5 shows relatively larger differences between the cases compared to Fig. 6. It indicates the presence of communication delay causes some aircraft to delay their arrival, but the impact is lower with TBO. Table. 4 presents the total flight time. TBO generally shows smaller total flight time, while the RPAs causes total flight time to increase in both the operations. The increments in total flight time with RPAs are much smaller with TBO.

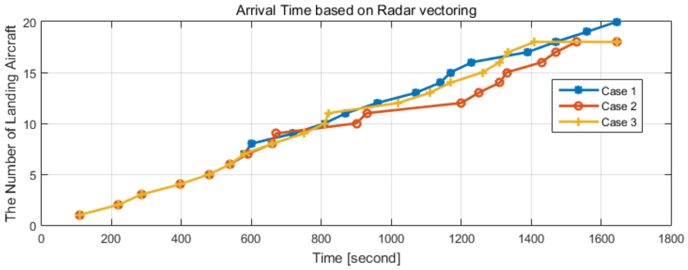

Figure 5. The number of arrival aircraft on Radar vectoring.

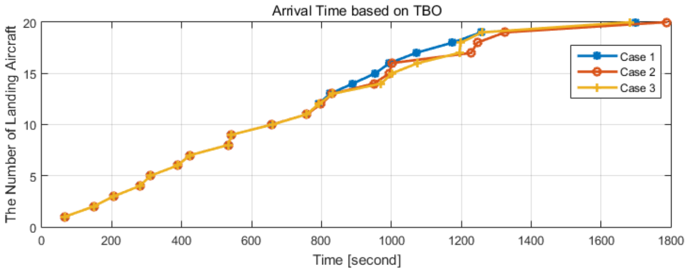

Figure 6. The number of arrival aircraft on TBO.

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Table 4. Total flight time comparison between Radar vectoring and TBO

	Case 1	Case 2	Case 3
Radar vectoring	17,250	19,780	19,865
TBO	13,972	14,477	14,327

Figures. 7 and 8 indicate the individual arrival times of all the aircraft. With TBO, other than one flight (ESR932) other flights do not show significant increase in the flight time even when RPAs are present.

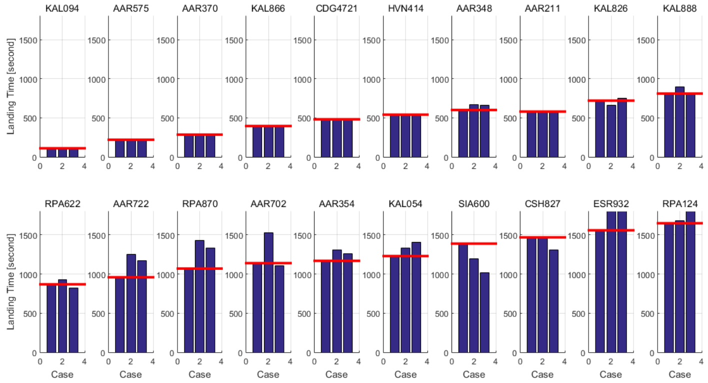

Figure 7. Arrival Time based on Radar vectoring.

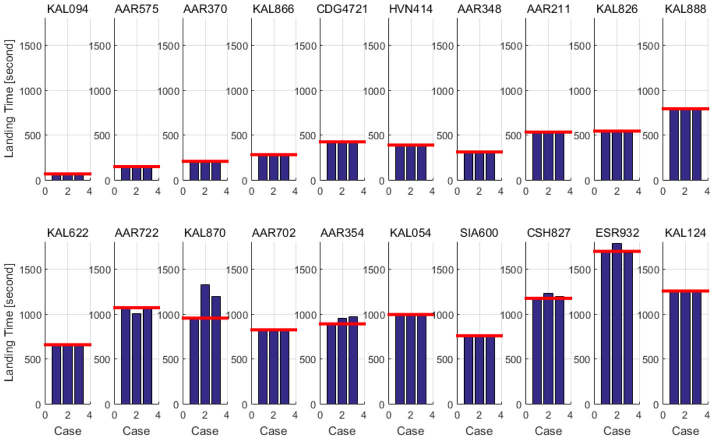

Figure 8. Arrival Time based on TBO.

B. Safety Analysis

1. *CIP*

Figure 9 shows the maximum CIP of radar vectoring and TBO respectively. The maximum CIP is the maximum value of CIP at each time step among all aircraft pair. The maximum CIP value very close to one at the beginning of the simulation shown in Fig. 9 (a) is due to overlapping initial position at the beginning of the simulation for radar vectoring. Other than the initial point, it can be observed that the maximum CIP remains mostly below 0.5 for radar vectoring. However for TBO, it can be observed that the maximum CIP is generally larger. For radar vectoring, introduction of RPAs do not show any noticeable trend in terms of changing the CIP values. For TBO, higher peaks are visible towards the end of the simulation.

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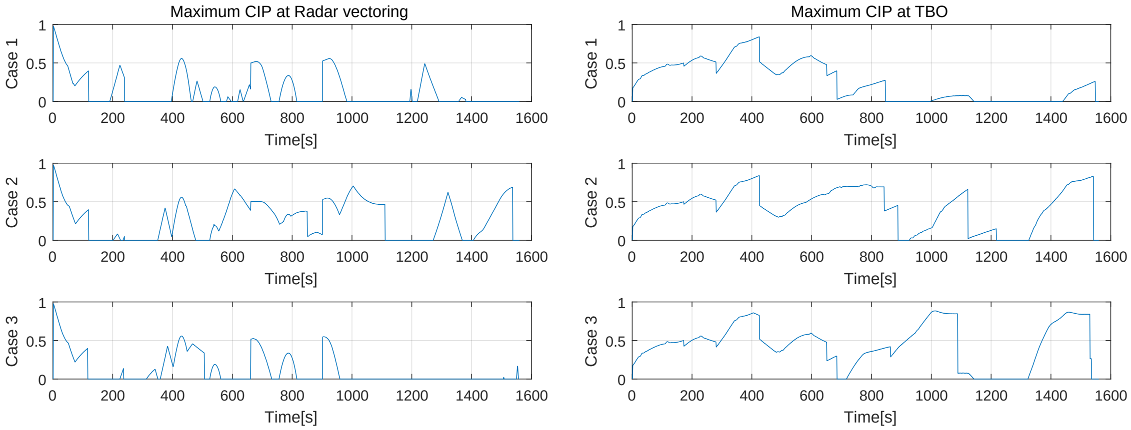
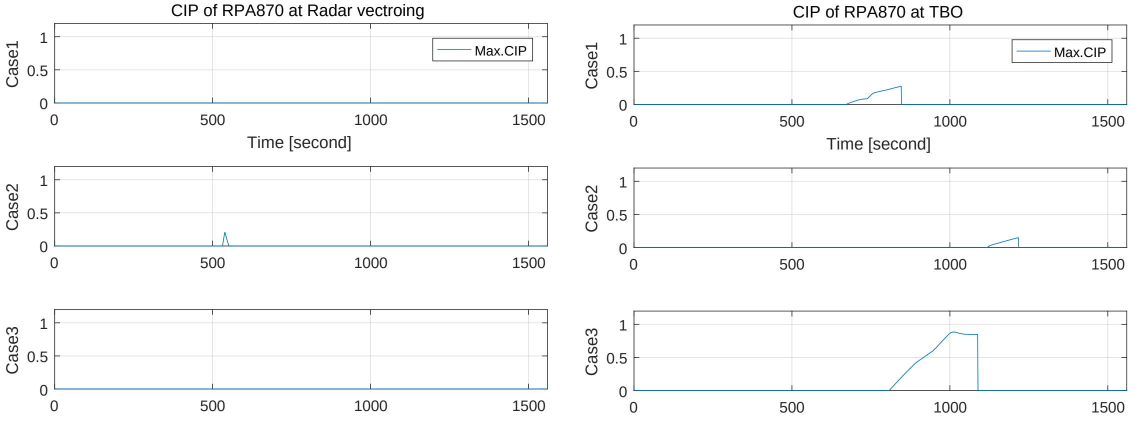


(a) Radar vectoring (b) TBO

Figure 9. Maximum CIP.

Figures 10 through 12 show the CIPs for the three individual RPAs. The unusually high CIP value of RPA870 at case 3 is analyzed later with the WCS metric. No specific tendency can be observed.



(a) Radar vectoring (b) TBO

Figure 10. CIP of RPA870.

2. WCS

Since the CIP considers only distances, a WCS metric that also uses time has a potention of being better at predicting safety. Figure 13 shows the maximum WCS among all aircraft pair at each time step. Figure 14 shows the sum of WCS of all aircraft pair at each time step. Both the maximum and total show that safety level is generally higher with the TBO in terms of WCS. WCS for TBO also show that introduction of RPAs at cases 2 and 3 noticeably increases the risk. Maximum WCS in Fig. 13 shows the WCS not exceeding four, which means no LOWC situation happened. If the maximum and total WCS are compared for TBO, it can be observed that the values are dominated by the maximum.

Figures 15 through 17 show the WCSs for the three individual RPAs. For radar vectoring, no RPA show even the lowest alert level. For TBO, higher risk moments can be observed with RPA870 in case 3 and RPA124 in case 2. One particular case of high CIP from Fig. 10 (b) coincides with high WCS in Fig. 15 (b) around 1,000 seconds. Figure 18 shows the snapshot of controller display at this moment. Two aircraft can be seen on the final approach paths for the two parallel runways, which is not an uncommon situation. The fact that CIP predicted near collision while WCS predicted warning alert that is one level below LOWC can

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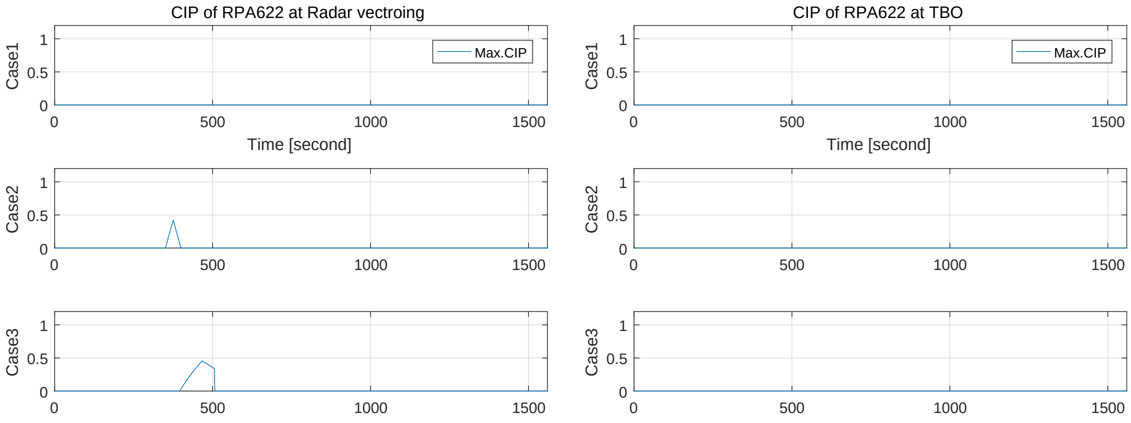
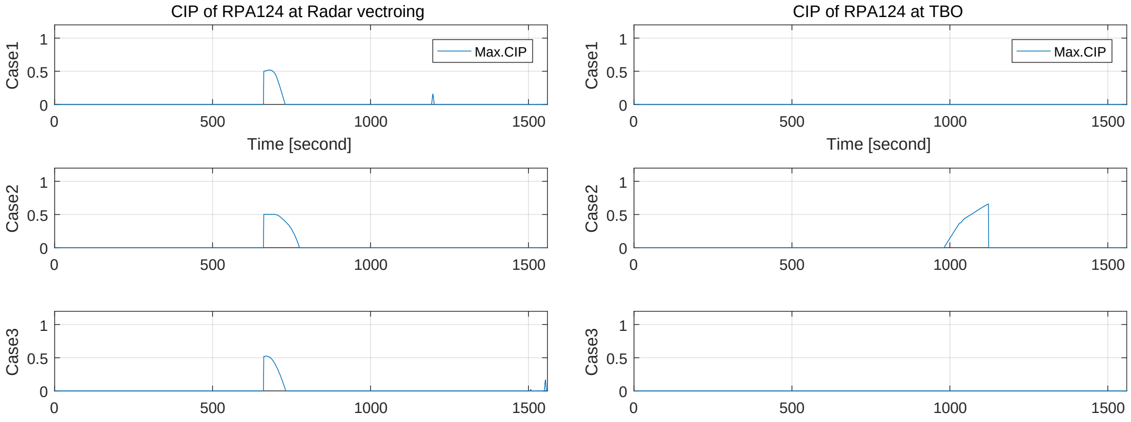


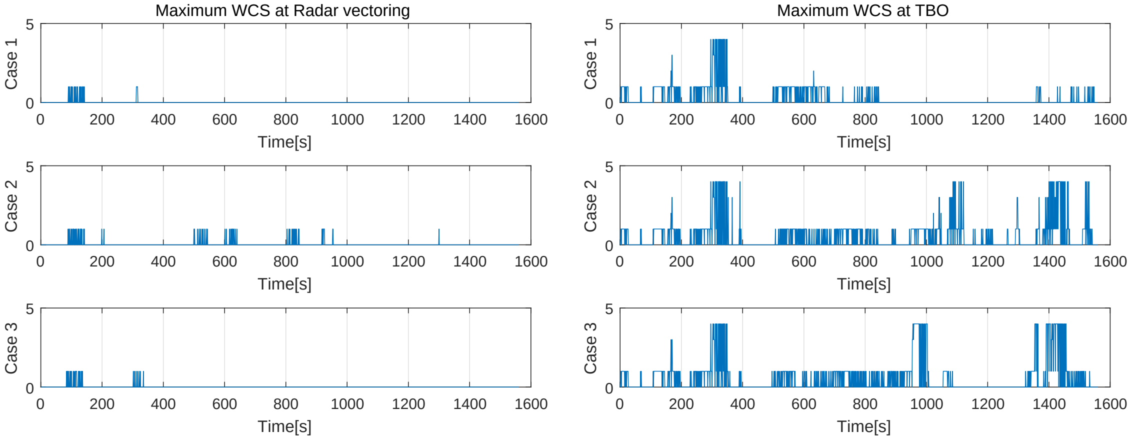
(a) Radar vectoring (b) TBO

Figure 11. CIP of RPA622.



(a) Radar vectoring (b) TBO

Figure 12. CIP of RPA124.



(a) Radar vectoring (b) TBO

Figure 13. Maximum WCS.

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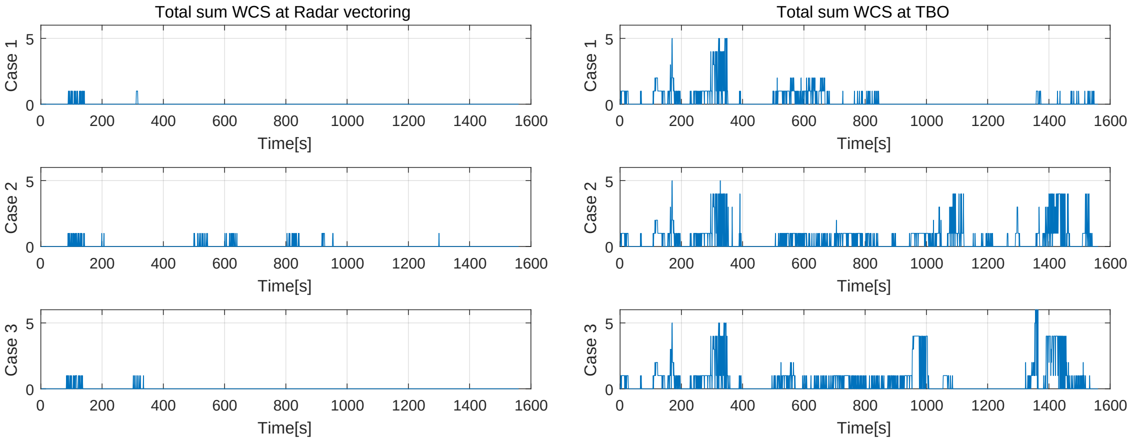
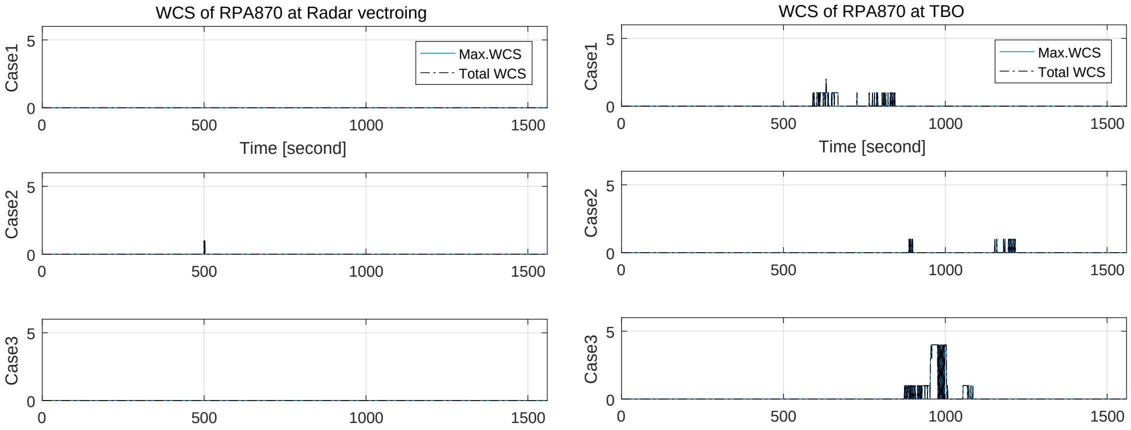


(a) Radar vectoring (b) TBO

Figure 14. Total sum of WCS.

be an evidence that WCS is a better metric that reflects the realistic safety, especially inside the terminal area.

Both the CIP and WCS show generally better safety levels with radar vectoring. It is likely to be due to the fact that controller pays more attention managing individual separation with radar vectoring while the major concern in TBO environment is managing the in trail separation. However, further investigation will be necessary to find more definite answer.



(a) Radar vectoring (b) TBO

Figure 15. WCS of RPA870.

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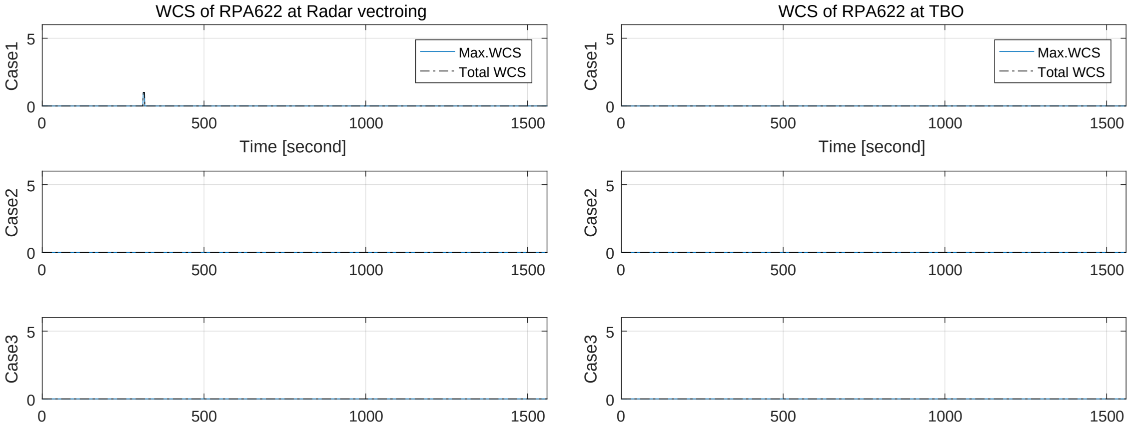
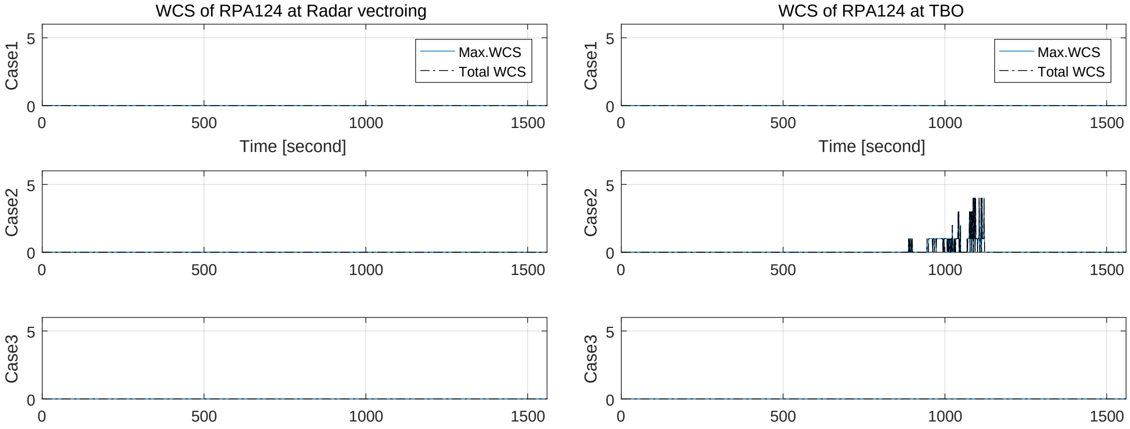


(a) Radar vectoring

(b) TBO

Figure 16. WCS of RPA622.



(a) Radar vectoring

(b) TBO

Figure 17. WCS of RPA124.

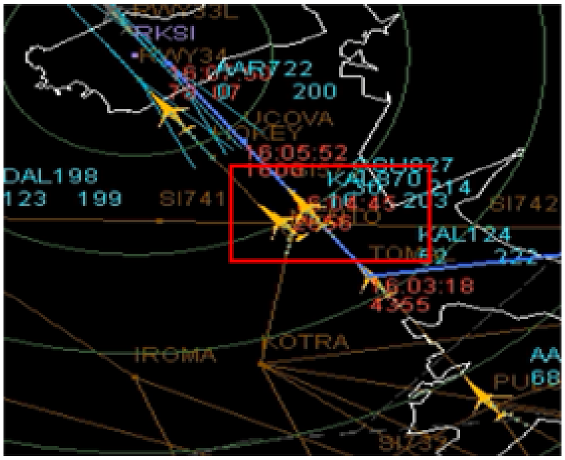


Figure 18. Maximum WCS of RPA870 at TBO in Case 3.

C. Controller Workload

1. *NASA TLX*

NASA TLX result is shown in Table. 5. It shows that the presence of RPAs increased the TLX in both the cases. TBO shows generally smaller TLX values compared to radar vectoring.

Table 5. NASA-TLX

	Radar vectoring	TBO	difference [%]
Case 1	47.00	31.33	-33.34
Case 2	66.00	53.65	-18.71
Case 3	78.67	52.99	-32.64

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2. *Instantaneous Self-Assessment*

ISA results are indicated in Figs. 19 and 20. Similarly, the results for the ISA show that the workload of the controller increases when RPAs are present. Both the figures show that ISA decreases with time if no RPAs are present. However, when RPAs are present, ISA shows slightly increasing trend with radar vectoring while decreasing trend with TBO.

Both NASA TLX and ISA show significant workload increase when RPAs are present. With TBO, the workloads are reduced, but it can be noticed that the work load with RPAs in TBO is still higher than the workload without RPAs in radar vectoring.

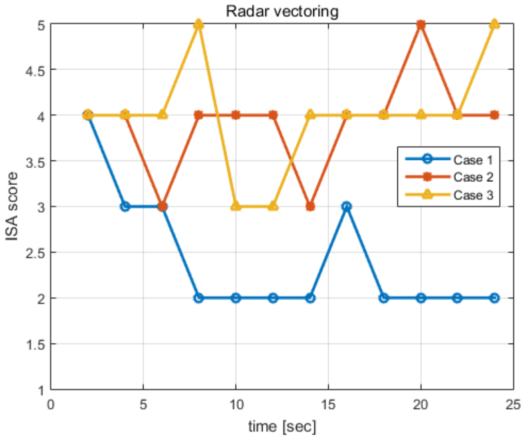

Figure 19. ISA at Radar vectoring.

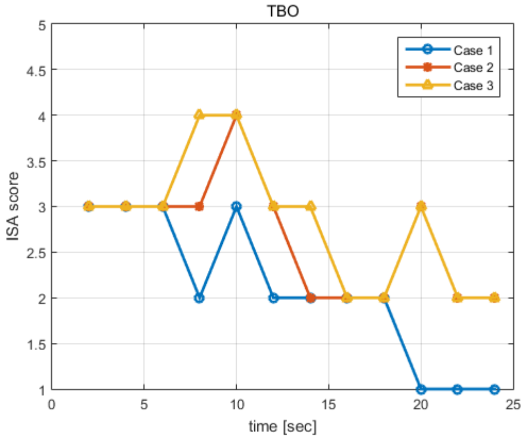

Figure 20. ISA at TBO.

VII. Conclusion

To evaluate the impacts of communication delays of RPAs in TBO environment, HiTL simulations were performed using a scenario based on the recorded trajectory data around the Incheon International Airport. Experienced trainee controller acted as the approach controller while two pseudo pilots maneuvered arriving aircraft. CIP and WCS were computed as safety metrics. Arrival delays were used for efficiency metrics. For workload metrics, NASA-TLX and ISA were computed. With TBO, the overall air traffic flow was improved, while the adverse impacts of RPA presence was reduced compared to conventional radar vectoring. Moreover, TBO was found to be especially effective in reducing the controller workload when RPAs were present. Between CIP and WCS, WCS was found to be better metric for assessing safety in terminal area. For TBO, WCS showed reduced safety when RPAs are present. Future work will include further analysis of the safety metrics and additional quantitative measure of workload such as eye tracking.

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