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RESEARCH ARTICLE

SINGLE CROSS-BORDER FREE ROUTE AIRSPACE CONCEPT IN THE ASEAN REGION

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Abstract

Single Cross-Border Free Route Airspace (FRA) represents the ultimate long-term idealistic routing rules allowing airspace users freely plan a route in en-route airspace, which is not immediately possible from the administrative and technological point of view. In Single Cross-Border FRA, the whole ASEAN airspace is treated as a single-large FRA where all 12 Flight Information Regions (FIRs) implement FRA, with direct routing between the entry (horizontal entry into FIR or end of Standard Instrument Departure Route, SID) and the exit (horizontal exit from FIR or beginning of Standard Arrival Route, STAR). Single Cross-Border FRA is the most fuel-efficient reference that we could ever reach in the future.All otherhypothetical routing rules fall between the Single Cross-Border FRA and those hypo-thetical routing rules in terms of fuel efficiency. In this paper, we described the potential in fuel efficiency (or 'benefit achievement scaling') with refer-ence to this ultimate basic fuel requirement and scaled the excess fuel with different routings. We evaluated the fuel burn with a fast-time simulation (FTS) in 12 different scenarios (3 traffic volume levels × 4 routing scenarios). As for the traffic volume scenarios, we simulated 1-day of commercial ASEAN flight schedule data of 3 traffic volume levels (100%, 150%, and 200% of pre-COVID19 traffic volume). As for four routing scenarios with increasing levels of directness: conventional Air Traffic Service route network (ATS) (R1), hypothetical Several-Small FRA route network (R2), Single Cross-Border FRA route network with Danger Areas (R3) and Single Cross-Border FRA network without Danger Areas (R4). Results showed that flight time, fuel burn, and distance travelled were less in R2, R3, and R4 than in R1. There was an average difference of 2.2% in flight time, 1.9% in fuel burn, and 2.2% in distance travelled from R1 to R4.

Introduction:-

Free Route Airspace (FRA) lets airspace users to freely plan a route in en-route airspaces within certain restrictions such as avoiding special use airspaces including military airspaces as well as entry and exit waypoint requirements. This study was built upon the findings from (Tominaga et al., 2023) further to investigate the benefits of FRA in the ASEAN-level context. In the previous study, the FRA concept was applied to all the 12 Flight Information Regions (FIRs) in the ASEAN Region independently and then the results were summed together for ASEAN-wide assessment. From the results, it was concluded that the FRA scenario performed better as compared with

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conventional routing in terms of flight efficiency (fuel, distance traveled), and operations (potential conflicts, cluster of conflicts).

In this paper, we assessed the benefits of a Single Cross-Border FRA in the ASEAN Region, where the whole ASEAN airspace is treated as a single-large FRA where all the Member States implement FRA, with Direct To (DCT) routing between the entry (horizontal entry into FIR or end of SID, Standard Instrumental Departure Route) and the exit (horizontal exit from FIR or beginning of STAR, Standard Arrival Route).

Single Cross-Border FRA represents the ultimate long-term idealistic routing rules, which is not necessarily immediately possible from the administrative and technological point of view. Because the Single Cross-Border FRA is the most fuel-efficient reference that we could ever reach in computation, all other hypothetical routing rules fall between the Single Cross-Border FRA and those hypothetical routing rules in terms of fuel efficiency. The goal of this study is to describe the potential in fuel efficiency with reference to this ultimate basic fuel requirement. In other words, for en-route phases of the flights:

1. How much more fuel is needed to fly according to the present routing rules when compared to the ultimate idealistic routing by Single Cross-Border FRA?
2. How much more fuel is needed to fly via hypothetical Several-Small FRAs when compared to the ultimate idealistic routing by a Single Cross-Border FRA?
3. How much more fuel is needed to fly via Single Cross-Border with avoidance of high-altitude danger areas when compared to the ultimate idealistic routing by Single Cross-Border FRA (without avoiding danger areas)?

Free Route Airspace Concept:-

EUROCONTROL (2016) defines FRA as the following. "A specified airspace within which users may freely plan a route between a defined entry point and defined exit point, with the possibility to route via intermediate (published or unpublished) waypoints, without reference to the ATS route network, subject to airspace availability. Within this airspace, flights remain subject to air traffic control".

In 1999, the Eight-States Free Route Airspace Project (FRAP) was documented, and this was the earliest documented project on the FRA concept. (Eriksen 1999) conducted the real-time simulations (RTS) on the FRA concept from small scale (Eriksen 1999, 2000a, 2000b, 2000c) to large scale (Eriksen 2001, Eriksen and Bonnier 2001). The outcomes of these RTS studies produced mixed results. Some studies found that FRA had varying effects on human factors related to controller planning, with both increases and decreases noted when compared to conventional fixed routings.Additionally, environmental impact assessments were carried out as part of the project. These assessments utilized emission models, including the Advanced Emission Model (AEM3) and Boeing Method2 (EEC-BM2), revealing a reduction of approximately 1 to 2 percent in different emissions when implementing FRA in contrast to conventional routing.

In 2009, Portugal implemented FRA for the whole Lisboa FIR above FL 245.The implementation was well accepted in particular by airlines (ONATAP 2011).

Schäfer and Modin (2012) conducted a real-time simulation study assessing the feasibility of implementing FRA and Airborne Separation Assurance Systems (ASAS) within the Mediterranean Airspace. Although ASAS was not a mandatory requirement for FRA implementation butincluded in their study. Their findings suggested that FRA appeared to be a viable option for the Mediterranean Airspace. However, when it came to ASAS, the study couldn't definitively determine its utility, primarily due to the unexpected need for more extensive training than initially anticipated.

Aneeka and Zhong (2016) simulated the FRA concept for the ASEAN region and the results showed reductions in emissions of carbon dioxide and nitrogen oxides, 298 tonnes and 1.3 tonnes respectively, for 5482 flights per day.

Nava-Gaxiola et al. (2018a) evaluated the FRA benefits in North Europe. They evaluated its impact on potential conflicts and airspace complexity using the NEST fast-time simulator. The result showed that the potential conflicts per 1000 aircraft seemed related to the traffic volume and the airspace complexity did not change. Nava-Gaxiola et al. (2018b) applied the FRA to the whole Europe. Their findings indicated that the implementation of FRA did not have a significant impact on overall safety and airspace complexity. However, it did affect the nature of traffic conflicts, leading to an increase in conflicts in the horizontal plane while reducing conflicts in the vertical plane.

Renner et al. (2018) conducted a real-time simulation study of FRA over the Hungary airspace and made the following observations. First, the workload of air traffic controllers did not increase because of FRA. Second, a distinctive cluster of conflict points, commonly referred to as a “hotspot,” emerged near the sector boundary. Interestingly, participating air traffic controllers effectively managed the situation by reducing the frequency changes, a strategy akin to ‘skipping’ shorter sectors during aircraft transfers.

Kageyama and Nakamura (2018) conducted a study using a custom-built fast-time simulator to simulate aircraft trajectories within an Air Traffic Control Center (ACC) sector in Japanese airspace. Their primary objective was to assess the various types of conflicts that FRA traffic typically encounters. Their findings indicated that the predominant workload in FRA operations was associated with conflict resolution, as opposed to the more predictable and routine tasks. Consequently, they concluded that the adoption of a more precise and high-fidelity flight profile would be instrumental in reducing uncertainty when assessing both the magnitude and nature of the workload.

Tominaga et al. (2023) conducted a benefit and operational feasibility study of FRA within the ASEAN region. They simulated approximately 10000 flights per day for 15 days for two routing scenarios (conventional Air Traffic Services airways rules vs. FRA rules). The results showed that the environmental metrics are fewer in FRA than in conventional Air Traffic Services airways by 2% in fuel burn, flight duration, and flown distance. The number of potential conflicts, an operational feasibility metric, was also fewer in FRA.

Simulator experiments:-

Design of experiment

A 3 × 4 factorial design on two factors (traffic volume and lateral routing) are considered in this study. Traffic volume represents the demand for the commercial use of the ASEAN airspaces, having three levels (100%, 150% and 200% of pre-COVID19 traffic). Lateral routing represents the lateral routing rule, having four levels (the conventional ATS Route Network (R1), realistic FRA route (R2), Single Cross-Border FRA with Danger areas (R3), and Single cross-border FRA without Danger areas (R4)). For ease of reference, the scenarios were represented by routing followed by traffic volume (ex: R1_100 scenario represents the current traffic (100%) with ATS Routes). All 12 scenarios are listed in

Table **1**.

Table 1:- Simulation scenarios.

	Lateral Routing			
Traffic Volume	**R1_100** -100% of pre-COVID19 Traffic -R1	**R2_100** -100% of pre-COVID19 Traffic -R2	**R3_100** -100% of pre-COVID19 Traffic -R3	**R4_100** -100% of pre-COVID19 Traffic -R4
	R1_150 -150% of pre-COVID19 Traffic -R1	**R2_150** -150% of pre-COVID19 Traffic -R2	**R3_150** -150% of pre-COVID19 Traffic -R3	**R4_150** -150% of pre-COVID19 Traffic -R4
	R1_200 -200% of pre-COVID19 Traffic -R1	**R2_200** -200% of pre-COVID19 Traffic -R2	**R3_200** -200% of pre-COVID19 Traffic -R3	**R4_200** -200% of pre-COVID19 Traffic -R4

As for simulation, we ran one day of simulation, starting at 00:00 UTC and ending at 23:59 UTC. There is necessary warm-up and cool-down hours added, but these hours are not monitored for metrics.The synopsis of the traffic scenarios is listed in

Table 2.

Table 2:- Synopsis of traffic scenarios.

<table>
<tr><th>Class</th><th>Designation</th><th>High-level representation</th><th>Main description</th><th>Key source data</th><th>Key modification/limitation for simulation</th></tr>
<tr><td rowspan="3">Traffic Volume</td><td>100%</td><td>Pre-COVID19 busiest demand</td><td>Approximately 10000 flights per day (for entire ASEAN)</td><td rowspan="3">Commercial flight schedule</td><td rowspan="3">• Flights that are neither arriving nor departing from ASEAN are not simulated (1-2 percent)
• Limited representation of cargo flights (1-2 percent)</td></tr>
<tr><td>150%</td><td>Possible future demand in late 2020sor early 2030s</td><td>150% of pre-COVID19</td></tr>
<tr><td>200%</td><td>Possible future demand in late 2030s or early 2040s</td><td>200% of pre-COVID19</td></tr>
<tr><td rowspan="4">Lateral Routing</td><td>R1</td><td>Present routing rules (ATS)</td><td>ATS airways + STARs/SIDs</td><td rowspan="4">ASEAN static airspace data (Lido) as per February 2021</td><td rowspan="4">• Omission of FLAS/FLOS levels in each FIR</td></tr>
<tr><td>R2</td><td>Several small FRAs</td><td>DCT segments between the TOC waypoints (avoids D areas, kept each FRA within FIR boundaries) + STARs/SIDs</td></tr>
<tr><td>R3</td><td>Single large FRA with D areas</td><td>DCT segments between the (avoids D areas) STARs/SIDs</td></tr>
<tr><td>R4</td><td>Single large FRA without D areas</td><td>DCT segments between the STARs/SIDs</td></tr>
</table>

Traffic volume

We consider three levels of volume of traffic in this study: 100%, 150%, and 200% of pre-COVID19 traffic.

Traffic Volume: 100% of pre-COVID19 traffic

100% of pre-COVID19 traffic represents the one day of high season traffic of the pre-COVID19 era.

Traffic Volume: 200% of pre-COVID19 traffic

The 200% traffic volume scenario represents a future traffic volume, probably sometime in the late 2030s, after the demand picks up in the possible post-COVID19 era. It is derived from the current traffic volume scenario by duplicating every flight.

Traffic Volume: 150% of pre-COVID19 traffic

The 150% traffic volume scenario represents a future traffic volume, probably sometime in the late 2020s, after the demand picks up in the possible post-COVID19 era. 150% traffic was created by combining 100% and the 50% of duplicated flights from 200%. Reason for creation of 150% is to assesses the benefits in near-term.

Lateral Routing

In this study, we consider four levels of lateral routing: R1, R2, R3 and R4. Summary of lateral routing scenarios are provided in Table **3**and each scenario is depicted in **Figure 1**. For each origin-destination pair, the shortest possible was computed according to the rule for en-route routing (the middle row in Table **3**).

Table 3:- Lateral routing scenarios in the present study.

Lateral Routing Scenario	**R1**	**R2**	**R3**	**R4**
Departure routing	Via SID if available, else DCT to a nearby waypoint, ignored for non-ASEAN airports			
En-route routing	Via ATS airways	Via Transfer of Control (TOC) waypoints (DCT between), avoidance of Danger areas	DCT between the entry (horizontal entry into FIR OR end of SID) and the exit (horizontal exit from FIR or beginning of STAR), avoidance of Danger areas	DCT between the entry (horizontal entry into FIR OR end of SID) and the exit (horizontal exit from FIR or beginning of STAR).
Arrival routing	Via STAR if available, else DCT from a nearby waypoint, ignored for non-ASEAN airports			

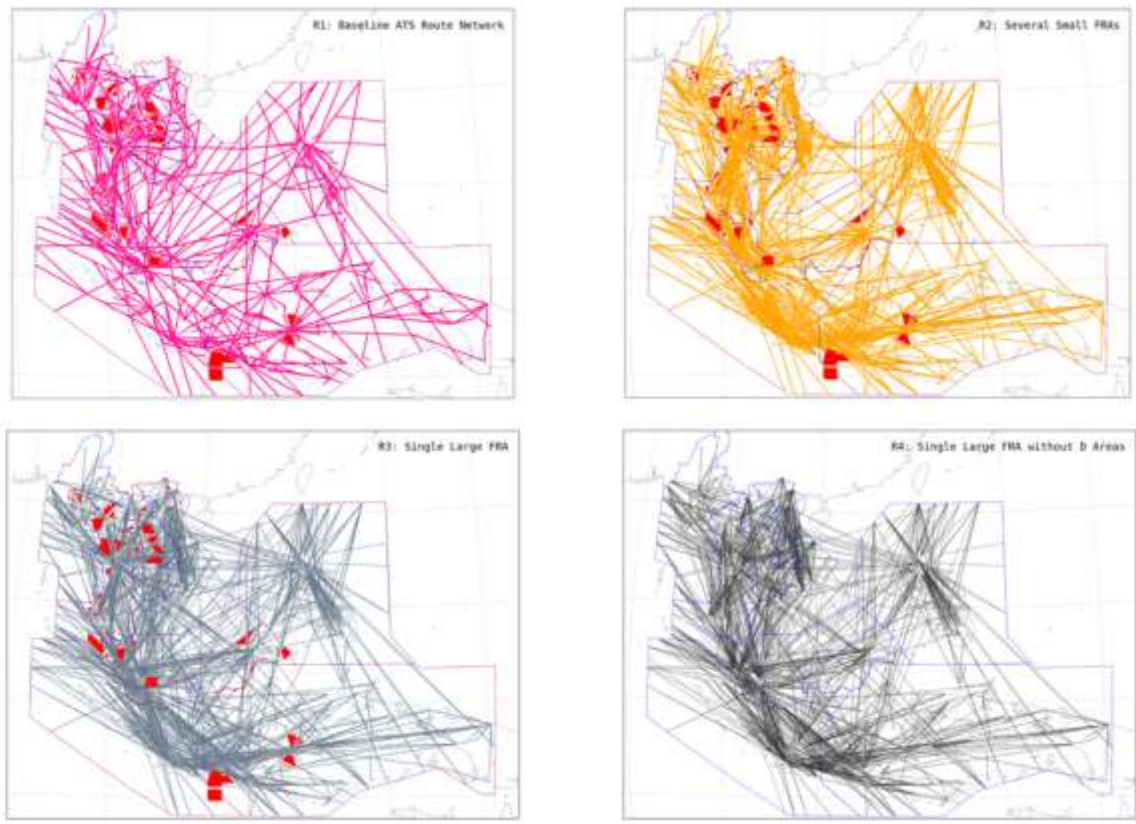


Figure 1:- Lateral routing scenarios R1 (Upper left), R2 (Upper right), R3 (Lower left), and R4 (Lower right).

Lateral Routing: ATS Route Network (R1)

As the name suggests, the routing is via airways in the ATS route Network. We compute the shortest path from the entry waypoint to the exit waypoint via the network (segments) of airways.

Lateral Routing: Realistic FRA route(R2)

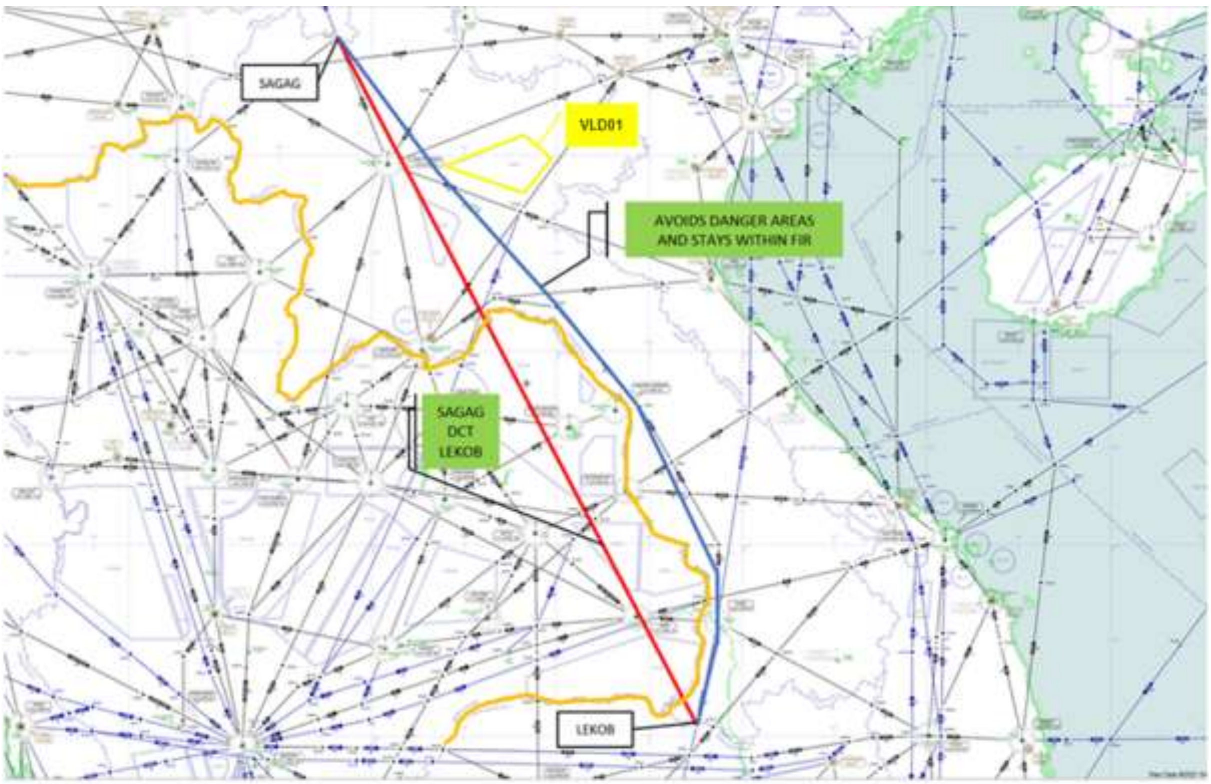
The Realistic Lateral Routing Scenario for FRA presents a potential near-future application of FRA within the ASEAN region. This scenario considers Letters of Agreement (LOAs) between Air Traffic Control Centers (ACCs). Additionally, we also considered the allocation of specific airspaces for military purposes, thereby we excluded them from commercial air traffic usage.

FRA routing is established based on the following procedure: Commencing from the entry waypoint or the commencement of the en-route phase (specifically, after completing the SID), all the connecting Transfer of Control (TOC) points that interface with adjacent FIRs are taken into account. Subsequently, a network of TOC points to TOC points is considered as potential segment options. This process is then repeated as the aircraft transitions into the next FIR. Ultimately, the connection of segments leads to the destination FIR. Within this FIR, routes from the TOC point candidates to the exit waypoint or the conclusion of the en-route phase of the flight (typically, the beginning of the STAR) are evaluated. This procedure effectively generates a mathematical graph encompassing all conceivable routes. This graph can be used to compute the shortest path using the Dijkstra's algorithm. The following matters are additionally considered:

Avoiding restrictive areas. P (prohibited), D (danger), and R (restricted) areas are considered as 'airspace reservation' in FRA in this study and routings must avoid them with a minimum 2.5 NM around it. We compute the shortest path while avoiding these areas using a mathematical algorithm.

Staying within the FIR. The FRA routing within an FIR must remain in the FIR unless some arrangements are made with the adjacent control authorities. In this study, we assume that such arrangements where a shortcutting of routing into adjacent ACC or FIR is not made. The flights are to stay away from the FIR boundary with minimum 2.5 NM around it.

An example of the R2 route is depicted in Figure 2, where the route avoids theD area (VLD01) and stays within the Vientiane FIR.



Legend
Red: Invalid route, Blue: Proposed FRA routing, Yellow: Danger Area, Orange: VTBB FIR

Figure 2:- Routing R2 avoiding Danger Areas and stays within FIR.

Lateral Routing: Single Cross-Border FRA with Danger areas (R3)

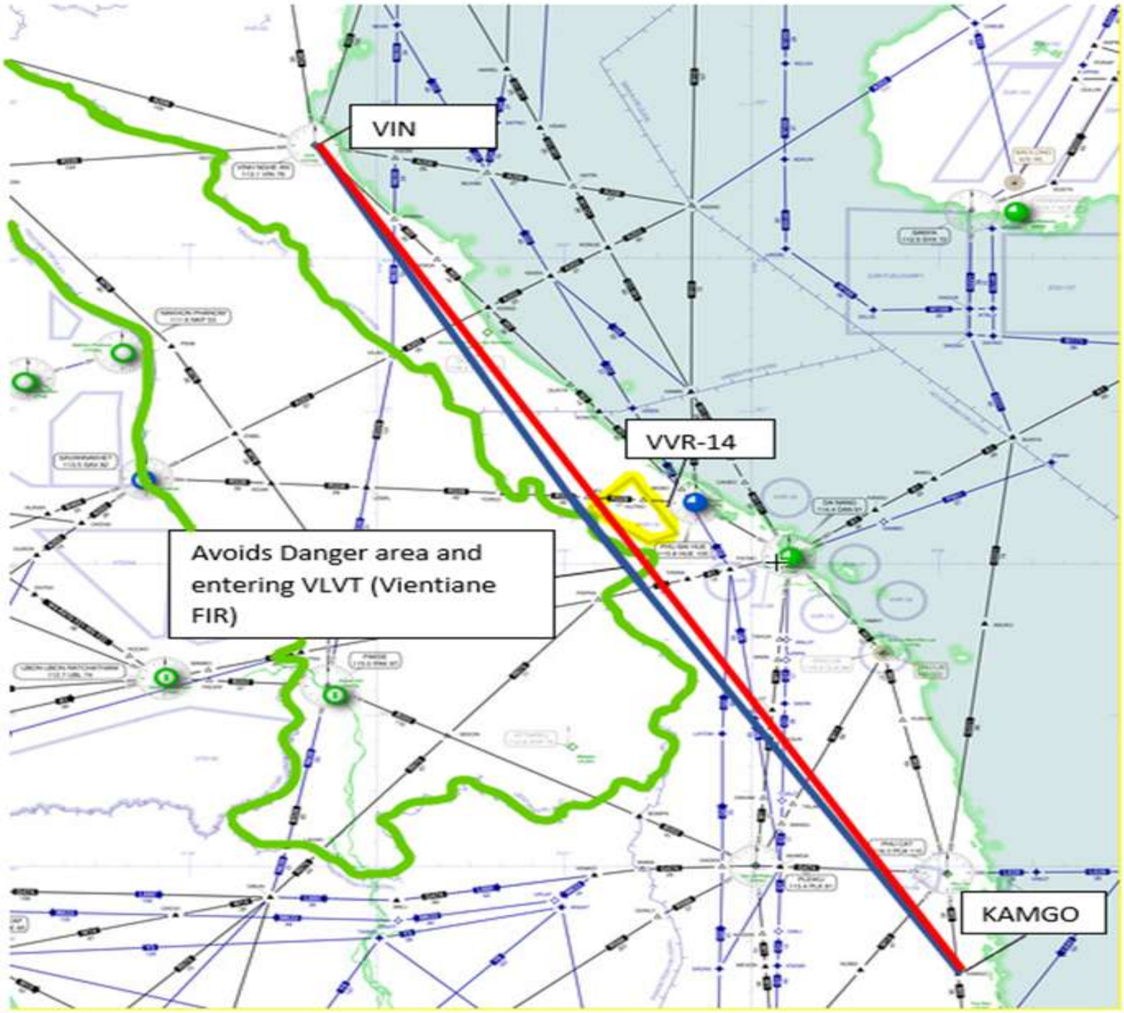
The R3 routing scenario represents a long-term implementation of Single Cross-Border FRA in the ASEAN region, where TOC 'border lines', not 'points', are considered. We also consider military use of certain airspaces to be excluded from usage by commercial traffic.

The routing is determined (or 'drawn') according to the following. From the entry waypoint or the beginning of the en-route phase (i.e., the end of SID), to the exit waypoint or the end of en-route phase of flight are considered (i.e., at the beginning of STAR). The following matters are additionally considered:

Avoiding restrictive areas. P (prohibited), D (danger), and R (restricted) areas are considered as 'airspace reservation' in Single Cross-Border FRA in this study and routings must avoid them.

No restriction on staying within the FIR.In this study, we assume that the arrangements are made with the adjacent control authorities to allow a shortcutting of routing into adjacent ACC or FIR unless it's entering outside ASEAN FIR. If the route is entering outside ASEAN FIR, we flagged those routes and made them pass via ASEAN FIR only.

An example of Routing R3 is shown in **Figure 3**, where R3 enters the Vientiane FIR for a short period of time to avoid the D area (VVR-14).



Legend

Red: Invalid route, Blue: Proposed Single Cross-Border FRA route, Yellow: Danger Area, Green: VLVT FIR

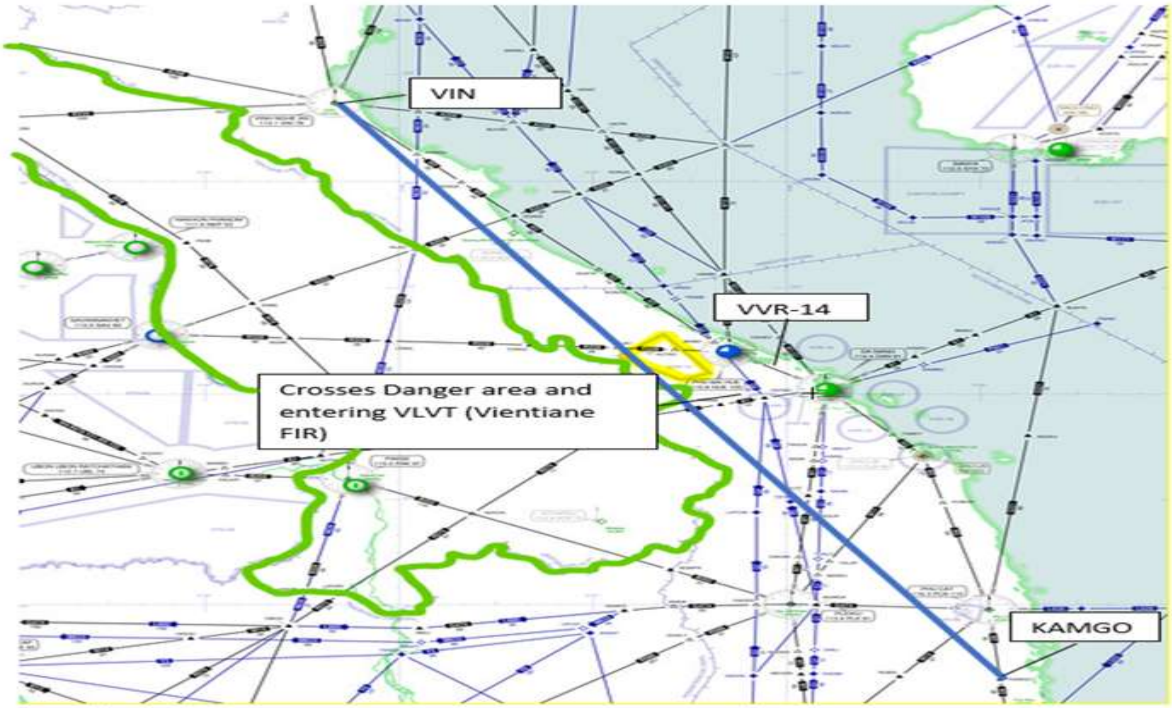
Figure 3:- R3 Routing avoids Danger Areas and entering other FIR.

Lateral Routing: Single cross-border FRA without Danger areas (R4)

The R4 routing scenario represents the ultimate long-term idealistic Single Cross-Border FRA in the ASEAN region.

The routing is determined (or 'drawn') according to the following. From the entry waypoint or the beginning of the en-route phase (i.e., the end of SID), to the exit waypoint or the end of en-route phase of flight are considered (i.e., at the beginning of STAR). This routing is idealistic fuel-efficient routing, where all the en-route routing rules such as FLAS/FLOS levels, time spacing, entry/exit locations and Danger areas across FIRs are ignored.

An example ofR4 is shown in Figure 4, where R4 crosses the D areas and enters Vientiane FIR.



Legend
Blue: Idealistic Single Cross-Border FRA route, Yellow: Danger Area, Green: VLVT FIR

Figure 4:- R4 Routing crosses Danger Areas and entering other FIR.

Monitored Metrics

The following metrics are extracted from simulation runs and used for comparison between the scenarios.

Potential conflict: Potential conflicts are identified when any two aircraft lose both lateral and vertical separation requirements (< 5 NM and < 1000 feet, respectively, in this study).

Fuel burn**:**Amount of fuel burned during the flight journey. Fuel burn was calculated based on the Base of Aircraft Data (BADA) 3 aircraft performance models.

Track miles**:** Flown distance in NM.

Flown Duration**:** Duration of the flight in hours.

Results:-

Discussion on Cross-FIR Perspective vs FIR-Specific Perspective

We consider (i) cross-FIR metrics for understanding the overall benefits and feasibility by switching from ATS (R1) to FRA (R2, R3, R4) in the regional scale and (ii) FIR-specific metrics for understanding how uniformly (or disproportionately) the benefits and feasibility metrics are distributed among the FIRs. The FIR-specific metrics are computed in post-processing of the simulated traffic, zooming in to each respective FIRs.

Unlike the FIR-specific metrics, these cross-FIR metrics may highlight more efficient cross-border routings brought about by an ASEAN FRA. Airspace users may choose to alter:

- The number of times that a flight transit through a FIR;
- The sequence of FIRs that a flight transit through; and
- The routing of a flight within an FIR, which might be shorter/longer and might enter/exit via a different TOC waypoint.

It is therefore possible that some FIRs may become more 'popular' with more flights transiting and/or with longer routing, whereas other FIRs may become less 'popular'. This can cause disproportionate partitioning of the ATS burden among the ASEAN ANSPs (

Table 4). An example case for the 'popular' FIR is depicted in Figure 5, where R2 route transit through Manila FIR, but not Kota Kinabalu and Singapore FIRs.

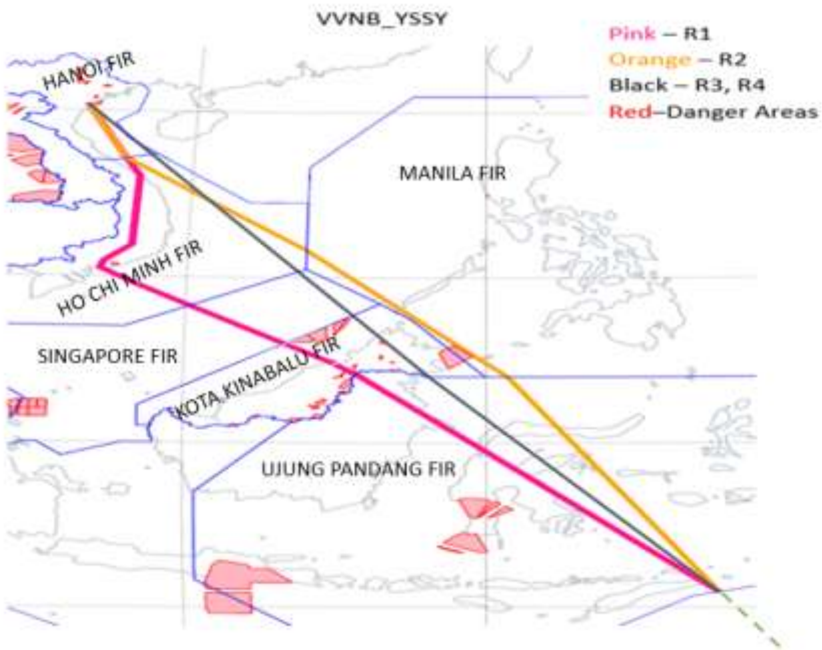


Figure 5:- Example difference in routing. In this case, R2 routing transits through Manila FIR, but not Kota Kinabalu and Singapore FIRs.

Table 4:- Benefits and Cost of R2, R3, and R4 vs R1 seen from various perspectives.

Perspective	Benefits	Cost
'More popular' FIRs (in R2, R3, R4 than in R1), where the ANSPs serve more flights for a longer time flown.	In some traffic patterns the ANSP might still enjoy fewer potential conflicts despite more flights, more flight distance, more flight time.	Concerns on having more potential conflicts, more flights to provide ATS, longer flight distance and time to provide ATS. In R3, R4 the number of handovers between the 'popular' FIRs and its adjacent FIRs will increase.

'Less popular' FIRs (in R2, R3, R4 than in R1)	Fewer potential conflicts, fewer flights to provide ATS, shorter flight distance and time to provide ATS.	Changes in hotspots.
Airspace user	Shorter flight time, less fuel burn	Nil
Environment metric	Less fuel burn	Nil

Cross-FIR Metrics
In this section, we present the cross-FIR, flight-specific metrics for operational feasibility (
Table **5**, Table 6, and

Table **7**). These are useful when one evaluates the overall, macroscopic benefits of the Single Cross-Border FRA concept.In each scenario, compared with R1, the remaining three routings (R2, R3, R4) yielded better values in all en-route cross-FIR metrics relating to Environment metrics and Potential Conflicts. These include (in 100% of pre-COVID19 scenario) 1.6%, 2.1%, and 2.2% shorter flight time, 1.3%, 1.8% and 1.9% less fuel burn, and 1.6%, 2.1% and 2.2% shorter distance. In both 150% and 200% of pre-COVID19 scenarios results are similar to 100% pre-COVID19 scenario.

Table 5:- 100% of pre-COVID19 scenario cross-FIR metrics for 1-day of simulation.

	100% of pre-COVID19				**Difference (%)**		
	R1	**R2**	**R3**	**R4**	**R1vs R2**	**R1vs R3**	**R1vs R4**
Potential Conflicts (total)	3349	2854	2586	2468	-14.8	-22.8	-26.3
Potential Conflicts (+FL285)	2093	1595	1328	1207	-23.8	-36.6	-42.3
Potential Conflicts (FL130-FL285)	1256	1259	1258	1261	0.2	0.2	0.4
Flight Time (hour)	11278	11093	11042	11028	-1.6	-2.1	-2.2
Fuel (tonne)	36927	36431	36262	36220	-1.3	-1.8	-1.9
Flight Distance (1000 NM)	4930	4851	4828	4821	-1.6	-2.1	-2.2
Number of Flights	10509	10509	10509	10509	0	0	0

Table 6:- 150% of pre-COVID19 scenario cross-FIR metrics for 1-day of simulation.

	150% of pre-COVID19				**Difference (%)**		
	R1	**R2**	**R3**	**R4**	**R1 vs R2**	**R1 vs R3**	**R1 vs R4**
Potential Conflicts (total)	7135	6058	5365	5109	-15.1	-24.8	-28.4
Potential Conflicts (+FL285)	4498	3487	2828	2571	-22.5	-37.1	-42.8
Potential Conflicts (FL130-FL285)	2637	2571	2537	2538	-2.5	-3.8	-3.8
Flight Time (hour)	16633	16369	16293	16271	-1.6	-2.0	-2.2
Fuel (tonne)	54359	53643	53388	53326	-1.3	-1.8	-1.9
Flight Distance (1000 NM)	7266	7152	7117	7107	-1.6	-2.0	-2.2
Number of Flights	15473	15473	15473	15473	0	0	0

Table 7:- 200% of pre-COVID19 scenario cross-FIR metrics for 1-day of simulation.

	200% of pre-COVID19				**Difference (%)**		
	R1	**R2**	**R3**	**R4**	**R1 vs R2**	**R1 vs R3**	**R1 vs R4**
Potential Conflicts (total)	12353	10363	9310	8867	-16.1	-24.6	-28.2
Potential Conflicts (+FL285)	7869	6015	4936	4470	-23.6	-37.3	-43.2
Potential Conflicts	4484	4348	4374	4397	-3.0	-2.5	-1.9

(FL130-FL285)							
Flight Time (hour)	22078	21735	21636	21608	-1.6	-2.0	-2.1
Fuel (tonne)	72447	71493	71160	71079	-1.3	-1.8	-1.9
Flight Distance (1000 NM)	9653	9504	9459	9447	-1.5	-2.0	-2.1
Number of Flights	20445	20445	20445	20445	0	0	0

Conclusions:-

From the flight efficiency metrics in all simulation scenarios, there was an average difference of 2.2% in flight time, 1.9% in fuel burn and 2.2% in distance travelled from R1 (ATS) to R4 (Idealistic Single Cross-Border FRA). By implementing R2 (hypothetical Several-Small FRAs), R2 can achieve savings of 73% in flight time, 72% in distance travelled and 70% in fuel burn of what R4 can achieve. By implementing R3 (Single Cross-Border FRA with avoidance of D areas), R3 can achieve savings of 94% in flight time, distance travelled and fuel burn of what R4 can achieve.

In each scenario, compared with R1, the remaining three routings (R2, R3, R4) yielded better values in all en-route cross-FIR metrics relating to Environment metric and Potential Conflicts. Although there were improvements with R2, R3, and R4 (i.e., simply by allowing lateral routing changes), the routings R3 and R4 may pose operational feasibility challenges compared with the R1 and R2. In R3 and R4 routing, Aircraft can cross the ASEAN FIRs at any point along the FIR boundary lines even for a short period of time, which increases the workload of ATC in terms of handovers and communications with adjacent FIRs.

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