On-demand Conflict Resolution Procedures for Air Traffic Intersections

Jeff D. Yoo and Santosh Devasia

Abstract—This article presents a Conflict Resolution Procedure (CRP) for intersecting routes in en-route Air Traffic Control (ATC). Recent works have developed provably-safe CRP, which solve the conflict resolution in a decoupled manner for en-route intersections. However, the original CRP for intersecting routes is inefficient because it always on— even in the absence of conflicts. In contrast, the current article develops provably-safe CRPs that can be activated on-demand to accommodate an impending conflict. Conditions are developed to guarantee safety during activation and deactivation, and the CRP is illustrated through an example route intersection.

I. INTRODUCTION

This article presents a Conflict Resolution Procedure (CRP) for intersecting routes in en-route Air Traffic Control (ATC). Recent works [1], [2] have developed provably-safe CRP, which solve the conflict resolution in a decoupled manner for en-route intersections. An advantage of the decoupling CRP is that it does not require a reduction of the flow capacity in each route; therefore, it can aid in increasing the efficiency of en-route ATC, e.g., in the design of capacity-maintaining protocols for adverse weather rerouting [1]. While the always-on CRP is acceptable for the case of dense aircraft flow in each of the intersecting routes, it is inefficient if the conflicts are rare, e.g., because one of the routes has intermittent traffic. In such rare-conflicts case, the always-on CRP leads to: (i) unwanted maneuvers; (ii) additional ATC effort, (iii) increased travel distance (fuel cost); and (iv) increased time (delay). In contrast, the current article develops provably-safe CRPs that can be activated on-demand to accommodate an impending conflict — the CRP is then deactivated when not needed. Conditions are developed to guarantee safety during activation and deactivation, and the CRP is illustrated through an example route intersection in the Cleveland sector.

For guaranteeing safety, CRPs should always lead to a solution of the conflict resolution problem. Previous works on CRPs range from non-local probabilistic approaches that handle uncertainties [3] to local deterministic approaches that resolve conflicts in a collaborative manner [4]. Other studies [5] involve minimizing path deviations when combining decentralized aircraft preferences with centralized air traffic control authority where each aircraft performing their desired heading. These include studies on the merging of multiple flows with minimal amount of turning were shown [6]. Effects of uncertainties (e.g., in weather [7]), perturbations (e.g., in speed due wind conditions), errors from aircraft weight and surveillance, navigational errors [8] were studied as well. From the context of provably-safe CRP, conditions for separation assurance related to different traffic density were also studied in Refs. [9], [10]. Moreover, conditions for CRP stability were studied, for intersecting routes, in [11]. Moreover, a challenge is to ensure that modifications of flight trajectories, for resolving a local conflict, do not lead to a domino effect: i.e., resolution of a conflict should not lead to new conflicts, whose resolution again leads to additional conflicts, and so on [12].

The current work aims to increase the efficiency of the CRP design in [1], [2], which satisfied conditions for guaranteed safety, and led to decoupled CRPs for multiple en-route intersections without the domino effect. Briefly, the main ideas of a decoupling CRP are: (i) route-splitting into multiple paths; (ii) equal-length maneuvers; and (iii) path merging into original routes. Splitting each route in an intersection into multiple paths increases the spacing between aircraft in each of the split paths — the increased spacing allows conflict-free intersections between paths. After the intersection, the paths are merged back into the original routes, which implies that new conflicts will not be generated outside of the CRP region. Therefore, domino effects can be avoided if the route intersections (and as a consequence, the CRP regions) are sufficiently sparse in the airspace. Finally, since the split paths are of equal length, the CRP maintains the original minimal arrival spacing and sequence of aircraft in each route. Therefore, the state of aircraft arrival (minimal spacing and sequence) at the next intersection along the route is not adversely impacted by the current CRP — this enabled decoupled CRP design. However, as mentioned earlier, these CRPs are always on — to improve efficiency, the current work aims to only activate the CRPs [1], [2] when needed. In particular, it is shown that with sufficient preview of an impending conflict, the decoupling CRP can always be activated on-demand in a safe manner. Additionally, conditions are developed to guarantee safe deactivation of the CRP to allow aircraft to follow the nominal route when conflicts are not present.

II. THE DECOUPLING CRP

The decoupling CRP [1] is briefly reviewed in this section to clarify the on-demand activation and deactivation problem.

A. The Conflict Resolution Problem (CRP)

The CRP is studied for intersecting aircraft routes, which can occur, e.g., in highway-like route structures [13], [14]. These routes, if sufficiently dense in the airspace and variable...
over time [15], could provide the flexibility needed for accommodating varying weather patterns, missed connections, and traffic congestion by choosing different flight segments in a Free-flight-like setting while maintaining a structure for the aircraft routes. As in previous works, the routes are assumed to be at a fixed altitude with a perpendicular intersection, as illustrated in Fig 1. Moreover, the intersections are assumed to be spatially sparse leading to a sufficiently-large local region $L$, around each intersection (conflict point $CP$), where the local region $L$ is conflict free from all other routes and other CPs in the airspace. The CRP can use this local region $L$ to resolve conflicts at the intersection without potentially causing additional conflicts as long as the route modifications due to CRP procedures are contained within the local region $L$. Aircraft along the nominal routes ($R_1$ and $R_2$) arrive into this local region $L$ at arrival points $A_1, A_2$ with a fixed nominal speed $v_{sp}$ and exit at $E_1, E_2$ as shown in Fig. 1. It is assumed that aircraft, arriving at the local region $L$ are separated by at least distance $D$ at the arrival points $A_1, A_2$, where the minimal arrival spacing $D$ is greater than the minimum required separation distance $D_{sep}$, to avoid conflicts.

![Fig. 1. Local region L of the airspace around two perpendicularly intersecting routes, $R_1, R_2$, the corresponding arrival points $A_1, A_2$ into region $L$, and exit points $E_1, E_2$ from region $L$.](image)

**Remark 1:** In general, conflict resolution can be achieved using maneuvers that change the heading, speed and altitude. However, heading changes are preferred over speed changes, which require additional fuel for accelerating and decelerating the aircraft. Similarly, heading changes are preferred over altitude changes, which tend to incur passenger discomfort and can cause conflicts in the other altitudes.

### B. Conditions for Decoupled CRP

Previous work has shown that the following conditions enable decoupled CRP designs for multiple enroute conflicts [1].

**Definition 1:** [CRP Decoupling Conditions] The problem is to find a CRP using heading change maneuvers (with bounds on the rate of heading change) such that conflicts are avoided between aircraft and the following CRP-decoupling conditions are satisfied:

1) **local intent:** aircraft on each route ($R_1, R_2$) exit along the same route at the corresponding exit point $E_1, E_2$;
2) **local liveness:** aircraft on each route exit the local region $L$ within a specified bounded maximum time $T < \infty$;
3) **local fairness:** the passage through the local region $L$ is first-come-first-served (FCFS) within each route; and
4) **local exit spacing:** aircraft exiting the local region $L$ (at each point $E_1, E_2$) are separated by at-least distance $D$.

### C. Path-Split CRP

An example CRP (with a two-path split) is shown in Fig. 2 — it consists of splitting of each route ($R_1, R_2$) into two equal-length paths (diverge) and choosing one of the paths for each arriving aircraft. The aircraft in each path is merged back into the original routes after the intersection.

![Fig. 2. The CRP splits aircraft in each route (using diverging procedures) into multiple paths — with increased spacing between aircraft in each path. Aircraft in these paths (with sufficiently large spacing between aircraft) can then pass through the intersection without conflicts as shown in Ref. [1]. After the intersections, aircraft in the different paths are merged back to the original routes.](image)

The two paths $\{R_{1,1}, R_{1,2}\}$ for route $R_1$ (shown in Fig. 2) are described by a set of way points (v): 

$$
R_{1,1} = \{v_1, v_2, v_3, v_4, v_5, v_6\} \\
R_{1,2} = \{v_1, v_7, v_8, v_9, v_{10}, v_6\}
$$

and the two paths $\{R_{2,1}, R_{2,2}\}$ for route $R_2$ are

$$
R_{2,1} = \{v_{11}, v_{12}, v_4, v_9, v_{14}, v_{16}\} \\
R_{2,2} = \{v_{11}, v_{13}, v_3, v_8, v_{15}, v_{16}\}.
$$

**Definition 2:** [Cyclic, Path-Assignment Procedure] Let the scheduled time of arrival (STA) of aircraft at the initial way-points ($v_1$ for route $R_1$ and $v_{11}$ for route $R_2$ in Fig. 2) be at discrete time instants 

$$
t_k = k \left(\frac{D}{v_{sp}}\right) = kT_D
$$

where the index $k$ is a nonnegative integer. Then, assign paths $R_{1,1}$ and $R_{2,1}$ (for routes $R_1$ and $R_2$, respectively) for arrivals at time $t_{k+1}$ if the current paths, for arrivals at time $t_k$, are $R_{1,2}$ and $R_{2,2}$ (for routes $R_1$ and $R_2$, respectively). Similarly, assign paths $R_{1,2}$ and $R_{2,2}$ (for routes $R_1$ and $R_2$, respectively) for arrivals at time $t_{k+1}$ if the current paths, for arrivals at time $t_k$, are $R_{1,1}$ and $R_{2,1}$ (for routes $R_1$ and $R_2$, respectively). The path allocation rule is cyclic and repeats after every two discrete time instants.

**Remark 2:** Synchronization procedures needed to achieve a desired STA has been well studied in the literature, e.g., to schedule arrivals at airports [16], [17]. Such approaches can be adapted to manage asynchronous arrivals and achieve STAs for the CRP, as shown in Ref. [1].

6338
D. CRPs are Decoupled and Conflict Free

The path-split CRP satisfies decoupling conditions as shown in [1], [2]. Due to equal length paths, the CRP does not change the sequence of aircraft in each route and maintains a minimal separation of $D$ (i.e., the route-flow capacity for which the CRP is designed) at the exit. Therefore, if aircraft in one of the routes ($R_1$ or $R_2$) reaches another conflict point then the CRP at the second intersection point can be designed independent of the previous CRP, provided the intersections are sufficiently separated from each other, i.e., the associated local regions needed for conflict resolution are disjoint. These CRPs can be designed to be provably safe [1], [2], provided the arrival spacing $D$ is sufficiently large, as stated formally, below.

Lemma 1: The two-path split CRP can be designed to be conflict free if the minimal arrival spacing $D$ satisfies

$$D > d_{\pi/2} = 2\sqrt{2}D_{\text{sep}}. \quad (4)$$

Proof: The proof for Lemma 1, such as conflict-free design of the CRP with bounds on turn turn rates, was provided in [2]. The main concept is to generate sufficient spacing in the split paths to ensure conflict free intersection.

Remark 3: The number of path splits $n$ needed in the CRP is determined by the spacing requirement $d_{\pi/2}$ at the intersection from Lemma 1 and the arrival spacing in the route $\overline{D}$, i.e.

$$nD > d_{\pi/2} = 2\sqrt{2}D_{\text{sep}}. \quad (5)$$

III. CRP ACTIVATION/DEACTIVATION APPROACH

Given a safe CRP, the deactivation problem is to collapse the CRP into the routes without the CRP (e.g., as in Fig. 1) in the absence of conflicts between aircraft in the two routes. The reverse problem is to guarantee safe, on-demand, activation of the CRP whenever a conflict arises for aircraft on the two routes. Because the CRP maintains safety (even if the aircraft in the original routes did not have a conflict), deactivation is not critical and can be done when safe deactivation conditions are met. However, there is no such flexibility for activation of the CRP in the presence of an impending conflict (in the original routes) — there should be some guarantee that the CRP can always be activated, on-demand, in a safe manner. Otherwise, the CRP needs to be always on to guarantee safety.

A. CRP Activation Conditions

The activation conditions are developed below — in particular, it is shown that the CRP can always be activated on-demand in a safe manner.

Lemma 2: Let a given CRP (in Fig. 2) be conflict free if it is always on. Furthermore, let there be no aircraft in the conflict region $L$ and arriving along one of the routes (either $R_1$ or $R_2$) at or before a discrete time instant $t_k$ as shown in Fig. 3(a). Then, there are no conflicts if aircraft arriving before time instant $t_k$ follow the original route (without the CRP), and the aircraft arriving at and after time instant $t_k$ follow the CRP paths, as specified below.

1) If route $R_1$ is empty (in the region $L$) before time instant $t_k$, then the CRP is initiated by assigning paths $R_{1,1}$ and $R_{2,1}$ for arrivals at time $t_k$ (as in Fig. 3b).
2) Otherwise, if route $R_2$ is empty (in the region $L$) before time instant $t_k$, the CRP is initiated by assigning paths $R_{1,2}$ and $R_{2,2}$ for arrivals at time $t_k$.

Fig. 3. Example CRP activation. (a) Aircraft $a_{k}$ on route $R_1$ at time $t_k$ (at the initial waypoint $v_1$ of CRP) has conflict with aircraft $b_{k}$ (at the initial waypoint $v_{11}$) on route $R_2$. (b) Split path CRP is applied from time $t_k$ onwards, e.g., for aircraft $a_{k}$, $a_{k+1}$, $b_{k}$, and $b_{k+1}$. Aircraft arriving earlier travel on the nominal route (e.g., $b_{k-1}$ on $R_2$), the conflict regions $L$.

Proof: The proof is provided for the case when route $R_1$ has no aircraft in the region $L$ before time instant $t_k$ (as in Fig. 3b). The other case when route $R_1$ has no aircraft, in the region $L$ before time instant $t_k$, follows by a similar argument. Note that there are no conflicts between aircraft arriving (on either route) at or after time $t_k$ because the CRP is conflict free. The issue is to prove that there are no conflicts between aircraft arriving before time $t_k$ (e.g., $b_{k-1}$) and aircraft arriving at or after time $t_k$ on: (case 1) the other route $R_2$, e.g., aircraft $a_k$; and (case 2) the same route $R_1$, e.g., aircraft $b_k$. The proof is divided into these two cases.

Case 1: no conflict between aircraft $b_{k-1}$ and $a_k$. Consider the case when the aircraft $b_{k-1}$ arriving at $t_{k-1}$ is at the intersection of the route $R_2$ and the path $R_{1,1}$ as shown in Fig. 3b. Then, the distance $d_{b_{k-1},a_k}$ between aircraft $b_{k-1}$ and the first new aircraft $a_k$ in route $R_1$ is (from Eq. 4)

$$d_{b_{k-1},a_k} \geq 1.5\overline{D} > 1.5D_{\text{sep}} > \sqrt{2}D_{\text{sep}} = 0.5d_{\pi/2} \quad (6)$$

because (i) the closest horizontal spacing between aircraft $b_{k-1}$ and $b_k$ is the distance $\overline{D}$ between waypoints $v_{12}$ and $v_{11}$ in Fig. 3, (ii) by symmetry, the closest distance between aircraft $a_k$ and waypoint $v_3$ is also $\overline{D}$, and (iii) the distance between the paths $R_{2,2}$ and $R_{2,1}$, placed equidistant from the original route $R_2$, is $\overline{D}$. The lack of conflict between aircraft $b_{k-1}$ and the first new aircraft $a_k$ follows from arguments similar to the proof of Lemma 1 since the aircraft will move along perpendicular paths and are separated by more than $0.5d_{\pi/2}$. There can be no conflicts between aircraft $a_k$ and those arriving in route $R_2$ earlier than $t_{k-1}$ since those aircraft will be further away from aircraft $a_k$ than aircraft $b_{k-1}$, when aircraft $a_k$ arrives at waypoint $v_2$.

Case 2: no conflict between aircraft $b_{k-1}$ and $b_k$. The horizontal spacing is $\overline{D}$ between aircraft $b_{k-1}$ and $b_k$ at time $t_{k-1}$ when aircraft $b_{k-1}$ is at the initial waypoint $v_{11}$ of route $R_2$. This horizontal spacing cannot decrease (as shown below) and therefore there can be no conflict between the forward aircraft $b_{k-1}$ and the aft aircraft $b_k$, and consequently, there
can be no conflict between aircraft $b_{k-1}$ and $b_j$ provided aircraft $b_j$ follows the CRP. To demonstrate this increase of horizontal distance, it is noted that the forward aircraft $b_{k-1}$ follows a straight route $R_2$ while the relative heading angle $\theta$ as in Fig. 4 (and therefore the velocity) of the aft aircraft $b_k$ cannot deviate more than ninety degrees ($\theta \leq \pi/2$) from the direction of the straight route $R_2$. Then, the relative horizontal velocity $V_{h,b_{k-1},b_k}$ of the forward aircraft $b_{k-1}$ with respect to the aft aircraft $b_k$ is given by

$$V_{h,b_{k-1},b_k} = v_{sp} - v_{sp} \cos(\theta) = v_{sp} [1 - \cos(\theta)] \geq 0,$$

which implies that the horizontal distance cannot decrease below $D$. Therefore, the total distance between the aircraft remains larger than the (safe) arrival spacing $D > D_{sep}$. Finally, there can be no conflicts between aircraft $b_{k-1}$ and those arriving in route $R_2$ later than $t_k$ since those aircraft will be further away from aircraft $b_{k-1}$ than aircraft $b_k$.

**Remark 4:** The CRP initiation in Lemma 2, e.g., assigning paths $R_{1,1}$ and $R_{2,1}$ for arrivals at time $t_k$ if route $R_1$ is empty (in the region $L$) before time instant $t_k$ (as in Fig. 3b), is important to guarantee safety. For example, a conflict can occur between aircraft $b_{k-1}$ and $a_k$ if paths $R_{1,2}$ and $R_{2,2}$ were assigned instead.

### B. CRP Deactivation Conditions

The deactivation conditions are developed below — in particular, the space needed between arriving aircraft to safely deactivate the CRP is quantified.

**Lemma 3:** Let a given CRP (in Fig. 2) be conflict free if it is always on. Furthermore, let there be no aircraft arriving along one of the routes (either $R_1$ or $R_2$) at or after a discrete time instant $t_k$ as shown in Fig. 5. Then, there are no conflicts if: (i) aircraft arriving at or before time instant $t_k$ follow the CRP paths; (ii) aircraft arriving after time instant $t_k$ follow the original route (without the CRP); (iii) aircraft arriving after time instant $t_k$ from each route $R_1$ and $R_2$ do not arrive at the initial waypoint ($v_{11}$ for $R_2$ and $v_1$ for $R_1$) at the same time instance; (iv) $D > 4R(\phi - \sin(\phi))$; and (v) the arrival spacing $d_{k,2}(t_k)$ at time $t_k$ between aircraft arriving at the initial waypoint (e.g., $v_{11}$) at the time instant $t_k$ and the next arrival at time $t_{k+2}$ is large enough, i.e.,

$$d_{k,2}(t_k) \geq D + \delta,$$

where $\delta$ is the difference between the CRP-path length and the route length from the initial waypoint to the final waypoint in the CRP, e.g., from waypoint $v_{11}$ to $v_{16}$.

**Proof:** The proof is omitted for brevity. The main concept is that when there are no incoming aircraft on the intersecting route for $2k$ time instants ($t_{k+1}$ and $t_{k+2}$) after while an aircraft arrives at the initial way point at time instance $t_k$, this aircraft can travel on the deactivated nominal route (no CRP) without causing conflict since this time interval provides enough spacing.

### IV. RESULTS AND DISCUSSION

An example is presented below to illustrate the proposed CRP activation and deactivation. Example Nominal values for the example (such as aircraft arrival rates, speed, and spacing) are based on aircraft data from a perpendicularly intersecting route in the Cleveland sector ZOB59 (see Fig. 6). The data was obtained using the Future ATM Concepts Evaluation Tool (FACET) for May 1st, 2004 at 35000ft altitude during the time interval [305, 65735] Coordinated Universal Time (UTC) seconds which corresponds to about 18 hours of data. During this period, 35 aircraft passed through the east-to-west route, and 19 aircraft passed through the north-to-south route. The average of all aircraft speeds in the date were used as the nominal aircraft speed $v_{sp} = 0.122$ Nautical Miles (NM) per second in the example. Moreover, the minimal arrival spacing, $D_{min} = 9.23$ NM was considered to be the arrival spacing after synchronization $D = D_{min}$. With this arrival spacing $D$, a 2-way split CRP provides sufficient spacing between aircraft in the split paths for conflict free intersections of the paths, i.e., $n = 2$ in Eq. (5), Remark 3. Details of the CRP design are provided in previous work [2].

![Fig. 5. Example CRP deactivation when aircraft are not present on route $R_1$ and after time $t_k$. (a) Split path CRP is used before time $t_k$. (b) Aircraft arriving at and after time $t_k$ travel on the nominal route (e.g., $b_{k+2}$ on $R_2$).](image)

![Fig. 6. Example perpendicularly intersecting routes in Cleveland Sector.](image)
initial entrance data was within 2.16 NM of the averaged value. The routes for the example were considered as straight lines between these averaged arrival and departure points, which were then used to identify the route intersection point as well as the initial waypoints for each route, i.e., \( v_1 \) for route \( R_1 \) and \( v_{11} \) for route \( R_2 \) in Figure 2. The estimated time of arrival (ETA) \( t_{\text{ETA}} \) of the aircraft at the initial waypoints were synchronized to a scheduled time of arrival (STA) \( \text{STA} = kT_\text{D} \) if \( \text{ETA} \in \left[ \frac{2k - 1}{2} T_\text{D}, \frac{2k + 1}{2} T_\text{D} \right] \) (9)

which assigns a discrete time \( t_k = kT_\text{D} \) to the arrival of each aircraft at the initial waypoint. These original and modified arrival times (ETAs, STAs, and \( k \)) for all aircraft in the data are presented in Tables I and II.

### TABLE I
**North-to-south route \( R_1 \)**

<table>
<thead>
<tr>
<th>#</th>
<th>Aircraft I.D.</th>
<th>ET A (sec)</th>
<th>( k )</th>
<th>ST A (sec)</th>
<th>CRP Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31</td>
<td>3010</td>
<td>40</td>
<td>3028</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>117</td>
<td>37780</td>
<td>499</td>
<td>37774</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>130</td>
<td>39010</td>
<td>515</td>
<td>38985</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>136</td>
<td>39580</td>
<td>523</td>
<td>39590</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>145</td>
<td>40810</td>
<td>539</td>
<td>40802</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>196</td>
<td>44440</td>
<td>587</td>
<td>44435</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>203</td>
<td>45370</td>
<td>599</td>
<td>45344</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>221</td>
<td>46180</td>
<td>610</td>
<td>46176</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>222</td>
<td>46240</td>
<td>611</td>
<td>46252</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>227</td>
<td>46480</td>
<td>614</td>
<td>46479</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>296</td>
<td>51700</td>
<td>683</td>
<td>51702</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>298</td>
<td>51880</td>
<td>685</td>
<td>51854 ( R_{1,2} )</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>301</td>
<td>52180</td>
<td>689</td>
<td>52156</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>314</td>
<td>53080</td>
<td>701</td>
<td>53065</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>316</td>
<td>53380</td>
<td>705</td>
<td>53368 ( R_{1,1} )</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>328</td>
<td>55180</td>
<td>729</td>
<td>55184</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>351</td>
<td>57040</td>
<td>754</td>
<td>57077</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>431</td>
<td>64180</td>
<td>848</td>
<td>64193</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>428</td>
<td>64240</td>
<td>849</td>
<td>64268</td>
<td></td>
</tr>
</tbody>
</table>

**CRP activation** For the arrival spacing of this example, a conflict occurs (without the use of CRP) if both aircraft have the same STA. If the arrivals on two routes are separated by one time arrival interval \( T_\text{D} \), then there are no conflicts since the conditions of the conflict-free intersection (in Lemma 1) would be met with an arrival spacing of \( \Delta = 9.23 \text{ NM} \), which is greater than the distance needed for a perpendicular intersection of 0.5\( d_r/2 \). There were two cases of conflicts — between aircraft 298 from \( R_1 \) and aircraft 287 from \( R_2 \) at \( k = 685 \) (from Table II and Table I), and between aircraft 316 from \( R_1 \) and 303 from \( R_2 \) at \( k = 705 \).

For the first conflict case in the data at \( k = 685 \), the CRP is activated where aircraft 298 is assigned to path \( R_{1,2} \), and aircraft 287 is assigned to path \( R_{2,2} \) in the CRP since previous aircraft 296 (arriving before aircraft 298) travels along the nominal route \( R_1 \), as per Lemma 2. Aircraft 301 (aft of aircraft 298) in route \( R_1 \) also travels on the CRP path and is assigned to path \( R_{1,1} \) from the cyclic path assignment. In addition, the CRP cannot be deactivated for aircraft 301 since the arrival spacing between aircraft 298 and aircraft 301 is \( \Delta \) which does not satisfy the deactivation condition in Eq. (8).

**CRP deactivation** The CRP can be deactivated if: (i) there are no same time arrivals at the initial way points; and (ii) the last aircraft to travel on the CRP path arrives at the initial way point is at least 2 arrival time intervals (\( k \)) earlier (within a route) than the aircraft to travel on the deactivated nominal route as per Lemma 3, with \( \Delta = 9.23 \text{ NM} > 4R(\phi - \sin \phi) = 3.24 \text{ NM} \) also from Lemma 3.

For this example, after the first activation of the CRP, since both aircraft 301 (aft of aircraft 298 in Table I) and aircraft 300 (aft of aircraft 287 in Table II) arrive at the initial way point more than 2\( k \) intervals later than aircraft 298 and 287, aircraft 301 and 300 would travel on the deactivated nominal routes.

An additional requirement for deactivation is that there should be sufficient spacing between aircraft on the same route as in Eq. (8), Lemma 3. This requires an additional
spacings of $\delta$ (the difference between the CRP path and the direct route) more than the standard arrival spacing of $D$. For this example, the additional arrival spacing is $\delta = 4R(\phi - \sin(\phi)) = 3.24$ NM, which corresponds to an additional arrival time interval of 0.351$k$. Therefore, if the aircraft in the same route are separated by $2k$ (due to arrival times at integer values of $k$), then there is sufficient space to avoid conflicts and maintain a departure spacing of $D$ in a route, when the CRP is deactivated. This is satisfied in each deactivation case.

Next CRP activation and deactivation The second case of conflict arises at $k = 705$. The CRP should be activated and aircraft 316 should be assigned path $R_{1,1}$, and aircraft 303 be assigned path $R_{2,1}$, as per Lemma 2, since aircraft 302 (forward of aircraft 303 in route $R_2$) travels in the nominal intersection region. Deactivations for this case occurs after aircraft 302 and 303 have passed the final way point of the CRP.

Advantage of activation and deactivation Overall, the example shows that the number of on-demand activations are two and also the number of deactivations that could be safely be done is also two. Throughout the time interval of the given data, the on-demand CRP is safe without any conflicts. While such safety can be guaranteed with the CRP remaining on all the time, the proposed activation/deactivation procedures avoid unwanted CRP maneuvers, and associated delays and effort, for the other 33 aircraft on route $R$. Only 4 aircraft out of 54 need to use the CRP, in this example. Thus, the use of the proposed CRP activation and deactivation can lead to substantial performance improvement over the case with an always-on CRP.

V. CONCLUSION

This article presented a decoupled conflict resolution procedure (CRP) that includes on-demand activation of the split path CRP and deactivation by collapsing the split path depending on the traffic density of the incoming flows and was illustrated with an example. Additional work is needed to optimize the CRP, e.g., to minimize the time delay generated by the CRP. Future work should also consider issues such as optimization of the proposed CRPs for non-perpendicular intersections, and variations in aircraft speeds.

REFERENCES