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SOLUTION SPACE DIAGRAM IN CONFLICT DETECTION SCENARIOS

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Graphical abstract
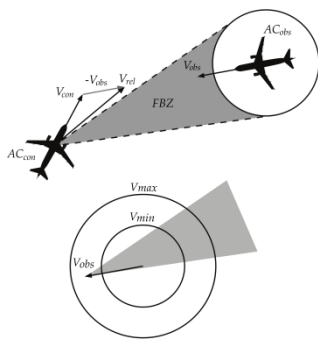
Abstract

This research investigates the use of Solution Space Diagram (SSD) as a measure of sector complexity and also as a predictor of performance and workload, focusing on the scenarios regarding Air Traffic Controller (ATCO)'s ability to detect future conflicts. A human-in-the-loop experiment with varying intercept angle within the same sector layout has been designed and conducted. A short duration and a single predetermined conflict for each scenario were programmed to ensure a controlled experiment environment. The main aim of this experiment is to investigate whether the SSD can predict the workload ratings and subject performance in a conflict detection task. Based on the results, no common pattern can be observed, which can directly associate workload ratings and SSD area properties for various intercept angles. As conflict presented in the experiment between the converging aircraft, it was found that smaller SSD observation angles correlate better with the workload rating. These results were anticipated, as in converging conditions aircraft ahead of the velocity vector will be captured as the main focus. The SSD also does not represent a trigger for conflict detection. There is no consistent SSD area percentage where ATCO would start detecting conflict. Thus, it is concluded that the SSD does not represent a trigger for conflict detection.

Keywords: Air traffic control, sector complexity, solution space diagram

1.0 INTRODUCTION

Controller's workload and sector complexity has been an important topic of research in the Air Traffic Control (ATC). Based on previous research projects, the ability of the controller to ascertain whether or not an aircraft pair will lose separation (more commonly known as conflict detection), is affected by variety of variables that include but not limited to sector properties such as convergence angle [1,2,3,4] and number of aircraft [5].

In a preliminary investigation of varying intercept angle situation, a simulation of two-aircraft situation with direct collision path while having varying intercept angle were carried out. Results from the preliminary investigation have shown that a larger Solution Space Diagram (SSD) area percentage is gathered with smaller Time To Conflict (TTC) [6]. It is also concluded that smaller intercept angles produce a larger SSD area percentage for the same TTC.

This experiment is aimed at systematically analysing the capability of the SSD to illustrate changes in the sector complexity, and also at using the method to obtain an objective measurement of the sectors complexity. Also, it is intended to investigate whether conflict detection time correlates to the size of the covered SSD area.

1.1 Solution Space Diagram as Sector Complexity Measure

In this research, focus is being brought forward in searching an objective measure, which is independent of sector layout, individual differences

and also with direct translation towards current situation. This study is focusing on investigating whether sector complexity construct and workload can be translated using the SSD and also to investigate whether the method can indeed represent an objective measure to quantify sector complexity which is independent of sector, traffic and controller individual differences.

The conflict zones of Van Dam et al. [7] have been the basis for representing the SSD. It is based on analysing conflicts between aircraft in the relative velocity plane. Figure 1 (a) shows two aircraft, the controlled aircraft (AC_{con}) and the observed aircraft (AC_{obs}). In this diagram, the Protected Zone (PZ) of the observed aircraft is shown as a circle with radius of 5NM (the common separation distance) centred on the observed aircraft. Intrusion of this zone is called a conflict, or, loss of separation. Two tangent lines to the left and right hand sides of the PZ of the observed aircraft are drawn towards the controlled aircraft. The area inside these tangent lines is called the Forbidden Beam Zone (FBZ).

From the relative space, the FBZ can be projected to the absolute space by transposing the AC_{obs} velocity vector to the SSD of AC_{con} performance limit as seen in Fi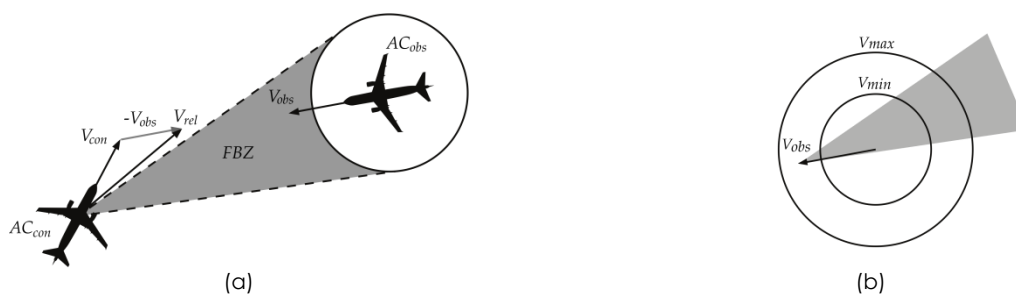gure 1 (b). This example serves for a single observed aircraft situation. Additional aircraft would result in more FBZs, thus resulting in fewer options for control. The main assumption is that the fewer options a controller has to control an aircraft, the more complex the task is.

Three SSD area properties were measured in this experiment, namely the Conflict Area ($A_{conflict}$), the Mean of Total Area (A_{total}) and the Mean Area (A_{mean}). The SSD area properties were measured every 30 seconds (during the workload rating instances) and also based on the time from starting of the scenario to identifying the conflict pair ($T_{identify}$) as well as resolving conflict pair ($T_{resolve}$). However, in this paper, only the results with regards to $T_{identify}$ that will be discussed further. The $A_{conflict}$ represent unsafe area caused only by the conflicting aircraft and the A_{total} represent the mean unsafe area of the two conflicting aircraft. The A_{mean}, on the other hand, represent the sum of unsafe area A_{whole} for all individual aircraft in the sector divided by the total number of aircraft in the sector. The SSD properties were measured based on three observation angle conditions (45°, 90° and 180° observation angle). These observation angles were defined as the semi-sided angle relative to the velocity vector.

| (a) | (b) |

Figure 1: Two aircraft condition (a) Plan View of conflict. (b) Basic SSD for the AC_{con} (Adapted from Mercado-Velasco et al. [8]).

2.0 EXPERIMENTAL

The experiment was conducted using the standalone simulator illustrated in Figure 2. The display consists of two parts, the Plan View Display (PVD) area and the control panel area. The left part of the screen is the PVD area that shows the sector under control, the surrounding area of this sector and the aircraft within the area. The right part of the display contains the control panel area where heading command can be given to selected aircraft. The subject can only give commands to aircraft that are inside the controlled area.

2.1 Subjects.

A total of 10 male subjects participated in the study. The test group subject represents a population of subjects that participated in an extensive ATC introductory course or have extensive knowledge of Air Traffic Controller (ATCO) tasks. The subjects' age ranged between 27 and 50 years (μ = 33.10, δ = 7.89).

The subjects were instructed to identify and resolve a future separation violation problem in a two-minutes scenario situation.

2.2 Scenarios.

In this paper we want to study the limit of intercept angle where the performance and reaction time is different based on different traffic density. We have created a total of 40 scenarios through combinations of the independent variables. The independent variables in the experiment are: (1) the intercept angle of the conflict pair, which has five levels: 30°, 60°, 90°, 120° and 150°, and (2) the traffic density, which has two levels: low (8 aircraft) and high (14 aircraft) traffic density. The independent variables provide a total number of 10 experiment conditions. The presentation order of the first 20 scenarios was randomized (in a batch of 5 scenarios) to counterbalance a possible order effect on the dependent measures in the experiment. The last 20 scenarios were the representation of the first 20

scenarios, which was rotated at 180° and again randomize in a batch of 5 scenarios.

2.3 Procedure.

The subjects were instructed to detect a pair of aircraft that was on a collision course as quickly as possible. They then had to try to resolve the future conflict by giving only heading instructions, after which they had to direct the aircraft to its original

heading again. The conflicting pair will experience a direct collision within the next 120 seconds and there is only one type of aircraft present with a known speed limit of 200 - 240 knots. During the experiment, the participants were asked to rate their perceived workload every 30 seconds. An automated stimulus provided a message on the display that triggered the participants to rate their workload by means typing a number between 1 (low workload) and 7 (high workload) on the keyboard.
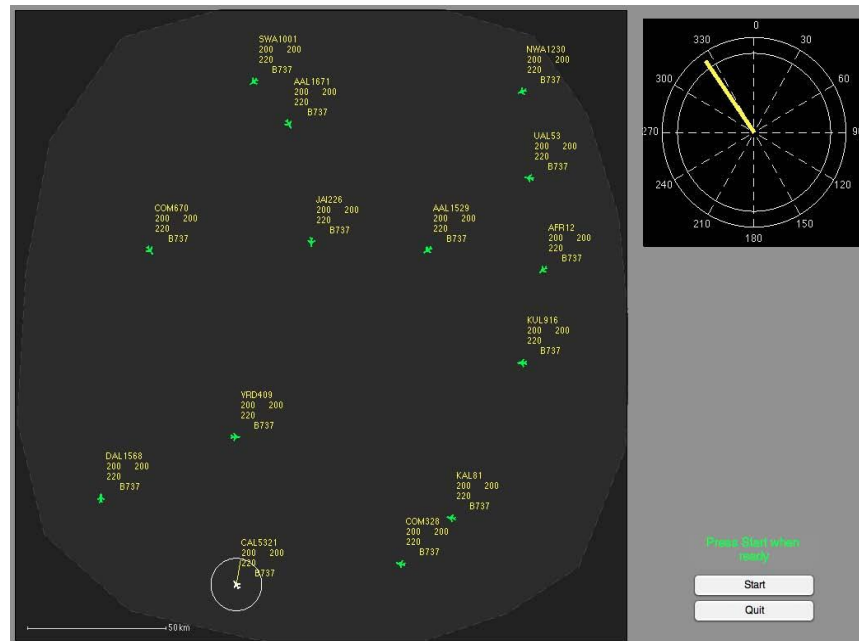

Figure 2: Experiment simulator

3.0 RESULTS AND DISCUSSION

To compare with the results gathered from initial analysis of two aircraft with future direct collision path in [6], analysis on SSD area properties with regards to time measures ($T_{identify}$) were conducted. Figure 3 illustrates the scatter plots of $A_{conflict}$ gathered from the experiment. The plot matches the outcome of the initial analysis of two aircraft with future direct collision path in previous study [6].

To show the effects of other aircraft within sector, A_{total} were illustrated and compared with the previous $A_{conflict}$ findings. When considering the A_{total}, the effect of other aircraft within the sector became more predominant (Figure 4) as it changes the pattern of SSD area. However, the same relation between intercept angle and the SSD area where smaller intercept angle has higher SSD area properties is visible within the same background

scenario. This has shown that the background scenario does have an effect in the behaviour of the A_{total}, but to the same degree that the behaviour of smaller intercept angle has higher SSD area properties is still visible. This can be observed when comparing Figure 4 (a) to Figure 4 (b).

Figure 5 shows the scatter plot of A_{mean} at the time of conflict identification ($T_{identify}$), in order to illustrate the overall sector complexity construct. Based on the figures, it can be seen that a higher $T_{identify}$ result in a higher A_{mean} values regardless of the intercept angle (Figure 5 (a)) and background scenario (Figure 5 (b)). This is expected, due to the fact that the further away in time the situation progresses, the higher the SSD area covered for each individual aircraft, as both sector contain several crossing aircraft. Thus, much later conflict identification results in higher SSD area properties.
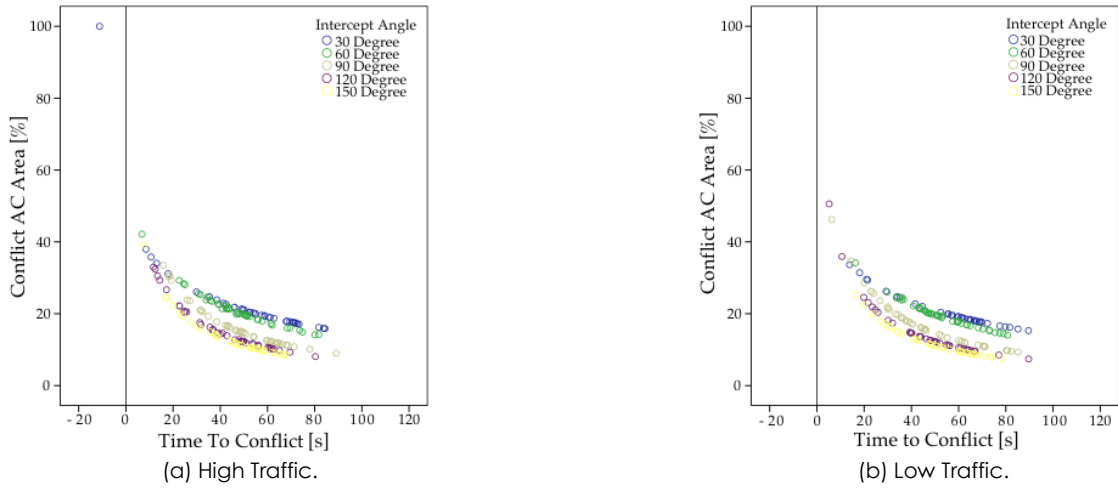
(a) High Traffic.   (b) Low Traffic.

Figure 3: $A_{conflict}$ during of conflict identification ($T_{identify}$) based on intercept angle.

(a) Different intercept angle.   (b) Different background scenario
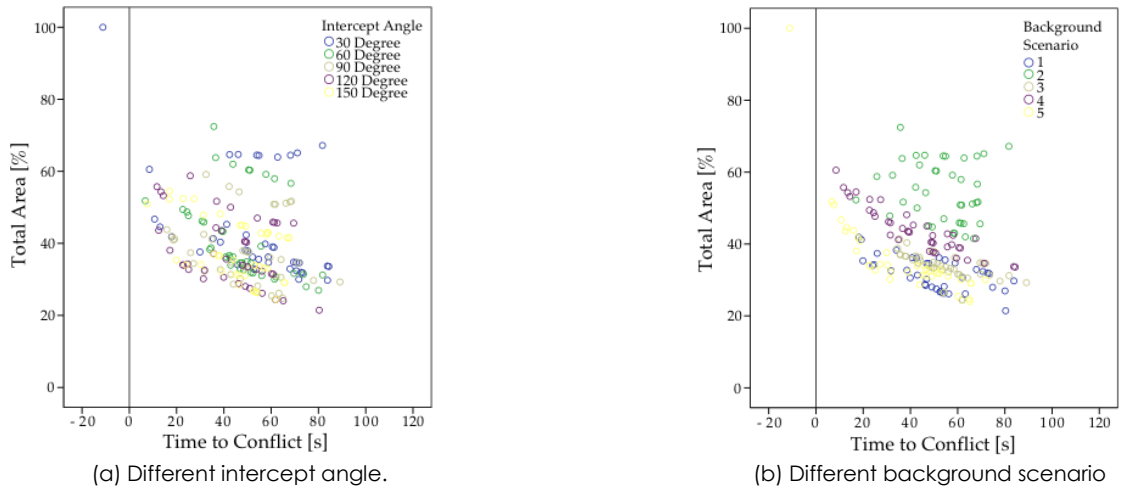
Figure 4: A_{total} during of conflict identification ($T_{identify}$) for high traffic density situation.

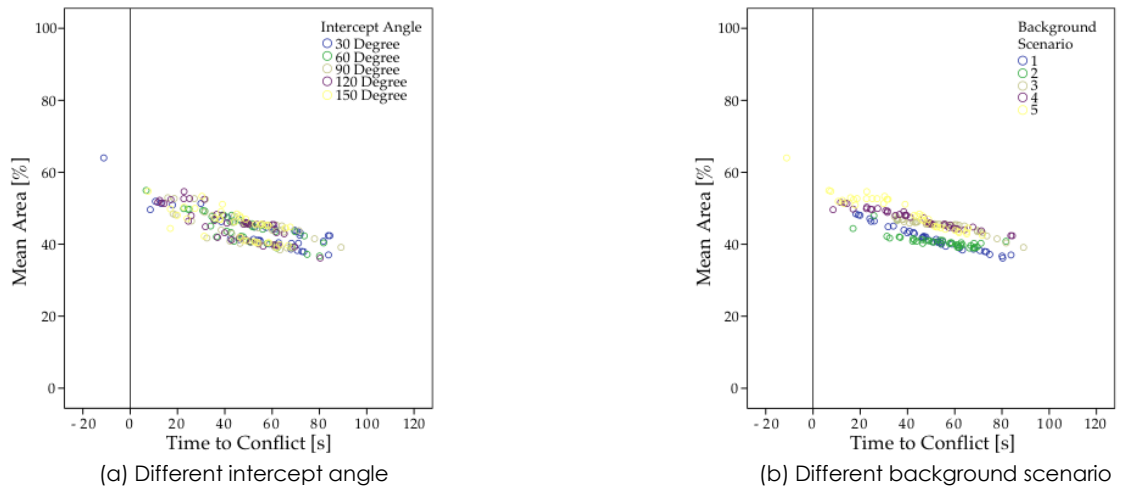(a) Different intercept angle   (b) Different background scenario

Figure 5: A_{mean} during conflict identification ($T_{identify}$) for high traffic density situation.

However, the relation where smaller intercept angle has higher SSD area properties is not visible with the A_{mean}. The A_{mean} of different intercept angles is distributed within the same range (Figure 5 (a)), with a strong association to different background scenarios (Figure 5 (b)). This also conclude that the effect of background scenarios has a more significant impact for A_{mean}, compared to previous situation in $A_{conflict}$ and A_{total} as it overshadows the different intercept angles behaviour.

The area percentages for A_{mean} for both high and low traffic are approximately between 20% to 50% or 40% to 60%, respectively. Even when A_{mean} data showed to be more concentrated than $A_{conflict}$ and A_{total} data, there are still quite a large spread of area percentage covered when the conflict were detected. Thus, no common SSD area property, which may trigger identification of conflict pair, was found. It is concluded that the SSD metric is not suitable for prediction of conflict detection time.

As for the workload rating, it is observed that the largest correlations were detected between workload rating and $A_{conflict}$ with the smallest observation angle (45° observation angle). This also indicated that the area within the 45° observation angle is best at representing the controller's workload rating compared to other area properties (90° and 180° observation angle). The fact that SSD area properties of 45° observation angle have a better correlation with workload rating suggests that the area which is in the direction of the velocity vector has more impact in determining the level of difficulty that subject's has to undergo in a scenario where one separation violation situation is known to take place.

Figure 6 illustrates the trend of the $A_{conflict}$ area property at 45°, 90° and 180° observation angle together with workload rating of a single subject from the experiment. Based on the figure, it is visible that the $A_{conflict}$ with 45° observation angle does shows the highest correlation with the workload rating.
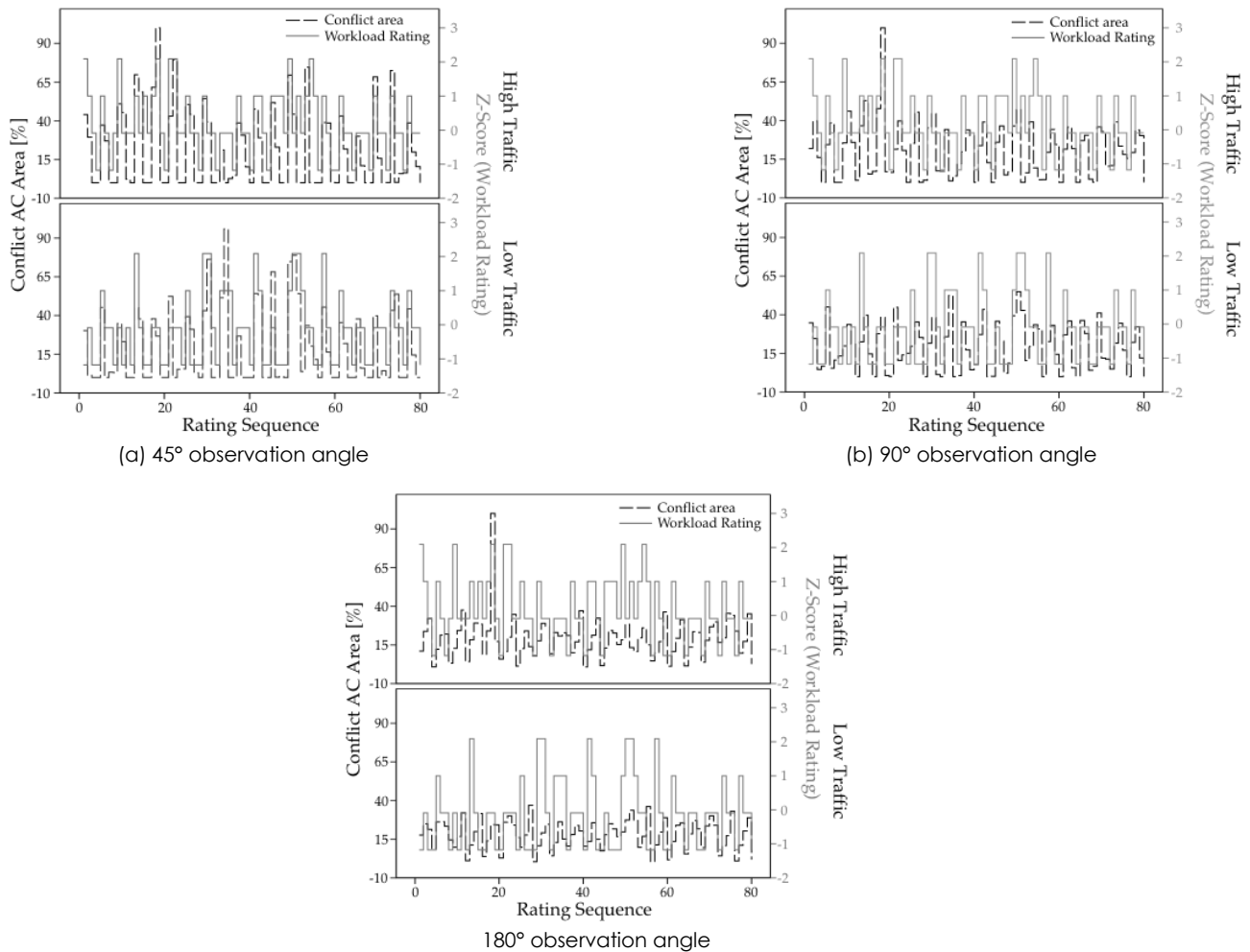

(a) 45° observation angle

(b) 90° observation angle

180° observation angle

Figure 6: Workload rating with $A_{conflict}$ at three different observation angles.

4.0 CONCLUSIONS AND RECOMMENDATION

Investigating single sector complexity variable in a dynamic environment has shown to be a complicated task. This is due to the fact that the investigation of single sector complexity variable (based on scenario of only two converging aircraft) might not deliver the 'same' effect as it would deliver in 'real' situation. However, adding another element by introducing other non-conflicting aircraft in the sector might interfere with the controller's attention from the issue that is being investigated. A trade-off has to be made between investigating single element of sector complexity variable and presenting a closer environment of actual condition to ATCO. In this experiment, several background scenarios have been introduced, to present the latter.

The results gathered from this experiment conclude that no common pattern can be observed, which can directly associate workload ratings and SSD area properties for various intercept angles. It is concluded, based on the findings in this experiment, that intercept angle is an intricate matter to be investigated as a single sector complexity construct, in a situation where the difficulty of identifying conflicting aircraft pair is not only influenced by controller behaviour but also by the neighbouring traffic within the sector.

The experiment also discovered that a larger $A_{conflict}$ based on $T_{identify}$ is gathered for smaller intercept angles. This is a result of a larger intercept angle or a bigger horizontal distance between aircraft at identification and resolution instances. However, the sector complexity construct also depends on other aircraft within the sector. These were illustrated through A_{total} and A_{mean}, which also incorporated the surrounding aircraft within the SSD construction. Difference in the behaviour of the A_{total} and A_{mean} area properties compared to $A_{conflict}$ indicate that other aircraft within a sector will also give an important effect on the space that an aircraft has to manoeuvre.

Nevertheless, the pattern with shorter TTC would result in more area within the SSD need to cover, remained the same. This is expected, due to the fact that the further away in time the situation progresses, the higher the SSD area covered for each individual aircraft. Having said that, the experiment also did not gather a clear threshold on SSD area percentage where a controller would start to detect a conflict pair. Thus, it is concluded that the SSD does not represent a trigger for conflict detection.

Acknowledgement

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