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THE APPLICATION OF AXIOMATIC DESIGN THEORY AND CONFLICT TECHNIQUES FOR THE DESIGN OF INTERSECTIONS: PART 1

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ABSTRACT

Today the design and analysis of traffic intersections is most commonly done using traditional traffic conflict techniques. In this paper, we compare and combine traditional traffic conflict techniques and axiomatic design theory. Both the conflict techniques and axiomatic design theory are applied to a generic 4-way intersection. Strategies to improve the intersection including separation of space and separation of time are considered. The limitations and implications of conflict techniques, axiomatic design theory, and the two strategies are addressed. Finally, the future implications of this work are discussed.

Keywords: Intersection, Conflict, Traffic, Axiomatic Design

1 INTRODUCTION

The design of intersections can greatly affect the safety and efficiency of traffic flow. Most intersections today are designed and analyzed using traditional traffic conflict techniques. However, there are some limitations association with conflict analysis. This work examines the suitability of axiomatic design theory for traffic intersections. Axiomatic design theory is compared to traditional conflict techniques and combined with them to examine a generic 4-way intersection, explore strategies to improve this type of intersections, and determine the benefits and limitations of this approach.

2 PRIOR ART

Our literature search did not uncover any previous examples of traffic intersections which were designed or analyzed using axiomatic design theory. However, there are examples from the literature share some similarities with AD. Czarczyski et al. [1997] presented a multi-level approach to the design of traffic control systems using hierarchical functional requirements with four levels of detail. White [1999] presented an objective's tree that was used to help redesign an intersection in Charlottesville along the US29 corridor. The objectives tree also resembles a decomposed set of functional requirements for the design task. Reijmers [2006] discusses "protection matrices" for traffic intersections. These matrices note the primary and secondary conflict directions between the various traffic streams in an intersection and share some similarities with the hybrid design matrices discussed in this work.

3 BACKGROUND

3.1 TYPES OF CONFLICTS

There are three basic types of vehicle-to-vehicle traffic conflicts in traditional traffic conflict analysis: merging conflicts, diverging conflicts, and crossing conflicts (figure 1). For this work, we will include a fourth type of conflict: sequential conflicts. Vehicle-to-environment and vehicle-pedestrian conflicts will be neglected.

3.1.1 SEQUENTIAL CONFLICTS

Sequential conflicts occur between two vehicles travelling in sequences (one following the other). An accident will only occur when the following vehicle is travelling faster than the leading vehicle.

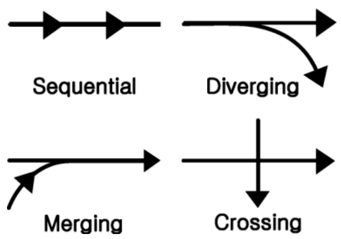

Figure 1. The four types of vehicular conflicts (diverging, merging, crossing and sequential conflicts)

If the leading vehicle is stationary, this is referred to as a queuing conflict [USDOT].

3.1.2 DIVERGING CONFLICTS

Diverging conflicts are created when the flow of traffic travelling in a single direction separates into different directions. These are generally considered to be the least problematic of the four conflict types. Diverging roadways create a reverse bottleneck, with traffic moving from a more congested and constrained space to a more open space. This, in itself, is not a problem. However, vehicles tend to slow when changing directions or making navigation decisions. Thus, the faster moving following traffic can be negatively impacted by the slower moving leading traffic. In this sense, diverging conflicts are similar to sequential conflicts.

3.1.3 MERGING CONFLICTS

Merging conflicts occur when vehicles from different lanes or directions merge into a single lane moving in a single direction. This situation creates a bottleneck and forces the traffic to move from a larger space and less congested state into a narrower space and a more congested state.

3.1.4 CROSSING CONFLICTS

Crossing conflicts occur when vehicles from different directions attempt to cross paths at a single location. Crossing conflicts are considered to be the most dangerous type of conflict and are a major concern during traffic intersection design.

3.2 COMPARISON OF CONFLICTS

Each type of conflict has different characteristics and different prevention methods. [SUDAS] The US Department of Transportation recommends considering four factors when considering traffic conflicts: (1) the existence of conflicts, (2) the exposure of the conflict, (3) the severity of the conflict, and (4) the vulnerability of the vehicles to the conflict. The exposure is "measured by the product of the two conflicting stream volumes at a given conflict point." [USDOT] Exposure represents the traffic volume at the conflict point. As the opportunity for collisions to occur increases, the probability of a collision also increases.

The severity is "based on the relative velocities of the conflicting streams (speed and angle)." [USDOT] The severity of the conflict can be easily visualized using the velocity vectors of the two vehicles (figure 2). The magnitude of the resulting velocity vector $|v_1$ - indicates the severity of a potential impact.

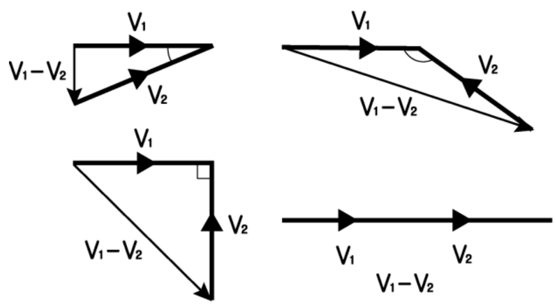

Figure 2. Examples of the relative velocity between two vehicles in conflict

The vulnerability is "based on the ability for a member of each conflicting stream to survive a crash" [USDOT] and is a function of where the impact occurs on each vehicle body. For example, impacts on the rear or rear corners of the vehicle are substantially less dangerous than side or front impacts. The direction of the resulting velocity between two vehicles vector indicates where the impact will likely occur on the vehicles.

3.3 STRATEGIES FOR INTERSECTION DESIGN

Based on the discussions above, it is clear that there are some common strategies for mitigating conflict and minimizing the probability of collision. The probability and severity of all conflicts can be reduced by decreasing the relative velocity of the two vehicles. The probability and severity of merging and diverging conflicts can also be reduced by decreasing the relative angle between the vehicles (figure 3). Sequential and diverging conflicts can be reduced by increasing the number of lanes in an intersection. However, there is no easy way to moderate crossing conflicts. Thus, most re-design efforts focus on eliminating crossing conflicts from the intersection.

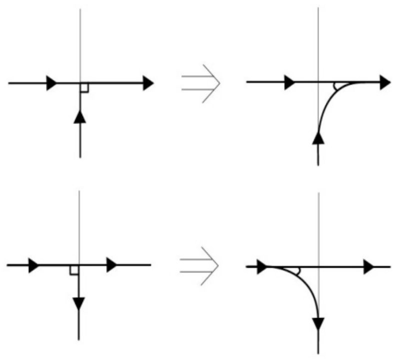

Figure 3. Examples of angle reduction for merging and diverging conflicts

4 APPLYING AXIOMATIC DESIGN AND CONFLICT TECHNIQUES TO A TYPICAL FOUR-WAY INTERSECTION

Applying traditional traffic conflict techniques to a generic unregulated two-lane four-way intersection results in a total of 32 conflicts (figure 4) including 16 crossings, 8 diverging conflicts and 8 merging conflicts.

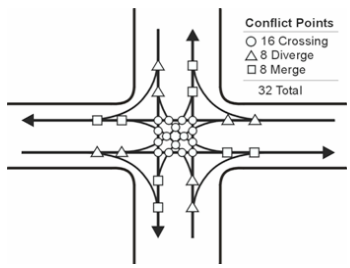

Figure 4. Conflict points of a typical two-lane four-way intersection or driveway [SUDAS]

If we consider the same intersection from the viewpoint of axiomatic design theory, we can see that a generic four-way intersection performs 12 basic functions (FRs): it permits vehicles from each of the four directions to travel in one of the three remaining directions (figure 5). For convenience, we will assume that our generic intersection aligns with the four cardinal directions (north, south, east, and west). Although intersections may perform a variety of other functions, only the 12 FRs associated with navigation through an intersection will be considered for this work.

FR1 N→S	FR7 E→S
FR2 N→W	FR8 E→N
FR3 N→E	FR9 E→W
FR4 W→E	FR10 S→W
FR5 W→S	FR11 S→E
FR6 W→N	FR12 S→N

Figure 5. The 12 functional requirements

The design parameters associated with these 12 FRs are the sections of the roadway that will allow the vehicles to traverse the intersection from their origin to their destination. The definition of FRs and DPs allows us to create the design matrix for the intersection (figure 6).

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12
FR1	X	X	X	X	X	X	X	O	X	X	O	O
FR2	X	X	X	O	O	O	O	O	X	X	O	O
FR3	X	X	X	X	O	X	X	O	X	O	X	X
FR4	X	O	X	X	X	X	X	O	O	X	X	X
FR5	X	O	O	X	X	X	X	O	O	O	O	O
FR6	X	O	X	X	X	X	O	X	X	X	O	X
FR7	X	O	X	X	X	O	X	X	X	X	O	X
FR8	O	O	O	O	O	X	X	X	X	O	O	X
FR9	X	X	X	O	O	X	X	X	X	X	O	X
FR10	X	X	O	X	O	X	X	O	X	X	X	X
FR11	O	O	X	X	O	O	O	O	O	X	X	X
FR12	O	O	X	X	O	X	X	X	X	X	X	X

Figure 6. Design matrix for generic 4-way intersection

4.1 Hybrid Design Matrix

Clearly the generic 4-way intersection is a fully coupled design. However, the type of coupling or conflict is not clear. The traditional design matrix from axiomatic design theory can be combined with traditional traffic conflict techniques to create a hybrid design matrix that specifies the type of traffic conflict between each FR/DP pair (figure 7). This helps the designer to identify appropriate strategies for eliminating or reducing the coupling and conflict in the system and produce a better design.

In traditional axiomatic design matrices, strong coupling is sometimes indicated by a large X and weak coupling is represented by a small x. In our hybrid matrix, there are four symbols which indicate coupling between the FRs and DPs: a large x (X) represents strong coupling and a crossing conflict, a square (□) represents moderate coupling and a merging conflict, a triangle (△) represents weak coupling and a diverging conflict, and a zero (O) indicates no coupling or conflict at all.

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12
FR1	X	△	△	X	□	X	□	O	X	X	O	O
FR2	△	X	△	O	O	O	O	O	□	□	O	O
FR3	△	△	X	□	O	X	X	O	X	O	□	X
FR4	X	O	□	X	△	△	X	O	O	X	□	X
FR5	□	O	O	△	X	△	□	O	O	O	O	O
FR6	X	O	X	△	△	X	O	□	X	X	O	□
FR7	□	O	X	X	□	O	X	△	△	X	O	X
FR8	O	O	O	O	O	□	△	X	△	O	O	□
FR9	X	□	X	O	O	X	△	△	X	□	O	X
FR10	X	□	O	X	O	X	X	O	□	X	△	△
FR11	O	O	□	□	O	O	O	O	O	△	X	△
FR12	O	O	X	X	O	□	X	□	X	△	△	X

Figure 7. Hybrid design matrix with conflict specification for generic 4-way intersection

4.2 Symmetry in the Hybrid Design Matrix

The generic four-way intersection exhibits C4 cyclic symmetry with each cell having rotational symmetry at 90 degree (360/4) angles. Either the cardinal directions (N-S and E-W) or the intermediate directions (NE-SW and NW-SE) can be used to draw the lines of symmetry (figure 8).

In comparison, the design matrix exhibits D2 dihedral symmetry with reflection across both diagonals and rotational symmetry at 180 degree (360/2) angles.

Figure 8. Lines of Symmetry for a Generic Intersection (left) and Corresponding Hybrid Design Matrix (right)

5 SEPARATION IN SPACE

There are two basic strategies for attempting to decouple the design of a generic intersection design: separation in space and separation in time (periodicity). Within separation in space, there are two basic sub-strategies: two-dimensional (2D) separation, and three-dimensional (3D) separation.

5.1 2D Separation

Two dimensional separation involves a lateral separation of co-planar FRs or DPs. For example, a dangerous crossing intersection can be transformed into a less dangerous intersection with a merging conflict, a straight away, and a diverging conflict (figure 9).

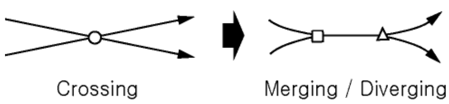

Figure 9. The transformation of a crossing conflict using 2D separation

Rotaries, roundabouts, or traffic circles are examples of traffic intersections which have made use of 2D separation (figure 10). A rotary fulfils the same 12 functional requirements as the generic four-way intersection in figure 4. However, it only has a total of 8 conflicts (4 merging and 4 diverging conflicts) in comparison to the 32 conflicts in the generic intersection.

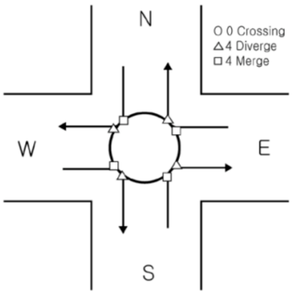

Figure 10. Conflict points of a typical rotary

Fig. 11 shows the hybrid design matrix for a typical rotary. Here, a triangle within a square (⍍) indicates a merging-diverging conflict and the double triangle within a square (⊠) symbolizes the combination of two pairs of merging-diverging conflicts.

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12
FR1	X	△	△	⍍	□	⍍	□	O	⍍	⍍	O	O
FR2	△	X	△	O	O	O	⍍	O	□	□	O	O
FR3	△	△	X	□	⍍	⍍	⍍	O	⍍	⊠	□	⍍
FR4	⍍	O	□	X	△	△	⍍	O	O	⍍	□	⍍
FR5	□	O	⍍	△	X	△	□	O	O	O	O	O
FR6	⍍	O	⍍	△	△	X	⊠	□	⍍	⍍	⍍	□
FR7	□	⍍	⍍	⍍	□	⊠	X	△	△	⍍	O	⍍
FR8	O	O	O	O	O	□	△	X	△	⍍	O	□
FR9	⍍	□	⍍	O	O	⍍	△	△	X	□	O	⍍
FR10	⍍	□	⊠	⍍	O	⍍	⍍	⍍	□	X	△	△
FR11	O	O	□	□	O	⍍	O	O	O	△	X	△
FR12	O	O	⍍	⍍	O	□	⍍	□	⍍	△	△	X

Figure 11. Hybrid design matrix for a typical rotary

This design matrix is a substantial improvement over the 4-way intersection matrix shown in figure 7. All of the Xs have turned into ⍍s, which reduces the coupling in the matrix and the severity of the conflict. However, some of the FRs which were originally independent now show some degree of coupling (i.e. many of the Os have turned into either ⊠ or ⍍.) This is still a fully coupled matrix.

5.2 3D SEPARATION

3D separation involves both vertical and lateral separation of the roadway and can include both tunnels and overpasses. One of the most common examples is a clover-leaf shaped highway interchange (figure 12).

By separating the intersection in three dimensions, all of the crossing conflicts are transformed into merging and diverging conflicts. All of the Xs in the matrix from figure 7 have turned to Os and ⍍s. This design has twice the conflicts of the 2D case: 8 merging and 8 diverging conflicts. However, no additional coupling has been added to the design matrix, making it the least coupled of the three non-periodic intersections discussed (figure 13). In addition, the 3D intersection has greater capacity and less severe angles which will permit vehicles to travel through the intersection at higher speeds.

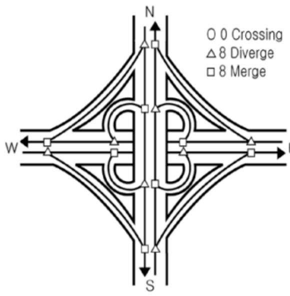

Figure 12. Conflict points of a typical clover-leaf interchange

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12
FR1	X	△	△	O	□	O	□	O	O	O	O	O
FR2	△	X	△	O	O	O	O	O	□	□	O	O
FR3	△	△	X	□	O	⍍	⍍	O	O	O	□	O
FR4	O	O	□	X	△	△	O	O	O	O	□	O
FR5	□	O	O	△	X	△	□	O	O	O	O	O
FR6	O	O	⍍	△	△	X	O	□	O	⍍	O	□
FR7	□	O	⍍	O	□	O	X	△	△	⍍	O	O
FR8	O	O	O	O	O	□	△	X	△	O	O	□
FR9	O	□	O	O	O	O	△	△	X	□	O	O
FR10	O	□	O	O	O	⍍	⍍	O	□	X	△	△
FR11	O	O	□	□	O	O	O	O	O	△	X	△
FR12	O	O	O	O	O	□	O	□	O	△	△	X

Figure 13. Hybrid design matrix for a typical interchange

5.3 LIMITATIONS

By separating the intersection in space we gained several advantages including increased temporal efficiency and a reduction of complexity. However, this is done at the cost of physical and financial resources in the form of additional space required for the intersection and additional construction and maintenance costs. Thus, the viability of 2D or 3D separation as a design option is determined by the constraints of the system. If there is insufficient space or money to create such an intersection, or if there is an insurmountable conflict in the system then these strategies cannot be used.

6 SEPARATION IN TIME

Unregulated traffic intersections are clearly examples of time dependent combinatorial complexity as defined by Nam P. Suh in his book on Complexity Theory. To mitigate some of the complexity of these types of systems and to increase their overall robustness and probability of success, Suh [2005] suggests transforming combinatorial systems into periodic systems.

Following this line of logic, the generic intersection from figure 4 was transformed from a combinatorial intersection to a periodic intersection using a traffic signal to separate the various stages of operation. Two different options for implementing periodic intersections are presented below. Each option has four time steps (T1, T2, T3 and T4) which repeat periodically. The design matrices for each of the four steps are shown for each option.

6.1 PERIODIC PULL INTERSECTION

The first option for periodic transformation is an example of a "pull" intersection. In each step, vehicles from 3 different directions merge into the last direction, thus the fourth direction pulls traffic from the other three (figure 14).

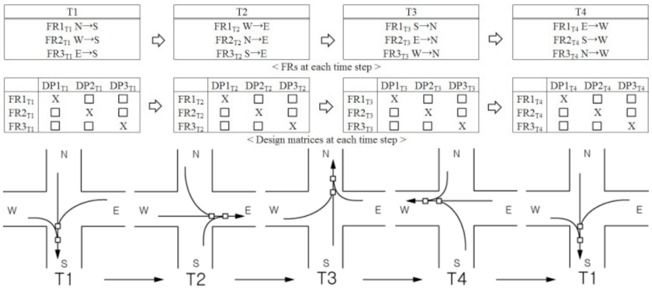

Figure 14. Sub-steps of a two-lane periodic pull intersection

This scenario can be represented by four 3x3 matrices. In each sub-step, the design matrix is fully coupled but each off-diagonal term represents only moderate coupling due to merging conflicts. All of the strong coupling has been removed from the design matrix.

From a traffic conflict perspective, the situation is also improved. The intersection now has 2 merging conflicts per sub-step, for a total of 8 merging conflicts per period.

6.2 PERIODIC PUSH INTERSECTION

The second option for periodic transformation is an example of a "push" intersection. In each step, vehicles are pushed from one direction to the other three directions (figure 15).

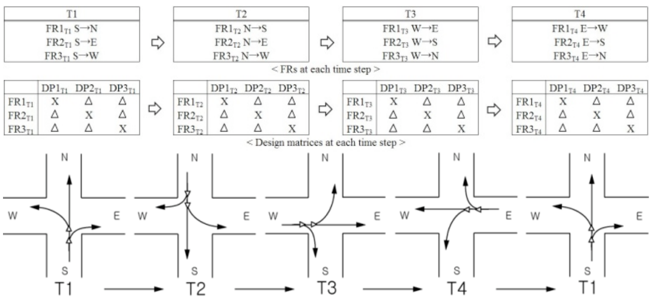

Figure 15. Sub-steps of a two-lane periodic push intersection

This scenario can also be represented by four 3x3 matrices. In each sub-step, the design matrix is also fully coupled but each coupling term represents only weak coupling within the matrix or a diverging conflict. From an axiomatic design perspective, option 2 is more ideal than option 1 because the strength of the coupling has been reduced.

From a traffic conflict perspective, the situation is also improved. The intersection now has 2 diverging conflicts per sub-step for a total of 8 diverging conflicts period, compared to 8 merging conflicts from option 1.

6.3 LIMITATIONS

In the above examples, the introduction of periodicity reduced coupling and conflict in the intersection by separating the various functions in time. However, it also only permitted cars in one of the four sub-steps to travel at any given time. The rest of the cars had to wait for the next appropriate sub-step. In light traffic, a single vehicle might only have to wait one period for the next appropriate sub-step. But in heavy traffic, a vehicle might have to wait for multiple periods until it is their turn to travel, until there are no queuing conflicts to prevent movement, and until there is space in the appropriate lane to receive them. Thus, there is a contradiction between avoiding conflicts and decreasing travel time.

The elimination of conflict is one of the cornerstones of TRIZ. Altshuller observed that "when improving a system by conventional means, one system's attribute [A] is usually improved at the expense of deteriorating another attribute [B]." Conventional design urges "the designer to seek the least expensive compromise" whereas TRIZ requires the designer to solve the contradiction. [Fey and Rivin, 2005] Similarly, axiomatic design theory helps to identify the coupling between the factors that cause contradiction and requires the user to develop new uncoupled solutions instead of seeking a compromise. [Deo, et al., 2004]

In our previous examples, we decreased the number of possible traffic conflicts (A), while increasing the time that each vehicle takes to pass through the intersection (B). Sensors, traffic predictions, clever traffic light timing, and other options can be used as compromises to reduce the conflict, but they cannot eliminate the conflict entirely.

In addition, two-lane periodic push and pull intersections are both at risk of sequential or queuing conflicts that result from a single traffic stream having multiple destinations. This could further reduce the temporal efficiency of the intersection.

7 SEPARATION IN SPACE AND TIME

Thus far, we have presented decoupling options for generic intersections with only one lane for travel in each of the four directions. However, many major intersections use a combination of separation in time (via traffic signals) and separation in space (via separate lanes).

7.1 MULTI-LANE PERIODIC PULL INTERSECTION

Consider a six-lane version of the periodic pull intersection from section 6.1. The vehicles from each of the three donating directions now have a dedicated lane to receive them (figure 16). The merging conflicts in the receiving lane are eliminated as is the coupling in the design matrix. This intersection now has no traffic conflicts and is represented by an uncoupled design matrix.

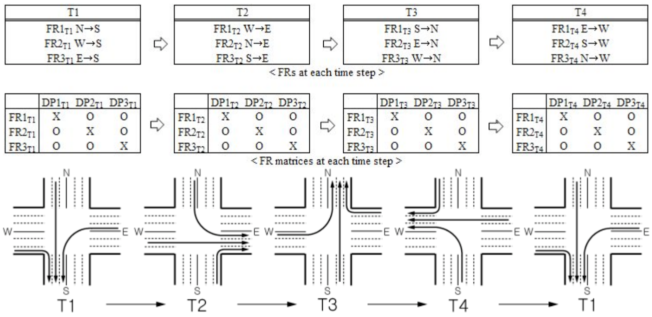

Figure 16. Sub-steps of a six-lane periodic pull intersection

7.2 MULTI-LANE PERIODIC PUSH INTERSECTION

A six-lane version of the periodic push intersection from 6.2 will have similar benefits. The vehicles from the donating direction will each have a dedicated lane based on their direction of travel (figure 17). The diverging conflicts in the donating lane are eliminated as is the coupling in the design. Again, the intersection now has no traffic conflicts and is represented by an ideal uncoupled design matrix.

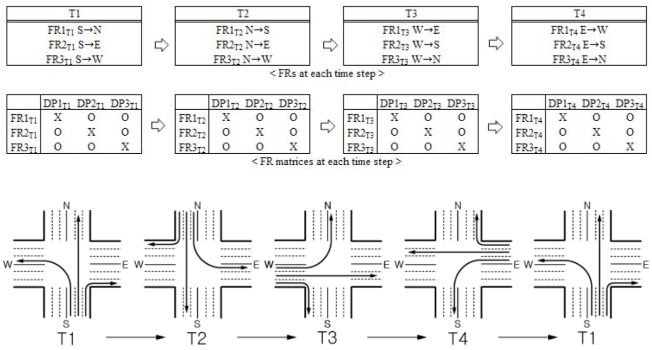

Figure 17. Sub-steps of a six-lane periodic push intersection

7.3 MULTI-LANE PERIODIC ALTERNATING INTERSECTION

The combination of the two strategies presents a third option for periodic transformation which most closely resembles current intersections. In each step, vehicles travel from and to opposite directions (figure 18). This option requires a minimum of two lanes for the donating traffic: one of the straight/right turns and one for the left turns. If the donating traffic were not separated into individual lanes, sequential or queuing conflicts would prevent traffic flow.

This third scenario is represented by two 2x2 matrices and two 4x4 matrices. In the six-lane version, each of the four matrices is uncoupled and no conflicts are present. If right turns are permitted during T1 and T3 in a four-lane intersection, four diverging conflicts will be added and a small degree of coupling will be added to the design matrix. Alternate versions of this periodic option are also possible.

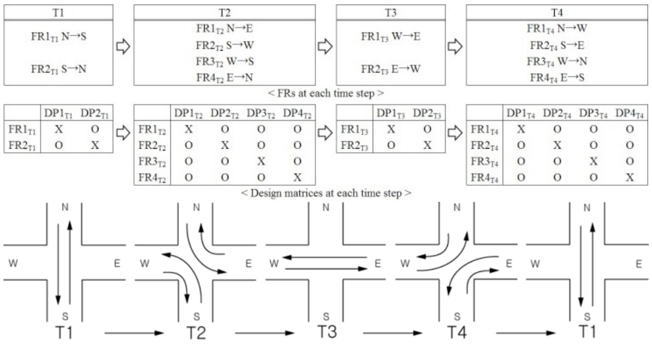

Figure 18. Sub-steps of a multi-lane periodic alternating intersection

7.4 LIMITATIONS

The separation of intersections in both time and space proved to be the most successful strategy according to both the traffic conflict theory and axiomatic design theory. However, the conflict between speed (travel time) and safety (conflicts) remains unresolved. In addition, six-lane intersections require more physical space than their two-lane counterparts and may not be an option in some areas.

8 CONCLUSIONS

In this work, axiomatic design theory has been combined with traditional traffic conflict theory to examine strategies for the design of intersections. A generic 4-way intersection was considered. The number and types of conflicts for the intersection were identified and a hybrid design matrix was constructed to highlight the various types of coupling in the system. The intersection was then considered using separation in time and separation in space. Both techniques successfully reduced the number and severity of conflicts in the system and eliminated strong coupling in the design matrix. However, the periodic intersections led to a conflict between safety and speed, which could result in longer travel times for vehicles. The 2D and 3D intersections required more space and money to construct and were more strongly affected by the constraints of the system. The intersections which employed both periodicity and separation in space were uncoupled and had no conflicts, but did not successfully resolve the conflict between time and safety.

It has been demonstrated that axiomatic design theory provides valuable insight into the design and operation of intersections that is not available by conflict theory alone. It has great potential for both the design and analysis of intersections in the future.

It is concluded that separation in time, separation in space and the combination of the two are viable options for reducing conflict and coupling in intersections. The choice of which method to use is dictated by the constraints in the system (available space and financial resources) and by the selection criteria of the design (including minimizing the travel time of all vehicles in the system.)

9 FUTURE WORK

Three additional issues must be considered during the design and analysis of intersections: sequential or queuing conflicts, the effect of adjacent intersections, and the temporal efficiency of the intersection. In this work, all three topics have been touched upon, but none have been addressed in detail. These topics will be the subject of future work.

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