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THE APPLICATION OF AXIOMATIC DESIGN THEORY AND CONFLICT TECHNIQUES FOR THE DESIGN OF INTERSECTIONS: PART 2

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ABSTRACT

This work presents two case studies which use a combination of Axiomatic Design (AD) Theory, traditional traffic conflict analysis, and TRIZ to re-design urban intersections for improved efficiency. The first case study involves several options for the re-design of a generic 4-way intersection from the literature. The second case study involves the conceptual redesign of an existing intersection located in Daejeon, South Korea. The impact of various design strategies on the functional requirements, the traffic conflicts in the intersection, and the coupling in the design matrix are examined. Both holistic and modular approaches to modelling intersections are demonstrated and compared. Finally, symmetry, redundancy, and the effects of neighboring intersections are discussed.

Keywords: Intersection, Conflict, Traffic, Axiomatic design

1 INTRODUCTION

Traffic intersections play an important role in city planning and human society, and have been the focus of numerous research projects. Such studies commonly contain information about how to improve the efficiency of traffic systems and maintain control [Gazis 2002, and Levinson and Chen]. However, it is uncommon for these projects to use formal design theories or methodologies.

This work focuses on understanding and improving the design of urban intersections to reduce traffic congestion and increase the efficiency of transportation networks. Traditional traffic conflict techniques are used in combination with two formal design theories, Axiomatic Design (AD) Theory and TRIZ, to examine two case studies. The first case study involves examples of a redesigned intersection from the literature. The second case study examines a real intersection located in Daejeon, South Korea, which is a common location of traffic jams during rush hour.

2 PRIOR ART

To our knowledge, there are no examples of intersection design and implementation using Axiomatic Design theory in the literature. However, there are at least two examples of intersection design which involve hierarchical requirements that are similar to AD's functional requirements [Czarczyski 1997 and White 1999] and at least one example of a "conflict matrix" which resembles AD's design matrix [Reijmers 2006].

Previous examples of applying AD to traffic-related subjects include the design of a machine control system that could be implemented for traffic systems [Lee et al. 2001] and the design of a new system to transport cargo from large-sized container ships to the coast using a "mobile harbor." The mobile harbor project was initiated by N. P. Suh and is currently being run by the Department of Ocean Systems Engineering at KAIST. Finally, transportation in the context of supply chain design has been conceptualized using AD [Favaro 2008].

TRIZ has been used in case-studies for solving contradictions in traffic systems. One example involved the analysis of traffic congestion based on the stress and other emotional states of the drivers in four different types of traffic congestion [Mann 2007].

Other frameworks have also been used in previous studies for traffic systems. A classifier system and fuzzy logic were used to design a traffic junction controller [Cao et al., 1999], and a multilevel traffic control system was designed using a structural hierarchy resulting directly from tasks and functions of this system for medium and large urban agglomerations [Czarczyski et al.,1997].

3 METHODS

Two design thinking approaches have been used in this work: Axiomatic Design (AD) Theory and TRIZ. AD is a formal design methodology which is intended to help users approach design in a rational, conscious, and systematic manner. It is based on a mapping process across the four domains: the customer, functional, physical, and process domains. In AD, the designer must decide what they want to achieve functionally before considering how to achieve it physically, so functional requirements (FRs) are defined before the design parameters (DPs). The definition of FRs and the subsequent assignment of DPs are both dependent on the information axiom. The independence axiom states that the independence of the functional requirements must be maintained to minimize coupling and avoid conflict. The design matrix identifies coupling between FR/FR and FR/DP pairs so it can be reduced or eliminated [Suh, 2001]. In this work, the second axiom, the information axiom, will not be considered.

TRIZ, also known as the Theory of Inventive Problem Solving, is an algorithmic approach to technical problem solving and idea generation [Fey and Rivin, 2005]. The parts of the theory used here are contradiction resolution and the law of ideality. Both of the theories direct to developing better designs of systems by avoiding conflicts [Yang and Zhang, 2000].

The successes of various intersection designs through this work are evaluated in three ways. First, traditional traffic conflict techniques [USDOT] are used to determine the number and type of traffic conflicts in the system. Second, the functional requirements and design parameters of the system are considered and the changes made in the process of redesigning an intersection are discussed. Finally, a hybrid design matrix using both AD and traffic conflict theory is used to determine the nature of the coupling in the system.

4 CASE STUDY #1

The first case study comes from a series of examples in the Iowa Statewide Urban Design Manuals. [SUDAS] Three options for redesigning a generic unregulated 4-way intersection (figure 1) using three different types of raised medians are presented. Each option is intended to reduce the number of conflict points in the intersection. For convenience, we will assume that each intersection is aligned with the cardinal directions (north, south, east, and west.)

4.1 ORIGINAL DESIGN

Traditional traffic conflict techniques reveal 32 conflicts associated with the generic 4-way intersection. [SUDAS] This number includes 16 crossings, 8 diverging conflicts and 8 merging conflicts. In part 1 of this work, we demonstrated that 12 functional requirements associated with navigation can be identified for this intersection (figure 2) and a hybrid design matrix can be constructed (figure 3).

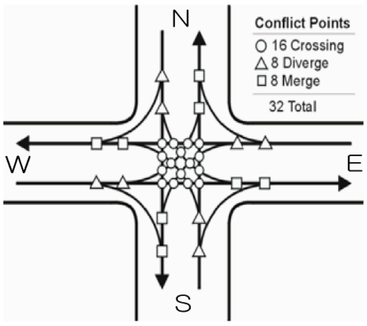
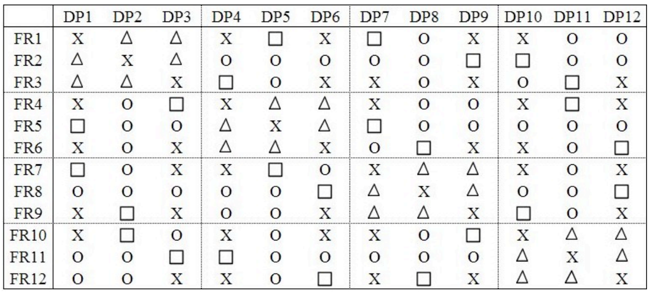


Figure 1. Conflict points of a typical two-lane four-way intersection or driveway [SUDAS]

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 2. The 12 functional requirements



	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 3. Hybrid design matrix with conflict specification for a generic 4-way intersection

4.2 ALTERNATIVE #1

The first alternative intersection presented in the design manual uses a continuous raised median to separate the east-west and west-east traffic streams. The redesigned intersection permits each lane of traffic to exit or enter from the right.

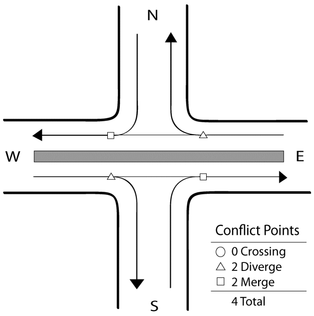


Figure 4. Conflict points for the first alternative to the generic 4-way intersection

From a traditional traffic conflict perspective, the first alternative is a major improvement over the previous intersection. The total number of conflicts has been reduced from 32 to 4. In addition, all crossing conflicts have been eliminated.

However, from an axiomatic design perspective, the situation is more complicated. By adding the raised median, the functional requirements of the intersection have been changed. Instead of having 12 FRs for the intersection, the design now has 6 FRs (figure 7). The design matrix is still fully coupled (figure 8), but all of the coupling within the matrix is either weak or moderate coupling. All of the strong coupling has been eliminated.

FR1 N→W
FR2 W→E
FR3 W→S
FR4 E→N
FR5 E→W
FR6 S→E

Figure 7. Functional requirements for alternative #1

	DP1	DP2	DP3	DP4	DP5	DP6
FR1	X	O	O	O	□	O
FR2	O	X	Δ	O	O	□
FR3	O	Δ	X	O	O	O
FR4	O	O	O	X	Δ	O
FR5	□	O	O	Δ	X	O
FR6	O	□	O	O	O	X

Figure 8. Hybrid design matrix for alternative #1

4.3 ALTERNATIVES #2 AND #3

The second and third alternative designs use a raised median with a through-way cut to permit vehicles to travel across it from one direction (figure 9).

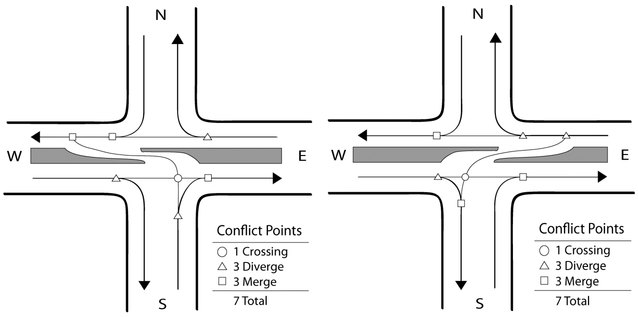


Figure 9. Conflict points for Alternative #2 (right) and Alternative #3 (left) [modified from SUDAS]

Again, the number of conflicts for each alternative has been substantially reduced compared to the original intersection. Both intersections now have a total of 7 conflicts: 1 crossing, 3 diverging, and 3 merging.

And again, the modifications to the intersection have changed the functional requirements (figure 10). Both alternatives feature 7 FRs instead of the original 12. The hybrid design matrices for each of the alternatives are fully coupled and exhibit two instances of strong coupling due to the crossing conflicts. The hybrid design matrices are shown in figures 11 and 12.

FR1 N→W
FR2 W→E
FR3 W→S
FR4 E→N
FR5 E→W
FR6 S→W
FR7 S→E

FR1 N→W
FR2 W→E
FR3 W→S
FR4 E→S
FR5 E→N
FR6 E→W
FR7 S→E

Figure 10. Functional requirements for 2nd (left) and 3rd (right) alternatives

	DP1	DP2	DP3	DP4	DP5	DP6	DP7
FR1	X	O	O	O	□	□	O
FR2	O	X	Δ	O	O	X	□
FR3	O	Δ	X	O	O	O	O
FR4	O	O	O	X	Δ	O	O
FR5	□	O	O	Δ	X	□	O
FR6	□	X	O	O	□	X	Δ
FR7	O	□	O	O	O	Δ	X

Figure 11. Hybrid design matrix for alternative #2

	DP1	DP2	DP3	DP4	DP5	DP6	DP7
FR1	X	O	O	O	O	□	O
FR2	O	X	Δ	X	O	O	□
FR3	O	Δ	X	□	O	O	O
FR4	O	X	□	X	Δ	Δ	O
FR5	O	O	O	Δ	X	Δ	O
FR6	□	O	O	Δ	Δ	X	O
FR7	O	□	O	O	O	O	X

Figure 12. Hybrid design matrix for alternative #3

4.4 DISCUSSION

In the examples above, the number of traffic conflicts in the system and the coupling in the hybrid design matrix were reduced by eliminating some of the functional requirements of the intersections. From a TRIZ perspective, this indicates a contradiction between the functionality and safety of traffic intersections that must be resolved to permit further innovation.

From an axiomatic design perspective, it is equally problematic. Functional requirements represent the "minimum set of independent requirements that completely [characterize] the functional needs of the product." [Suh, 2001] If the functional requirements of the intersection must be changed to produce an acceptable design, either the initial set of FRs did not represent the minimum set of required functions or the final set of DPs does not satisfy the minimum set of required FRs.

Ultimately, the FRs that were removed from these designs will have to be added to another part of the traffic system. They may be spread out over longer stretches of roads, incorporated into other intersections, or satisfied through other road features like u-turn lanes, but they cannot be eliminated entirely. Axiomatic design theory may be very useful for keeping track of various requirements as they are shuffled between various parts of the traffic network.

4.5 PROPOSED SOLUTION

In this case, there is a simple way to resolve the conflict. Two u-turns could be added through the raised median (figure 13). This would permit all of the original functional requirements to be met with a total cost of 8 traffic conflicts (4 merging and 4 diverging) and substantially less coupling in the design matrix.

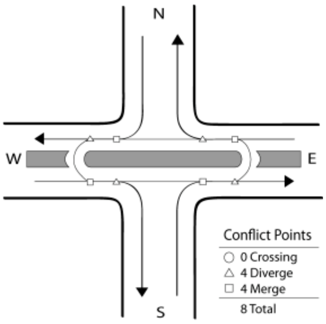


Figure 13. Conflict points of proposed solution

Unlike the previous intersections, this design does not have 12 FRs. It has 16 FRs (figure 15) because the inclusion of the u-turn areas permits vehicles to turn around and go back in the direction that they came from. Thus, this set of FRs represents the full minimum set of independent FRs for a 4-way intersection. The hybrid design matrix for the proposed intersection is shown in Figure 16.

FR1 N→N	FR9 E→S
FR2 N→S	FR10 E→N
FR3 N→W	FR11 E→W
FR4 N→E	FR12 E→E
FR5 W→W	FR13 S→W
FR6 W→E	FR14 S→E
FR7 W→S	FR15 S→N
FR8 W→N	FR16 S→S

Figure 15. The 16 FRs of the proposed solution

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12	DP13	DP14	DP15	DP16
FR1	X	△	△	△	⊠	⍍	⍍	□	⊠	□	⊠	⊠	⊠	⍍	□	⊠
FR2	△	X	△	△	⊠	⍍	□	⍍	□	O	⍍	⍍	⍍	O	O	□
FR3	△	△	X	△	□	O	O	O	⍍	O	□	⍍	□	O	O	⍍
FR4	△	△	△	X	⊠	□	⍍	⍍	⍍	O	⍍	□	⊠	□	⍍	⊠
FR5	⊠	⊠	□	⊠	X	△	△	△	⊠	⍍	□	⊠	□	⍍	⍍	⊠
FR6	⍍	⍍	O	□	△	X	△	△	⍍	O	O	□	⍍	□	⍍	⊠
FR7	⍍	□	O	⍍	△	△	X	△	□	O	O	⍍	O	O	O	□
FR8	□	⍍	O	⍍	△	△	△	X	⊠	□	⍍	⊠	⍍	⍍	□	⊠
FR9	⊠	□	⍍	⍍	⊠	⍍	□	⊠	X	△	△	△	⍍	O	⍍	□
FR10	□	O	O	O	⍍	O	O	□	△	X	△	△	⍍	O	□	⍍
FR11	⊠	⍍	□	⍍	□	O	O	⍍	△	△	X	△	□	O	⍍	⍍
FR12	⊠	⍍	⍍	□	⊠	□	⍍	⊠	△	△	△	X	⊠	□	⊠	⊠
FR13	⊠	⍍	□	⊠	□	⍍	O	⍍	⍍	⍍	□	⊠	X	△	△	△
FR14	⍍	O	O	□	⍍	□	O	⍍	O	O	O	□	△	X	△	△
FR15	□	O	O	⍍	⍍	⍍	O	□	⍍	□	⍍	⊠	△	△	X	△
FR16	⊠	□	⍍	⊠	⊠	⊠	□	⊠	□	⍍	⍍	⊠	△	△	△	X

Figure 16. Hybrid design matrix of proposed solution (16 FR Version)

If removing FRs in the previous examples was questionable, is adding FRs not equally problematic? Again, the answer seems to lie in the transportation network and not within the intersection itself. The ability to return to one's origin is almost always possible. However, it usually requires using four generic 4-way intersections (to turn right, right, right, and then left) to retrace one's path instead of being able to do so within a single intersection. Thus, from the networks' perspective, we have not added any FRs. We have simply used physical integration to bring them all into a single intersection.

5 CASE STUDY #2

5.1 CURRENT INTERSECTION

The second case study is a real intersection located in a heavily travelled part of Daejeon, South Korea (figure 17). This intersection does not align with the cardinal directions (north, south, east and west), but we will assume that it does for convenience.

This intersection connects three roads: a major 10-lane north-south highway, a large 6-lane east-west road, and another smaller 2-lane east-west road.

This intersection is located along the raised bank of a small river (the Gapcheon). The smaller east-west two-lane road is connected to the larger east-west six-lane road via a section of road that goes under the 10-lane highway along the river bed. This under-bridge (UB) section can flood in heavy rains.

A large supermarket and department store (Homever) is also located at one corner of the intersection. One of the two entrances into the store is located along the six-lane east-west road and frequently adds to traffic congestion.

The 10-lane highway is divided by a raised median. U-turns along this road are not possible. However, the six lane road is divided only by a painted median. U-turns across the media from the east-west direction are legal and common.

There are no traffic lights present in any part of this intersection, although there are traffic signals located in adjacent intersections in all directions.

Figure 17. Google Earth map of the current intersection

The intersection was considered from two different perspectives. First, a holistic approach was used to consider the intersection. Then, the intersection was broken down into various components and considered from a modular perspective.

5.2 HOLISTIC ANALYSIS OF CURRENT INTERSECTION

Traditional traffic conflict techniques reveal a total of 19 conflicts in this intersection (figure 18) including 3 crossing conflicts, 8 diverging conflicts, and 8 merging conflicts. The majority of the conflicts, including all of the crossing conflicts, are located at the west end of the under-bridge section. The conflicts themselves rarely cause traffic accidents because vehicle speeds here are low, but they can cause significant traffic delays.

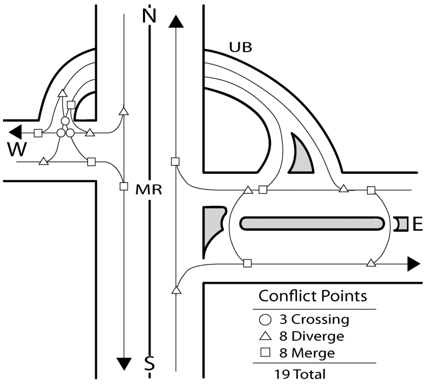


Figure 18. Conflict points of the current intersection

From an axiomatic design perspective, the entire intersection performs 16 functions: it allows vehicles from any direction to travel to any direction, including the direction that they came from (figure 19). The hybrid design matrix for the intersection is fully coupled, and includes a number of strong coupling terms associated with the crossing intersections (figure 20). Since this intersection is asymmetric, the design matrix associated with it is also asymmetric.

FR1 N→N	FR9 E→S
FR2 N→S	FR10 E→N
FR3 N→W	FR11 E→W
FR4 N→E	FR12 E→E
FR5 W→W	FR13 S→W
FR6 W→E	FR14 S→E
FR7 W→S	FR15 S→N
FR8 W→N	FR16 S→S

Figure 19. Functional requirements of the current intersection

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12	DP13	DP14	DP15	DP16
FR1	X	△	△	△	⍍	⍍	o	□	o	□	o	⍍	o	o	□	o
FR2	△	X	△	△	o	o	□	o	□	o	o	o	o	o	o	□
FR3	△	△	X	△	X□	X	o	X	X	o	□	o	□	o	o	X
FR4	△	△	△	X	⍍	□	o	⍍	o	⍍	o	□	⍍	□	o	⍍
FR5	⍍	o	X□	⍍	X	△	△	△	X⍍	⌺	□	⌺	□	⍍	o	X⍍
FR6	⍍	o	X	□	△	X	△	△	X	⍍	o	□	⍍	□	o	X⍍
FR7	o	□	o	o	△	△	X	△	□	o	o	o	o	o	o	□
FR8	□	o	X	⍍	△	△	△	X	X	□	o	⍍	o	o	□	X
FR9	o	□	X	o	X⍍	X	□	X	X	△	△	△	⍍	o	o	□
FR10	□	o	o	⍍	⌺	⍍	o	□	△	X	△	△	⍍	o	□	⍍
FR11	o	o	□	o	□	o	o	o	△	△	X	△	□	o	o	⍍
FR12	⍍	o	o	□	⌺	□	o	⍍	△	△	△	X	⌺	□	o	⌺
FR13	o	o	□	⍍	□	⍍	o	o	⍍	⍍	□	⌺	X	△	△	△
FR14	o	o	o	□	⍍	□	o	o	o	o	o	□	△	X	△	△
FR15	□	o	o	o	o	o	o	□	o	□	o	o	△	△	X	△
FR16	o	□	X	⍍	X⍍	X⍍	□	X	□	⍍	⍍	⌺	△	△	△	X

Figure 20. Hybrid design matrix for the current intersection

5.3 ASYMMETRY IN THE DESIGN MATRIX

The asymmetry of this matrix is interesting from a design perspective. In part 1 of this work, all of the intersections considered were symmetric, thus vehicles traveling from and to each direction were equally affected. In this work, the intersections in figure 9 and the intersection in figure 18 are all asymmetric. Travelers from some directions are more negatively impacted than others. For example, in figure 18 the south-north and north-south travelers on the major highway are relatively unaffected by the problems in the intersection design. However, travelers who are traveling to or from the west via the smallest road are confronted with the majority of the traffic conflicts.

The hybrid design matrix is especially effective at showing the extent of the coupling for each of the various routes. The number and types of conflicts that will be encountered by vehicles traveling along any path can be found by looking at the horizontal line in the matrix associated with that FR. For example, FR2 shows 3 diverging and 3 merging conflicts for a vehicle traveling from the north to the south while FR16 has 4 crossing conflicts, 1 double merging-diverging conflict, 5 merging-diverging conflicts, 3 merging and 3 diverging conflicts for vehicles coming from and returning to the south.

A single conflict is counted multiple times in the design matrix based on the number of traffic streams that are affected by it. For example, a N-S vehicle will only encounter one diverging conflict but may be affected by that conflict up to three times as the N-W, N-E and N-N traffic streams diverge there.

Ultimately, it should be possible to assign weights to each type of conflict and add the relative conflict contributions in each horizontal line in the matrix. This would help to quantitatively identify the paths that are most negatively affected by the current design and identify areas of the intersection design that are in the greatest need of improvement.

5.4 MODULAR ANALYSIS OF CURRENT INTERSECTION

Alternatively, the intersection can be viewed as being composed of five different modules (figure 21). The functional requirements for each sub-intersection or module can be defined as sub-FRs of the entire design. The conflict points can be identified and the hybrid design matrix can be constructed for each (figures 22 - 26). The various modules can then be recombined to create the overall hybrid design matrix (figure 27).

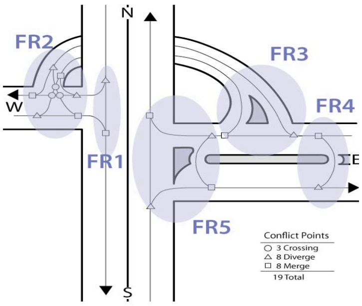
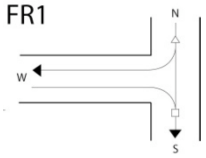


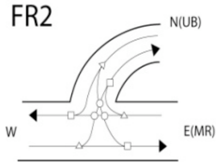
Figure 21. Modular view of current intersection



FR11 N→S
FR12 N→W
FR13 W→S

	DP1	DP11	DP12	DP13
FR1	X			
FR11		X	△	□
FR12		△	X	O
FR13		□	O	X

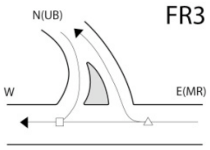
Figure 22. Module #1



FR21 N→E FR24 W→N
FR22 N→W FR25 E→W
FR23 W→E FR26 E→N

	DP2	DP21	DP22	DP23	DP24	DP25	DP26
FR2	X						
FR21		X	△	□	X	X	O
FR22		△	X	O	O	□	O
FR23		□	O	X	△	O	O
FR24		X	O	△	X	X	□
FR25		X	□	O	X	X	△
FR26		O	O	O	□	△	X

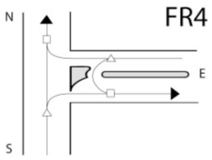
Figure 23. Module #2



FR31 N→W
FR32 E→W
FR33 E→N

	DP3	DP31	DP32	DP33
FR3	X			
FR31		X	□	O
FR32		□	X	△
FR33		O	△	X

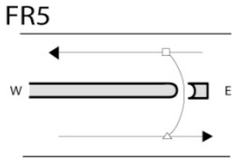
Figure 24. Module #3



FR41 S→N
FR42 S→E
FR43 E→N
FR44 E→E

	DP4	DP41	DP42	DP43	DP44
FR4	X				
FR41		X	△	□	O
FR42		△	X	O	□
FR43		□	O	X	△
FR44		O	□	△	X

Figure 25. Module #4



FR51 W→E
FR52 W→W
FR53 E→W

	DP5	DP51	DP52	DP53
FR5	X			
FR51		X	△	O
FR52		△	X	□
FR53		O	□	X

Figure 26. Module #5

In many ways, the modular view of the intersection is more useful than the holistic view. It is immediately obvious that the second module performs the most sub-functions and is the only location that exhibits strong coupling due to crossing conflicts. The easy identification of the most troubled spot in the design is a great help to designers who can then focus their attention on that module.

However, the modular view also raises some difficult questions. How do we handle the inter-modular dependencies? They are clearly linked by roadways and thus are physically coupled. The question is: are they functionally coupled? The answer seems to depend on the capacity of the roadways connecting the modules and on the traffic volume.

In light traffic, there are few cars on the road and each module may be functionally independent. All of the additional terms in the design matrix will be 0's.

However, in heavy traffic, vehicles may begin to accumulate behind a problematic intersection. When the number of vehicles in the queue to enter the intersection exceeds the capacity of the road between the two modules, the first module will begin to affect the second. The two modules are now coupled. During rush hour, this intersection is fully coupled with all off-diagonal terms turning to X's.

The capacity of any road is a function of the length of the road and the number of lanes, and is generally a fixed quantity. (The size of the vehicles in the queue will also affect the capacity, but in general the variation due to vehicle size will be small and can be neglected.)

The distance between conflicts within the same module will also affect the coupling between them. Conflicts that are located close together will have a stronger negative impact on traffic than conflicts that are further apart.

In a more careful axiomatic analysis, these distances can be included in the design architecture as design parameters. This will be the subject of future work.

It should also be possible to apply this technique to traffic systems instead of single intersections. This will also be the subject of future work.

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33	DP4	DP41	DP42	DP43	DP44	DP5	DP51	DP52	DP53
FR1	X																							
FR11		X	△	□																				
FR12		△	X	o																				
FR13		□	o	X																				
FR2					X																			
FR21						X	△	□	X	X	o													
FR22						△	X	o	o	□	o													
FR23						□	o	X	△	o	o													
FR24						X	o	△	X	X	□													
FR25						X	□	o	X	X	△													
FR26						o	o	o	□	△	X													
FR3												X												
FR31													X	□	o									
FR32													□	X	△									
FR33													o	△	X									
FR4																X								
FR41																	X	△	□	o				
FR42																	△	X	o	□				
FR43																	□	o	X	△				
FR44																	o	□	△	X				
FR5																					X			
FR51																						X	△	o
FR52																						△	X	□
FR53																						o	□	X

Figure 27. Hybrid design matrix for modular version of current intersection

5.5 PROPOSED SOLUTION

Based on the above discussion, it should be possible to redesign this intersection to reduce the number of traffic conflicts and reduce the coupling in the design matrix while maintaining all 16 of the original FRs. We propose a modified clover-leaf type interchange with u-turns to satisfy the last 4 FRs (figure 28).

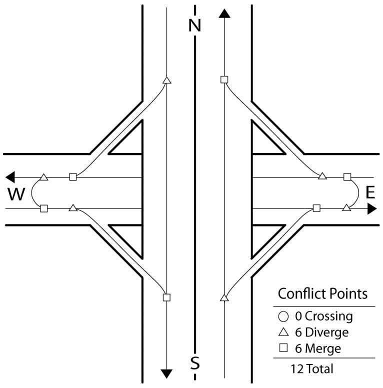


Figure 28. Conflict points for the proposed solution

Figure 28 is not to scale. The u-turns should be further away from the on- and off-ramps in a real intersection to prevent additional problems. If necessary, the u-turns could be incorporated into the intersections immediately upstream and downstream from this one.

This new design results in a total of 12 conflicts (6 diverging and 6 merging.) This design does not lend itself as well to the modular approach, so the holistic hybrid design matrix was created instead.

The hybrid design matrix shows the same characteristics of the clover-leaf matrix in part 1 of this work. All of the crossing conflicts have been eliminated and replaced with 0's. However, some of the terms which were previously uncoupled now have single or double merging-diverging conflicts. The overall coupling of the design matrix has been reduced, but the system still has a fully coupled matrix.

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12	DP13	DP14	DP15	DP16
FR1	X	△	△	△	⊠	▨	▨	□	⊠	□	⊠	⊠	⊠	▨	□	⊠
FR2	△	X	△	△	o	o	□	o	□	o	o	o	o	o	o	□
FR3	△	△	X	△	□	o	o	o	▨	o	□	▨	□	o	o	▨
FR4	△	△	△	X	⊠	□	▨	▨	▨	o	▨	□	⊠	□	o	⊠
FR5	⊠	o	□	⊠	X	△	△	△	⊠	▨	□	⊠	□	▨	o	⊠
FR6	▨	o	o	□	△	X	△	△	▨	o	o	□	▨	□	o	⊠
FR7	▨	□	o	▨	△	△	X	△	□	o	o	▨	o	o	o	□
FR8	□	o	o	▨	△	△	△	X	⊠	□	▨	⊠	▨	▨	□	⊠
FR9	⊠	□	▨	▨	⊠	▨	□	⊠	X	△	△	△	▨	o	o	□
FR10	□	o	o	o	▨	o	o	□	△	X	△	△	▨	o	□	▨
FR11	⊠	o	□	▨	□	o	o	▨	△	△	X	△	□	o	o	▨
FR12	⊠	o	▨	□	⊠	□	▨	⊠	△	△	△	X	⊠	□	o	⊠
FR13	⊠	o	□	⊠	□	▨	o	▨	▨	▨	□	⊠	X	△	△	△
FR14	▨	o	o	□	▨	□	o	▨	o	o	o	□	△	X	△	△
FR15	□	o	o	o	o	o	o	□	o	□	o	o	△	△	X	△
FR16	⊠	□	▨	⊠	⊠	⊠	□	⊠	□	▨	▨	⊠	△	△	△	X

Figure 25. Hybrid design matrix for the proposed solution

The proposed design does not take into account any of the constraints of the current design. It is not known if there are geotechnical issues associated with the available land or other factors which would exclude these changes. Instead, the proposed solution is presented merely as an example.

5.6 REDUNDANCY IN THE DESIGN

Redundancy becomes an issue in intersection designs which include all 16 FRs. Consider the example in figure 28. There are two possible ways to travel N-S and S-N: (1) the vehicle can continue to travel straight on the highway, or (2) it could exit the highway onto the W-E travelling road, make a u-turn, and re-enter the highway from the E-W travelling road. The first option was intentionally created by the designers. The second option was a by-product of different FRs and DPs in the design. Is the intersection redundant? Or does the fact that one option is clearly better than the other make this a non-issue?

Consider a slightly different example. What if N-S and S-N u-turns had been added into the design in figure 28? This would have made FR1 (N-N) and FR16 (S-S) substantially simpler. But it would have created 12 redundant paths: N-S, S-

N, W-E, E-W, E-S, S-W, N-E, W-N, N-N, S-S, E-E, and W-W. Does the improved ease of travel in two directions justify the increase in redundancy in the intersection?

It seems that there is a conflict between minimizing the length of each path in the system and reducing the redundancy in the system. This will be considered further in future work.

6 CONCLUSIONS

In this paper, axiomatic design theory, traditional traffic conflict techniques, and TRIZ were used to examine two intersections: one from the literature and one that is currently in use. It was demonstrated that a generic 4-way intersection can have up to 16 FRs associated with navigation, although most intersections only have 12 FRs. It was shown that common strategies to redesign intersections frequently result in an unnecessary loss of functional requirements. A complex intersection was viewed both holistically and from a modular perspective to demonstrate the differences in functional requirements and the hybrid design matrix. The holistic approach is helpful for examining the complete path of any vehicle. The modular approach seems to have advantages for considering different components of complex intersections and has great potential for exploring larger networks of intersections. Finally, redundancy in intersection design and symmetry in the design matrix were discussed.

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