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QUANTIFYING THE IMPACT OF COUPLING IN AXIOMATIC DESIGN: CALCULATING THE COUPLING IMPACT INDEX FOR TRAFFIC INTERSECTIONS

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ABSTRACT

This work proposes a new method to quantify the coupling in hybrid design matrices for traffic intersections by taking into account the presence of coupling, the types of conflict that coupling may introduce, and the impact that the conflict may have on the intersection. The result is a single numerical value, called the coupling impact index, which can be used to select the safest intersection design for a given situation. This technique is demonstrated with a case study which calculates the coupling impact index for three traffic intersections based on two sets of traffic conditions and suggests the best intersection for the anticipated traffic volumes provided.

Keywords: Traffic Intersections, Coupling, Coupling Impact Index, Hybrid Design Matrix, Axiomatic Design

1 INTRODUCTION

An unregulated 4-way traffic intersection can be modeled as a system with 16 functional requirements (FRs) that permit travel to and from every direction and a corresponding set of 16 design parameters (DPs) which represent sections of the roadway [Thompson *et al.*, 2009a]. At the center of the intersection, each travel vector must share a portion of the road with some or all of the others. Thus, each FR is related to multiple DPs, resulting in a fully coupled design matrix. This coupling offers great potential for conflict between traffic streams, which in turn can reduce the safety and efficiency of the intersection.

Axiomatic Design (AD) Theory urges the designer to reduce the coupling in all systems in order to reduce the complexity and increase the probability of success of the design [Suh 2001]. Similarly, TRIZ requires the designer to seek out and eliminate physical and technical contradictions within the design [Altshuller, 2005]. Both can be accomplished by using traffic signals to introduce periodicity into the system and separate the traffic streams in time. However, this strategy increases the safety of intersection at the cost of efficiency.

For systems with high throughput and vehicles travelling at high speeds, the use of traffic signals to reduce the coupling in the system is not an option. In these cases, the traffic streams must be separated in space instead of time. A number of unregulated intersections and interchanges have been developed for this purpose, ranging from traditional rotaries and clover-leaf interchanges to more complex grade-separated options like single point urban interchanges [Bonneson and Messer, 1989], and echelon interchanges [Shin *et al.*, 2008]. However, which intersection to use at a given location is often unclear.

This work proposes a new method to quantify the coupling in hybrid design matrices for traffic intersections by taking into account the presence of coupling, the types of conflict that coupling may introduce, and the impact that the conflict may have on the intersection. The result is a single numerical value, called the coupling impact index, which can be used in the intersection or interchange selection process. This technique is demonstrated with a case study which calculates the coupling impact index for three traffic intersections based on two sets of traffic conditions and suggests the safest intersection for the anticipated traffic volumes provided.

2 PRIOR ART

One of the first attempts to quantify coupling in the design matrix came from Suh and Rinderle [1982] who defined coupling as the partial derivative of each FR with respect to each DP. In order to estimate the degree of coupling in a design, Suh [1990] proposed calculating the "reangularity" R and the "semangularity" S of the design matrix based on the angular relationship between the design matrix vectors for each DP. Bae *et al.* [2002] applied those measures to evaluate three types of suspension systems. However, Cebi and Kahraman [2010] noted that "the calculation procedure of R and S values is inconvenient when the number of FRs and DPs increase." Instead, they proposed using fuzzy set theory to quantify the degree of independence of the design by calculating the "coupled ratio" and the "uncoupled ratio" based on the entries in the design matrix.

Most of the existing methods to quantify coupling in the design matrix rely on deriving mathematical relationships between the elements of a quantitative design matrix. However, AD is equally (and perhaps more) useful for the design of systems where a qualitative or binary design matrix is more appropriate or where a quantitative design matrix cannot be constructed. In these cases, another method to quantify the coupling in the design matrix is needed.

3 METHODS

In this work, the hybrid design matrix introduced by Thompson et al. [2009a, 2009b] is constructed for each intersection of interest. Each element in the hybrid design matrix is assigned a numerical value based on the severity of the conflict that it represents. A second numerical value is assigned based on the predicted frequency of collisions caused by that conflict. The impact of the coupling in that element is determined by multiplying these two values. Finally, the coupling impact index of the entire matrix is calculated by summing the impact of each element in the hybrid design matrix.

Once the coupling impact index for each traffic intersection has been calculated, the values can be compared to determine which intersection is the most desirable both from the perspective of the Independence Axiom and from traditional traffic conflict theory. The coupling impact index can then be used as part of a formal concept selection process.

3.1 CONSTRUCTING THE HYBRID DESIGN MATRIX

The hybrid design matrix for traffic intersections combines elements of Axiomatic Design Theory, TRIZ, and traditional traffic conflict techniques [Parker and Zegeer, 1989]. The functional requirements (FRs) represent each travel vector, while the design parameters (DPs) represent the sections of the roadway that connect each origin to its destination. Each element of the hybrid design matrix is composed of one or more symbols which denote the presence of coupling and the type of traffic conflict which may occur as a result of that coupling. When multiple conflicts are present in a single location, multiple symbols are used in the design matrix.

In this work, four different types of vehicular conflicts [Rodegerdts *et al.*, 2004] are included in the hybrid design matrix and a fifth symbol is added to those from the previous study. Crossing (angle) conflicts, which are generated by two through traffic streams, are indicated by a ●. Crossing (left-turn) conflicts, which occur when one or both traffic streams are turning left, are indicated by an X. Merging conflicts are denoted by a square □ and diverging conflicts are denoted by a triangle ∆. A lack of coupling and conflict in the design matrix is denoted by an O.

In the event that two traffic streams have multiple opportunities to interact and collide, the symbols for each conflict encountered during travel are combined. For example, vehicles in a rotary may experience one merging conflict □, one diverging conflict ∆, one merging and one diverging conflict □∆, or two merging and two diverging conflicts 2□∆ during their trip around the circle [Thompson *et al.* 2009a].

3.2 DEFINING THE IMPACT OF CONFLICT IN TRAFFIC INTERSECTIONS

Coupling in AD can be thought of as the potential for conflict, and thus harm, in a design. There is no guarantee that changing one DP will interfere with the success of another FR. Whether or not harm occurs will depend on the relationships between the coupled FRs and DPs.

Similarly, conflict in a traffic intersection can be thought of as the potential for harm (i.e. a traffic accident or collision) rather than the presence of harm itself. Amundsen and Hyden [1977] defined traffic conflict as "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remained unchanged." [Chin and Quek, 1977] There is no guarantee that one vehicle will cause harm to another. Whether or not harm occurs depends on the conditions of the road, the conditions of the vehicles, and the actions of the drivers.

As a result, we cannot simply measure the coupling in a given intersection. We must measure the impact that the coupling has or may have on the performance of the intersection. In this work, we will focus on the impact of coupling on the safety of the intersection and set aside considerations of efficiency for future work.

Hauer [1982] proposed that system safety should be defined as "the expected number of accidents in each severity class" and that the number of accidents should be "proportional to the number of conflicts occurring" in a given system. Sayed and Zein [1998] confirmed this proportionality, reporting that a number of researchers including Spicer *et al.* [1979] and Salman and Al-Maita [1995] "investigated the relationship between traffic conflicts and volumes" and found that "the total number of traffic conflicts is proportional to the square root of the product of the conflicting volumes." This referred to by Sayed and Zein as the "product of entering vehicles" (PEV):

$$\text{PEV} = ((V_1)(V_2))^{0.5} \qquad (1)$$

where V_1 and V_2 represent the traffic volumes (vehicles/hour) of two conflicting traffic streams.

Based on Hauer's definition of safety, we can characterize the impact of coupling on the safety of any given intersection as the product of the PEV at each conflict point i multiplied by the severity of the potential collision caused by the presence of that traffic conflict point summed over all of the traffic conflict points in the intersection.

$$\text{Coupling Impact Index} = \sum_i (\text{PEV}_i)(\text{Severity}_i) \qquad (2)$$

Many factors contribute to the risk of injury and the ultimate severity of automotive collisions including the relative sizes and weights of the vehicles [Nordhoff, 2005], the design of the vehicles [Kockelman and Kweon, 2002], the type of collision, the location of the passengers in the car, the use of seatbelts [McGwin et al, 2003], the use of alcohol [Kockelman and Kweon, 2002], and the age [McGwin et al, 2003] and gender [Kockelman and Kweon, 2002] of the vehicle occupants.

Although few severity models take all of these factors into account, Nassar *et al.* [1994] proposed a comprehensive "disaggregate model for predicting the extent of personal injury and death sustained in road accidents." Their model included a dynamic estimate of the "impact forces generated in each accident based on principles of momentum and kinetic energy" as well as active and passive risk factors such as driver conditions (normal or impaired), driver seating position, seat belt use, vehicle mass, and occupant age.

This work uses the dynamic term for two vehicle accidents developed by Nassar et al. to estimate the severity of traffic conflict in the hybrid design matrix. The relation is given by:

$$\text{Severity} = \Delta KE = 1/2\,(m_1((v_1 \sin\theta_1)^2 + (v_1 \cos\theta_1)^2) + (m_2((v_2 \sin\theta_2)^2 + (v_2 \cos\theta_2)^2)) - 1/2\,(m_1 + m_2)v_f \quad (3)$$

where m and v represent the mass and velocity of each vehicle, θ is the "angle of orientation between each vehicle and the direction of travel," and v_f is the final velocity of the fused mass of the two cars. v_f is estimated by assuming that the change in momentum ΔM is zero:

$$\Delta M = [(m_1 v_1 \sin\theta_1 + m_2 v_2 \sin\theta_2)^2 + (m_1 v_1 \cos\theta_1 + m_2 v_2 \cos\theta_2)^2]^{0.5} - (m_1 + m_2)v_f = 0 \quad (4)$$

In this work, the first vehicle in any potential conflict is assumed to have an initial velocity of 50 km/hour. For crossing (angle) conflicts, the second vehicle is assumed to be travelling at the same velocity and the angle between the two vehicles is assumed to be 90˚. The velocities and vehicular angles for the other traffic conflicts were taken from Nassar et al. and are shown in table 1. Crossing (left-turn) conflicts are assumed to be equivalent to the turning conflicts in Nassar et al. Diverging conflicts are assumed to be equivalent to lane changes. All of the vehicles in this work are assumed to have the same mass.

Table 1. Velocity and angle for each conflict type.

Conflict type	Velocity (km/hour)	Angle
Crossing (Angle)	$v_1 = 50$, $v_2 = 50$	90˚
Crossing (Left-Turn)	$v_1 = 50$, $v_2 = 12.5$	0˚
Merging	$v_1 = 50$, $v_2 = 35$	15˚
Diverging	$v_1 = 50$, $v_2 = 45$	10˚

The severity is given by the change in kinetic energy (ΔKE) of a collision caused by each conflict type and is calculated by equations (3) and (4). The severity is greatest in crossing (angle) conflicts, followed by crossing (left-turn), merging, and diverging conflicts (table 2).

Table 2. Severity weights by conflict type.

Conflict type	Symbol	ΔKE	Severity
Crossing (Angle)	●	1250M	54.35
Crossing (Left-Turn)	X	352M	15.30
Merging	□	86M	3.73
Diverging	∆	23M	1

3.3 Calculating The Coupling Impact Index

The coupling impact index for the hybrid design matrix is calculated using equation (2). First, each symbol in the hybrid design matrix is replaced by the corresponding value shown in table 2. This represents the severity weighting for each type of conflict present in the intersection. The severity weighting in each cell is then multiplied by the product of entering vehicles (equation 1) calculated based on the measured or anticipated traffic volume streams in each direction. Finally, the resulting products from the cells of the hybrid design matrix are summed to yield a single numerical value which represents the risk associated with the traffic intersection.

If multiple conflicts are present in a given cell of the hybrid design matrix, the sum of the severity values for all of the symbols present is calculated before multiplying by the PEV. This is done for convenience since the sum of each conflict/PEV product will be the same as the product of the PEV and the sums of the conflicts as long as the PEV value remains unchanged.

4 CASE STUDY: IMPACT OF INTERSECTION GEOMETRY ON COUPLING IMPACT

To demonstrate this technique, a small case study was conducted to compare three types of intersection designs: a generic unregulated four-way intersection, a staggered unregulated four-way intersection, and a clover-leaf intersection. Each intersection allows travel in 16 directions including u-turns. Traffic volumes (vehicles/hour) were randomly assigned to each traffic direction, assuming that the largest demand comes from through traffic, followed by left and right turn traffic, and then u-turn traffic (table 3). The same traffic volumes are used for all three intersections.

Table 3. Traffic volumes (vehicles/hr) by direction.

Traffic direction	Traffic volume	Traffic direction	Traffic volume
N→N	20	E→S	180
N→S	200	E→N	110
N→W	100	E→W	500
N→E	100	E→E	20
W→W	20	S→W	80
W→E	300	S→E	60
W→S	160	S→N	100
W→N	110	S→S	20

4.1 Original Design: Generic Unregulated 4-Way Intersection

A generic unregulated 4-way intersection has 128 traffic conflict points: 48 diverging conflicts, 48 merging conflicts, 24 crossing (left-turn) conflicts, and 8 crossing (angle) conflicts (table 4). The hybrid design matrix for this intersection is shown in figure 1. The severity matrix is shown in figure 2. And the coupling impact matrix with severity and traffic volumes is shown in figure 3. Summing the values in the matrix yields a coupling impact index of 182,433.

Table 4. Number of conflict points in case #1.

Conflict type	Symbol	Count
Independent	○	112
Diverging	∆	48
Merging	□	48
Crossing (Left-Turn)	X	24
Crossing (Angle)	●	8

		North Bound				West Bound				East Bound				South Bound			
		N→N	W→N	E→N	S→N	W→W	N→W	E→W	S→W	N→E	W→E	E→E	S→E	N→S	W→S	E→S	S→S
North Bound	N→N		□	□	□	O	△	O	O	△	O	O	O	△	O	O	O
	W→N	□		□	□	△	O	X	X	X	△	O	O	X	△	O	O
	E→N	□	□		□	O	O	△	O	O	O	△	O	O	O	△	O
	S→N	□	□	□		O	O	●	△	X	●	O	△	O	O	X	△
West Bound	W→W	O	△	O	O		□	□	□	O	△	O	O	O	△	O	O
	N→W	△	O	O	O	□		□	□	△	O	O	O	△	O	O	O
	E→W	O	X	△	●	□	□		□	X	O	△	O	●	O	△	O
	S→W	O	X	O	△	□	□	□		O	X	O	△	X	O	X	△
East Bound	N→E	△	X	O	X	O	△	X	O		□	□	□	△	O	X	O
	W→E	O	△	O	●	△	O	O	X	□		□	□	●	△	X	O
	E→E	O	O	△	O	O	O	△	O	□	□		□	O	O	△	O
	S→E	O	O	O	△	O	O	O	△	□	□	□		O	O	O	△
South Bound	N→S	△	X	O	O	O	△	●	X	△	●	O	O		□	□	□
	W→S	O	△	O	O	△	O	O	O	O	△	O	O	□		□	□
	E→S	O	O	△	X	O	O	△	X	X	X	△	O	□	□		□
	S→S	O	O	O	△	O	O	O	△	O	O	O	△	□	□	□	

Figure 1. Hybrid design matrix of the original intersection.

		North Bound				West Bound				East Bound				South Bound			
		N→N	W→N	E→N	S→N	N→W	W→W	E→W	S→W	N→E	W→E	E→E	S→E	N→S	W→S	E→S	S→S
North Bound	N→N		3.73	3.73	3.73	1	0	0	0	1	0	0	0	1	0	0	0
	W→N	3.73		3.73	3.73	0	1	15.3	15.3	15.3	1	0	0	15.3	1	0	0
	E→N	3.73	3.73		3.73	0	0	1	0	0	0	1	0	0	0	1	0
	S→N	3.73	3.73	3.73		0	0	54.35	1	15.3	54.35	0	1	0	0	15.3	1
West Bound	N→W	1	0	0	0		3.73	3.73	3.73	1	0	0	0	1	0	0	0
	W→W	0	1	0	0	3.73		3.73	3.73	0	1	0	0	0	1	0	0
	E→W	0	15.3	1	54.35	3.73	3.73		3.73	15.3	0	1	0	54.35	0	1	0
	S→W	0	15.3	0	1	3.73	3.73	3.73		0	15.3	0	1	15.3	0	15.3	1
East Bound	N→E	1	15.3	0	15.3	1	0	15.3	0		3.73	3.73	3.73	1	0	15.3	0
	W→E	0	1	0	54.35	0	1	0	15.3	3.73		3.73	3.73	54.35	1	15.3	0
	E→E	0	0	1	0	0	0	1	0	3.73	3.73		3.73	0	0	1	0
	S→E	0	0	0	1	0	0	0	1	3.73	3.73	3.73		0	0	0	1
South Bound	N→S	1	15.3	0	0	1	0	54.35	15.3	1	54.35	0	0		3.73	3.73	3.73
	W→S	0	1	0	0	0	1	0	0	0	1	0	0	3.73		3.73	3.73
	E→S	0	0	1	15.3	0	0	1	15.3	15.3	15.3	1	0	3.73	3.73		3.73
	S→S	0	0	0	1	0	0	0	1	0	0	0	1	3.73	3.73	3.73	

Figure 2. Severity matrix of the original intersection.

4.2 ALTERNATIVE #1: STAGGERED UNREGULATED 4-WAY INTERSECTION

The first alternative is formed by separating the north-south cross street along the east-west road (figure 4). In this design, north-south through travel requires one left and one right turn.

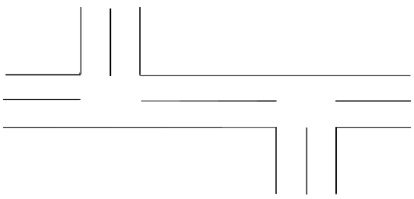

Figure 4. Schematic of Staggered Intersection.

Table 5 shows the number of conflict points in alternative #1. Figure 5 shows the hybrid design matrix for alternative #1. And figure 6 shows the coupling impact matrix for alternative #1. The staggered intersection has a total of 130 traffic conflicts: 48 diverging conflicts, 48 merging conflicts, 28 crossing (left-turn) conflicts, 4 merging/diverging conflicts and 2 double crossing (left-turn) conflicts. While the total number of conflicts is slightly higher than the original design, it contains no crossing (angle) conflicts which pose the greatest threat to vehicles and their passengers.

Table 5. Number of conflict points in alternative #1.

Conflict type	Symbol	Count
Independent	O	110
Diverging	△	48
Merging	□	48
Crossing (Left-Turn)	X	28
Crossing (Angle)	●	0
Merging / Diverging	□△	4
Double Crossing (Left-Turn)	XX	2

The staggered intersection contains two types of double conflicts: merging/diverging conflicts (□△) and double crossing (left-turn) conflicts (XX). As stated above, the severity for combined conflicts is calculated by summing the severity values for all of the conflicts at that location before multiplying them by the PEV. For example, the severity of the merging/diverging conflict is 4.73 (3.73 for the merging conflict plus 1 for the diverging conflict.) Similarly, the severity of the double crossing (left-turn) conflict is 30.6 - twice of the severity of crossing (left-turn) conflict. Note that the severity of the double conflicts is still less than the severity of the crossing (angle) conflict.

The coupling impact index for the staggered intersection is 103,183 compared to 182,433 in the original design. This is more than a 43% improvement.

		North Bound				West Bound				East Bound				South Bound			
		N→N	W→N	E→N	S→N	N→W	W→W	E→W	S→W	N→E	W→E	E→E	S→E	N→S	W→S	E→S	S→S
North Bound	N→N		□	□	□	△	O	O	O	△	O	O	O	△	O	O	O
	W→N	□		□	□	O	△	X	X	X	△	O	O	X	△	O	O
	E→N	□	□		□	O	O	△	O	O	O	△	O	O	O	△	O
	S→N	□	□	□		O	O	□△	△	X	X	O	△	O	O	X	△
West Bound	N→W	△	O	O	O		□	□	□	△	O	O	O	△	O	O	O
	W→W	O	△	O	O	□		□	□	O	△	O	O	O	△	O	O
	E→W	O	X	△	□△	□	□		□	X	O	△	O	X	O	△	O
	S→W	O	X	O	△	□	□	□		XX	X	O	△	X	O	X	△
East Bound	N→E	△	X	O	X	△	O	X	XX		□	□	□	△	O	X	O
	W→E	O	△	O	X	O	△	O	X	□		□	□	□△	△	X	O
	E→E	O	O	△	O	O	O	△	O	□	□		□	O	O	△	O
	S→E	O	O	O	△	O	O	O	△	□	□	□		O	O	O	△
South Bound	N→S	△	X	O	O	△	O	X	X	△	□△	O	O		□	□	□
	W→S	O	△	O	O	O	△	O	O	O	△	O	O	□		□	□
	E→S	O	O	△	X	O	O	△	X	X	X	△	O	□	□		□
	S→S	O	O	O	△	O	O	O	△	O	O	O	△	□	□	□	

Figure 5. Hybrid design matrix of alternative #1.

4.3 ALTERNATIVE #2: CLOVER LEAF INTERSECTION

The second alternative uses grade separation of vertically crossing roads and lateral separation of turning traffic streams to create a clover leaf intersection (figure 7).

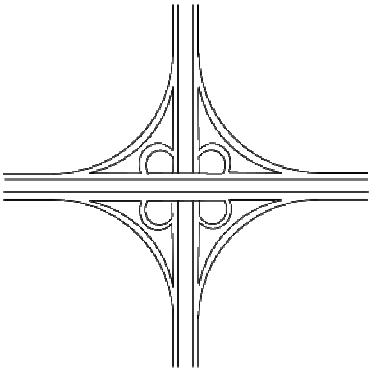

Figure 7. Schematic of Clover Leaf Intersection.

Table 6 shows the number of conflict points in alternative #2. Figure 8 shows the hybrid design matrix for alternative #2. And figure 9 shows the coupling impact matrix for alternative #2. The clover leaf intersection has a total of 136 conflict points: 48 diverging conflicts, 48 merging conflicts, 36 merging/diverging conflicts and 4 double merging / diverging conflicts.

Table 6. Number of conflict points in alternative #2.

Conflict type	Symbol	Count
Independent	O	104
Diverging	Δ	48
Merging	□	48
Crossing (Left-Turn)	X	0
Crossing (Angle)	●	0
Merging / Diverging	□Δ	36
Double Merging / Diverging	2□Δ	4

		North Bound				West Bound				East Bound				South Bound			
		N→N	W→N	E→N	S→N	N→W	W→W	E→W	S→W	N→E	W→E	E→E	S→E	N→S	W→S	E→S	S→S
North Bound	N→N		□	□	□	△	□△	O	□△	△	□△	□△	O	△	O	□△	2□△
	W→N	□		□	□	O	△	O	□△	□△	△	□△	O	O	△	O	□△
	E→N	□	□		□	O	O	△	O	O	O	△	O	O	O	△	O
	S→N	□	□	□		O	O	O	△	O	O	O	△	O	O	O	△
West Bound	N→S	△	O	O	O	△	O	O	O	△	O	O	O		□	□	□
	N→W	△	O	O	O		□	□	□	△	O	O	O	△	O	O	O
	W→W	□△	△	O	O	□		□	□	□△	△	2□△	O	O	△	□△	□△
	E→W	O	O	△	O	□	□		□	O	O	△	O	O	O	△	□△
East Bound	S→W	□△	□△	O	△	□	□	□		O	O	□△	△	O	O	□△	△
	N→E	△	□△	O	O	△	□△	O	O		□	□	□	△	O	□△	□△
	W→E	□△	△	O	O	O	△	O	O	□		□	□	O	△	O	O
	E→E	□△	□△	△	O	O	2□△	△	□△	□	□		□	O	O	△	□△
South Bound	S→E	O	O	O	△	O	O	O	△	□	□	□		O	O	O	△
	W→S	O	△	O	O	O	△	O	O	O	△	O	O	□		□	□
	E→S	□△	O	△	O	O	□△	△	□△	□△	O	△	O	□	□		□
	S→S	2□△	□△	O	△	O	□△	□△	△	□△	O	□△	△	□	□	□	

Figure 8. Hybrid design matrix of alternative #2.

In this design, all crossing conflicts are completely removed. Although the total number of conflicts is higher than for the original and staggered intersection, the coupling impact index for the clover leaf intersection is 34,099. This is a 67% improvement over the staggered intersection and an 81% improvement over the original design.

5 CASE STUDY: IMPACT OF INTERSECTION THROUGHPUT ON COUPLING IMPACT

From the first part of the case study, it is clear that the number of conflict points in a given intersection is not as important as the relative impact of the potential collisions that may result from that conflict. Thus, substituting higher severity conflict types with lower severity conflict types is a feasible strategy for improving intersection design. Similarly, reducing the severity of the conflict in the most common directions of travel will reduce the overall exposure of the intersection and also increase its safety.

However, this also means that the relative advantages of one design over another may change depending on traffic conditions. To examine how the coupling impact changes with respect to traffic volume, the same three intersections were analyzed using a different set of traffic volumes (table 7). In the first part of the case study, the highest traffic volumes were associated with through traffic. In the second part, we will consider the effects of high volumes of turns and u-turns and reduced through traffic.

Repeating the analysis above with the new traffic volumes yields a coupling impact index value of 52,064 for the original design. The staggered intersection now has a coupling impact index value of 36,143 which is a 30.5% improvement. Similarly, the clover leaf intersection now has a coupling impact index value of 36,535 which is a 30% improvement. Since both alternatives are equally good for a situation with lower traffic flows and more turns, other factors such as efficiency, cost, and the amount of space required for each intersection become more important in selecting the best design alternative.

Table 7. Variation of traffic volume (vehicles/hour).

Traffic direction	Traffic volume	Traffic direction	Traffic volume
N→N	150	E→S	50
N→S	30	E→N	110
N→W	100	E→W	30
N→E	20	E→E	150
W→W	150	S→W	20
W→E	50	S→E	60
W→S	160	S→N	100
W→N	50	S→S	150

A summary of the coupling impact index values for the three intersection designs and the two sets of traffic throughput values discussed in this work and the percent differences between those values are given in tables 8 and 9.

Table 8. Coupling impact index values based on intersection geometry and throughput.

Traffic Volume	Original design	Alternative #1	Alternative #2
Case 1 (Table 3)	182,433	103,183	34,099
Case 2 (Table 7)	52,064	36,143	36,535

		North Bound				West Bound				East Bound				South Bound			
		N→N	W→N	E→N	S→N	N→S	N→W	W→W	E→W	S→W	N→E	W→E	E→E	S→E	W→S	E→S	S→S
North Bound	N→N		1.75E+2	1.75E+2	1.67E+2	6.32E+1	4.47E+1	0.00E+0	0.00E+0	0.00E+0	4.47E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
	W→N	1.75E+2		4.10E+2	3.91E+2	2.27E+3	0.00E+0	4.69E+1	3.59E+3	1.44E+3	1.60E+3	1.82E+2	0.00E+0	0.00E+0	1.33E+2	0.00E+0	0.00E+0
	E→N	1.75E+2	4.10E+2		3.91E+2	0.00E+0	0.00E+0	0.00E+0	2.35E+2	0.00E+0	0.00E+0	0.00E+0	4.69E+1	0.00E+0	0.00E+0	1.41E+2	0.00E+0
	S→N	1.67E+2	3.91E+2	3.91E+2		0.00E+0	0.00E+0	0.00E+0	1.22E+4	8.94E+1	1.53E+3	9.41E+3	0.00E+0	7.75E+1	0.00E+0	2.05E+3	4.47E+1
West Bound	N→S	6.32E+1	2.27E+3	0.00E+0	0.00E+0		1.41E+2	0.00E+0	1.72E+4	1.94E+3	1.41E+2	1.33E+4	0.00E+0	0.00E+0	6.67E+2	7.08E+2	2.36E+2
	N→W	4.47E+1	0.00E+0	0.00E+0	0.00E+0	1.41E+2		1.67E+2	8.34E+2	3.34E+2	1.00E+2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
	W→W	0.00E+0	4.69E+1	0.00E+0	0.00E+0	0.00E+0	1.67E+2		3.73E+2	1.49E+2	0.00E+0	7.75E+1	0.00E+0	0.00E+0	5.66E+1	0.00E+0	0.00E+0
	E→W	0.00E+0	3.59E+3	2.35E+2	1.22E+4	1.72E+4	8.34E+2	3.73E+2		7.46E+2	3.42E+3	0.00E+0	1.00E+2	0.00E+0	0.00E+0	3.00E+2	0.00E+0
East Bound	S→W	0.00E+0	1.44E+3	0.00E+0	8.94E+1	1.94E+3	3.34E+2	1.49E+2	7.46E+2		0.00E+0	2.37E+3	0.00E+0	6.93E+1	0.00E+0	1.84E+3	4.00E+1
	N→E	4.47E+1	1.60E+3	0.00E+0	1.53E+3	1.41E+2	1.00E+2	0.00E+0	3.42E+3	0.00E+0		6.46E+2	1.67E+2	2.89E+2	0.00E+0	2.05E+3	0.00E+0
	W→E	0.00E+0	1.82E+2	0.00E+0	9.41E+3	1.33E+4	0.00E+0	7.75E+1	0.00E+0	2.37E+3	6.46E+2		2.89E+2	5.00E+2	2.19E+2	3.56E+3	0.00E+0
	E→E	0.00E+0	0.00E+0	4.69E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.00E+2	0.00E+0	1.67E+2	2.89E+2		1.29E+2	0.00E+0	6.00E+1	0.00E+0
South Bound	S→E	0.00E+0	0.00E+0	0.00E+0	7.75E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.93E+1	2.89E+2	5.00E+2	1.29E+2		0.00E+0	0.00E+0	3.46E+1
	W→S	0.00E+0	1.33E+2	0.00E+0	0.00E+0	6.67E+2	0.00E+0	5.66E+1	0.00E+0	0.00E+0	0.00E+0	2.19E+2	0.00E+0	0.00E+0		6.33E+2	2.11E+2
	E→S	0.00E+0	0.00E+0	1.41E+2	2.05E+3	7.08E+2	0.00E+0	0.00E+0	3.00E+2	1.84E+3	2.05E+3	3.56E+3	6.00E+1	0.00E+0	6.33E+2		2.24E+2
	S→S	0.00E+0	0.00E+0	0.00E+0	4.47E+1	2.36E+2	0.00E+0	0.00E+0	0.00E+0	4.00E+1	0.00E+0	0.00E+0	0.00E+0	3.46E+1	2.11E+2	2.24E+2	

Figure 3. Coupling impact matrix of the original intersection.

		North Bound				West Bound				East Bound				South Bound			
		N→N	W→N	E→N	S→N	N→W	W→W	E→W	S→W	N→E	W→E	E→E	S→E	N→S	W→S	E→S	S→S
North Bound	N→N		1.75E+2	1.75E+2	1.67E+2	4.47E+1	0.00E+0	0.00E+0	0.00E+0	4.47E+1	0.00E+0	0.00E+0	0.00E+0	6.32E+1	0.00E+0	0.00E+0	0.00E+0
	W→N	1.75E+2		4.10E+2	3.91E+2	0.00E+0	4.69E+1	3.59E+3	1.44E+3	1.60E+3	1.82E+2	0.00E+0	0.00E+0	2.27E+3	1.33E+2	0.00E+0	0.00E+0
	E→N	1.75E+2	4.10E+2		3.91E+2	0.00E+0	0.00E+0	2.35E+2	0.00E+0	0.00E+0	0.00E+0	4.69E+1	0.00E+0	0.00E+0	0.00E+0	1.41E+2	0.00E+0
	S→N	1.67E+2	3.91E+2	3.91E+2		0.00E+0	0.00E+0	1.06E+3	8.94E+1	1.53E+3	2.65E+3	0.00E+0	7.75E+1	0.00E+0	0.00E+0	2.05E+3	4.47E+1
West Bound	N→W	4.47E+1	0.00E+0	0.00E+0	0.00E+0		1.67E+2	8.34E+2	3.34E+2	1.00E+2	0.00E+0	0.00E+0	0.00E+0	1.41E+2	0.00E+0	0.00E+0	0.00E+0
	W→W	0.00E+0	4.69E+1	0.00E+0	0.00E+0	1.67E+2		3.73E+2	1.49E+2	0.00E+0	7.75E+1	0.00E+0	0.00E+0	0.00E+0	5.66E+1	0.00E+0	0.00E+0
	E→W	0.00E+0	3.59E+3	2.35E+2	1.06E+3	8.34E+2	3.73E+2		7.46E+2	3.42E+3	0.00E+0	1.00E+2	0.00E+0	4.84E+3	0.00E+0	3.00E+2	0.00E+0
	S→W	0.00E+0	1.44E+3	0.00E+0	8.94E+1	3.34E+2	1.49E+2	7.46E+2		2.74E+3	2.37E+3	0.00E+0	6.93E+1	1.94E+3	0.00E+0	1.84E+3	4.00E+1
East Bound	N→E	4.47E+1	1.60E+3	0.00E+0	1.53E+3	1.00E+2	0.00E+0	3.42E+3	2.74E+3		6.46E+2	1.67E+2	2.89E+2	1.41E+2	0.00E+0	2.05E+3	0.00E+0
	W→E	0.00E+0	1.82E+2	0.00E+0	2.65E+3	0.00E+0	7.75E+1	0.00E+0	2.37E+3	6.46E+2		2.89E+2	5.00E+2	1.16E+3	2.19E+2	3.56E+3	0.00E+0
	E→E	0.00E+0	0.00E+0	4.69E+1	0.00E+0	0.00E+0	0.00E+0	1.00E+2	0.00E+0	1.67E+2	2.89E+2		1.29E+2	0.00E+0	0.00E+0	6.00E+1	0.00E+0
	S→E	0.00E+0	0.00E+0	0.00E+0	7.75E+1	0.00E+0	0.00E+0	0.00E+0	6.93E+1	2.89E+2	5.00E+2	1.29E+2		0.00E+0	0.00E+0	0.00E+0	3.46E+1
South Bound	N→S	6.32E+1	2.27E+3	0.00E+0	0.00E+0	1.41E+2	0.00E+0	4.84E+3	1.94E+3	1.41E+2	1.16E+3	0.00E+0	0.00E+0		6.67E+2	7.08E+2	2.36E+2
	W→S	0.00E+0	1.33E+2	0.00E+0	0.00E+0	0.00E+0	5.66E+1	0.00E+0	0.00E+0	0.00E+0	2.19E+2	0.00E+0	0.00E+0	6.67E+2		6.33E+2	2.11E+2
	E→S	0.00E+0	0.00E+0	1.41E+2	2.05E+3	0.00E+0	0.00E+0	3.00E+2	1.84E+3	2.05E+3	3.56E+3	6.00E+1	0.00E+0	7.08E+2	6.33E+2		2.24E+2
	S→S	0.00E+0	0.00E+0	0.00E+0	4.47E+1	0.00E+0	0.00E+0	0.00E+0	4.00E+1	0.00E+0	0.00E+0	0.00E+0	3.46E+1	2.36E+2	2.11E+2	2.24E+2	

Figure 6. Coupling impact matrix of alternative #1.

		North Bound				West Bound				East Bound				South Bound			
		N→N	W→N	E→N	S→N	N→W	W→W	E→W	S→W	N→E	W→E	E→E	S→E	N→S	W→S	E→S	S→S
North Bound	N→N		1.75E+2	1.75E+2	1.67E+2	4.47E+1	9.46E+1	0.00E+0	1.89E+2	4.47E+1	3.66E+2	9.46E+1	0.00E+0	6.32E+1	0.00E+0	2.84E+2	1.89E+2
	W→N	1.75E+2		4.10E+2	3.91E+2	0.00E+0	4.69E+1	0.00E+0	4.44E+2	4.96E+2	1.82E+2	2.22E+2	0.00E+0	0.00E+0	1.33E+2	0.00E+0	2.22E+2
	E→N	1.75E+2	4.10E+2		3.91E+2	0.00E+0	0.00E+0	2.35E+2	0.00E+0	0.00E+0	0.00E+0	4.69E+1	0.00E+0	0.00E+0	0.00E+0	1.41E+2	0.00E+0
	S→N	1.67E+2	3.91E+2	3.91E+2		0.00E+0	0.00E+0	0.00E+0	8.94E+1	0.00E+0	0.00E+0	0.00E+0	7.75E+1	0.00E+0	0.00E+0	0.00E+0	4.47E+1
West Bound	N→W	4.47E+1	0.00E+0	0.00E+0	0.00E+0		1.67E+2	8.34E+2	3.34E+2	1.00E+2	0.00E+0	0.00E+0	0.00E+0	1.41E+2	0.00E+0	0.00E+0	0.00E+0
	W→W	9.46E+1	4.69E+1	0.00E+0	0.00E+0	1.67E+2		3.73E+2	1.49E+2	2.12E+2	7.75E+1	1.89E+2	0.00E+0	0.00E+0	5.66E+1	2.84E+2	9.46E+1
	E→W	0.00E+0	0.00E+0	2.35E+2	0.00E+0	8.34E+2	3.73E+2		7.46E+2	0.00E+0	0.00E+0	1.00E+2	0.00E+0	0.00E+0	0.00E+0	3.00E+2	4.73E+2
	S→W	1.89E+2	4.44E+2	0.00E+0	8.94E+1	3.34E+2	1.49E+2	7.46E+2		0.00E+0	0.00E+0	1.89E+2	6.93E+1	0.00E+0	0.00E+0	5.68E+2	4.00E+1
East Bound	N→E	4.47E+1	4.96E+2	0.00E+0	0.00E+0	1.00E+2	2.12E+2	0.00E+0	0.00E+0		6.46E+2	1.67E+2	2.89E+2	1.41E+2	0.00E+0	6.35E+2	2.12E+2
	W→E	3.66E+2	1.82E+2	0.00E+0	0.00E+0	0.00E+0	7.75E+1	0.00E+0	0.00E+0	6.46E+2		2.89E+2	5.00E+2	0.00E+0	2.19E+2	0.00E+0	0.00E+0
	E→E	9.46E+1	2.22E+2	4.69E+1	0.00E+0	0.00E+0	1.89E+2	1.00E+2	1.89E+2	1.67E+2	2.89E+2		1.29E+2	0.00E+0	0.00E+0	6.00E+1	9.46E+1
	S→E	0.00E+0	0.00E+0	0.00E+0	7.75E+1	0.00E+0	0.00E+0	0.00E+0	6.93E+1	2.89E+2	5.00E+2	1.29E+2		0.00E+0	0.00E+0	0.00E+0	3.46E+1
South Bound	N→E	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0		0.00E+0	0.00E+0	0.00E+0
	W→S	0.00E+0	1.33E+2	0.00E+0	0.00E+0	0.00E+0	5.66E+1	0.00E+0	0.00E+0	0.00E+0	2.19E+2	0.00E+0	0.00E+0	6.67E+2		6.33E+2	2.11E+2
	E→S	2.84E+2	0.00E+0	1.41E+2	0.00E+0	0.00E+0	2.84E+2	3.00E+2	5.68E+2	6.35E+2	0.00E+0	6.00E+1	0.00E+0	7.08E+2	6.33E+2		2.24E+2
	S→S	1.89E+2	2.22E+2	0.00E+0	4.47E+1	0.00E+0	9.46E+1	4.73E+2	4.00E+1	2.12E+2	0.00E+0	9.46E+1	3.46E+1	2.36E+2	2.11E+2	2.24E+2	

Figure 9. Coupling impact matrix of alternative #2.

Table 9. Change of coupling impact index values (%) based on intersection geometry and throughput.

Traffic Volume	Original design	Alternative #1	Alternative #2
Case 1 (Table 3)	-	- 43%	- 81%
Case 2 (Table 7)	-	- 30.5%	- 30%

6 CONCLUSIONS

This work proposes a new concept selection method for traffic intersections by calculating the coupling impact index using the hybrid matrix developed by Thompson et al. The impact of coupling in intersection designs was defined as the severity of the conflict for each conflict point i multiplied by the product of the entering traffic volume streams that cross that point summed over the entire hybrid design matrix. It was shown that intersection geometry and intersection demand can have a major impact on the coupling impact index and that simply summing the number of conflicts in the hybrid design matrix would not produce the same results. The coupling impact index has two advantages. First, it assists the decision making in selecting the safest intersection design which isn't fully covered by traffic simulation only. Second, it is an intuitive method that allows the designer to explore all of the issues associated with the intersection's behaviour without being overwhelmed by the complex output of a simulation. It has two disadvantages. First, it doesn't consider the non-linear relationship of severity and risk of conflict by taking numerical approach. Second, the severity can be underestimated by taking the average value instead of maximum value for the purpose of simplicity. These limitations will be addressed in future work.

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