

Calculating Time-To-Collision for analysing right turning behaviour at signalised intersections

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Abstract

Intersections are among the most dangerous places on the road network. Right turn against crashes, in countries with left hand drive vehicle or left turn against in other countries, are a major crash type taking place at intersections. Transportation researchers have utilised different conflict analysis methods to explore the influence of driver behaviours such as acceleration, deceleration, perception reaction time, gap acceptance, and stop/go decision at the onset of amber on right turn against crashes. However, there is not any conflict technique that is sensitive to the different trajectories taken by the drivers turning right at intersections. This paper outlines a calculation method to estimate Time-To-Collision (TTC) for right turn against conflicts. In this method the curvature function of the vehicle trajectory is considered in the calculation formula. This enables the researchers to compare the risk of different right turning trajectories taken by the drivers at intersections. The calculation method has been applied to a signalised intersection in Melbourne, Australia and the results are interpreted.

Keywords: right turning behaviour, time-to-collision, conflicts, driver behaviour

1. Research background:

Intersections are among the most dangerous places on the road network. This is due to the multiple conflicting manoeuvres occurring at intersections. Furthermore, severe crashes such as side crash and angle crash take place at intersections (Abdel-Aty and Keller, 2005; Wang and Abdel-Aty, 2008).

Right turn against crash¹ is a severe crash occurring between the vehicles turning right and the opposing vehicles moving straight at intersections. Several studies have been conducted to investigate the factors influencing the number and severity of right turn against crashes at intersections. These studies have explored the issue based on conflict and crash analysis.

Some transport researchers have utilised crash analysis to study right turn against crashes at intersections. They have investigated the relationship between the number and severity of crashes with road, traffic, vehicle and human characteristics. They have utilised statistical analysis techniques such as Nested Logit and Ordered Probit models to model the number and severity of right turn against crashes at intersections (Abdel-Aty and Keller, 2005; Wang and Abdel-Aty, 2008; Wang and Abdel-Aty, 2008; Wang et al., 2009; Haleem and Abdel-Aty, 2010).

¹ This is "opposing left-turn crash" in left side driving system.

The main disadvantage of crash analysis is that the influence of human behaviour is difficult to be investigated in details because the relevant information is rarely available in crash databases. Furthermore, the lack of crash data, its slowness in being collected and the difficulty in observing some accident situations have encouraged researchers to look at other approaches. Other researchers have tended to use conflict analysis instead of crash analysis. The researchers to conduct conflict analysis have used two methods. The first method is to analyse real world data to explore the conflicts. In this method, researchers have utilised real world data to analyse the conflicts based on human behaviour, traffic and geometry characteristics of intersection. Then they have defined a measure of road safety to measure the safety level of intersections (Tarrall and Dixon, 1998; Ching-Yao, 2006; Mueller et al., 2007; Yan and Radwan, 2007; Oh et al., 2010; Santiago-Chaparro et al., 2010). The second method is to utilise micro-simulation to conduct conflict analysis. Surrogate safety measures have been defined to estimate number and severity of conflicts using micro-simulation models (Amundsen and Hyden, 1977; Hyden, 1987; Sayed et al., 1994; Hyden, 1996; Douglas and Larry, 2003; Archer, 2005; Douglas et al., 2008; Lareshyn et al., 2010). The impact of drivers' behaviours such as perception-reaction time, gap acceptance, red light running and stop/go decision of the driver at the onset of amber have been explored by the researchers using conflict analysis.

In summary, the researchers to investigate right turn against crashes have used crash analysis and conflict analysis. These studies improve the understanding of factors influencing right turn against crashes at intersections. However, no study investigated the effect that the different right turning manoeuvres have on crash risk. The different manoeuvres affects the crash risk of right turn against conflicts since the drivers take different right turning trajectories at signalised intersections. In this paper a conflict technique is developed to assess the risk of different right turning manoeuvres at intersections. In order to do this evaluation a mathematical equation is derived to calculate Time-To-Collision (TTC) for turning manoeuvres. Then, the risk of different drivers' right turning behaviours is evaluated using the developed TTC calculation method.

The following section of this paper outlines the methodology developed to calculate TTC for turning manoeuvres. Then, a case study is presented to show the application of the TTC calculation method to evaluate drivers' turning manoeuvres at signalised intersections. The paper closes with discussion of results and conclusion

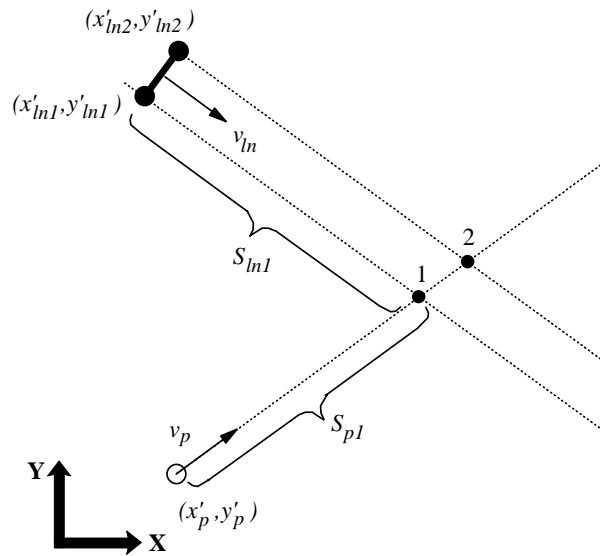
2. Calculating TTC for turning movements:

The aim of the study reported in this paper is to assess different right turning manoeuvres at signalised intersections based on TTC analysis. This section of the paper outlines the calculation method of TTC for turning manoeuvres.

Time-To-Collision (TTC) is a simulation based surrogate safety measure which has been extensively used by the researchers to estimate number and severity conflicts (Hoffmann and Mortimer, 1994; Hyden, 1996; Minderhoud and Bovy, 2001; Vogel, 2003; Archer, 2005; Kiefer et al., 2005). Lareshyn et al. (Lareshyn et al., 2010) developed a mathematical equation to calculate TTC for angle crashes. They suggested that for angle crashes different collision types are possible to take place since the vehicles approach each other with different angles. They have investigated different angle crashes in their study and concluded that it is always the corner of one of the vehicles that hits the side of the other one. If the shape of the cars is assumed to be a rectangle then for each car there are four corners and four sides. Therefore, 32 combinations could be happened in a collision. The TTC is calculated for all the combinations of crash possibilities and the minimum TTC is considered as the TTC of the conflict. Since the corner of the first car always meets the side

of the other car in a crash [12] the mathematical equation for calculating TTC is derived using a point (corner of a car) and a line section (side of the other car) system colliding together (Figure 1). Equation 1 shows the mathematical formula derived to calculate TTC for angle crashes by Laureshyn et al. (Laureshyn et al., 2010).

Figure 1: Calculation of TTC for a point and line section (Laureshyn et al., 2010)



$$t_{coll.} = \frac{(y'_p - y'_{ln1}) - k(x'_p - x'_{ln1})}{(v_{py} - v_{lny}) - k(v_{px} - v_{lnx})} \quad (1)$$

$$k = \frac{y'_{ln2} - y'_{ln1}}{x'_{ln2} - x'_{ln1}} \quad (2)$$

Where:

v_{lnx} : Projection of the line speed on the x axis.

v_{lny} : Projection of the line speed on the y axis.

v_{px} : Projection of the point speed on the x axis.

v_{py} : Projection of the point speed on the y axis.

(x'_p, y'_p) : Initial position of the point.

(x'_{in1}, y'_{in1}) and (x'_{in2}, y'_{in2}) : Initial position of the line section ends.

k : Parameter describing line slope.

In the Equation (1) TTC is calculated based on linear motion of the vehicles. Also, the acceleration of the vehicles involving in the conflict is neglected. This Equation is not appropriate for use where there are turning movements involved. The reasons are:

- In turning movements at least one of the vehicles involving in conflict does not have linear motion.
- Sometimes in turning movement one of the vehicles should give way to opposing vehicles. This vehicle will accelerate to complete its movement.

Therefore, an equation should be developed to calculate TTC for crashes that involve turning manoeuvres. Figure 2 shows a right turning conflict at an intersection. The type of crash occurring in this case is angle crash. Thus, the point and the line section system developed by Laureshyn et al. (Laureshyn et al., 2010) is used to calculate the TTC for the type of conflict shown in the Figure 2.

In the point and line section system either line section or the point can be associated with the turning manoeuvre. Therefore, two different derivation processes should be conducted. The first derivation process is conducted when the corner of the turning vehicle hits the side of the opposing vehicle. The second derivation process is based on the condition that the side of the turning vehicle hits the corner of the opposing vehicle. Figure 3 shows the point and line section system used for these two derivation processes. All the parameters shown in Figure 3 are known from either micro-simulation modelling or intersection information.

Figure 2: Right turning conflict at intersection

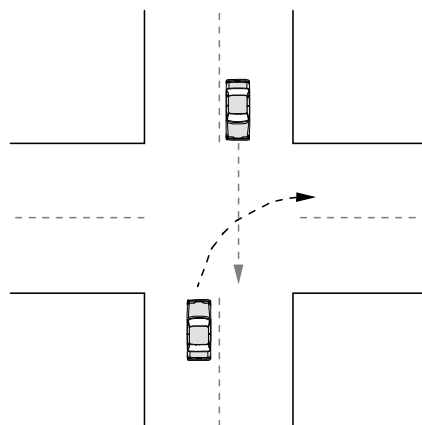


Figure 4 shows the situation in which the point and the line sections collide. In Figure 4, (x_p, y_p) is the current coordinates of the point; (x_{in1}, y_{in1}) and (x_{in2}, y_{in2}) are the current coordinates of the end of the line section.

Figure 3: Calculation of TTC for turning movement:

(a) the point takes turning movement

(b) the line section takes turning movement

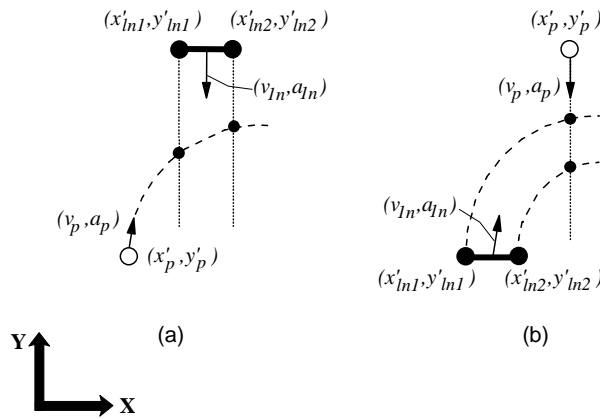
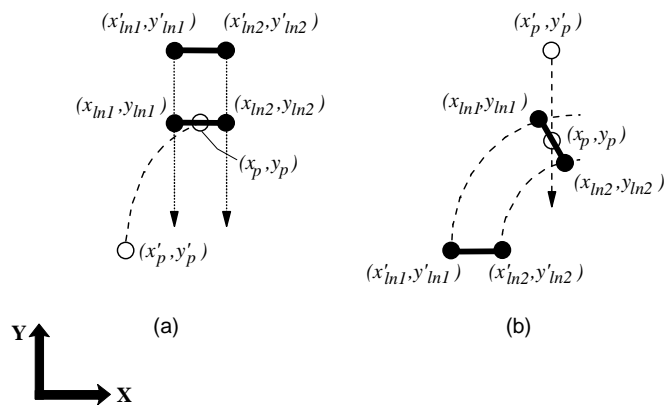


Figure 4: The collision of the point and the line section:

(a) the point takes turning movement

(b) the line section takes turning movement



First the derivation process based on Figure 3a and Figure 4a is explained. This is when the corner of the turning vehicle hits the side of the opposing vehicle. Based on Newtonian Mechanics we can calculate the ends of coordinates of the line section. Equations (3) to (6) show the mathematical formula.

$$x_{ln1} = x'_{ln1} + \frac{1}{2} a_{ln,x} t^2 + v_{ln,x} t \quad (3)$$

$$y_{ln1} = y'_{ln1} + \frac{1}{2} a_{ln,y} t^2 + v_{ln,y} t \quad (4)$$

$$x_{ln2} = x'_{ln2} + \frac{1}{2} a_{ln,x} t^2 + v_{ln,x} t \quad (5)$$

$$y_{ln2} = y'_{ln2} + \frac{1}{2} a_{ln,y} t^2 + v_{ln,y} t \quad (6)$$

Where $a_{ln,x}$ and $a_{ln,y}$ are the projections of the line acceleration on X and Y axes and t shows the time. Equation (7) shows the mathematical representation of the line section.

$$y - y_{ln1} = k(x - x_{ln1}) \quad (7)$$

$$k = \frac{y_{ln2} - y_{ln1}}{x_{ln2} - x_{ln1}} = \frac{y'_{ln2} - y'_{ln1}}{x'_{ln2} - x'_{ln1}} \quad (8)$$

The collision point shown in Figure 4a is a point in Equation (7) which represents the mathematical shape of the line section. Therefore, we have:

$$y_p - y_{ln1} = k(x_p - x_{ln1}) \quad (9)$$

As was shown in the Figure 4a, the Equation (9) is correct when the vehicles hit each other. Therefore, the associated t is TTC. The TTC can be calculated using Equations (3), (4), (8) and (9). Before solving these simultaneous equations, x_p and y_p should be estimated based on the known initial coordinates of the point which are x'_p and y'_p . In order to estimate x_p and y_p the length of the turning curve should be determined. Figure 5 shows the calculation process of the turning curve length.

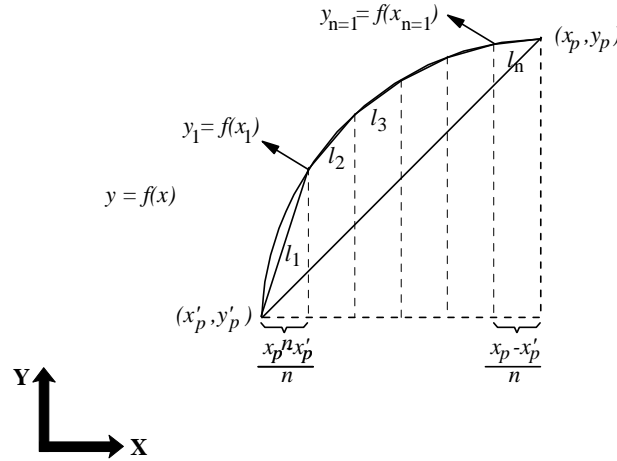
Let l be the length of the curvature. According to the Figure 5 we have:

$$l = \sum_{i=1}^n l_i \quad (10)$$

Therefore:

$$l = \sum_{i=1}^n \sqrt{\left(\frac{x_p - x'_p}{n}\right)^2 + \left[f\left(x'_p + i\left(\frac{x_p - x'_p}{n}\right)\right) - f\left(x'_p + (i-1)\left(\frac{x_p - x'_p}{n}\right)\right) \right]^2} \quad (11)$$

Figure 5: Calculation of the length of a curvature



Equation (12) shows the calculation formula of l using Newtonian Mechanics.

$$l = \frac{1}{2} a_p t^2 + v_p t \quad (12)$$

Therefore, we have:

$$\frac{1}{2} a_p t^2 + v_p t = \sum_{i=1}^n \sqrt{\left(\frac{x_p - x'_p}{n}\right)^2 + \left[f\left(x'_p + i\left(\frac{x_p - x'_p}{n}\right)\right) - f\left(x'_p + (i-1)\left(\frac{x_p - x'_p}{n}\right)\right) \right]^2} \quad (13)$$

From equation (13) x_p can be calculated as a function of (t).

$$x_p = f_1(t, a_p, v_p, x'_p) \quad (14)$$

As it is shown in the Figure 5 y_p is a function of x_p ; therefore, y_p can be estimated as a function of (t).

$$y_p = f(x_p) \quad (15)$$

From Equations (3), (4), (8), (9), (14) and (15) TTC is calculated as a function of known parameters shown in Figure 3.

$$TTC = f_2(x'_p, a_{\ln x}, v_{\ln x}, a_{\ln y}, v_{\ln y}, x'_{\ln 1}, y'_{\ln 1}, k, a_p, v_p) \quad (16)$$

The derivation process based on Figure 3b and Figure 4b is the same as preceding derivation process. The difference is that the curvature length is estimated for line section; therefore, k is not constant. The mathematical formulas for calculating the TTC for this case are shown below:

$$x_p = x'_p + \frac{1}{2} a_{px} t^2 + v_{px} t \quad (17)$$

$$y_p = y'_p + \frac{1}{2} a_{py} t^2 + v_{py} t \quad (18)$$

$$k = \frac{y_{\ln 1} - y_{\ln 2}}{x_{\ln 1} - x_{\ln 2}} = \frac{f(x_{\ln 1}) - f(x_{\ln 2})}{x_{\ln 1} - x_{\ln 2}} \quad (19)$$

$$l = \sum_{i=1}^n l_i = \sum_{i=1}^n \sqrt{\left(\frac{x_{\ln 1} - x'_{\ln 1}}{n}\right)^2 + [f(x'_{\ln 1} + i(\frac{x_{\ln 1} - x'_{\ln 1}}{n})) - f(x'_{\ln 1} + (i-1)(\frac{x_{\ln 1} - x'_{\ln 1}}{n}))]^2} \quad (20)$$

$$l = \frac{1}{2} a_{\ln} t^2 + v_{\ln} t \quad (21)$$

$$\frac{1}{2} a_{\ln} t^2 + v_{\ln} t = \sum_{i=1}^n \sqrt{\left(\frac{x_{\ln 1} - x'_{\ln 1}}{n}\right)^2 + [f(x'_{\ln 1} + i(\frac{x_{\ln 1} - x'_{\ln 1}}{n})) - f(x'_{\ln 1} + (i-1)(\frac{x_{\ln 1} - x'_{\ln 1}}{n}))]^2} \quad (22)$$

From Equation (20) we have:

$$x_{\ln 1} = f_3(t, a_{\ln}, v_{\ln}, x'_{\ln 1}) \quad (23)$$

From Equations (9), (19), (20), (21), (22) and (23) TTC can be calculated as a function of known parameters shown in Figure 3b.

$$TTC = f_4(x'_p, a_{\ln}, v_{\ln}, a_{px}, v_{px}, x'_{\ln 1}, x'_{\ln 2}, y'_p, a_{py}, v_{py}) \quad (24)$$

TTC should be calculated for different combinations of collision of the corner of one car with the side of the other car. Minimum value of the TTC is considered as the TTC of the conflict.

In order to conduct the preceding calculation process the function of $y = f(x)$ should be determined. This function is determined using vehicles trajectory information.

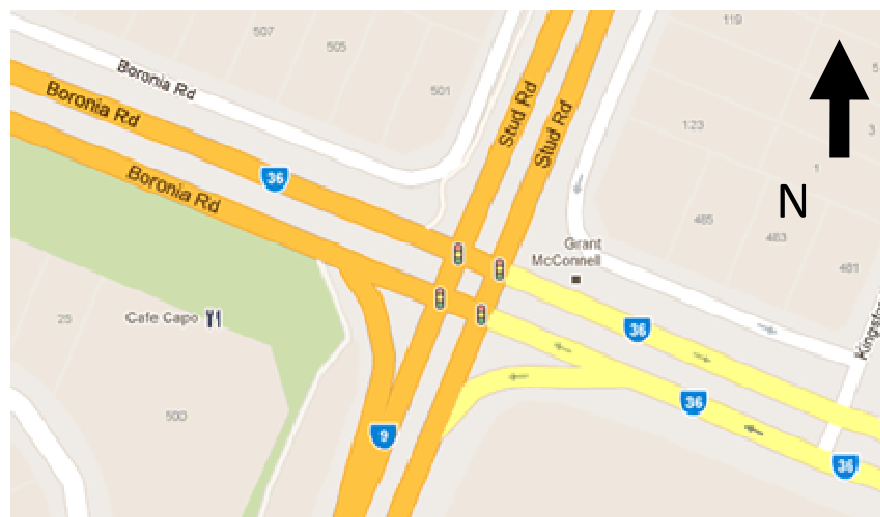
3. Case study:

In the previous section a methodology is developed to calculate TTC for turning movements. In this section a case study is conducted to show the application of the methodology. This case study is conducted to assess the risk of taking right turning manoeuvres at a signalized intersection in Melbourne, Australia.

3.1. Intersection characteristics:

The signalized intersection of Stud Road and Boronia Road in Melbourne, Australia is considered for this study. Figure 6 shows the layout of the intersection. The required information was collected using a recorded video of the intersection. A video camera was mounted on a roof of a hotel located at the corner of the intersection. The SAVA[®] image processing software (Archer, 2005) was utilized to collect the trajectories of the right turning vehicles at intersection.

Figure 6: Intersection layout



3.2. Right turning behaviours:

In this study, the turning behaviour of the vehicles turning right from the Stud Road-South has been investigated. This turning manoeuvre is not fully protected, so in some situations drivers must give way to opposing vehicles. If a driver fails to choose an appropriate gap then a conflict takes place. Figure 7 reveals the information of the investigated conflict. It can be seen from the Figure 7 that the investigated conflict is the conflict of right turning vehicles from Stud Road-South and the opposing vehicles moving straight on Stud Road-North. In the Figure 7 these vehicles are vehicle one and vehicle two respectively. Two distinct manoeuvres can be taken by a vehicle in order to complete its turning manoeuvre. The main difference of these two manoeuvres is in the location where the drivers choose to accept the gap and start the turning manoeuvre. In the first manoeuvre, the driver gives way to the opposing from behind the stop line while in the second manoeuvre the driver drives to the middle of the intersection then stop to give way to the opposing vehicle. In Figure 7 two

curves have been drawn to show these two manoeuvres. In this case study, these two turning manoeuvres are assessed by conducting a conflict analysis. TTC of conflicts is calculated and compared for these two manoeuvres.

3.3. Conflict analysis:

As mentioned in the previous sub-section two turning manoeuvres are taken by drivers to turn right at the intersection. In this sub-section the crash risk for each of these manoeuvres is analysed using a sensitivity analysis. This sensitivity analysis is conducted based on TTC analysis.

In order to calculate TTC, the curvature function of each manoeuvre should be determined. According to the drivers' right turning trajectories, collected from the recorded video, the best fitted curve to the turning trajectories is considered as the curvature function of the manoeuvre. The following equations show the determined curvature functions.

$$f_1(x) = -0.0468x^2 + 3.2537x - 32.153 \quad (25)$$

$$f_2(x) = -0.0146x^2 + 1.0853x + 3.6437 \quad (26)$$

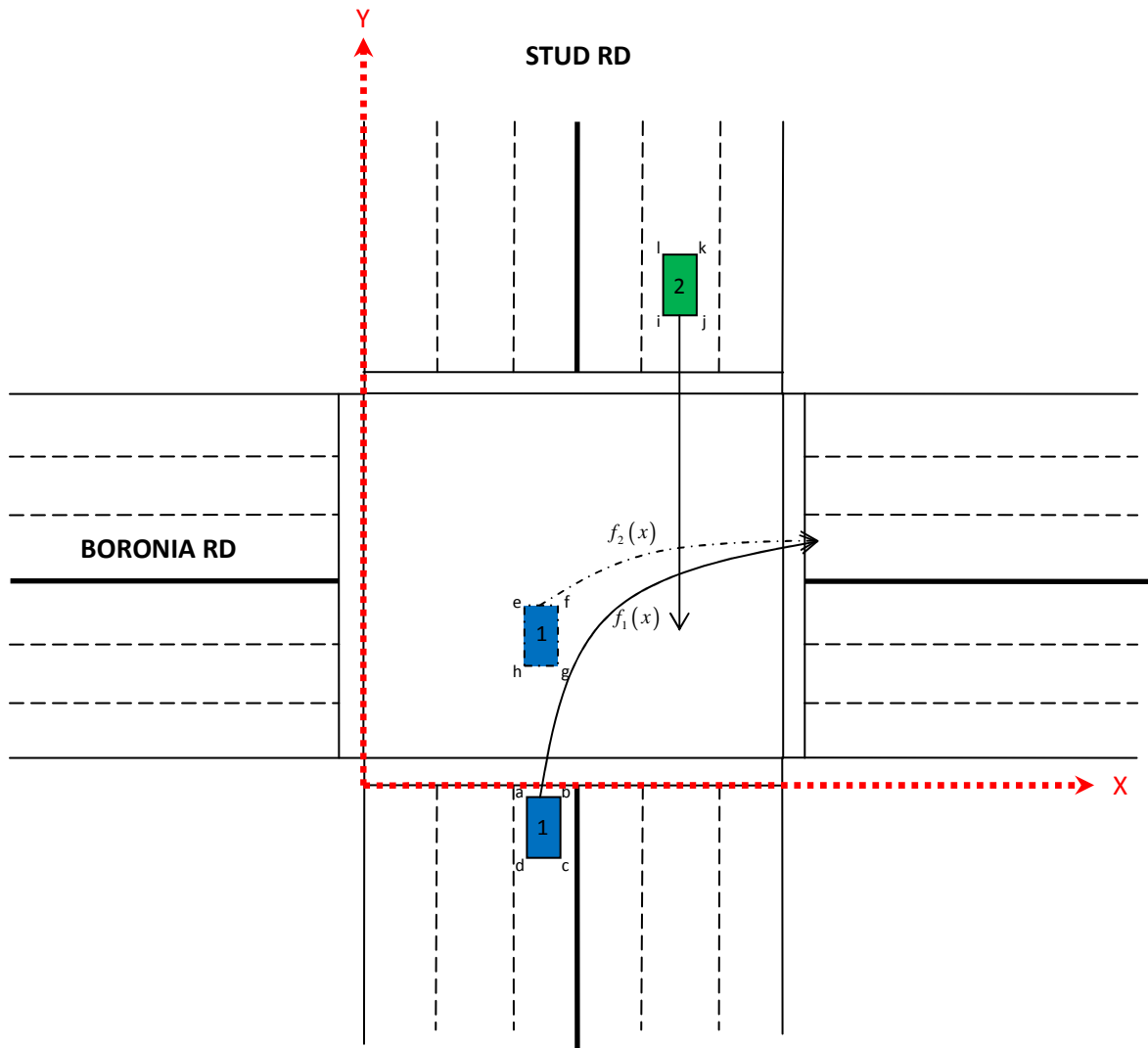
The r-square for the Equations (25) and (26) is 0.9872 and 0.9889 respectively. The Equation (25) is related to the first turning manoeuvre and the Equation (26) is related to the second turning manoeuvre. Therefore, the Equation (25) is named "First Turning Curve" and the Equation (26) is named "Second Turning Curve".

Vehicles involving in conflict are assumed to have a rectangle shape. As shown in the Figure 7, there are three rectangles. Rectangle **a-b-c-d** shows the turning vehicle which takes the first turning curve and rectangle **e-f-g-h** shows the turning vehicle taking the second turning curve. Rectangle **i-j-k-l** shows the opposing vehicle moving straight on Stud Road-North. Two conflicts are considered since there are two turning curves. The first conflict occurs between the vehicles **a-b-c-d** and **i-j-k-l** and the second conflict takes place between the vehicles **e-f-g-h** and **i-j-k-l**.

For the first conflict four scenarios are considered in the sensitivity analysis:

- **Scenario 1:** Vehicle number one (**a-b-c-d**) stops behind the stop line; gives way to the opposing vehicle; accepts a gap; takes the first turning curve and completes its manoeuvre with constant normal acceleration of 2 m/s².
- **Scenario 2:** Vehicle number one (**a-b-c-d**) drives to the stop line; gives way to the opposing vehicle; accepts a gap without stopping; takes the first turning curve and completes its manoeuvre with the constant speed of 20 km/hr.
- **Scenario 3:** Vehicle number one (**a-b-c-d**) drives to the stop line; gives way to the opposing vehicle; accepts a gap without stopping; takes the first turning curve and completes its manoeuvre with the constant speed of 25 km/hr.

Figure 7: The investigated conflict



- **Scenario 4:** Vehicle number one (**a-b-c-d**) drives to the stop line; gives way to the opposing vehicle; accepts a gap without stopping; takes the first turning curve and completes its manoeuvre with the constant speed of 30 km/hr.

The difference of the preceding scenarios is in the initial speed and acceleration of the turning vehicles.

For the second conflict, vehicle number one (**e-f-g-h**) drives to the middle of the intersection; stops there; gives way to the opposing vehicle; accepts a gap; takes the second turning curve; and completes its manoeuvre with constant normal acceleration of 2 m/s². Table 1 shows the detailed information of the vehicles for each conflict.

Based on the point and line system developed to calculate TTC for conflicts (Figure 3 and 4) there are different combinations of collision of the corner of one car with the side of the other car. Table 2 summarises different combinations of collisions for the two conflicts investigated in this study.

Table 1: Vehicle information for different scenarios

Conflict	Scenario	Curve Function	Initial Speed (km/hr)	Acceleration (m/s ²)
Conflict 1	Scenario 1	$f_1(x)$	0.0	2.0
	Scenario 2	$f_1(x)$	20.0	0.0
	Scenario 3	$f_1(x)$	25.0	0.0
	Scenario 4	$f_1(x)$	30.0	0.0
Conflict 2	-	$f_2(x)$	0.0	2.0

As can be seen from the Table 2, there are 4 collision combinations for each conflict. Thus, 4 TTCs should be calculated for each conflict. The minimum value of calculated TTCs, for different combinations, is the TTC of the conflict.

Table 2: Collision combinations of the conflicts and related information

Conflict	Curve Function	Vehicle 1	Vehicle 2	Collision Combination		Point Coordinate (X, Y) (m)	Line Coordinates (X, Y) (m)	
				Point	Line		Start Point	End Point
Conflict 1	$f_1(x)$	a-b-c-d	i-j-k-l	a	i-j	(9, 0)	(20.05, 50)	(21.55, 50)
		a-b-c-d	i-j-k-l	b	i-l	(10.5, 0)	(20.05, 50)	(20.05, 54.5)
		a-b-c-d	i-j-k-l	j	a-d	(21.55, 50)	(9, 0)	(9, -4.5)
		a-b-c-d	i-j-k-l	i	a-b	(20.05, 50)	(9, 0)	(10.5, 0)
Conflict 2	$f_2(x)$	e-f-g-h	i-j-k-l	e	i-j	(9, 17.11)	(20.05, 50)	(21.55, 50)
		e-f-g-h	i-j-k-l	f	i-l	(10.5, 17.11)	(20.05, 50)	(20.05, 54.5)
		e-f-g-h	i-j-k-l	j	e-h	(21.55, 50)	(9, 17.11)	(9, 12.61)
		e-f-g-h	i-j-k-l	i	e-f	(20.05, 50)	(9, 17.11)	(10.5, 17.11)

It should be mentioned that the coordinates of **i, j, k** and **l** are subject to change based on the distance of vehicle **i-j-k-l** from the stop line.

3.4. Results:

In this study two steps are taken to conduct the conflict analysis.

In the first step we determine if the vehicle is bound for a collision. A collision course is a pre-condition for a collision (Laureshyn et al., 2010). The collision course means two vehicles are in situation that if they continue their trajectories without any change in their initial speed and acceleration those vehicles will be involved in a collision. The “collision course bound” is a range of accepted gap that put both vehicles on a collision course. Larger “collision course bound” increases the risk of being involved in the collision course.

In the second step, TTC of conflicts is calculated given that the vehicle **i-j-k-l** is in the “collision course bound”. Thus, a range of TTC is calculated for each conflict. Equations (1) to (24) are used to calculate TTC of conflicts.

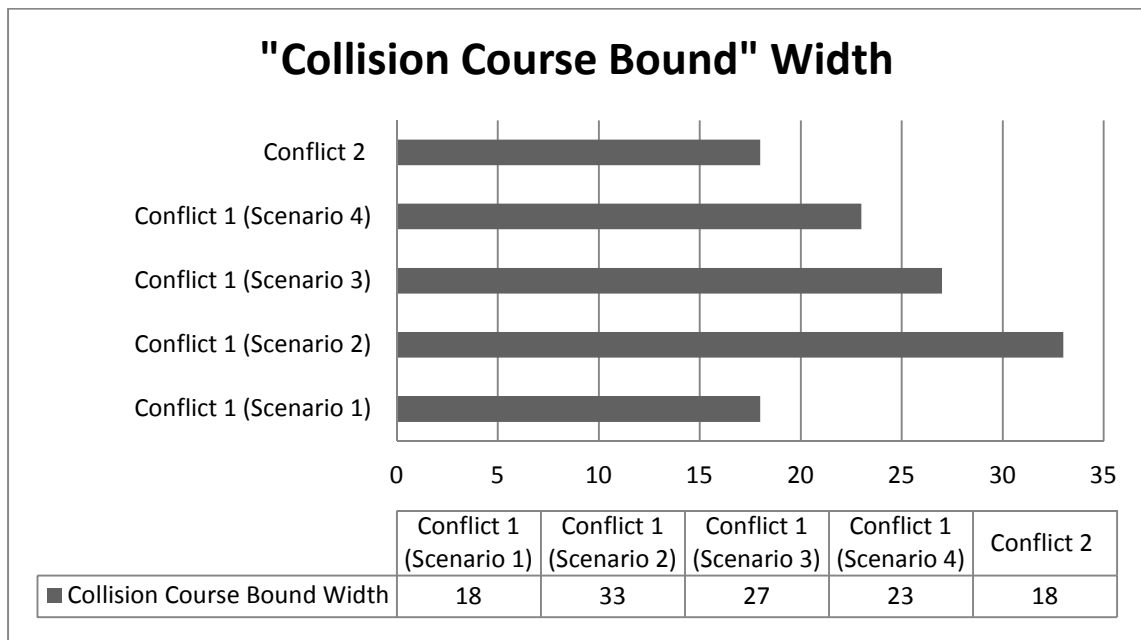
The results of “collision course bound” and TTC analysis are summarised in the Table 3.

A comparison of the width of “collision course bound” is outlined in Figure 8.

Table 3: Results of the conflict analysis

Conflict	Curve Function	Collision Course Bound		TTC (Sec) [Min-Max]	Average TTC (Sec)
		Accepted Gap (m) [Min-Max]	Distance From Stop Line (m) [Min-Max]		
Conflict 1 (Scenario 1)	$f_1(x)$	[108-126]	[67-85]	[4.22-4.94]	4.56
Conflict 1 (Scenario 2)	$f_1(x)$	[85-118]	[44-77]	[3.18-4.58]	3.86
Conflict 1 (Scenario 3)	$f_1(x)$	[71-98]	[30-57]	[2.55-3.68]	3.095
Conflict 1 (Scenario 4)	$f_1(x)$	[62-85]	[21-44]	[2.15-3.09]	2.60
Conflict 2	$f_2(x)$	[75-93]	[51-70]	[3.26-4.08]	3.66

Figure 8: Width of “collision course bound” for analyzed conflicts



3.5. Discussion of results:

In this sub-section the analysed conflicts are compared based on the results of the conflict analysis (Table 3 and Figure 8).

Comparison Based on “Collision Course Bound”

The risk of being involved in a collision course increases by increasing the width of the “collision course bound”. This is because it is more likely to accept a gap which is inside the “collision course bound” as the “collision course bound” width is increased.

As shown in the Figure 8, the width of “collision course bound” is the same for the first scenario of conflict 1 and conflict 2. However, the driver of vehicle 1 can accept smaller safe gaps in conflict 2 in comparison with the first scenario of conflict1.

On the other hand, the “collision course bound” of the second, third, and fourth scenario of the conflict 1 is larger than the “collision course bound” of the conflict 2. This means the risk of being involved in a collision course is higher for the second, third and fourth scenarios of conflict 1. Also, this risk is decreased as the constant speed increases in the last three scenarios of conflict 1. Similarly, smaller safe gaps can be accepted as the constant speed of vehicle 1 is increased.

Comparison Based on Time-To-Collision (TTC)

The value of TTC is related to the risk of being involved in a crash. Lower values of TTC shows more risky conflicts. This is because there is less amount of time for the driver to take an evasive action. As can be seen from the Table 3, the average value of TTC for conflict 2 is less than the average value of TTC for the first and second scenario of conflict 1. However, the average TTC of the third and fourth scenarios of conflict 1 is higher in comparison with the average TTC of the conflict 2. Therefore, the crash risk is lower in first scenario of conflict 1 based on the average value of TTC.

Similarly, the second, third and fourth scenarios of the conflict1 have lower values of the average TTC in comparison with the first scenario of conflict 1. This shows the risk of being involved in a crash is increased as the constant speed increases in the second, third and fourth scenarios of conflict1.

Overall Comparison

Overall, the conflict analysis, conducted based on “collision course bound” and TTC, shows that the first scenario is the safest among the four investigated scenarios of conflict 1 since it has lower value of TTC and smaller “collision course bound”. Similarly, based on the same analysis the first scenario of conflict 1 is safer than conflict 2, because the calculated average TTC is higher for the first scenario of conflict 1. Furthermore, it is shown that the smaller safe gaps can be accepted for the conflict 2 in comparison with the first scenario of conflict 1. This encourages the drivers to take the second turning curve in crowded intersections.

4. Conclusion:

This paper outlined a calculation method for Time-To-Collision (TTC) to assess the risk of different right turning manoeuvres taken by the drivers at intersections. Newtonian Mechanics was utilized to calculate TTC of right turn against conflicts.

The method was applied to a signalized intersection in Melbourne, Australia to assess the crash risk of different right turning trajectories. Two conflicts were investigated in the case study. For the first conflict four scenarios are considered:

- Scenario 1: The turning vehicle stops behind the stop line; gives way to the opposing vehicle; accepts a gap and completes its manoeuvre with constant normal acceleration of 2 m/s^2 .
- Scenario 2: The turning vehicle drives to the stop line; gives way to the opposing vehicle; accepts a gap without stopping and completes its manoeuvre with the constant speed of 20 km/hr.
- Scenario 3: The turning vehicle drives to the stop line; gives way to the opposing vehicle; accepts a gap without stopping and completes its manoeuvre with the constant speed of 25 km/hr.

- Scenario 4: The turning vehicle drives to the stop line; gives way to the opposing vehicle; accepts a gap without stopping and completes its manoeuvre with the constant speed of 30 km/hr.

For the second conflict, the turning vehicle drives to the middle of the intersection; stops there; gives way to the opposing vehicle; accepts a gap and completes its manoeuvre with constant normal acceleration of 2 m/s^2 .

The results of the conflict analysis showed that the first scenario is the safest among the four investigated scenarios investigate for conflict 1. Similarly, the first scenario of conflict 1 is safer than conflict 2, because the calculated average TTC is higher for the first scenario of conflict 1.

The calculation method developed to determine TTC enables the researchers to compare the risk of different right turning manoeuvres taken by the drivers at signalized intersections.

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