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USING A SIMULATION BASED ROAD SAFETY INDEX TO ASSESS RISK OF TURNING BEHAVIOUR AT SIGNALISED INTERSECTIONS

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This is an abridged version of the paper presented at the conference. The full version is being submitted elsewhere. Details on the full paper can be obtained from the author.

ISBN: 978-85-285-0232-9

13th World Conference on Transport Research

www.wctr2013rio.com

15-18 JULY 2013
Rio de Janeiro, Brazil

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ABSTRACT

Micro simulation models have increasingly been used for intersection safety modelling. Simulation models, developed for road safety assessment, utilised different conflict techniques to find out the number and severity of conflicts as a safety measure at intersections. According to the literature review of safety modelling, there is no micro simulation model capable of considering number of conflicts, severity of conflicts, crash risk and crash severity risk together as a measure of safety evaluation. This paper outlines the application of a new simulation based road safety index (RSI) to evaluate the risk of right turning manoeuvres at a signalised intersection in Melbourne, Australia. The RSI is calculated as a function of traffic volume, number of conflicts, severity of conflicts, crash risk and crash severity risk. The number and severity of conflicts is estimated using Time-To-Collision (TTC) calculated for right-turn-against conflicts at the intersection. Historical crash data of the intersection is used to find out the crash risk. A three step modelling approach is used to model the relationship between crash severity and conflict characteristics. VISSIM simulation model is calibrated to present traffic volume, number of conflicts and severity of conflicts at the intersection. The final results showed a good level of consistency between the estimated RSI and the historical right-turn-against crash data at the intersection.

Keywords: micro simulation, turning movements, intersection safety, road safety index

RESEARCH BACKGROUND

Micro simulation modelling approach grew out of the conflict analysis literature and considered surrogate safety measures for indicating the safety of facilities (Sayed et al. 1994; Archer 2005). Recently, Laureshyn et al., (2010) ; Archer and Young (2010), Cunto and Saccomanno (2008), and Federal Highway Administration (2008) incorporated the traffic conflict approach into traffic simulation models in order to estimate the number and type of conflicts. Archer and Young (2010) studied the application of surrogate safety measures for intersection safety assessment and their application in micro-simulation modelling and used a probability approach for developing a gap acceptance model for unsignalised T-intersections in order to determine the number and severity of conflicts. Cunto and Saccomanno (2008) developed a methodology for intersection safety evaluation using micro-simulation. They defined a “crash potential index” to assess the safety performance of intersections. The main contribution of this study was to calibrate and validate a simulation based surrogate safety measure to investigate safety performance of intersections using micro-simulation models. The Federal Highway Administration (2008) undertook further research that considers intersection safety evaluation. They developed Surrogate Safety Assessment Model (SSAM) for assessing the safety performance of different types of intersections. In order to do this, they developed a software package that supports traffic simulation models including VISSIM, AIMSUN, PARAMICS and TEXAS.

Although researchers endeavoured to define and utilise different conflict techniques to estimate various surrogate safety measures (explained above) to assess safety level of intersections using micro simulation models, there is not any simulation model capable of considering number of conflicts, severity of conflicts, crash risk and crash severity risk together as a measure of safety evaluation. This study outlines the application of a simulation based road safety index (RSI) to assess risk of right turning manoeuvres at a signalised intersection in Melbourne, Australia. The RSI is the first simulation based surrogate safety measure that is calculated as a function of traffic volume, number of conflicts, severity of conflicts, crash risk and crash severity risk. The main contribution of this study is to show the validity of the developed RSI to assess the risk of right turning behaviours at signalised intersections.

The next section of this paper outlines the theoretical framework developed to derive the simulation based RSI. The RSI is then applied to assess the risk of right turning manoeuvres at a signalised intersection in Melbourne, Australia. This is followed by results discussion and conclusions.

METHODOLOGY

This section provides a brief explanation to the theoretical framework developed to estimate the RSI. The framework consists of three main components each of which is explained in the following sub-sections (Figure 1).

Component 1: micro simulation model

The first component of the framework is to estimate the number and severity of conflicts using a micro-simulation model. Researchers have developed several conflict techniques to find out the number and severity of conflicts using micro simulation model (Hyden 1987; Hyden 1996; Archer 2005). The role of this component of the framework is to utilise one of these previously developed techniques to measure number and severity of conflicts depends on the road safety application (e.g. road type, road layout, control type, etc).

Inputs into the first component are the geometry and traffic characteristics of the road system. The output of the first component of the simulation framework is the characteristics of the serious conflicts, which have been generated in the micro simulation model.

Component 2: severity model

The second component of this framework is the measurement of the potential injury severity of each simulated conflict. In other words, crash severity risk is estimated here. The characteristics of the simulated conflict are used as input. These are the output of the first component of the simulation framework.

A three-step modelling approach is used to estimate the potential injury severity of conflicts. The detailed explanation of the models have been outlined in Sobhani et al. (2012).

In the first step, expected speed change of the subject vehicle (ΔVs) in the crash is estimated given the condition that the conflict leads to a crash. The expected ΔVs is estimated using conflict characteristics and driver's reaction before crash.

The second step is to utilise Newtonian Mechanics to estimate the magnitude of kinetic energy applied to the subject vehicle. Equation (1) shows the calculation formula of this kinetic energy according to the mass of subject vehicle and estimated ΔVs.

$$f_2 : KE_s = \frac{1}{2} \times m_s \times (\Delta V_s)^2 \tag{1}$$

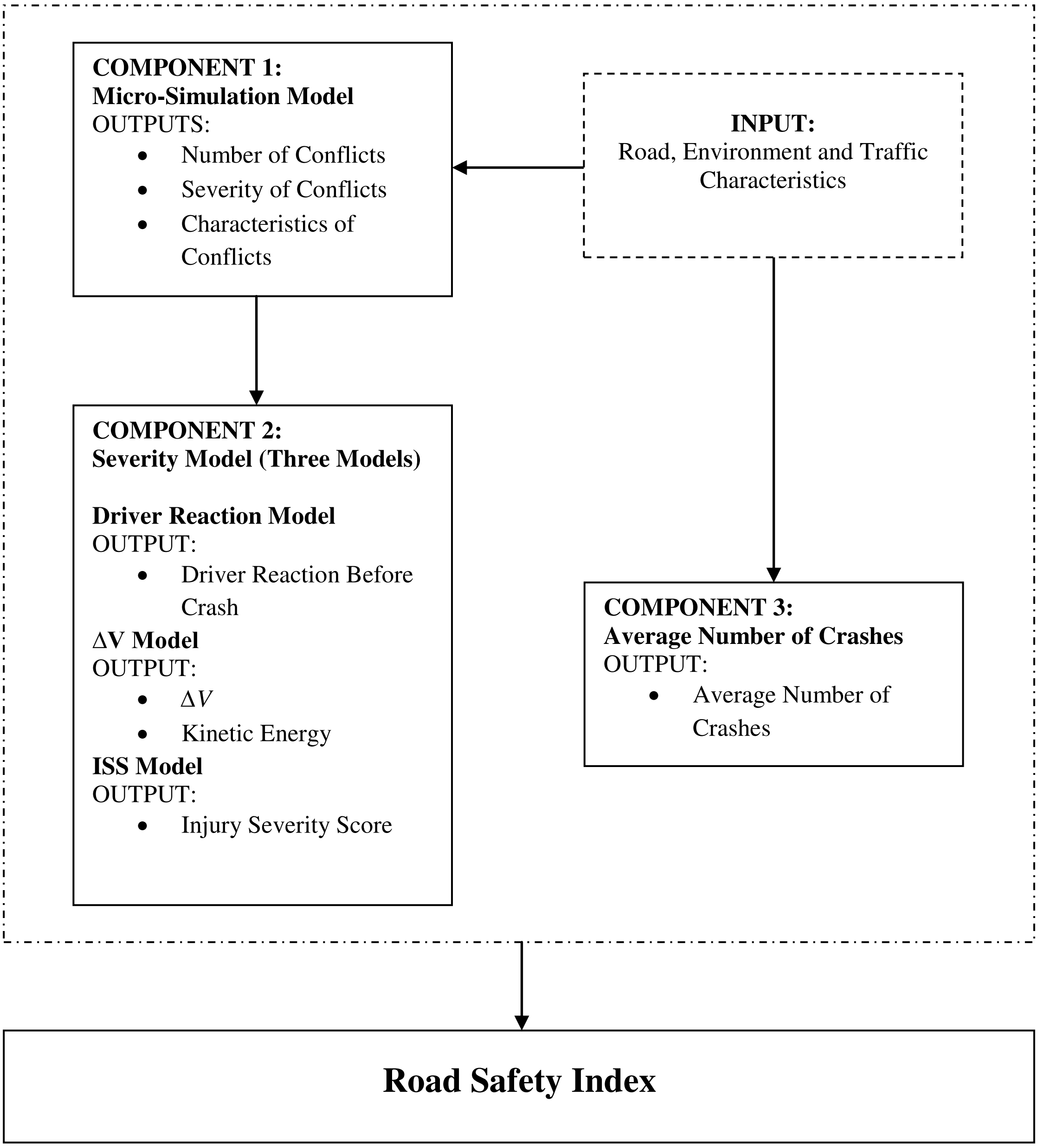

Figure 1: General framework for developing the mathematical road safety index

In Equation (1), KE_s is the kinetic energy applied to the subject vehicle; m_s is the mass of the subject vehicle; and ΔV_s is the speed change of the subject vehicle.

In the third step of this component, the expected Injury Severity Score (ISS) of the conflict is measured using estimated kinetic energy of the subject vehicle and the impact type of the expected crash.

Component 3: average number of crashes

The third component of the framework is to estimate average number of crashes. The average number of crashes is calculated using two methods:

- The first method is to simply calculate the average number of crashes based on historical crash data of the road location.

- The second method is to calculate average number of crashes based on the available crash prediction models. Lord and Mannering (2010) have conducted a comprehensive comparison among the available crash count models.

The second method is used when the historical crash data of the road location is not available.

Road safety index (RSI)

The final output of the framework is the safety level of the studied road location. The safety level of the road location is measured using a road safety index (RSI) derived based on the output of the three components of the framework. The RSI is derived based on the definition of crash severity risk (CSR). Equation (2) shows the definition of the CSR.

Crash Severity Risk (CSR) = Average Expected Severity x Probability of Crash (2)

In the Equation (2) the CSR indicates the road safety index, and average expected severity is the arithmetic average value of expected ISS which is the output of the severity model (see Equation (3)).

$$AISS = (\sum_{i=1}^{n_{con}} ISS) / n_{con} \tag{3}$$

Where:

$AISS$: The average expected ISS for serious conflicts

The probability of crash is calculated using the decision tree shown in the Figure 2.

Equation (4) shows the mathematical form of the road safety index derived based on the decision tree.

$$RSI = \left[(\sum_{i=1}^{n_{con}} ISS) / n_{con} \right] \times n_{cr} / \mu \tag{4}$$

In the Equation (4), n_{cr}, ISS, n_{con} and μ can be estimated from the output of the developed framework.

CONFLICT ANALYSIS FOR TURNING MOVEMENTS

Estimates of the level of conflict are calculated using the TTC. Time-To-Collision (TTC) is a surrogate safety measure which has been extensively used by the researchers to estimate number and severity conflicts. Laureshyn 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 occur since the vehicles approach each other with different angles. They have investigated various 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.

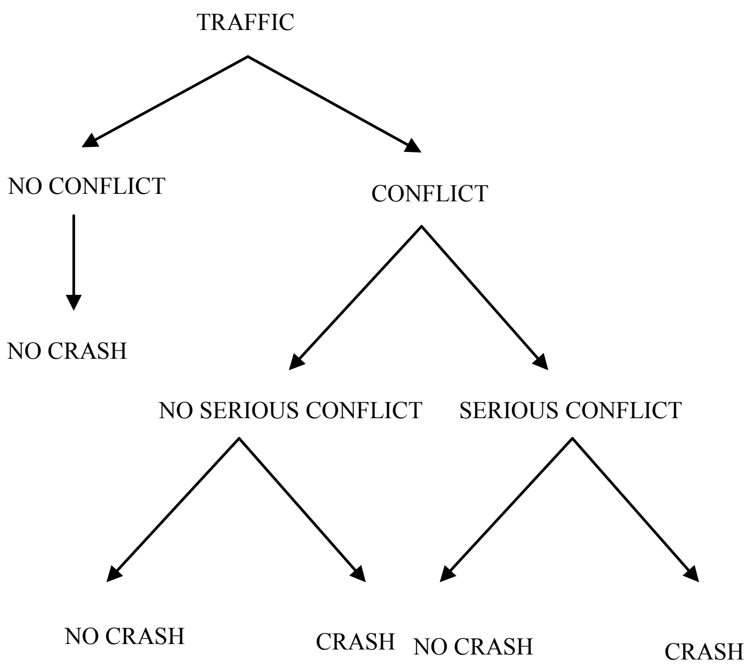

Figure 2: Decision tree for calculating the probability of crash

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 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. In their study 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. Therefore, an equation should be developed to calculate TTC for crashes that involve turning manoeuvres.

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 carried out. 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 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; $(x_{\ln 1}, y_{\ln 1})$ and $(x_{\ln 2}, y_{\ln 2})$ are the current coordinates of the line section ends.

First the derivation process based on Figure 3 (a) and Figure 4 (a) 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 coordinates of the line section ends. Equations (5) to (8) show the mathematical formula.

$$x_{\ln 1} = x'_{\ln 1} + \frac{1}{2} a_{\ln x} t^2 + v_{\ln x} t \tag{5}$$

$$y_{\ln 1} = y'_{\ln 1} + \frac{1}{2} a_{\ln y} t^2 + v_{\ln y} t \tag{6}$$

$$x_{\ln 2} = x'_{\ln 2} + \frac{1}{2} a_{\ln x} t^2 + v_{\ln x} t \tag{7}$$

$$y_{\ln 2} = y'_{\ln 2} + \frac{1}{2} a_{\ln y} t^2 + v_{\ln y} t \tag{8}$$

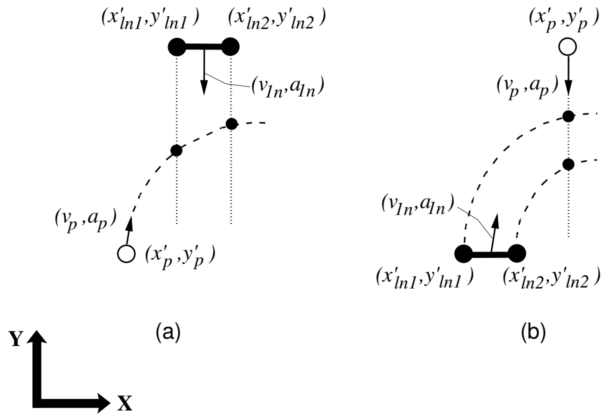

Figure 3: Calculation of TTC for turning movement:
(a) the point takes turning movement
(b) the line section takes turning movement

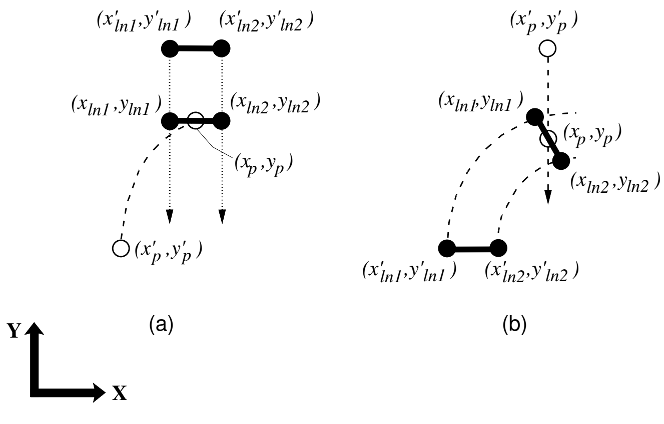

Figure 4: The collision of the point and the line section:
(a) the point takes turning movement
(b) the line section takes turning movement

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 (9) shows the mathematical representation of the line section.

$$y - y_{\ln 1} = k(x - x_{\ln 1}) \tag{9}$$

$$k = \frac{y_{\ln 2} - y_{\ln 1}}{x_{\ln 2} - x_{\ln 1}} = \frac{y'_{\ln 2} - y'_{\ln 1}}{x'_{\ln 2} - x'_{\ln 1}} \tag{10}$$

The collision point shown in Figure 4 (a) is a point of Equation (9) which represents the mathematical shape of the line section. Therefore, we have:

$$y_p - y_{\ln 1} = k(x_p - x_{\ln 1}) \tag{11}$$

As was shown in the Figure 4 (a), the Equation (11) is correct when the vehicles hit each other. Therefore, the associated t is TTC. The TTC can be calculated using Equations (5), (6), (10) and (11). 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:

$$l = \sum_{i=1}^{n} l_i \tag{12}$$

Therefore:

$$l = \sum_{i=1}^{n} \sqrt{\left(\frac{x_p - x'_p}{n}\right)^2 + \left[f\left(x'_p + i\left(\frac{x_p - x'_p}{n}\right)\right) - f\left(x'_p + (i-1)\left(\frac{x_p - x'_p}{n}\right)\right)\right]^2} \tag{13}$$

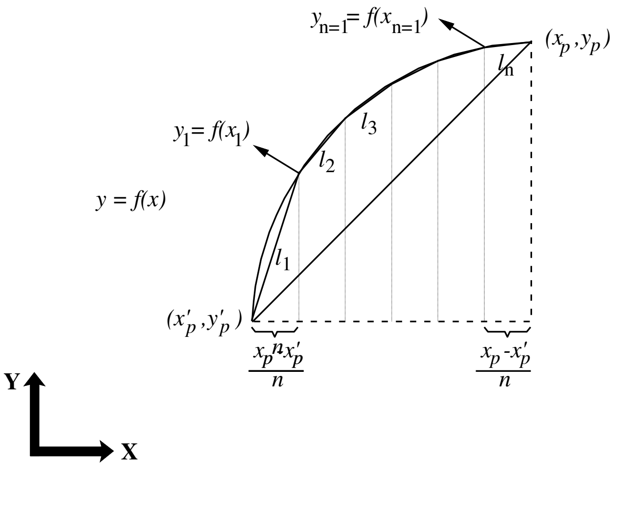

Figure 5: Calculation of the length of a curvature

Equation (14) shows the calculation formula of l using Newtonian Mechanics.

$$l = \frac{1}{2} a_p t^2 + v_p t \tag{14}$$

Therefore, we have:

$$\frac{1}{2} a_p t^2 + v_p t = \sum_{i=1}^{n} \sqrt{(\frac{x_p - x'_p}{n})^2 + [f(x'_p + i(\frac{x_p - x'_p}{n})) - f(x'_p + (i-1)(\frac{x_p - x'_p}{n}))]^2} \tag{15}$$

From equation (15) x_p can be calculated as a function of (t).

$$x_p = f_1(t, a_p, v_p, x'_p) \tag{16}$$

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).

$$y_p = f(x_p) \tag{17}$$

From Equations (5), (6), (10), (11), (16) and (17) TTC is calculated as a function of known parameters shown in Figures 3 (a) and 4 (a).

$$TTC = f_2(x'_p, a_{\ln x}, v_{\ln x}, a_{\ln y}, v_{\ln y}, x'_{\ln 1}, y'_{\ln 1}, k, a_p, v_p) \tag{18}$$

The derivation process based on Figure 3 (b) and Figure 4 (b) 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:

$$x_p = x'_p + \frac{1}{2} a_{px} t^2 + v_{px} t \tag{19}$$

$$y_p = y'_p + \frac{1}{2} a_{py} t^2 + v_{py} t \tag{20}$$

$$k = \frac{y_{\ln 1} - y_{\ln 2}}{x_{\ln 1} - x_{\ln 2}} = \frac{f(x_{\ln 1}) - f(x_{\ln 2})}{x_{\ln 1} - x_{\ln 2}} \tag{21}$$

$$l = \sum_{i=1}^{n} l_i = \sum_{i=1}^{n} \sqrt{(\frac{x_{\ln 1} - x'_{\ln 1}}{n})^2 + [f(x'_{\ln 1} + i(\frac{x_{\ln 1} - x'_{\ln 1}}{n})) - f(x'_{\ln 1} + (i-1)(\frac{x_{\ln 1} - x'_{\ln 1}}{n}))]^2} \tag{22}$$

$$l = \frac{1}{2} a_{\ln} t^2 + v_{\ln} t \tag{23}$$

$$\frac{1}{2} a_{\ln} t^2 + v_{\ln} t = \sum_{i=1}^{n} \sqrt{(\frac{x_{\ln 1} - x'_{\ln 1}}{n})^2 + [f(x'_{\ln 1} + i(\frac{x_{\ln 1} - x'_{\ln 1}}{n})) - f(x'_{\ln 1} + (i-1)(\frac{x_{\ln 1} - x'_{\ln 1}}{n}))]^2} \tag{24}$$

From Equation (22) we have:

$$x_{\ln 1} = f_3(t, a_{\ln}, v_{\ln}, x'_{\ln 1}) \tag{25}$$

From Equations (11), (21), (22), (23), (24) and (25) TTC can be calculated as a function of known parameters shown in Figures 3 (b) and 4 (b).

$$TTC = f_4(x'_p, a_{\ln}, v_{\ln}, a_{px}, v_{px}, x'_{\ln 1}, x'_{\ln 2}, y'_p, a_{py}, v_{py}) \tag{26}$$

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.

APPLLICATION OF THE METHOD

In this section the application of the simulation based road safety index (RSI) to assess risk of right turning manoeuvres at a signalised intersection in Melbourne, Australia is presented.

The studied intersection

The signalised intersection between Stud Road and Boronia Road, Wantirna, Melbourne, Australia (Figure 6) was chosen for the case study. The type of the intersection is a cross intersection controlled by traffic lights in the both approaches. Information associated with the geometric design, the traffic volume, traffic signals, the origin destination matrix and drivers' behaviour were collected from a video recorded at the intersection.

In this study, the turning behaviour of the vehicles turning right from the Stud Road (South) and Stud Road (North) has been investigated. These turning manoeuvres are not fully protected, so in some circumstances drivers must give way to opposing vehicles. If a driver fails to choose an appropriate gap then a conflict takes place.

Table 1: Vehicle movements at Stud Rd/Boronia Rd intersection for morning peak

	Stud Rd (N)	**Stud Rd (S)**	**Boronia Rd (E)**	**Boronia Rd (W)**
Stud Rd (N)		538 veh/hr	18 veh/hr	132 veh/hr*
Stud Rd (S)	678 veh/hr		211 veh/hr**	62 veh/hr
Boronia Rd (E)	59 veh/hr	31 veh/hr		1423 veh/hr
Boronia Rd (W)	35 veh/hr	481 veh/hr	778 h/hr	

* The number of vehicles doing give way maneuver is 26 veh/hr
** The number of vehicles doing give way maneuver is 35 veh/hr

Table 2: Vehicle movements at Stud Rd/Boronia Rd intersection for afternoon peak

	Stud Rd (N)	**Stud Rd (S)**	**Boronia Rd (E)**	**Boronia Rd (W)**
Stud Rd (N)		710 veh/hr	11 veh/hr	97 veh/hr*
Stud Rd (S)	706 veh/hr		315 veh/hr**	48 veh/hr
Boronia Rd (E)	51 veh/hr	46 veh/hr		730 veh/hr
Boronia Rd (W)	24 veh/hr	561 veh/hr	1491 veh/hr	

* The number of vehicles doing give way maneuver is 19 veh/hr
** The number of vehicles doing give way maneuver is 61 veh/hr

Table 1 and Table 2 summarise vehicle movements for morning and afternoon peaks respectively.

Micro simulation model

The VISSIM traffic simulation model was used to model traffic movements in the intersection. The main reasons for selecting VISSIM is its flexibility regarding roadway design, vehicle performance and road user behaviour (Archer, 2005). The driver reaction model, ΔV_s model and ISS model described in the previous section are incorporated in the VISSIM model using COM Interface programming.

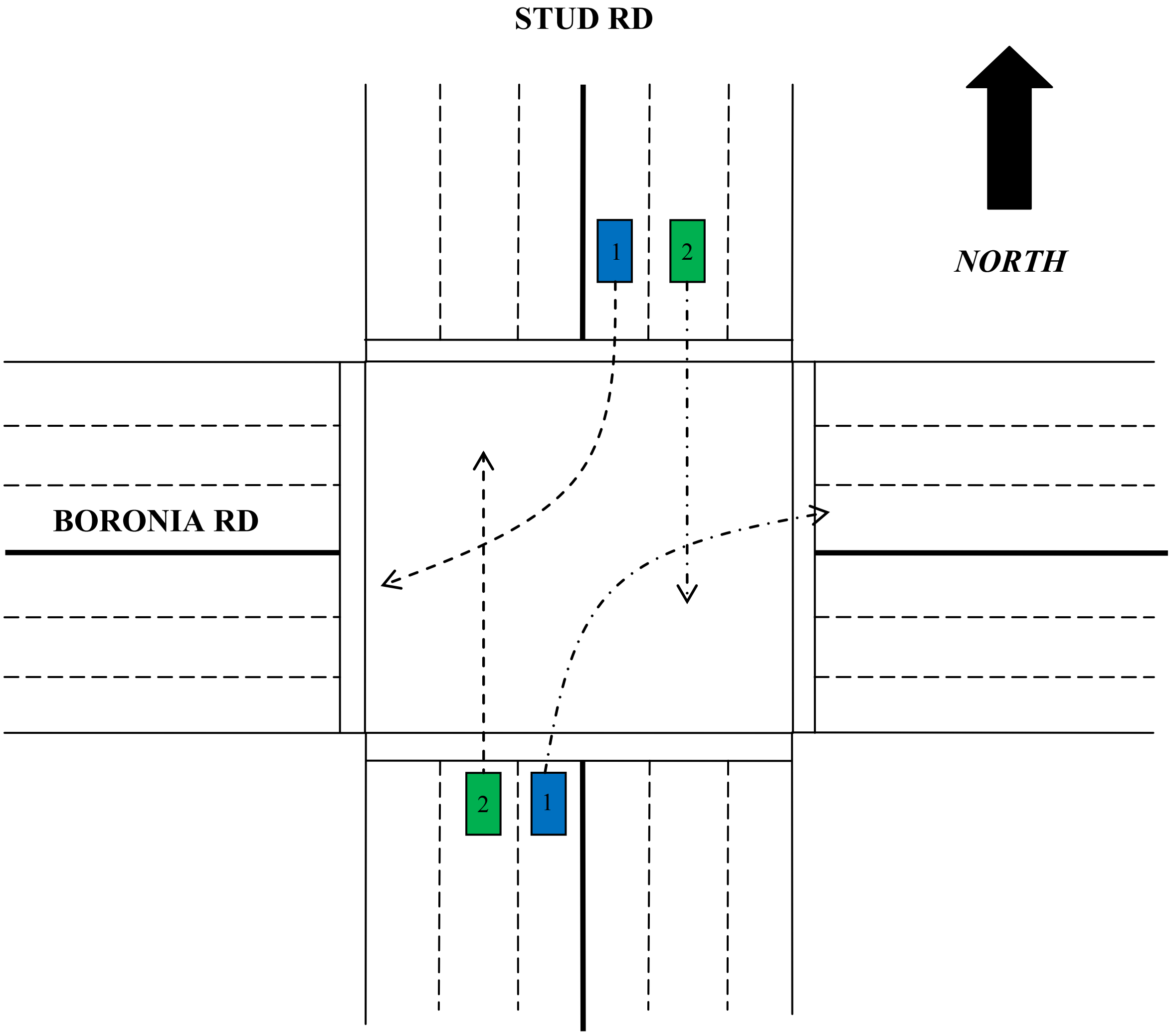

Figure 6: Intersection layout

Model calibration

The model was calibrated to represent the headway and accepted time-gap distributions at the intersection with 95% confidence level.

Headway distribution is the main calibration concern to show time-gap distributions. Initially, the standard default car following parameters in the Wiedemann 74 model was used. The comparison of time-gap distributions revealed a poor level of agreement between observed and simulated data. Wiedmann 74 model has two parameters related to safe distance of vehicles when they are in following status. These two variables were adjusted to achieve a better fit between the observed and simulated data.

In order to validate the gap-acceptance behaviour of the drivers it is necessary to compare the accepted time-gap distributions. Both “conflict areas” and “priority rules” have been tested in VISSIM to model the gap-acceptance behaviour of the drivers turning right from the Stud Road (South) and Stud Road (North). The “conflict areas” provided better calibration results for the model (Huang et al. 2013).

Conflict analysis

In this case study two conflicts have been considered (see Figure 6).

- The first conflict is the conflict occurring between the vehicles turning right from Stud Road (South) to Boronia Road (East) and the vehicles driving straight in from Stud Road (North) to Stud Road (South)
- The second conflict is the conflict taking place between the vehicles turning right from Stud Road (North) to Boronia Road (West) and the vehicles moving straight from Stud Road (South) to Stud Road (North).

Figure 6 shows the right turn from Stud Road (South) into Boronia Road (East) used in this study. The type of crash occurring in this case is an angle crash. Thus, the conflict analysis method explained above is used to calculate the TTC for this conflict.

In order to conduct the TTC calculation process explained above the function of $y = f(x)$ should be determined. This function is determined using vehicles trajectory information collected from the recorded video at the intersection. Equations (35) shows this function for Stud Road (North) to Boronia Road (East) and Stud Road (South) to Boronia Road (West) manoeuvres.

$$f_1(x) = -0.0468x^2 + 3.2537x - 32.153 \tag{27}$$

In order to determine conflict severity required braking rate (RBR) measure is calculated for each conflict (Archer, 2005). According to the definitions proposed by Hyden (1996), a RBR of more than -4 (m/s2) was considered as a serious conflict.

Results

The VISSIM simulation model was run for a three hour for morning peak and afternoon peak periods. Ten runs of each simulation model are undertaken and the average values of the outputs used to describe the safety performance of the manoeuvre. The overall results of the model is summarised in Table 3 and Table 4. Tables 3 and 4 show the value of average number of conflicts, the average expected ISS for all conflicts, and the mathematical road safety index. Table 5 shows the number and severity of the observed crashes for the considered right turning manoeuvres in this case study. As can be seen from the Table 5, historical crash data of the intersection illustrates that during day time the risk of Stud Rd (S) Boronia Rd (E) manoeuvre is more than the risk of Stud Rd (N) Boronia Rd (W) manoeuvre since more number of severe crashes occurred in this manoeuvre.

Two samples t-test with 95% confidence level was performed to compare the simulation results for the two manoeuvres. The results showed that there is significant difference between the average mathematical road safety index for the two simulated scenarios during morning peak period. Therefore, the model results for morning peak period shows that the risk of being involved in a severe crash for Stud Rd (S) Boronia Rd (E) manoeuvre is more than the risk of being involved in a severe crash for Stud Rd (N) Boronia Rd (W) manoeuvre. This is in accordance with the observed data which indicated the number of severe crashes for Stud Rd (South) Boronia Rd (East) is higher than the Stud Rd (North) Boronia Rd (West). On the other hand, the results showed there is no significant difference between the average mathematical road safety indexes for the two simulated scenarios during afternoon peak period. Therefore, the results of this example show that the mathematical road safety index (RSI) can measure the risk of being involved in a severe crash through quantifying traffic flow, conflicts, severe conflicts, crash risk and severe crashes risk.

CONCLUSION

This study outlined the application of a simulation based road safety index (RSI) to assess risk of right turning manoeuvres at a signalised intersection in Melbourne, Australia. The developed RSI is the first simulation based surrogate safety measure that is calculated as a function of traffic volume, number of conflicts, severity of conflicts, crash risk and crash severity risk. VISSIM simulation model was calibrated to represent traffic flow, number of conflicts and severity of conflicts. . In this study, the turning behaviour of the vehicles taking right turning manoeuvre at the intersection was investigated. The number and severity of conflicts is estimated using Time-To-Collision (TTC) calculated for right-turn-against conflicts at the intersection. The severity of conflicts was determined using the magnitude of the Required Braking Rate (RBR) for the conflict. The final results showed a good level of consistency between the estimated RSI and the historical right-turn-against crash data at the

Table 3: Final results of the model for morning peak period

Manoeuvre	Average number of conflicts [95% Confidence Interval]	Actual Value of The Number of Conflicts	Average ISS [95% Confidence Interval]	1000*RSI [95% Confidence Interval]
Stud Rd (N) Boronia Rd (W)	5.6 [2.7-8.5]	4	28.5 [21.3-35.7]	0.0397 [0.0366-0.0428]
Stud Rd (S) Boronia Rd (E)	7.8 [4.3-11.3]	5	41.7 [36.2-48.2]	0.0453 [0.0429-0.0477]

Table 4: Final results of the model for afternoon peak period

Manoeuvre	Average number of conflicts [95% Confidence Interval]	Actual Value of The Number of Conflicts	Average ISS [95% Confidence Interval]	1000*RSI [95% Confidence Interval]
Stud Rd (N) Boronia Rd (W)	4.1 [1.9-6.3]	2	20.5 [11.6-29.4]	0.0377 [0.0289-0.0465]
Stud Rd (S) Boronia Rd (E)	11.1 [6.4-15.8]	7	38.1 [27.0-49.2]	0.0242 [0.0182-0.0302]

Table 5: Number and severity of observed crashes for the studied manoeuvres

Manoeuvre	Time of Day	Crash Severity Level	No of Observed Crashes for Studied Manoeuvres
Stud Rd (N) Boronia Rd (W)	Day Time	Fatality	0
		Injury	2
		Fatality	0
		Injury	4
Stud Rd (S) Boronia Rd (E)	Night Time	Fatality	0
		Injury	0
		Fatality	0
		Injury	0

intersection. This paper contributes on safety modelling through investigating the validity of the developed RSI to assess the risk of right turning behaviours at signalised intersections.

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