SAFETY ASSESSMENT OF UNCONTROLLED INTERSECTIONS USING BOTH CONFLICT PROBABILITY AND SEVERITY

Yingying Ma, Ph.D.
South China University of Technology, Department of Transportation Engineering
381 Wushan Road, Jiaotong Building
Guangzhou, Guangdong, 510640, P. R. China
Telephone: 86-20-87111030-3317, Fax: 86-20-87114460
Email: mayingying@scut.edu.cn

Xiaoran Qin
South China University of Technology, Department of Transportation Engineering
381 Wushan Road, Jiaotong Building
Guangzhou, Guangdong, 510640, P. R. China
Telephone: 86-15800011092, Fax: 86-20-87114460
Email: qin.xiaoran@mail.scut.edu.cn

Offer Grembek, Ph.D.
University of California, Berkeley, Safe Transportation Research and Education Center
2614 Dwight Way #7374
Berkeley, CA 94720
Telephone: 510-642-5553, Fax: 510-643-9922
E-mail: grembek@berkeley.edu

Zhiwei Chen
South China University of Technology, Department of Transportation Engineering
381 Wushan Road, Jiaotong Building
Guangzhou, Guangdong, 510640, P. R. China
Telephone: 86-18814111567, Fax: 86-20-87114460
Email: c.zw02@mail.scut.edu.cn

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ABSTRACT

This paper presents a method to assess the safety of uncontrolled intersections considering both conflict probability and severity, which are two major properties of traffic conflicts. This method provides not only the safety level of the entire intersection but also the distribution of safety within intersections. Intersections are modelled by a two-dimensional Cartesian coordinate system and the internal space of intersections is divided into cells. Firstly, vehicle movement characteristics of at uncontrolled intersections are modelled. Secondly, conflict probability of each cell within the intersection is estimated considering approaching probability and lateral migration probability of vehicles. The quantification of conflict severity is based on kinetic energy loss of potential crashes. Grey cluster analysis is used to combine conflict probability and severity to model the safety assessment of each cell. Thirdly, the application of this method discussed, and an overall safety index of intersections is proposed considering weighted safety level and relative value of area with different safety levels. Finally, a case study, which includes three different designs, is presented along with visualization technique to demonstrate the results. The results not only show the validity of the model, but also indicate that the proposed method can be applied for: i) safety evaluation of existing or designed intersections; ii) dangerous position management within intersections; iii) safety assessment of designed intersections and iv) safety level comparison among different intersections or various designs for the same intersection. Using this method, engineers and planners can better evaluate and improve the safety of existing or the future uncontrolled intersections. The future work will use this approach to develop the models of other types of intersections and different road users.

Keywords: Safety assessment, Uncontrolled intersection, Conflict probability, Conflict severity, Grey cluster

INTRODUCTION

Intersections are bottlenecks of urban roads and junctions of pedestrian, bicycle and vehicle flows, apart from being nodes where road users change their directions and traffic conflicts and accidents concentrate in. Statistics reveal that from 2013 to 2015, head-on collision, broadside collision and collision of vehicle and pedestrian that primarily happened at intersections occupied 47.1% out of 9859 traffic accidents in San Francisco*(1)* while 50% of vehicle crashes took place at intersections in Victoria, Australia*(2)*. The safety problem of intersections has always been of great public concern, thereby being an extremely important problem in the domain of traffic conflict analysis and safety assessment of intersections.

Currently, safety assessment of intersections mainly incorporates statistical model-based method and simulated conflicts-based method. Statistical model-based method using safety performance functions (SPFs) is recommended in the Highway Safety Manual and has been applied in some states such as California in the United States*(3)*. Besides, several studies have been conducted to develop the crash prediction models as follows: generalized linear regression model *(4)*, regression model *(5)*, binary probit model *(6)*, gray evaluation model*(7, 8)* and experience model. However, comprehensive historical crash data spanning multiple years are necessary and when using statistical model-based method *(9)*. A high probability of a traffic crash can be represented by traffic conflict *(10)*, which can indirectly reflect the safety situation of an specific intersection. Therefore traffic conflict can be used in safety assessment of intersections.

Simulated conflicts-based method was proposed by Perkins and Harris in 1968 *(11)* and has been recently highlighted*(12-14)*. The definition and process of traffic conflict are firstly determined *(15)* and studies on two key steps of this methods are profound. On one hand, running characteristics of vehicles such as trajectories, velocity and acceleration are mainly analyzed through microscopic traffic simulation models *(16-18)* . On the other, surrogate indicators such as time-to-collision and post-encroachment time *(19-21)*, time to zebra*(22)*, possibility index for collision with urgent deceleration *(23)*, time to accident *(24)* and deceleration of safety *(25)* are defined and utilized for safety or risk assessment. Meanwhile, the validity and applicability of traffic techniques are also proved *(26)*. Beyond these two safety evaluation methods, other methods including hybrid fuzzy clustering *(13) (27)*, system analysis *(28) (29)* and traffic simulation *(30)* are proposed in recent studies.

Studies on safety assessment of uncontrolled intersections are profound, but several problems haven't been solved yet. Firstly, most of previous studies simplify the vehicle as a particle and the vehicle trajectory as a line by neglecting the actual size of the vehicle, which is different from the real world situation. Secondly, the entire intersection is assessed as a whole based on historical crashes in most studies, whereas details within the intersection, such as traffic conflict, safety degree and the unreasonable design causing accidents, are totally omitted, weakening its role in intersection design. However, traffic accident is not a complete indicator of safety of intersections, risk of crash is another significant indicator. Therefore, conflict probability and severity should be integrated to ameliorate the safety assessment of intersections.

In this paper, a safety assessment approach of uncontrolled intersections considering conflict probability and severity is developed. Intersections are divided into cells to detail the safety information of the intersections. The safety level of each specific cell at internal space of intersections could be calculated and shown in a visualization picture. To evaluate the safety level of the entire intersection, an overall safety assessment method for intersections is presented, which could be used for comparing safety situation of multiple intersections or alternatives of a certain intersection. The rest of this paper is organized as follows: section 2 proposes methods of modelling intersections and vehicle running characteristics at uncontrolled intersections. Section 3 develops the methodology of safety assessment within the intersection. Section 4 provides the performance metrics and the safety assessment method of entire intersection. Section 5 applies the proposed methodology to evaluate the safety situation of 3 alternatives and existing scenario of an intersection in China. Section 6 concludes this paper with some remarks.

MODELING RUNNING CHARACTERISTICS OF VEHICLES AT UNCONTROLLED INTERSECTIONS

The running characteristics of vehicles at uncontrolled intersections determine the distribution of traffic conflicts, and have a crucial influence on the safety level of intersections. Therefore, the analysis and modeling running characteristics are the foundation work of safety assessment.

Assumptions

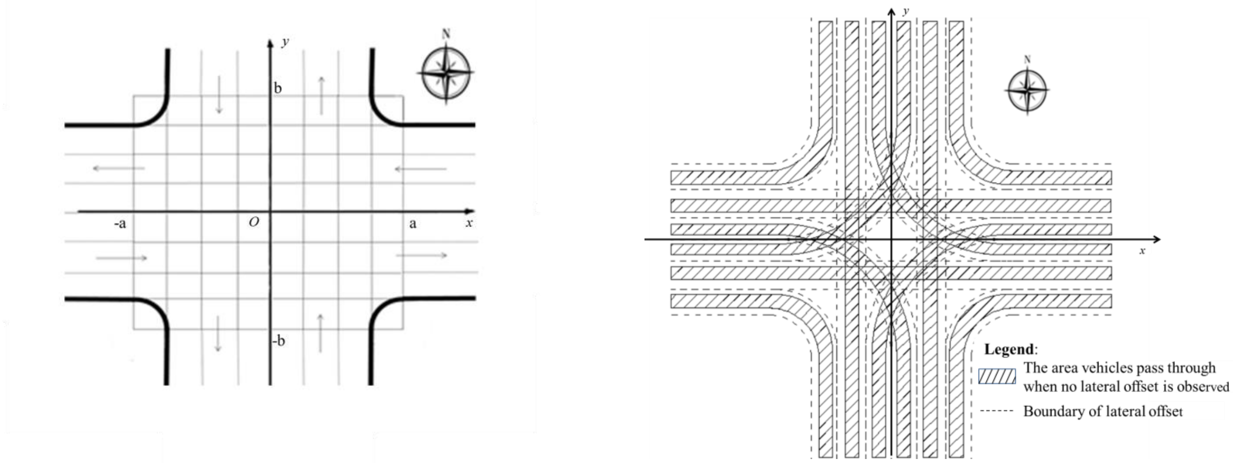
This paper take a 4-leg intersection which has 3 lanes at each approach as an example, the basic assumptions are as follows:

1) Each approach has one left-turn lane, one straight lane and one right-turn lane.
2) Only take motor vehicles into consideration, the impacts of pedestrian and non-motor vehicle are ignored.
3) Vehicles are all cars, and there are no buses or trucks.
4) Running vehicles stay in one lane and won't change lanes when they pass intersections.
5) Width of lanes at each approach and exit are the same;
6) Only consider the conflicts at the internal space of intersections, the merging and diverging conflicts at approaches and exits of intersections are not covered.

Modeling intersection and vehicle trajectories

Build a two-dimensional Cartesian coordinate system: the center of the intersection defined as coordinate origin, the center line of west-to-east road as the x-axes and that of south-to-north road as the y-axes. Assume that the length of intersection is $2a$, and the width is $2b$, equally divide the length and width into n parts separately: $-a = x_0 < ... < x_n = a$, $-b = y_0 < ... < y_n = b$, so the entire intersection is divided into N cells (FIGURE 1(a)), where $N=n^2$. As the number of cells $N \to \infty$, the area of each cell $s \to 0$. $Cell(ij)$ denotes the i^{th} from west and j^{th} from south cell (abbreviated to ij in equations below). Let (x_{ij}, y_{ij}) represents the coordinate of $Cell(ij)$, which is the centroid of $Cell(ij)$, and equals to $(x_i - \frac{a}{n}, y_j - \frac{b}{n})$ while $i, j = 1, 2, ..., n$.

According to the design of intersection diversion route*(31)*, the trajectories of straight forward vehicles are generally within the range between the links of approach and exit lane line, while the turning vehicles running in the curved diversion route which is at least the same width with lane*(32)*. Taken the width of vehicles into consideration, the vehicle trajectories of each approach and conflict areas are drawn on the simplified intersection plan (FIGURE 1(b)). The description of trajectory can not only be applied to intersections with a same lane width of approach and exit, but also the situation of different lane width; the parameters' value of trajectory functions is the main difference.



(a) Coordinate system of intersection and grid processing **(b) Vehicle trajectories and conflict areas**

FIGURE 1 Modeling uncontrolled intersections and vehicle trajectories

The straight forward trajectory scope from east or west approach is regarded as $y \in \Phi_y$, where Φ_y donates to the set of y value; while the north or south approach trajectory is regarded as $x \in \Phi_x$,where Φ_x is the set of x value.

The turning trajectory range of each approach is shown as Eq. 1.

$$(x-x_c)^2+(y-y_c)^2=R^2,\ R\in\left[R_d-\frac{D}{2},R_d+\frac{D}{2}\right] \tag{1}$$

where x_c, y_c are the abscissa and ordinate of arc trajectory center; R is the radius range, while R_d is the design radius of left or right turn trajectories; and D is the width of the lane.

TABLE 1 Coordinate values of vehicle trajectories scope*

Approach	Straight forward trajectory lower limit	Straight forward trajectory upper limit	Left-turn trajectory center	Right-turn trajectory center
East approach	$\frac{3D+A}{2}-\frac{D}{2}$	$\frac{3D+A}{2}+\frac{D}{2}$	$(R_{dl}-\frac{D}{2},-(R_{dl}-\frac{D}{2}))$	$(R_{dr}+\frac{5D}{2},R_{dr}+\frac{5D}{2})$
West approach	$-\frac{3D+A}{2}-\frac{D}{2}$	$-\frac{3D+A}{2}+\frac{D}{2}$	$(-(R_{dl}-\frac{D}{2}),R_{dl}-\frac{D}{2})$	$(-(R_{dr}+\frac{5D}{2}),-(R_{dr}+\frac{5D}{2}))$
South approach	$\frac{3D+A}{2}-\frac{D}{2}$	$\frac{3D+A}{2}+\frac{D}{2}$	$(-(R_{dl}-\frac{D}{2}),-(R_{dl}-\frac{D}{2}))$	$(R_{dr}+\frac{5D}{2},-(R_{dr}+\frac{5D}{2}))$
North approach	$-\frac{3D+A}{2}-\frac{D}{2}$	$-\frac{3D+A}{2}+\frac{D}{2}$	$(R_{dl}-\frac{D}{2},R_{dl}-\frac{D}{2})$	$(-(R_{dr}+\frac{5D}{2}),R_{dr}+\frac{5D}{2})$

* where A donates the width of the median separator (A=0 if there is no median separator), R_0 the radius of the curb; R_{dl} is the design radius of left turn trajectories while R_{dr} refers to the right one.

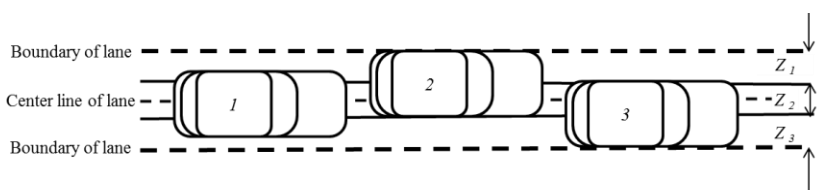
Modeling vehicle lateral migration

The lateral migration happens frequently when vehicles running in a lane, which is caused by driver operating behavior. According to data collection and statistics, it is proposed that the offset (distance between center line of vehicle and lane) of vehicles on the bend basically follows the normal distribution*(33)*, and later, it is proved that the finding can also be applied to straight forward vehicles*(34)*. The same conclusions are reached by driving characteristics analysis*(35)*. According to the results of previous literature, the probability decreases with the rise of lateral offset; the probability density function of lateral offset is shown below.

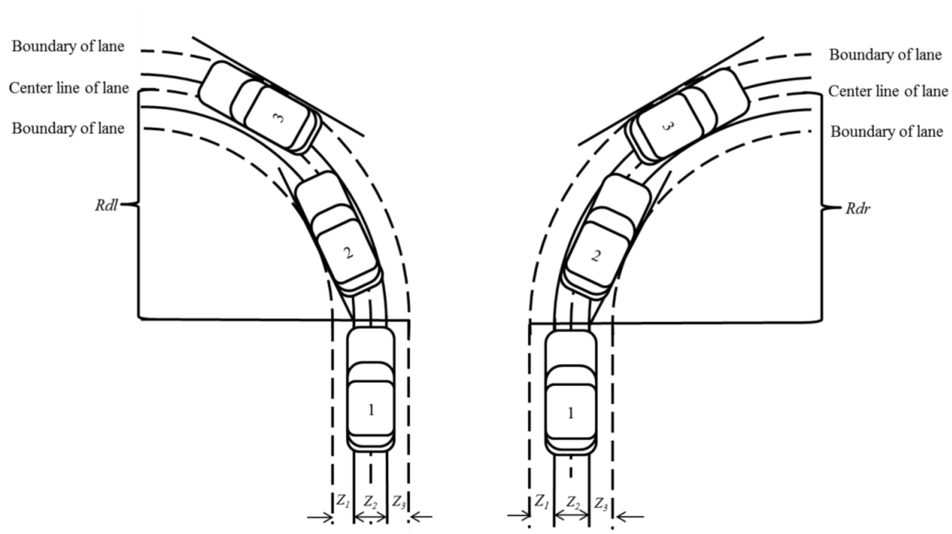
$$f(x)=\frac{1}{\sqrt{2\pi}\sigma}e^{\frac{(x-\mu)^2}{2\sigma^2}} \tag{2}$$

There are 3 extreme cases when vehicles are running in one lane (FIGURE 2a): Case 1 represents the condition that the center line of vehicle and lane coincide with each other; Case 2 is the condition that the vehicle's left edge coincides with the left boundary of the lane, while the Case 3 represents the coincidence of right edge of the vehicle and right boundary of the lane. Therefore, the lane is divided into three zones as shown in FIGURE 2. No matter where the vehicle migrates to, Z_2 is occupied by part of it all the time. However, whether the Z_1 and Z_3 on both sides are occupied depends on the lateral offset, and its probability should be determined by integration of density function (Eq. 2)

The lateral migration behavior of turning vehicles is similar to straight vehicles (FIGURE 2b). In particular, the center line of design turning route is regarded as the location with little offset. The reference lines of both sides are the tangent of vehicle edge, and it is used to compare with the tangent of turning diversion route during the analysis of lateral offset.



(a) The lateral migrations of straight forward vehicle



(b) Lateral migrations of turning vehicles

FIGURE 2 Lateral migrations illustration of vehicles running in the lane

METHODOLOGY

Data collection and preparation

There are four categories of data needed in this paper: geometry information of intersections, velocity of vehicles at intersections, traffic volume of each approach and vehicles related parameters.

TABLE 2 Main parameters' definition and representation

Data categories	Main content	Symbol	Collected way
Geometry information of Intersections	Width of lanes	D	Data of field measurement
	Width of median separators	A	
	Radius of curbs	R_0	
	Design radius of left-turn vehicles	R_{dl}	
	Design radius of right-turn vehicles	R_{dr}	
Vehicle velocity (left-turn, straight and right-turn)	Velocity of east approach	V_{el}, V_{es}, V_{er}	Investigation velocity or design velocity
	Velocity of west approach	V_{wl}, V_{ws}, V_{wr}	
	Velocity of south approach	V_{sl}, V_{ss}, V_{sr}	
	Velocity of north approach	V_{nl}, V_{ns}, V_{nr}	
Traffic volume (left-turn, straight and right-turn)	Arrival rate of east approach	λ_{el}, λ_{es}, λ_{er}	Design hourly volume or investigated hourly volume
	Arrival rate of west approach	λ_{wl}, λ_{ws}, λ_{wr}	
	Arrival rate of south approach	λ_{sl}, λ_{ss}, λ_{sr}	
	Arrival rate of north approach	λ_{nl}, λ_{ns}, λ_{nr}	
Vehicle related parameters	Length of standard vehicles	L	Related literature or investigation statistics
	Width of standard vehicles	B	
	Average lateral offset	μ	
	Lateral offset variance	σ	

Conflict probability prediction

Conflict is defined as situations where two or more road users would collide if neither of them made an evasive maneuver. The definition here in this paper is stricter: a conflict happens when two or more vehicles arrive at the same cell the same time. Define the following concepts: P_R is the approaching probability which is related to arrival rate, and it means the probability that vehicle passes the trajectory section which some cell belongs to. P_D is the lateral migration probability, and it means the probability that vehicle migrates to some cell at one trajectory section. Therefore the probability of a vehicle appears at $Cell(ij)$ ($P_{A_{ij}}$) can be expressed as the product of approaching probability and lateral migration probability for the same cell.

$$P_{A_{ij}} = P_{R_{ij}} \times P_{D_{ij}} \quad (3)$$

Approaching probability

Previous researches indicate that the Poisson distribution can be properly fit vehicle arrival*(36)*. So it can also be applied to express the approaching probability of $Cell(ij)$ during the observation period t. (Eq. 4)

$$P_{R_{ij}} = 1 - P(X=0) = 1 - e^{-\lambda_k t} \tag{4}$$

where λ_k (pcu/h) is the arrival rate of vehicles on trajectory k, t(s) is the observation period. From condition (b) to (c) shown in FIGURE 3, the running time of vehicle 1 is $t_1 = \frac{L+B}{v_1}$, while that of vehicle 2 is $t_2 = \frac{L+B}{v_2}$. So the observation period should be the minimum time interval that two vehicles don't conflict. (Eq. 5)

$$t = \min(\frac{L+B}{v_1}, \frac{L+B}{v_2}) \tag{5}$$

where v_1 and v_2 are the vehicle velocities that may conflict.

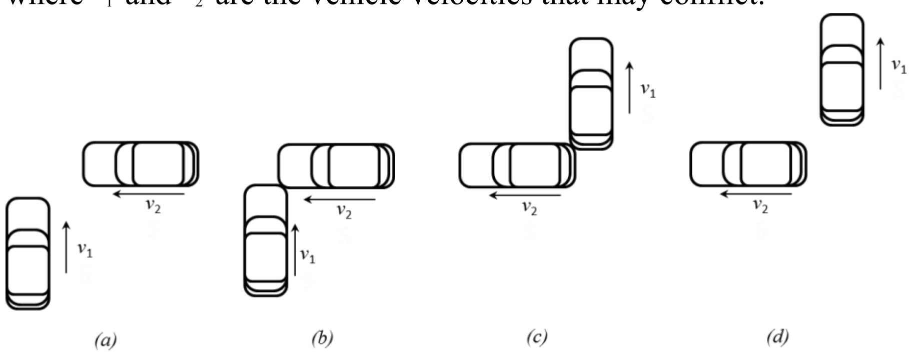


FIGURE 3 The conflict process illustration of two vehicles

Substituting Eq.5 into Eq.4, the approaching probability of $Cell(ij)$ during the observation period is obtained.

$$P_{R_{ij}} = 1 - e^{-\lambda_k \min(\frac{L+B}{v_1}, \frac{L+B}{v_2})} \tag{6}$$

Lateral migration probability

Derivation equation of lateral migration probability $P_{D_{ij}}$ is obtained on the basis of probability density function and interval segmentation.

$$P_{D_{ij}} = \begin{cases} \int_{l_1}^{u_1} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx, & Cell(ij) \in Z_1 \\ 1 \quad , & Cell(ij) \in Z_2 \\ \int_{l_2}^{u_2} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx, & Cell(ij) \in Z_3 \end{cases} \tag{7}$$

where u_i and l_i ($i = 1,2$ and $l_i < u_i$) are the bounds of integration which represent the lateral offset.

Since the lateral migration probability refers to the probability that a certain cell in the lane is occupied by vehicles, the bounds should be the range of lateral offset when the cell is occupied. Take the east approach for example to solve the integration bounds. Assume that $Cell(ij)$ is the cell within trajectory scope at east straight lane (straight lanes and turning lanes of other approaches are similar):

If $Cell(ij)$ falls in Z_2, which means $y_{ij} \in \left[2D-B+\frac{A}{2}, D+B+\frac{A}{2}\right]$, then $P_{D_{ij}}=1$;

If $Cell(ij)$ is in Z_1, which means $y_{ij} \in \left(D+B+\frac{A}{2}, 2D+\frac{A}{2}\right]$, then:

When vehicle migrates to the location that its right (or left) edge coincide with the cell, it is the first time that vehicle occupy the cell. This situation corresponds to the lower bound of integration (Eq.8).

$$l_1 = y_{ij} - y_0 = y_{ij} - \frac{3D+B+A}{2} \tag{8}$$

As vehicle moving right, and when the right (or left) edge of vehicle coincide with the right (or left) lane line, the cell is still occupied. This corresponds to the upper bound (Eq.9).

$$u_1 = y_m - y_0 = \frac{D-B}{2} \tag{9}$$

Substituting Eq.8 and Eq.9 into Eq.7, the lateral migration probability of cells in Z_1 is obtained (Eq.10).

$$P_{D_{ij}} = \int_{y_{ij}-\frac{3D+B+A}{2}}^{\frac{D-B}{2}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}} dy \tag{10}$$

Similarly, if $Cell(ij)$ falls in Z_3, which means $y_{ij} \in \left[D+\frac{A}{2}, 2D-B+\frac{A}{2}\right)$, then

$$P_{D_{ij}} = \int_{y_{ij}-\frac{3D-B+A}{2}}^{\frac{D-B}{2}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}} dy \tag{11}$$

According to the analytical method above, the straight lane lateral migration probabilities of the four approaches are shown as Eq.12.

$$P_{D_{ij}} = \begin{cases} \int_{y-\frac{3D+B+A}{2}}^{\frac{D-B}{2}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}} dy, & y \in \left(D+B+\frac{A}{2}, 2D+\frac{A}{2}\right] \\ 1, & y \in \left[2D-B+\frac{A}{2}, D+B+\frac{A}{2}\right] \\ \int_{y-\frac{3D-B+A}{2}}^{\frac{D-B}{2}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}} dy, & y \in \left[D+\frac{A}{2}, 2D-B+\frac{A}{2}\right) \end{cases} \tag{12}$$

where the value of y: east approach $y = y_{ij}$, west approach $y=-y_{ij}$, north approach $y=-x_{ij}$, south approach $y = x_{ij}$.

The turning lateral migration probabilities are shown as Eq.13.

$$P_{D_{ij}} = \begin{cases} \int_{R_w-\frac{B}{2}-R_{dw}}^{\frac{D-B}{2}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(R_w-\mu)^2}{2\sigma^2}} dR_w, & R_w \in \left(R_{dw}+B-\frac{D}{2}, R_{dw}+\frac{D}{2}\right] \\ 1, & R_w \in \left[R_{dw}-B+\frac{D}{2}, R_{dw}+B-\frac{D}{2}\right] \\ \int_{\left|R_w+\frac{B}{2}-R_{dw}\right|}^{\frac{D-B}{2}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(R_w-\mu)^2}{2\sigma^2}} dR_w, & R_w \in \left[R_{dw}-\frac{D}{2}, R_{dw}-B+\frac{D}{2}\right) \end{cases} \tag{13}$$

Where w denotes l or r. When w denotes l, the value of R_{dl} is: east approach $R_{dl} = \left|(x_m - x_n)^2 + (y_m - y_0)^2\right|^{1/2}$, west approach $R_{dl} = \left|(x_m - x_0)^2 + (y_m - y_n)^2\right|^{1/2}$, north approach $R_{dl} = \left|(x_m - x_n)^2 + (y_m - y_n)^2\right|^{1/2}$, south approach $R_{dl} = \left|(x_m - x_n)^2 + (y_m - y_0)^2\right|^{1/2}$. When w denotes r, the value of R_{dr}: east approach $R_{dr} = \left|(x_m - x_n)^2 + (y_m - y_n)^2\right|^{1/2}$, west approach $R_{dr} = \left|(x_m - x_0)^2 + (y_m - y_0)^2\right|^{1/2}$, north approach $R_{dr} = \left|(x_m - x_0)^2 + (y_m - y_n)^2\right|^{1/2}$, south approach $R_{dr} = \left|(x_m - x_n)^2 + (y_m - y_0)^2\right|^{1/2}$

Conflict probability

The trajectories diagram shows that there are up to three trajectories across the same cell. The three trajectories are marked as $k = a,b,c$, so the conflict probability at one cell is expressed as Eq.14.

$$P_{C_{ij}} = P_{A_{ij}}^a \times P_{A_{ij}}^b + P_{A_{ij}}^b \times P_{A_{ij}}^c + P_{A_{ij}}^a \times P_{A_{ij}}^c + P_{A_{ij}}^a \times P_{A_{ij}}^b \times P_{A_{ij}}^c \tag{14}$$

where $P_{A_{ij}}^k$ is the probability of a vehicle on trajectory k appears at $Cell(ij)$ (Eq.3).

Ignoring the infinitesimal of higher order, define the final conflict probability as follows:

$$P_{C_{ij}} = P_{A_{ij}}^a \times P_{A_{ij}}^b + P_{A_{ij}}^b \times P_{A_{ij}}^c + P_{A_{ij}}^a \times P_{A_{ij}}^c \tag{15}$$

Conflict severity assessment

Previous researches have provided several quantitative methods of traffic conflict severity: According to data of kinematics parameters of vehicles, the time to collision and non-complete braking time are taken as parameters to build quantitative severity value*(37)*. Velocity and time to conflict are also used to measure the severity of conflict*(38)*. Some studies have introduced the concept of influence coefficient based on the relationship between traffic conflict and traffic condition at intersections, and analyzed the severity using this concept*(39)*. A measurement of the crash hazard that considers crash occurrence probability as well as expected severity demonstrated by kinetic energy is proposed and is used to analyze the sensitivity*(9)*. According to previous studies, energy loss of a potential crash is a feasible way to demonstrate the severity of conflict. Given the worst situation, the assumptions are as follows:

1) The quality of vehicles is almost the same;
2) Before crash, vehicles don’t adopt brake measure and keep constant velocity;
3) During crash, the resultant internal force of the system is much larger than external force;

There are at least two trajectories of each conflict point, and the velocity vector can be easily obtained in terms of the conflict trajectories. Decomposed the velocity of crash vehicles to x and y-axes and combined with the theory of momentum conservation, the kinetic energy loss model is established. Kinetic energy loss per unit mass of each cell at the intersection can be obtained in Eq.16.

$$\Omega = \frac{\Delta E}{\overline{m}} = \frac{1}{4}(v_1^2 + v_2^2) - \frac{1}{2} v_1 v_2 \cos(\theta_1 - \theta_2) \quad (16)$$

where Ω donates the safety severity, $\overline{m}$ is the average mass of crash vehicles, v_1 and v_2 are the velocities of each vehicle before crash, and θ_1, θ_2 are the angle of vehicle velocity separately which are measured counterclockwise from the positive x-axis.

Define four levels of conflict severity based on the statistics of energy loss and crash severity: slight conflict, general conflict, severe conflict and serious conflict. The severity level of each cell can be determined according to its kinetic energy loss per unit mass*(40)*.

Integration of conflict probability and severity using gray cluster method

For the safety issue, conflict probability and conflict severity are two important indicators, therefore, it is necessary to take both of them into consideration when conducting safety assessment*(9)*. The purpose of the combination of these two factors is that one indicator can be used to reflect not only the possible of conflict, but also the severity. Thus the result could provide decision makers or designers with better support and reference.

The grey cluster analysis is a grey statistical strategy. It classifies the object into *n* categories using the whitenization weight function of different cluster indicators, thus achieves determination of cluster objects. This method can synthesize the impacts of multiple indexes and has the advantage of clear algorithm and strong practicality. Especially when there is explicit basis of whitenization value, the artificial influences of grey cluster can be reduced and its objectivity rises*(41)*. In this paper, the grey cluster analysis method is properly applied to satisfy the demand of a large number of cells that need to be assessed and two indicators, which are conflict probability and severity.

According to previous research, four safety levels are defined by conflict probability*(42)* and conflict severity*(40)* respectively. Therefore, four safety levels are used in this paper: level I means safe, level II means the marginally safe, level III means dangerous and level IV seriously dangerous. The whitenization values are shown in TABLE 3.

TABLE 3 The whitenization value of the two indicators

Indicators	**whitenization value**			
	λ_1	λ_2	λ_3	λ_4
Conflict probability*	0	0.001	0.025	0.036
Conflict severity(J/kg)**	0	50	100	150

*** Obtained from the cumulative frequency curve of TC/MPCU*(42)***
**** Obtained from the previous research*(40)***

Use whitenization values to solve the corresponding functions (Eq.17). (z is the number of indicators, x is independent variable)

$$f_z^1(x)=\begin{cases}1 & (x<\lambda_1)\\ \dfrac{\lambda_1-x}{\lambda_2-\lambda_1} & (\lambda_1<x<\lambda_2)\\ 0 & (x>\lambda_2)\end{cases} \qquad f_z^2(x)=\begin{cases}0 & (x<\lambda_1)\\ \dfrac{x-\lambda_1}{\lambda_2-\lambda_1} & (\lambda_1<x<\lambda_2)\\ \dfrac{x-\lambda_2}{\lambda_3-\lambda_2} & (\lambda_2<x<\lambda_3)\\ 0 & (x>\lambda_3)\end{cases}$$

$$f_z^3(x)=\begin{cases}0 & (x<\lambda_2)\\ \dfrac{x-\lambda_2}{\lambda_3-\lambda_2} & (\lambda_2<x<\lambda_3)\\ \dfrac{\lambda_4-x}{\lambda_4-\lambda_3} & (\lambda_3<x<\lambda_4)\\ 0 & (x>\lambda_4)\end{cases} \qquad f_z^4(x)=\begin{cases}0 & (x<\lambda_3)\\ \dfrac{x-\lambda_3}{\lambda_4-\lambda_3} & (\lambda_3<x<\lambda_4)\\ 1 & (x>\lambda_4)\end{cases} \tag{17}$$

The cluster weight could be obtained from experts. Because the conflict probability is primary factor in safety assessment, supplemented by conflict severity; the grey cluster coefficient of each cell is shown in Eq.18.

$$\sigma_{Cell(ij)}^k=\sum_{z=1}^{2} f_z^k(Cell(ij)_z)\times\eta_z \tag{18}$$

where $\sigma_{Cell(ij)}^k$ donates the coefficient that $Cell(ij)$ belongs to the k th cluster, $Cell(ij)_z$ is the z th indicator value of $Cell(ij)$, η_z the weight of z th indicator which could be determined by experts' experience, $f_z^k(x)$ the whitenization weight function of x.

The safety level of $Cell(ij)$ is $\sigma_{Cell(ij)}^{k^*}=\max\{\sigma_{Cell(ij)}^k\}$, which means the object $Cell(ij)$ belongs to the k^* th grey class and the safety level is k.

APPLICATION

Analysis above focuses on the safety assessment on each cell in the intersection which also provides basic data for intersection safety assessment. Several performance metrics can be extracted to assess the entire intersection based on safety level distribution within intersections.

TABLE 4 The major performance metrics and usage

Performance metrics	Explanation	Usage
Area of each safety level	The total area of cells in each safety level.	Give the detail information of each safety level within intersections. The larger the area with lower safety levels, the lower safety level of entire intersection. It could be used to compare the effect of alternatives for one intersection.
Relative value of area	Area of each safety level divided by the area of the safest level.	Give a relative value of each safety level unaffected by the area of intersections. It could be used to do comparison among intersections or alternatives for

		one intersection.
Number of conflict zones	Conflict zones can be observed easily by the visualization of cells' safety assessment. Cells whose safety level are from II to IV and are adjacent to each other could be seen as a conflict zone. Drivers may be distracted by too many conflict zones, which is bad for safety.	Give the information of conflict areas, and could be used to give the comparison among intersections or alternatives for one intersection.
Overall safety index	A relative safety index obtained by weighted relative value of area of each safety level	Give an overall safety assessment of one intersection. It could be used in safety comparison among intersections or alternatives for one intersection, and conflict hotspots identification.

Definition of Relative value of area

When assessing various intersections, the intersection area and condition of grid process are not the same. This phenomenon leads to the result that the conversion of absolute value to relative value is necessary to make comparison among intersections possible. Therefore, areas of each level are all divided by the area of safest level S_1, and then generate relative values which are independent of area. Use ρ_k to represent the relative value of area with level *k*.

$$\rho_k = \frac{S_k}{S_1} = (\frac{2a \times 2b}{N} \times n_k) \Big/ (\frac{2a \times 2b}{N} \times n_1) = \frac{n_k}{n_1} \quad (19)$$

where n_k donates to the number of cells belonging to k th level; $2a$, $2b$ are the length and width of the intersection.

Definition of Overall safety index

Cells with different safety levels have a different influence on the overall safety situation of the entire intersection. Instead of directly using the area of cells which belongs to a different level, the influence should be embodied by weight. The overall safety assessment model could be built by weighted summation of the relative value of areas as shown in Eq.20.

$$K = \sum_{k=1}^{4} \rho_k \times \varphi_k \quad (20)$$

where K is the overall safety index of the intersection; φ_k is the weight of k th level, which should be obtained by cost analysis, social investigation and calculation of accident loss. The lower the safety level is, the more loss and influence an accident has, and the higher the weight should be. ρ_k is the relative value of area with level *k*, which is shown in Eq.19.

CASE STUDY

Background

Yanjiang North Road- Xingfu Road 1st uncontrolled intersection in Kunming China has lower flow on north- south direction, but larger on west-east direction due to the commercial facilities along Xinfu Road 1st. To improve the present safety condition, three design scenarios need to be assessed.

Scenario 1 : Reduce the flow on west and east approach;
Scenario 2 : Prohibit left-turn vehicles from west and east approach;
Scenario 3 : Reduce the design velocity.

Relative parameters are obtained from field measurement and simulation (TABLE 5).

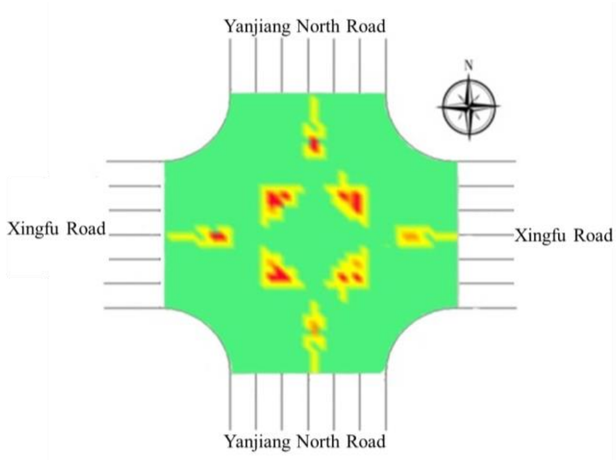
TABLE 5 The value of Parameters in case study

Constant parameters						
Parameter	D (m)	A (m)	L (m)	B (m)	μ	σ
Value	3.5	1	4	2	0.011	0.572
Parameter	V_{es} , V_{ns} (km/h)	V_{sl} , V_{nl} (km/h)	η_1	η_2	R_{dl} (m)	R_{dr} (m)
Value	40	20	0.6	0.4	21.75	11.25
Parameter	λ_{sl} , λ_{ss} , λ_{sr} (veh/s)	λ_{nl} , λ_{ns} , λ_{nr} (veh/s)	φ_1	φ_2	φ_3	φ_4
Value	0.263	0.289	1	4	7	10

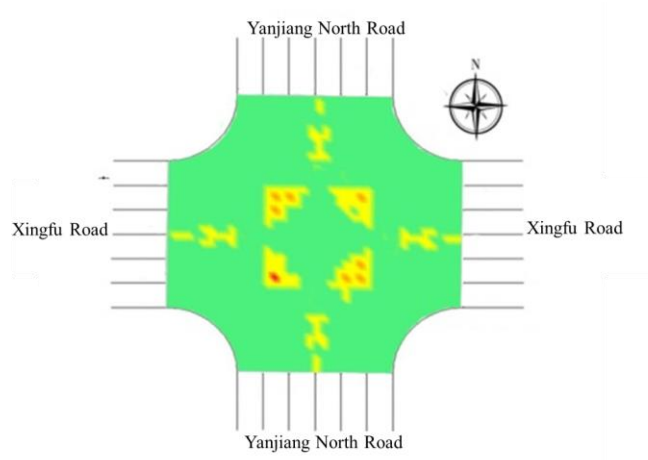
Scenario related variable parameters				
Basic parameter	**Existing Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**
V_{el} (km/h)	20	20	20	15
V_{er} (km/h)	35	35	35	25
V_{wl} (km/h)	20	20	20	10
V_{ws} (km/h)	40	40	40	20
V_{wr} (km/h)	35	35	35	15
V_{ss} (km/h)	40	40	40	45
V_{sr} (km/h)	35	35	35	30
V_{nr} (km/h)	35	35	35	30
R_{el} (veh/s)	0.477	0.127	0.000	0.477
R_{es} (veh/s)	0.477	0.157	0.477	0.477
R_{er} (veh/s)	0.477	0.137	0.477	0.477
R_{wl} (veh/s)	0.498	0.108	0.000	0.498
R_{ws} (veh/s)	0.498	0.138	0.498	0.498
R_{wr} (veh/s)	0.498	0.118	0.498	0.498

Results of assessment

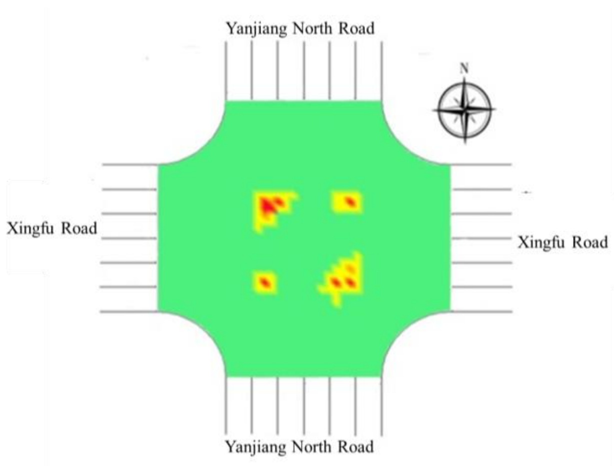
In order to visually present the assessment result, this paper assigns four colors: green, yellow, orange and red, to separately represent safety level I-IV. The intersection is divided into 1681 square cells with a length of 1m. The assessment results are calculated by Matlab software and shown in FIGURE 4 and the overall safety assessment of each scenario is shown in TABLE 6.



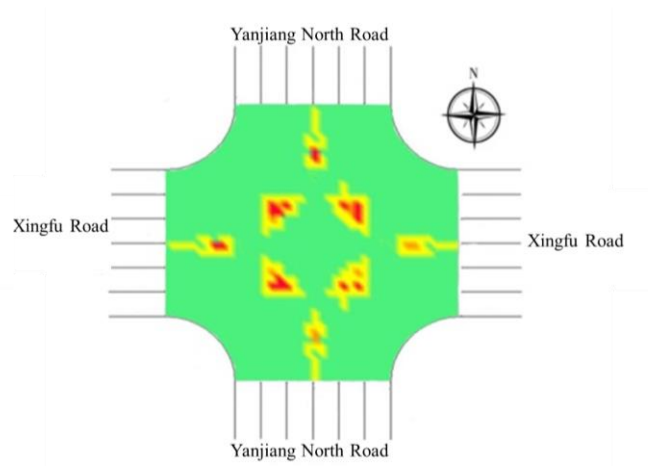
(a) Existing Scenario



(b) Scenario 1



(c) Scenario 2



(d) Scenario 3

Legend	Color	Safety level	Description	Legend	Color	Safety level	Description
■	Green	I	Safe	■	Orange	III	Dangerous
■	Yellow	II	Marginally safe	■	Red	IV	Seriously dangerous

FIGURE 4 Safety assessments of different scenarios

TABLE 6 Assessment results of each scenario

Scenarios		**Existing scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Level I	**Area(m^2)**	1227.5	1249.5	1327.5	1236.5
	Relative value	1	1	1	1
Level II	**Area(m^2)**	142	140	59	135
	Relative value	0.0939	0.0913	0.0366	0.0888
Level III	**Area(m^2)**	10	7	3	17
	Relative value	0.0087	0.0046	0.0019	0.0112
Level IV	**Area(m^2)**	18	1	8	9
	Relative value	0.0156	0.0007	0.0049	0.0059
Entire intersection	**Total Area(m^2)**	1397.5	1397.5	1397.5	1397.5
	Overall safety index	1.5925	1.4044	1.2087	1.4926

	Number of conflict areas	8	8	4	8

From the aspect of conflict area: There are a lot of conflicts at existing scenario of the intersection; scenario 2 sharply decreases the vehicle conflict area within the scope of the intersection. The four conflict areas close to each approach disappear due to the prohibition of left-turn vehicles from west-east direction, and the southwest as well as northeast conflict areas are greatly reduced; scenario 1 reduces the conflicts caused by vehicles on the west and east direction; the result of scenario 3 is similar to the existing scenario. As for the safety index, scenario 2 has the highest safety level. Although scenario 1 and 3 are close in overall safety index, the relative value of scenario 1 is much smaller than scenario 3. According to the analysis above, scenario 2 is the best alternative among the three scenarios. Meanwhile, the assessment results indicate that for this intersection, four conflict areas disappeared and safety level index is sharp down when only two left-turn flows are prohibited instead of four ones.

In conclusion, the three scenarios all make some improvements in safety condition of the intersection in this case. The proposed method can comprehensively assess the effect of alternatives on safety, including the number and distribution of conflict areas, the safety level of each cell and the entire intersection. The number of conflict areas is also an influencing factor of intersection safe operation, along with the overall safety index. The less the number of the conflict area, the easier for drivers to focus on it, so that the safety of driving is enhanced. The proposed method does a good performance on intersection safety assessment, especially for alternative design and improvement measures.

CONCLUSIONS

This paper proposes a more effective way of safety assessment for the uncontrolled intersection, which can assess not only the entire intersection but also the inner space of intersection. It was built on the analysis of vehicle trajectories within intersections. The grey cluster assessment method is used to consider both influences from conflict probability and conflict severity. The probability included approaching probability and lateral migration probability which described the main movement in a lane. While the severity uses kinetic energy loss during the crash, which estimates the real loss of conflict.

The case study shows that the safety assessment in this paper is operable and the visual output of safety assessment makes it more convenient to get the distribution and comparison results, specifically in: i) Safety evaluation of build-up intersections. The proposed assessment method, which is a proactive approach, only needs geometry data of intersections and designed or observed traffic volume, velocity and some other parameters related to vehicles instead of data of crashes history, which need a long time to collect. It could also be used to identify the hotspot intersections for vehicle conflicts. ii) Dangerous position management within intersections. The distribution of dangerous sites within intersections is important information to understand why crashes happen and formulate countermeasures to improve intersection safety. iii) Safety assessment of designed intersections. The proposed method, which doesn’t need history crashes data, is significant for finding hidden dangers of the scheme during the design stage, and providing a reference for scheme improvement before construction, so that the accident prevention and financial saving can be achieved. iv) Safety level comparison among different intersections or various designs for the same intersection. Indicators obtained from the proposed method, such as area of each safety level and their relative values, overall safety index and the number of conflict areas within intersections, provide multiple performance metrics to compare intersections or alternatives of a certain intersection from the perspective of traffic safety.

This paper takes a 4-leg intersection which has 3 lanes as an example to demonstrate the methodology. Other topologies of intersection would have the same application of the proposed approach. Further researches will focus on safety assessments of signal controlled intersections and inter-modes, for example, conflict between vehicles and pedestrians, vehicles, and bicycles.

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