The Parameters Analysis for the Intersection Collision Avoidance Systems Based on Radar Sensors

Jieh-Shian Young, and Chan Wei Hsu

Abstract—This paper mainly studies the analyses of parameters in the intersection collision avoidance (ICA) system based on the radar sensors. The parameters include the positioning errors, the repeat period of the radar sensor, the conditions of potential collisions of two cross-path vehicles, etc. The analyses of the parameters can provide the requirements, limitations, or specifications of this ICA system. In these analyses, the positioning errors will be increased as the measured vehicle approach the intersection. In addition, it is not necessary to implement the radar sensor in higher position since the positioning sensitivities become serious as the height of the radar sensor increases. A concept of the safety buffer distances for front and rear of the measured vehicle is also proposed. The conditions for potential collisions of two cross-path vehicles are also presented to facilitate the computation algorithm.

Keywords—Intersection Collision Avoidance (ICA), Positioning Errors, Radar Sensors, Sensitivity of Positioning.

I. INTRODUCTION

THE fatal collisions at intersections are disproportionately severe up to the present. At many intersections, some buildings or trees may obscure the crossing traffic near the road or other vehicles. Moreover, the vehicle sensors cannot often detect the threat conditions alone. Development of intersection collision countermeasures systems is a crucial and urgent challenge. The intersection collision avoidance (ICA) is one of the significant issues in developments of intelligent traffic system (ITS) [1]. The ICA is also an important issue in intelligent vehicle technologies [2]. Berndt et al have studied the driver braking behavior during intersection approaches [3]. The real-time kinematic GPS (RTKGPS) was utilized in their studies. Salim et al. have presented an algorithm which can increase the speed of collision detection calculation since the detection is not necessary for all possible pairs of vehicles at an intersections [4]. Rawashdeh and Mahmud have proposed an intersection collision avoidance system architecture [5]. They used the dedicated short range communication (DSRC) technology to build a so-called intelligent intersection traffic system (IITS). King et al have also described a wireless intersection collision avoidance system (WICAS) for highway intersection by a wireless sensor network architecture [6]. They proposed a Kalman prediction algorithm which can receive the updated position and velocity estimated from those wireless sensors deployed in lanes. The ICA system in wireless sensor networks was simulated by Kim et al [7]. In their paper, several kinds of simulations verified the feasibility of the ICA architecture. Lindner et al have also proposed an approach for the robust recognition of traffic signals [8]. DaimlerChrysler researchers have used the autonomous sensing for ICA [2]. They used monocular vision systems equipped on vehicles to recognize the traffic light and stop signs and then assist drivers in crossing the intersections safely.

ICA is a tough challenge although there were lots of studies in references. The complexity at each intersection will chiefly determine the high crash rate at intersections. In addition, each intersection is almost unique because of the diversity of characters for intersections [9, 10]. There is no unifying approach to the problem of ICA. In Japan, ICA was a significant portion of Phase I Research by Advanced Cruise-Assisted Highway System (AHS). The ICA work has focused on crossing collisions, right-turn collision, and pedestrian collisions, etc. The USA DOT initiated a new phase called Cooperative Intersection Collision Avoidance System (CICAS) in 2004 [11, 12]. The goat of CICAS is to develop and deploy the systems at 15% of the most hazardous intersections domestically. Furthermore, it is expected that the in-vehicle support can be 50% of the vehicle fleet. In Europe, the cooperative ICA study was an issue within the INTERSAFE Project, which is part of PReVent 6FE integrated Project [13]. This study contained two system development approaches. They are the basis intersection safety system (B-ISS) and the advanced intersection safety system (A-ISS). The B-ISS approach is near term and less complex while A-ISS is more complex and will offer higher performance at letter time. There is a tendency towards the cooperative researches of ICA.

In ICA systems, the positioning of the vehicles in lanes should be very accurate within some required tolerances before the vehicles cross the intersection. For instance, a vehicle will move 20m in 1 second if its speed is 72 km/hr. An ICA system architecture has to provide a mechanism to acquire reliable

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positioning of the approaching vehicles at an intersection. In general, the positioning accuracy tolerance is less than 1 m for a moving vehicle approaching the intersection with 100 km/hr [7]. Drane and Rizos have discussed the application of Global Positioning System (GPS) in ITS. Differential GPS (DGPS) and real-time kinematic (RTK) GPS can be applied to the ITS and ICA with communications between on-board units (OBU) in vehicles and roadside unit (RSU). However, DGPS and RTK GPS are not always affordable for all drivers. In addition, compulsory legislation for the OBU in vehicle may take time. Researchers of ICA systems have to find feasible approaches as alternatives in this transient period. A radar system is one of the feasible candidates of the ICA in this period.

denote the front and rear buffer distances of the measured vehicle, H_i is the height of the sensor, R_i is the range between the sensor and the vehicle, V_i is the speed of the vehicle, $\Delta\theta_i$ is the bore size angle of the radar transmitter, and the inclination angle of radar antenna is equal to $\theta_i + \dfrac{\Delta\theta_i}{2}$. H_i, θ_i, and $\Delta\theta_i$ are assigned when the radar system is installed. $D_{F,i}$ and $D_{R,i}$ depend on the traffic conditions of different lanes and can be assigned. $D_{F,i}$ and $D_{R,i}$ are suggested to be longer if the speed limit of the lane is higher. They can overcome the positioning errors and can comply the safety requirements. In addition, R_i and V_i can be measured by this radar system.
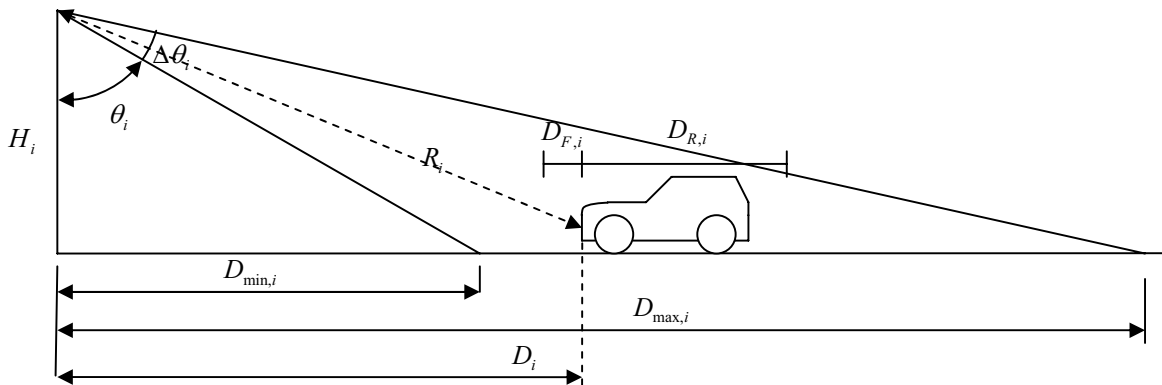

Figure 1. The configuration of the radar system in Lane i of an intersection.

The primary aim of this paper is to analysis the limitations, requirements, and characters of an ICA system based on the radar sensors which are used to detect and measure the statuses of the approaching vehicles. The positioning errors, positioning sensitivities, limitation of repeat frequency of radar system, and conditions of collisions between two cross-path vehicles at intersection are included. The safe buffer distances for both front and rear of a measured vehicle is proposed. The position of the moving vehicle is evaluated at the time of signal transmission from radar in terms of all possible parameters. The results show that the positioning errors become greater as the vehicle approaches the radar sensor. Moreover, to raise the height of the radar sensor is not necessary for the radar sensor.

This paper is organized as follows. Section II will address the configuration of the radar systems at an intersection. Section III will analyze the errors and the sensitivities of the measured vehicle positioning. Section IV will discuss the limitations and requirements of the repeat period of the radar signals and the conditions of collisions at intersections. Finally, Section V contains conclusion and the future work.

II. THE CONFIGURATION OF RADAR SENSORS

In Figure 1, the subscript i denotes the specified properties in Lane i of an intersection, e.g., D_i is the horizontal distance of a vehicle from the radar sensor at the intersection, $D_{max,i}$ and $D_{min,i}$ denote the maximal and minimal distances measured by the radar sensor, respectively, $D_{F,i}$ and $D_{R,i}$ respectively

Figure 1 shows a typical configuration of the radar system in Lane i at intersections for the ICA system. An overhead mounted microwave radar system transmits energy to an object and receives the reflected energy from a measured object. The reflected signal from a vehicle can be used to detect the positions, speeds, presences, lane occupancy, and passages of vehicles in the lane. There are two types of microwave radar sensors used in roadside applications. One is the continuous wave Doppler radar utilized to measure the speed of vehicles. The other is the frequency modulated continuous wave (FMCW) radar utilized to detect the positions of vehicles usually. The measured range, R_i, can be

$$R_i = \frac{c\Delta f_i}{4 f_{m,i}\Delta F_i},$$

where c is the light speed, Δf_i is the instantaneous difference in frequency of the transmitter at the times the signal transmitted and received, $f_{m,i}$ is radio frequency (RF) modulation frequency, and ΔF_i is the bandwidth of the modulated frequency. The range resolution, ΔR_i, resolved by an FMCW radar is

$$\Delta R_i = \frac{c}{2\Delta F_i}. \tag{1}$$

In case the radar operates in 10.5GHz band with the bandwidth 45MHz, the range resolution is 3.3m at best.

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III. POSITIONING ERRORS AND ITS SENSITIVITIES

In Figure 1,

$$D_i = \sqrt{R_i^2 - H_i^2} \ . \tag{2}$$

If FMCW is used in the radar system, the horizontal distance errors, ΔD_i, which is caused by the resolution of FMCW radar system becomes

$$\Delta D_i = \sqrt{(R_i + \Delta R_i)^2 - H_i^2} - \sqrt{R_i^2 - H_i^2} \ . \tag{3}$$

Substituting (1) into (3) gives

$$\Delta D_i = \sqrt{(R_i + \frac{c}{2\Delta F_i})^2 - H_i^2} - \sqrt{R_i^2 - H_i^2} \ .$$

Figure 2 shows the errors of the horizontal distances caused by different ranges from a measured vehicle to the radar sensor with $H_i = 4\text{m}$ and $\Delta F_i = 45\text{MHz}$. The resolution of the horizontal distance measurements will become worse as the vehicle approaches the radar sensor. The worst case is that the vehicle arrives at $D_{\min,i}$. In other words, $D_{\min,i} > 9.17\text{m}$ can be specified if the resolution of the horizontal distance is better than 3.50m due to the resolution of the range of the radar sensor. Figure 3 shows the errors of the horizontal distances from a measured vehicle to the radar sensor vs. the horizontal distance and ΔF_i with $H_i = 4\text{m}$ due to the resolution of ranges. $D_{\min,i}$ and ΔF_i have to compromise with each other if the error of the horizontal distance is specified.
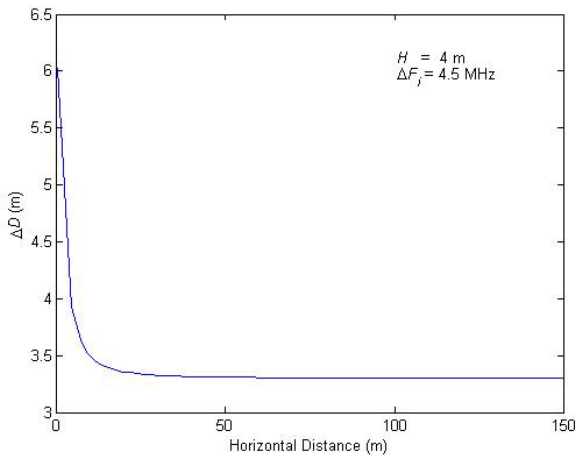

Figure 2. The resolution of horizontal distance.

Let T_T be the counter tick time of the system. From Figure 1,

$$R_i = \frac{c\Delta t_i}{2} \in \left[\frac{cT_T N_i}{2}, \frac{cT_T (N_i + 1)}{2} \right), \tag{4}$$

where N_i and Δt_i are the tick count and the electromagnetic (EM) wave flight time, respectively, from transmitter to the receiver of the radar system, i.e.,

$$\Delta t_i \in [T_T N_i, T_T (N_i + 1)).$$

Substituting (4) into (2) gives

$$D_i = \sqrt{\left(\frac{c\Delta t_i}{2}\right)^2 - H_i^2} \in \left[\sqrt{\left(\frac{cT_T N_i}{2}\right)^2 - H_i^2}, \sqrt{\left(\frac{cT_T (N_i + 1)}{2}\right)^2 - H_i^2} \right) \tag{5}$$

as $D_i \geq 0$. Let $D_{T,i}$ denote the evaluated horizontal distance, or true distance, of the vehicle from the radar sensor at the time as the signal is transmitted, i.e.,

$$D_{T,i} = D_i - \frac{V_i \Delta t_i}{2}, \tag{6}$$

or from (5), (6) becomes

$$D_{T,i} = \sqrt{\left(\frac{c\Delta t_i}{2}\right)^2 - H_i^2} - \frac{V_i \Delta t_i}{2}, \tag{7}$$

i.e.,

$$D_{T,i} \in \left[\sqrt{\left(\frac{cT_i N_i}{2}\right)^2 - H_i^2} - \frac{V_i T_i N_i}{2}, \sqrt{\left(\frac{cT_i (N_i + 1)}{2}\right)^2 - H_i^2} - \frac{V_i T_i (N_i + 1)}{2} \right).$$
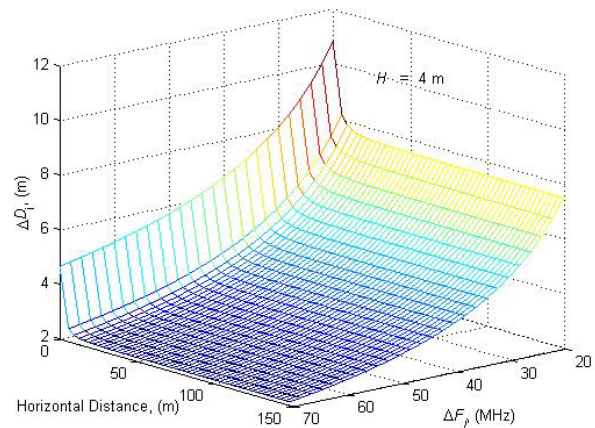

Figure 3. The resolution of horizontal distance vs. horizontal distance and ΔF_i.

Accordingly, the positioning error due to the counter time tick for two successive counts can be as follows

$$\Delta D_{T,i} = \sqrt{\left(\frac{cT_i (N_i + 1)}{2}\right)^2 - H_i^2} - \sqrt{\left(\frac{cT_i N_i}{2}\right)^2 - H_i^2} - \frac{V_i T_T}{2} \ . \tag{8}$$

In case $R_i \gg H_i$ or $\frac{c\Delta t_i}{2} \gg H_i$, (8) becomes

$$\Delta D_{T,i} \cong \left[\frac{c}{2} - \frac{V_i}{2} \right] T_T \ .$$

That is, as a vehicle is far away from the radar sensor compared with the height of the radar sensor, the positioning error is approximate to

$$\Delta D_{T,i} \cong \frac{cT_T}{2},$$

because of $c \gg V_i$. Figure 4 shows the positioning errors of the radar system due to different tick counts as $H_i = 4\text{m}$, $T_T = 10\text{ns}$, and $V_i = 100\text{km/hr}$. It illustrates that the positioning errors will also become worse as a vehicle approaches the intersection. In this condition, the maximal positioning error is 2.4106m at $N_i = 3$ without the constrains of the minimal distances since $N_i \geq 3$. In case $D_{\min,i} = 5\text{m}$, i.e., $N_i \geq 4$, the maximal positioning error will become 1.8722m.
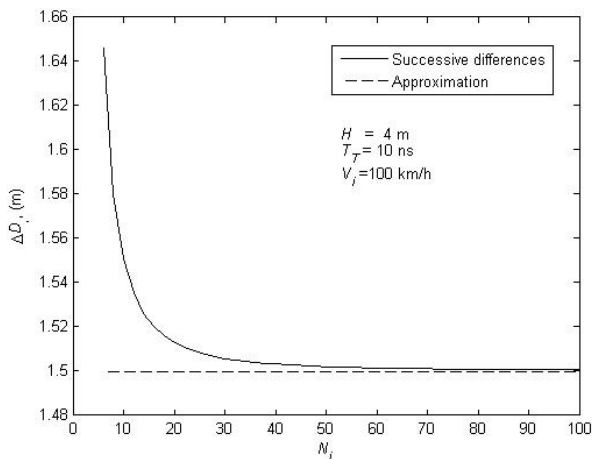
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Figure 4. The positioning error due to different tick counts.
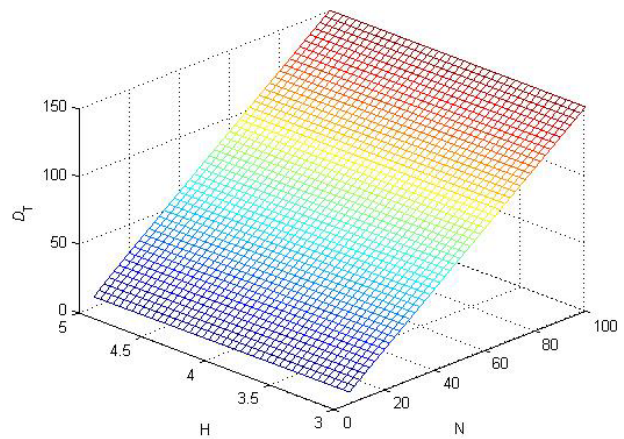

Figure 4. $D_{T,i}$ vs. H_i and N_i.

In (7), the sensitivities of $D_{T,i}$ due to Δt_i, V_i, and H_i, respectively, can be

$$\frac{\partial D_{T,i}}{\partial (\Delta t_i)} = \frac{c^2 \Delta t_i}{4\sqrt{\left(\frac{c\Delta t_i}{2}\right)^2 - H_i^2}} - \frac{V_i}{2}, \qquad (9)$$

$$\frac{\partial D_{T,i}}{\partial V_i} = \frac{\Delta t_i}{2}, \qquad (10)$$

and

$$\frac{\partial D_{T,i}}{\partial H_i} = \frac{-H_i}{\sqrt{\left(\frac{c\Delta t_i}{2}\right)^2 - H_i^2}}. \qquad (11)$$

Δt_i in (7) can be substituted by

$$\Delta t_i = T_T N_i \qquad (12)$$

to approximate to $D_{T,i}$. Figure 5 shows the mesh plot of $D_{T,i}$ vs. H_i and N_i as V_i =100km/hr and $T_T = 10$ns . (9), (10), and (11) can be represented as follows.

$$\frac{\partial D_{T,i}}{\partial N_i} = \frac{c^2 T_T^2 N_i}{4\sqrt{\left(\frac{cT_T N_i}{2}\right)^2 - H_i^2}} - \frac{V_i T_T}{2}, \qquad (13)$$

$$\frac{\partial D_{T,i}}{\partial V_i} = \frac{T_T N_i}{2}, \qquad (14)$$

and

$$\frac{\partial D_{T,i}}{\partial H_i} = \frac{-H_i}{\sqrt{\left(\frac{cT_T N_i}{2}\right)^2 - H_i^2}}. \qquad (15)$$

T_T depends on the processors of the radar system. The sensitivity of $D_{T,i}$ due to T_T is also a significant parameter of ICA system, i.e., a processor can be used in ICA system according as its tick time cause this sensitivity slight. Substituting (12) into (7), the sensitivity of $D_{T,i}$ due to T_T can be as follows.

$$\frac{\partial D_{T,i}}{\partial T_T} = \frac{c^2 T_T N_i^2}{4\sqrt{\left(\frac{cT_T N_i}{2}\right)^2 - H_i^2}} - \frac{V_i N_i}{2} \qquad (16)$$

(13) can indicate that the positioning sensitivity for unit tick count variation depends on the tick count and height of radar sensor if the counter tick time of system is constant because of $c \gg V_i$. (11) and (16) are respectively equal to $\frac{cT_T}{2}$ and $\frac{cN_i}{2}$ as $R_i \gg H_i$. In (14), the positioning sensitivity due to vehicle speed depends on the range between measured vehicle and radar sensor, i.e., the tick count and the tick time. In addition, (15) shows that the positioning sensitivity caused by the height of radar depends on the horizontal distance of the measured vehicle from the radar sensor and the height of radar.
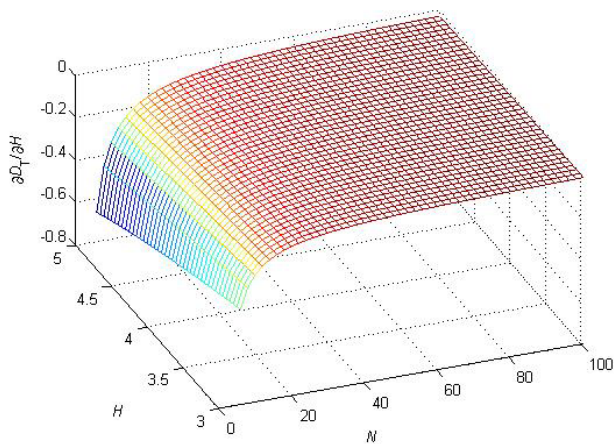
Figure 6 shows the positioning sensitivities due to tick count number (Figure 6.a) and height of radar sensor (Figure 6.b) for different count numbers and height of radar sensor in case V_i =100km/hr and $T_T = 10$ns . In these figures, the positioning is more sensitive as the measured vehicle approaches the intersection. Moreover, its sensitivities will be increased for their absolute values if the height of radar is increased. That means it is not necessary to equip the radar sensor in higher positions. However, the height of the radar sensor should depend on what the application is. Figure 7 is the mesh plot of $D_{T,i}$ vs. H_i and T_T as V_i =100km/hr and $N_i = 12$. $D_{T,i}$ seems be proportion to H_i and T_T. However, Figure 8 shows the positioning sensitivity due to T_T with, V_i =100km/hr and $N_i = 12$. The variation of the positioning error become

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more significant as H_i is higher and T_T is smaller. The positioning error is 2.0094m as T_T varies 1 ns at T_T=5ns and $H_i=4m$, or the positioning sensitive due to T_T is equal to 2.0094 m/ns.

vehicles in the interval of two successive transmissions will move .556m as V_i=100km/hr, i.e., the positioning error is 0.556m due to the repeat frequency of the radar signal transmission.
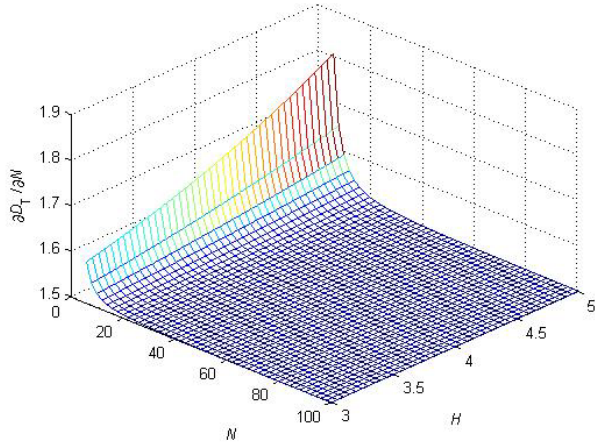
(a) Positioning sensitivity due to tick count.

(b) Positioning sensitivity due to height of radar sensor.

Figure 6. The positioning sensitivities.

Figure 7. $D_{T,i}$ vs. H_i and T_T.

Figure 8. The positioning sensitivity due to T_T.

IV. REPEAT PERIOD AND COLLISION CONDITIONS

A. Repeat Period of Radar Signals

Let $T_{S,i}$ denote the repeat period of the radar signals. Theoretically,

$$T_{S,i} > \frac{2\sqrt{H_i^2 + D_{\max,i}^2}}{c} + T_{P,i}, \qquad (17)$$

where $T_{P,i}$ denotes the process time in Lane i. In case $D_{\max,i}$=200m and H_i=4m, the first term of right side in (17) will be 1.3336 μs. In this case, $T_{P,i}$ dominates the value in the right side of (17). In general, $T_{S,i}$=20ms, or the repeated frequency equal to 50Hz, is enough for the process of the information before next transmission of the radar signal. The
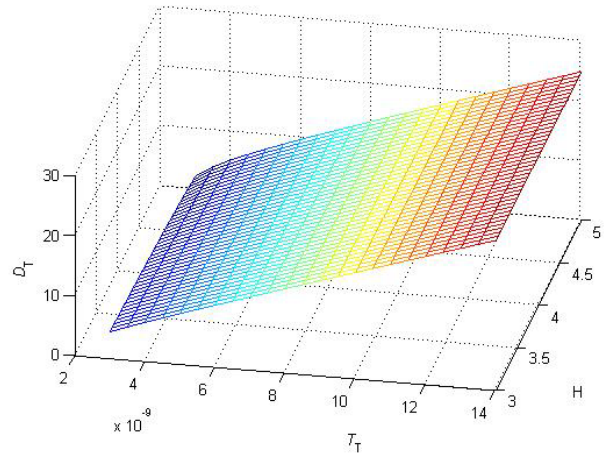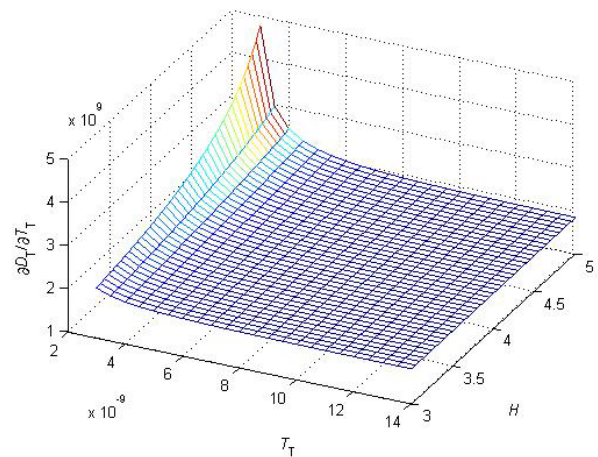
B. Conditions of the Collisions between Vehicles

Let T_{ji} denote the delay time of the radar sensor transmission in Lane j from the time of the radar sensor transmission in Lane i. $T_{F,i}$ and $T_{R,i}$ are the time intervals between the transmission time of the radar sensor in Lane i and the time of the front and rear of the measured vehicle arriving the intersection, respectively. In case the radar signal transmits at T in Lane i, from definition,

$$T_{F,i} = T + \frac{D_{T,i} - D_{F,i}}{V_i},$$

$$T_{R,i} = T + \frac{D_{T,i} + D_{R,i}}{V_i},$$

$$T_{F,j} = T + T_{ji} + \frac{D_{T,j} - D_{F,j}}{V_j},$$

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and

$$T_{R,j} = T + T_{ji} + \frac{D_{T,j} + D_{R,j}}{V_j}.$$

The two measured vehicles in Lane i and Lane j, respectively, will not collide as they cross the intersection if

$$T_{F,i} > T_{R,j} \text{ or } T_{F,j} > T_{R,i}.$$

In other words, the potential cross-path collision will happen for these two vehicles if

$$T_{F,i} \leq T_{R,j} \text{ and } T_{F,j} \leq T_{R,i}. \qquad (18)$$

(18) is the condition of collisions for the measured vehicles in any two cross-path lanes. For instance, if the values of the necessary parameters are as those listed in Table 1, the collision will potentially take place between these two vehicles in Lane i and Lane j since $T_{F,i} = 5.7600s$, $T_{R,i} = 6.9000s$, $T_{F,j} = 5.2250s$, and $T_{R,j} = 5.9450s$. In this example, the warning messages will be generated and sent to signal warning lights at the intersection to warn the approaching drivers.

TABLE 1
THE VALUES OF NECESSARY PARAMETERS FOR COLLISION DECISION.

Lane	i	j	Unit
D_T	100	60	m
D_F	4	2	m
D_R	15	6	m
V	60	40	Km/hr
T_{ji}	0	5	ms

(18) is available for any two lanes of cross-path to determine whether the measured vehicles in these two lanes will collide potentially. In case a 4-leg intersection and each has two approaching lanes, there will be 16 possible combinations to determine with (18).

V. CONCLUSION

This paper has presented the parameter analyses of the ICA system based on radar sensor. The accuracy of positioning is one of the most significant requirements for ICA systems. The positioning sensitivities are used to analyze the effects of parameter varying. This paper also adopted the buffer distances for front and rear of the measured vehicle to compensate the positioning errors and to comply with the safety issue. The results of this paper can be used when this kind of ICA systems is implemented. Furthermore, the ICA system can apply the conditions of the potential collisions of two cross-path vehicles to determine whether to signal the warnings or not. Some constraints of this proposed approach have to be concerned. For instance, the lane or lanes of the intersection are not straight. However, the analyses of the positioning errors can be applied with other possible positioning sensors for other architecture of ICA systems. In the future work, this proposed approach will be evaluated and the influence of multi-vehicles in one lane will be studied.

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