New Strategy for Automotive Crash Avoidance at Road Intersections

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Abstract: Estimates by the National Highway Traffic Safety Administration (NHTSA) indicate that crossing path crashes occurring at intersections represent approximately 26 percent of all police reported crashes each year [1].Thus, study on safety problems at intersections is of special interests. This paper through theoretic analysis and sampling tests concludes that braking, speeding down and speeding up are all actions which may force a crash that originally will not occur, and possibly can help to avoid a crash that initially will occur. And that braking is the final way for a vehicle to avoid a crash must be corrected. Most important thing is that only through integrating vehicle's passive and active safety systems, traffic safety problem can be well solved. Sensor and communication technologies have to be used together to realize intelligent crash avoidance systems and protect systems.

Keywords: Crash Zone, Sampling Tests, Vehicle Dynamic ID, Vehicle Active Communication

1 Introduction

An intersection is an area where highways or streets meet. Vehicles driving in different directions may conflict at intersections, thus there exists potential for crossing path crashes. National Agenda for Intersection Safety [2] recorded that in 2000, there were more than 2.8 million intersection-related crashes representing 44 percent of all reported crashes. Due to the complexity of intersection safety problem, it hasn't been well solved in more than 25 years despite improved intersection designs and more sophisticated applications of traffic engineering measures [2].

This paper focuses on new vehicle safety strategies applied to road intersections. Note that pedestrians are not involved in crashs discussed in this paper.

1.1 Problem Considered

The intersection of Figure 1-1-1 was situated in freeway. Vehicle A was a saloon car and running on the main road. Vehicle B was a passenger car and running on a single-lane road. They were both approaching the perpendicular-path intersection. Details of vehicle A and B are listed in Table 1-1-1. Parameters for calculation are listed in Table 1-1-2.

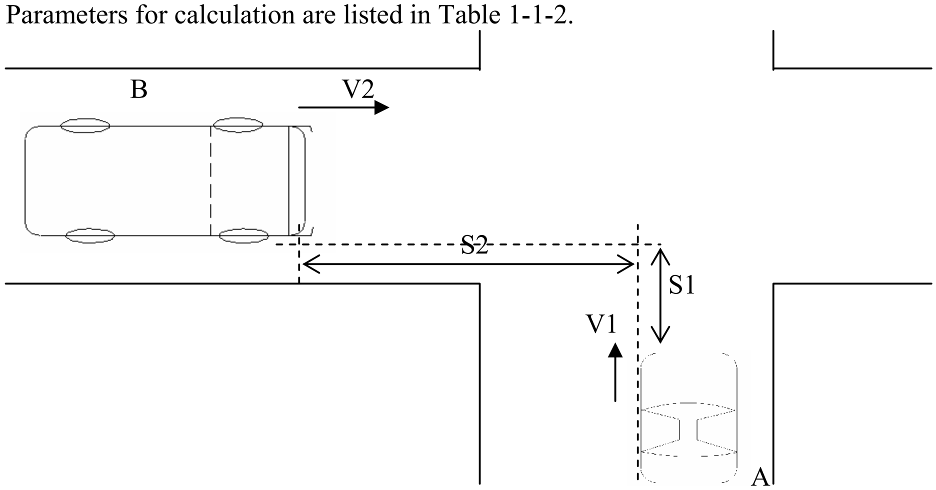

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Figure 1-1-1 Intersection Dynamic Scenario

Table 1-1-1 Details of vehicle A and B [3,4]

Vehicle	A Saloon Car	B Passenger Car
Type	TOYOTA VIZI-8A (CA7136 (STD))	DF EQ6781LD
Overall length*width *height (mm)	3640*1660*1520	7940*2280*3000
Top speed	170km/h	110km/h
0 ~100km/h accelerating time	11.9 seconds	
Braking distance		30km/h, ≤10m

Table 1-1-2 Parameters for Calculation

	Overall length (m)	Overall width (m)	Position (m)	Speed (km/h)
A	L1=3.640	B1=1.660	S1=8, 9	V1=110
B	L2=7.940	B2=2.280	S2=12	V2=90

Note the following hypothesizes:

- There were no working traffic control devices at the intersection or
- The driver of Vehicle A violated the traffic control deliberately or
- The driver of Vehicle A was inattentive and didn't notice that Vehicle B was approaching or the traffic control devices' requirement.
- Vehicle B drove at a constant speed all along during the course.

1.1.1 S1=8m

$$Tr1 = S1 / V1 = 8 \text{ (m)} / 110 \text{ (km/h)} = 8 \text{ (m)} / 30.6 \text{ (m/s)} = 0.26\text{s}$$
$$Tr2 = S2 / V2 = 12 \text{ (m)} / 90 \text{ (km/h)} = 12 \text{ (m)} / 25 \text{ (m/s)} = 0.48\text{s}$$

Because Tr1 < Tr2, Vehicle A would reach the intersection before Vehicle B. Whether it would clear the intersection before Vehicle B reached the intersection?

$$Tc1 = (S1 + L1 + B2) / V1 = (8 + 3.64 + 2.28) \text{ (m)} / 30.6 \text{ (m/s)} = 0.45\text{s} < 0.48\text{s} = Tr2$$

Because Tc1 < Tr2, Vehicle A would clear the intersection before Vehicle B reached the intersection. So the potential for a crash didn't exist originally. However, if at the moment the driver of Vehicle A suddenly noticed Vehicle B and braked strongly, thus a crash with Vehicle B inevitably occurred, since Vehicle A's speed was 110km/h (V1) and it was impossible for it to stop within 8m (S1).

1.1.2 S1=9m

$$Tr1 = S1 / V1 = 9 \text{ (m)} / 110 \text{ (km/h)} = 9 \text{ (m)} / 30.6 \text{ (m/s)} = 0.29\text{s}$$
$$Tr2 = S2 / V2 = 12 \text{ (m)} / 90 \text{ (km/h)} = 12 \text{ (m)} / 25 \text{ (m/s)} = 0.48\text{s}$$
$$Tc1 = (S1 + L1 + B2) / V1 = (9 + 3.64 + 2.28) \text{ (m)} / 30.6 \text{ (m/s)} = 0.488\text{s}$$

Because Tr1 < Tr2 < Tc1, Vehicle A would reach the intersection before Vehicle B, but it wouldn't clear the intersection before Vehicle B arrived. So the two vehicles would collide with each other.

Suppose that Vehicle A speeded up at the moment, thus it may clear the intersection (Tc1′) before Vehicle B arrived (Tr2), that is if Tc1′ < Tr2 can be fulfilled, the crash would be avoided.

$$Tc1' = 2 * (S1 + L1 + B2) / (V1a + V1) < Tr2 = S2 / V2 \quad \text{thus,}$$

$V1a > 2 * (S1 + L1 + B2) * V2 / S2 – V1 = 2*(9+3.64+2.28) \text{ (m)} * 25 \text{ (m/s)} / 12$

(m)-30.6(m/s) = 31.57m/s=113.64km/h

Considering that accelerating time is different according to different vehicles, then whether was it possible for Vehicle A to speed up from 110km/h to 113.64km/h during less than 0.48s (Tr2)?

Acceleration: A = (113.64-110) (km/h) / 0.48 (s) = (31.57-30.6) (m/s) / 0.48 (s) = 2.02m/s^2

According to Vehicle A's accelerating time given in Table 1-1-1, it was possible for Vehicle A to attain such acceleration.

Suppose that Vehicle A speeded down at the moment, thus it may reach the intersection (Tr1′) after Vehicle B cleared the intersection (Tc2), that is if Tr1′ > Tc2 can be fulfilled, the crash would be avoided.

Tc2 = (S2 + L2 + B1) / V2 = (12+7.94+1.66) (m) / 90 (km/h) = (12+7.94+1.66) (m) / 25 (m/s)=0.864s

Tr1′ = 2 * S1 / (V1d+V1) > Tc2 thus,

V1d < 2 * S1 / Tc2 – V1 = 2*9 (m) / 0.864 (s) –30.6(m/s) <0;

This indicates that Vehicle No.1 can't speed down to the needed degree of avoiding the crash with Vehicle No.2. So in this case, to Vehicle No.1, speeding down was not effective. And it was of course not possible for it to stop within S1(9m) since it was driving at 110km/h.

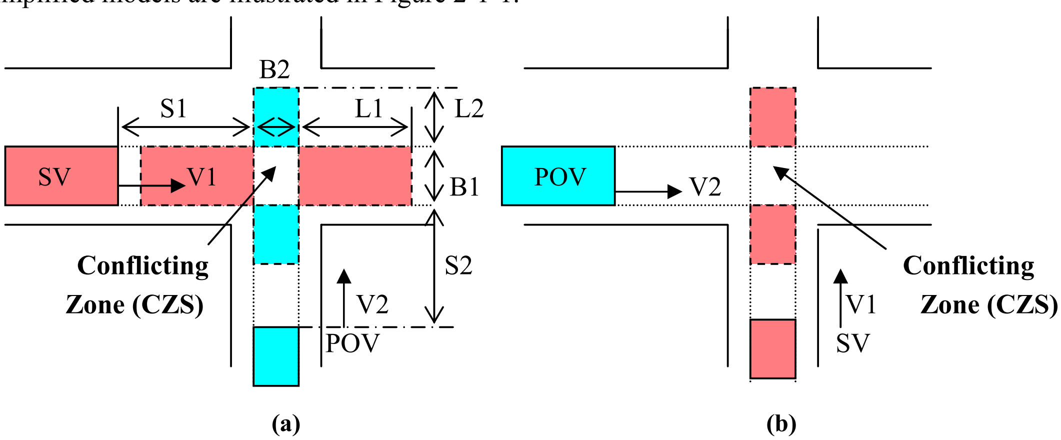
From this case, such conclusion can be made: speedup may be an effective way of avoiding crashs at intersections in certain cases.

2 Theoretic Analysis

The speciality of intersection configuration compared with common highways lies in: on one hand an intersection provides meeting space for traffic flow, which produces conflicting zone in space (CZS); on the other hand it provides departing chances for meeting vehicles, that is if two involved vehicles' time of reaching and clearing an intersection can be perfectly adjusted, it is possible for them to avoid the conflicting zone in time (CZT) so that the crash may be avoided.

2.1 Simplified Models

In the following discussion, only those vehicles that intend to go straightly are considered. Two simplified models are illustrated in Figure 2-1-1.



KEY: SV Subject Vehicle; the vehicle whose action precipitated the crash

POV Principal Other Vehicle; the other vehicle involved in the crash

Figure 2-1-1 Intersection Conflict Simplified Models: (a) POV drives on a single-lane road; (b) POV drives on a multilane road

(b) is more complicated than (a) because POV drives on the multilane road, thus other involved vehicles driving on other lanes of the multilane road have to be considered. This will bring multi-CZS to be considered. In this paper only (a) case is discussed.

2.2 Conflicting Zone in Space (CZS)

To avoid directly CZS mainly depends on perfect road construction. This is beyond the research scope of this paper. Indirectly avoiding CZS depends on avoiding CZT, which is discussed in this paper.

2.3 Conflicting Zone in Time (CZT)

The following calculation and analysis are based on (a) case in Figure 2-1-1 and Vehicle No.1 denotes SV and Vehicle No.2 denotes POV.

time of No.1 reaching CZS: $Tr1 = S1/V1$ (2.3.1)

time of No.2 reaching CZS: $Tr2 = S2/V2$ (2.3.2)

time of No.1 clearing CZS: $Tc1 = (S1 + L1 + B2)/V1$ (2.3.3)

time of No.2 clearing CZS: $Tc2 = (S2 + L2 + B1)/V2$ (2.3.4)

CZT:

I Tr1≤Tr2≤Tc1, Vehicle No.1 reaches CZS before No.2, but it can't clear CZS before No.2 reaches CZS, so the crash occurs;

II Tr2≤Tr1≤Tc2, Vehicle No.2 reaches CZS before No.1, but it can't clear CZS before No.1 reaches CZS, so the crash occurs.

Because the two predicted time intervals ([Tr1, Tc1], [Tr2, Tc2]) during which the two vehicles crossing the intersection overlaps with each other, there are potential for a crash. Intersection crash avoidance manner is to separate the two time intervals [5], which is to avoid the CZT.

2.4 Intersection Crash Avoidance Manner

Suppose that D10, A10 and D20, A20 are the maximum deceleration and acceleration of Vehicle No.1 and No.2 respectively. V1d and V2d are the velocities when Vehicle No.1 and No.2 slow evenly then reach CZS respectively. V1a and V2a are the velocities when Vehicle No.1 and No.2 speed up evenly then clear CZS respectively.

Ⅰ Braking, to stop within the distance to the conflicting point.

(1) Vehicle No.1 brakes, if V1*V1/(2*D10)<=S1;

(2) Vehicle No.2 brakes, if V2*V2/(2*D20)<=S2.

Ⅱ Slowing, to reach CZS after another vehicle clears CZS.

(3) Vehicle No.1 slows, if (2.4.1) and (2.4.2) can be satisfied.

$$\frac{S1}{(V1d + V1)/2} \geq \frac{S2 + L2 + B1}{V2} \quad (2.4.1) \qquad \frac{V1^2 - V1d^2}{2 * S1} \leq D10 \quad (2.4.2)$$

(4) Vehicle No.2 slows, if (2.4.3) and (2.4.4) can be satisfied.

$$\frac{S2}{(V2d + V2)/2} \geq \frac{S1 + L1 + B2}{V1} \quad (2.4.3) \qquad \frac{V2^2 - V2d^2}{2 * S2} \leq D20 \quad (2.4.4)$$

Ⅲ Speeding up, to clear CZS before another vehicle reaches CZS.

(5) Vehicle No.1 speeds up, if (2.4.5) and (2.4.6) can be satisfied.

$$\frac{S1 + L1 + B2}{(V1a + V1)/2} \le \frac{S2}{V2} \quad (2.4.5) \qquad \frac{V1a^2 - V1^2}{2*(S1 + L1 + B2)} \le A10 \quad (2.4.6)$$

(6) Vehicle No.2 speeds up, if (2.4.7) and (2.4.8) can be satisfied.

$$\frac{S2 + L2 + B1}{(V2a + V2)/2} \le \frac{S1}{V1} \quad (2.4.7) \qquad \frac{V2a^2 - V2^2}{2*(S2 + L2 + B1)} \le A20 \quad (2.4.8)$$

Ⅳ One vehicle speeds down while the other vehicle speeds up, to ensure that the vehicle speeding up clears CZS before the vehicle speeding down reaches CZS.

(7) Vehicle No.1 speeds up while No.2 speeds down, if (2.4.9) and (2.4.6) and (2.4.4) can be satisfied.

$$\frac{S1 + L1 + B2}{(V1a + V1)/2} \le \frac{S2}{(V2 + V2d)/2} \quad (2.4.9)$$

(8) Vehicle No.2 speeds up while No.1 speeds down, if (2.4.10) and (2.4.8) and (2.4.2) can be satisfied.

$$\frac{S2 + L2 + B1}{(V2a + V2)/2} \le \frac{S1}{(V1 + V1d)/2} \quad (2.4.10)$$

3 Sampling Tests

Sampling tests are based on the theoretic analysis above. The goal of sampling tests is to find out:

Ⅰ· Crashes originally not occurring rate and

· if any driver take wrong actions because of traffic control signals' requirement or the driver's himself misjudgment or other special reasons, crashes still not occurring rate and occurring rate;

Ⅱ· Crashes initially occurring rate and

· the effectiveness of braking and speeding down and speeding up to avoid crashes.

Whether a vehicle can brake or speed down effectively is decided by comparing the needed deceleration (D) with $8.5m/s^2$ which is supposed an average deceleration of a vehicle. And whether it can speed up effectively is decided by comparing the needed acceleration (A) with $2.5m/s^2$ which is supposed an average acceleration of a vehicle.

In the following six figures of section 3.1 and 3.2, both vehicles' distances to the conflicting point vary from 1.0m to 15.5m, every 0.5m one distance, total 30*30 distance combinations. Vehicle No.2's velocity varies from 30km/h to 180km/h, every 5km/h one velocity, total 31 different velocities, and Vehicle No.1's velocity is bigger than No.2's as 0, 5, 10, 15, 20(km/h). So each curve is the result of sampling total 31*30*30, that is 27900 numbers (combinations of S1, S2, V1, V2).

Considering that vehicle sizes have an effect on the result, sampling tests are divided into three small classes (SL, SS, LL) shown in Table 3-1.

Table 3-1 Three Small Classes

	SL	SS	LL
Overall length and width (m) of Vehicle No.1	L1 = 3.640 B1 = 1.660	L1 = 3.640 B1 = 1.660	L1 = 7.940 B1 = 2.280
Overall length and width (m) of Vehicle No.2	L2 = 7.940 B2 = 2.280	L2 = 3.640 B2 = 1.660	L2 = 7.940 B2 = 2.280

3.1 Crash Not Occurring Rate and Occurring Rate by Wrong Operation

First, two things are defined as bellow:

· the vehicle which will clear the intersection first: FV

· the other involved vehicle which will clear the intersection later: LV

When both vehicles drive at original velocities and don't take any actions, a crash originally will not occur. Of course, if FV speeds up or LV speeds down or brakes, the crash still will not occur. But if FV speeds down or brakes or LV speeds up, a crash may be forced to occur.

(1) FV or LV can stop within the distance to the conflicting point, so the crash still will not occur; else

(2) FV can speed down to the needed degree, to reach the intersection after LV clearing the intersection, so the crash still will not occur; or

(3) LV can speed up to the needed degree, to clear the intersection before FV reaching the intersection, so the crash still will not occur; or

(4) FV speeds down and LV speeds up to ensure LV clearing the intersection before FV reaching the intersection, so the crash still will not occur; else

(5) The crash will inevitably occur;

(6) One vehicle takes corresponding actions according to the other vehicle's wrong operation.

This case is complicated. And only from mathematical view, when FV speeds down, LV also speeds down; or when LV speeds up, and FV also speeds up, it is possible to ensure FV still will clear the intersection before LV reaches the intersection. Thus the crash still will not occur.

In Figure 3-1-1, 3-1-2, 3-1-3, point 2 and 3 denote case (1), and point 2 denotes the case when Vehicle No.1 is FV and point 3 denotes the case when Vehicle No.2 is FV; and point 4 and 5 denote case (5), and point 4 denotes the case when Vehicle No.1 is FV and point 5 denotes the case when Vehicle No.2 is FV.

In the sampling tests, case (1), (2), (3), (4), (5) are considered and (6) aren't considered. And as under all sampling tests conditions, the rate of (2), (3) and (4) is zero, so in the following three figures the rates of case (2), (3) and (4) aren't shown. And the total value of point 2, 3, 4, 5 in each curve is equal to 100 percent.

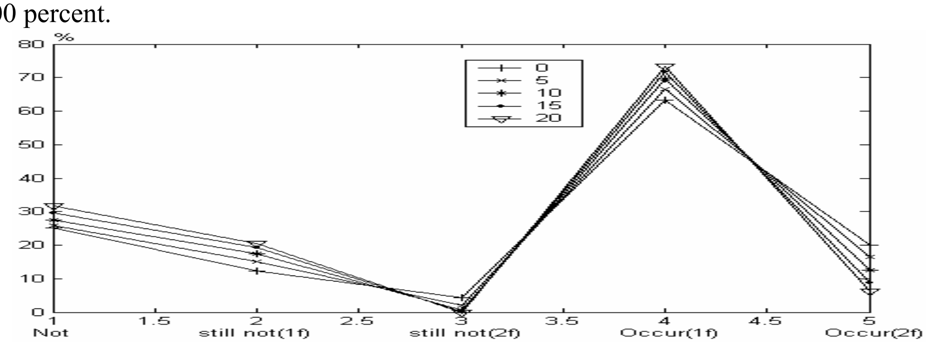


Figure 3-1-1 Crash Not Occurring Rate and Occurring Rate by Wrong Operation (SL)

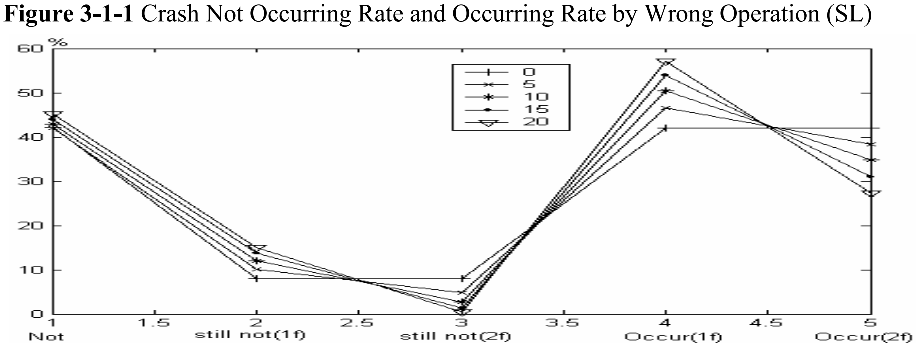


Figure 3-1-2 Crash Not Occurring Rate and Occurring Rate by Wrong Operation (SS)

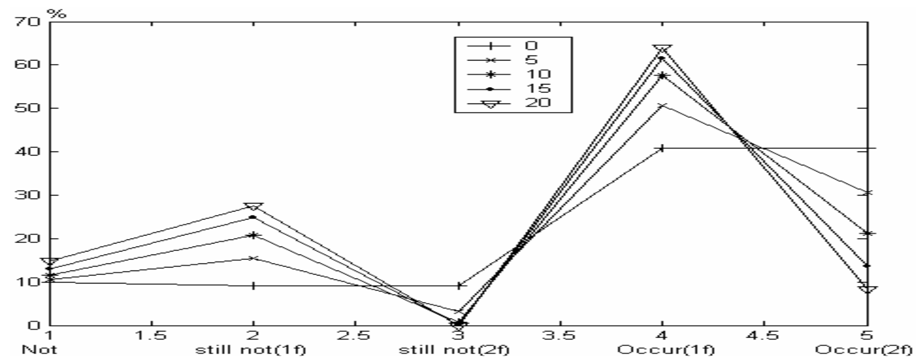


Figure 3-1-3 Crash Not Occurring Rate and Occurring Rate by Wrong Operation (LL)

Statistic data represented in Figure 3-1-1, 3-1-2, 3-1-3 indicate the following information:

Not-occurring rate (point 1 of each curve) of SS is the biggest and that of SL is smaller and that of LL is the smallest. This is because CZS of SS is the smallest and that of LL is the largest;

In each figure, with the velocity difference increasing, not-occurring rate becomes higher.

In each figure, point 4 and 5 are higher than point 2 and 3 respectively, so the case that a crash originally will not occur but due to driver's wrong operation, a crash is forced should not be ignored. It demands more sophisticated traffic control devices and driving assistant systems.

3.2 Effectiveness of Braking and Speeding Down and Speeding Up to Avoid Crashes

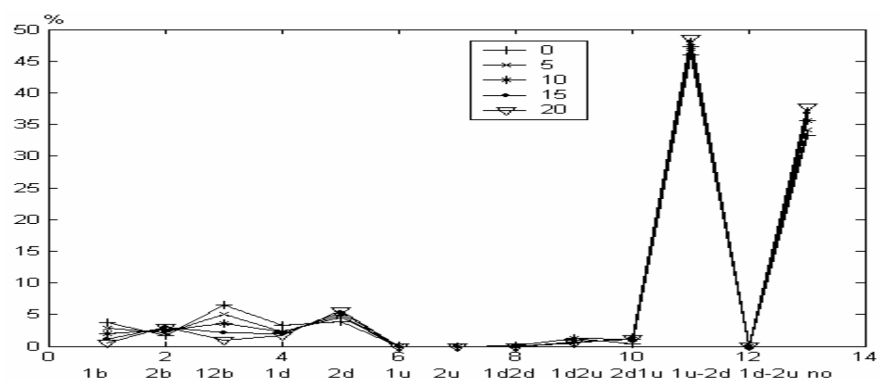


Figure 3-2-1 Crash Avoiding Rate by Taking Different Actions (SL)

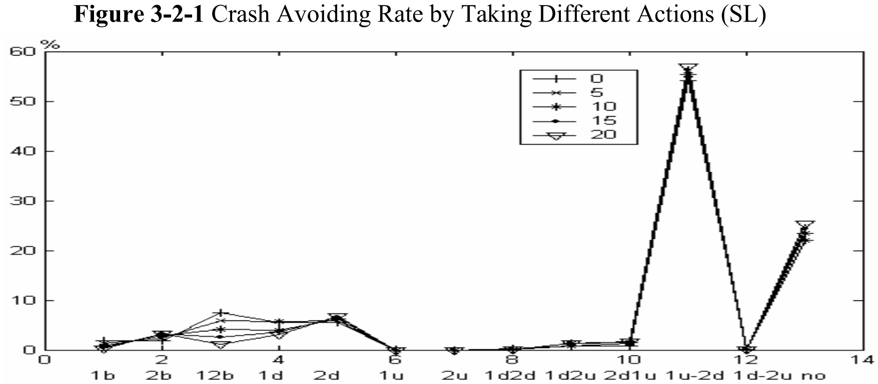


Figure 3-2-2 Crash Avoiding Rate by Taking Different Actions (SS)

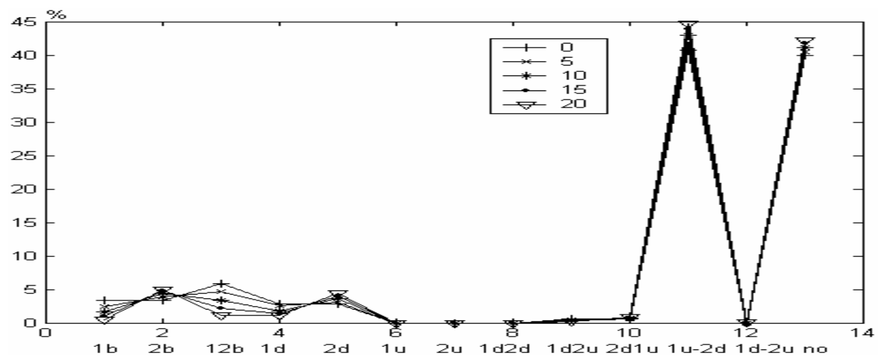


Figure 3-2-3 Crash Avoiding Rate by Taking Different Actions (LL)

When a crash is approaching, the considered actions taken to avoid the crash or if the crash is unavoidable to reduce the damage to the least are listed as below:

Any of the two vehicles can brake within the distance to the conflicting point. In the above three figures point 1,2,3 denote this case. Else

Any of the two vehicles can speed down effectively; Point 4, 5, 8 denote this case. Else

Any of the two vehicles can speed up effectively; Point 6, 7 denote this case. Else

One of the two vehicles can speed down effectively and one of the two vehicle can speed up effectively; Point 9, 10 denote this case. Else

One of the two vehicles speed down while the other vehicle speed up effectively; Point 11, 12 denote this case. Else

Crash can't be avoided and protecting system must be actuated at once; Point 13 denotes this case.

In the Figure 3-2-1, 3-2-2, 3-2-3, the total value of all of the points in each curve is equal to 100 percent.

Statistic data represented in Figure 3-2-1, 3-2-2, 3-2-3 indicate the following information:

Point 11 is much higher than other points except point 13 of each curve. This indicates that from theoretic view, when velocity difference is set, initially-will-occur crashes can be avoided through Vehicle No.1, which is driving at the same or bigger than the speed of Vehicle No.2, speeding up while Vehicle No.2 speeding down, by at least 40 percent, in the sampling tests of this paper.

Point 13 is also high. This indicates that from theoretic view, when velocity difference is set, initially-will-occur crashes, by at least 22 percent, can't be avoided in the sampling tests of this paper.

Point 6, 7and 12 are all equal to 0, but point 9, 10 and 11 are not equal to 0. This indicates that when one vehicle speeding up can make positive effect, the other vehicle speeding down also will work well or one vehicle speeding up depends on the other vehicle speeding down.

3.3 Discussion of the Whole Sampling Tests

As in each testing group, there are 27900 enough sampling numbers (combinations of S1, S2, V1, V2), the results obtained from sampling tests have significance.

In some cases crashes originally will not occur, but due to drivers' wrong actions, braking, speeding down, speeding up, crashes are forced to occur. This can't be ignored. Both traffic control devices and vehicles are required to be more intelligent.

When one vehicle speeding up can make positive effect, the other vehicle speeding down also will work well or one vehicle speeding up depends on the other vehicle speeding down.

When crashes initially will occur, through appropriate actions (braking, speeding down, speeding up, but steering isn't considered in this paper), crashes can be avoided by 57 to 78 percent in the sampling tests of the paper. From theoretic view, this makes significance.

As there are crashes which can't be avoided, so vehicle's passive safety and active safety should be integrated to improve vehicles' safety.

4 Intersection Safety Strategy

The rapid improvement of sensor and data processing technology has enabled the collection of large amounts of information from the vehicle environment. Sensor and communication technology make it possible of the detection of vehicle location and transmission of information between vehicles [1].

Many previous papers have described quite a lot of advanced Crash Avoidance Systems using sensor technology. Obstacle detection also has been further researched [6][7].

NHTSA's researchers explained that the Driver Advisory system and the Defensive systems were developed further, but the Communication System was dropped from consideration due to the long time frame required to equip all vehicle on the road with the system [1].

But it is the fact that traditional vehicle crash warning and avoidance systems use radar systems as a necessary detecting system, while most radar systems require line-of-sight for object detection, which do not perform well in the perpendicular path intersection case since in most intersection crash cases, the POV is out of line-of-sight of the SV until the crash is about to occur at once [8].

So to improve intersection safety, sensor and communication technology must be integrated [9]. Moreover, if crashes can't be avoided, to make protecting systems work well it is necessary to pre-sensing crashes, and this also requires sensor and communication technologies' integration. Figure 4-1 shows information flowing between vehicle and its driving environment.

In Figure 4-1 two concepts are put forward:

① Vehicle Dynamic ID (VDID): memorize

· vehicle's dimension, deadweight, load, accelerating and braking properties which are vehicle's inherent properties and;

· information about driver and passengers, for example, driver's attention, driver's and passengers' weights, etc.;

· vehicle's speed, acceleration and driving direction which should be dynamic updated.

② Vehicle Active Communication (VACM)

· vehicle itself brings a round communicating scope;

· the diameter of the round scope (D) varies due to the speed, position, road condition and traffic environment around the vehicle, and the decision of D is based on analysis of a large number of accident data;

· other vehicles within the round scope are dangerous because there exists potential for crashes with the subject vehicle;

· once other vehicles enter the round scope or the vehicle itself enters the round scopes of other vehicles, communication will actively be actuated among them;

· data memorized in VDID automatically shared by communicating vehicles;

· running results of the algorithm are provided to the subject vehicle itself and other involved vehicles, since actions taken to avoid crashes are adapted to all involved vehicles.

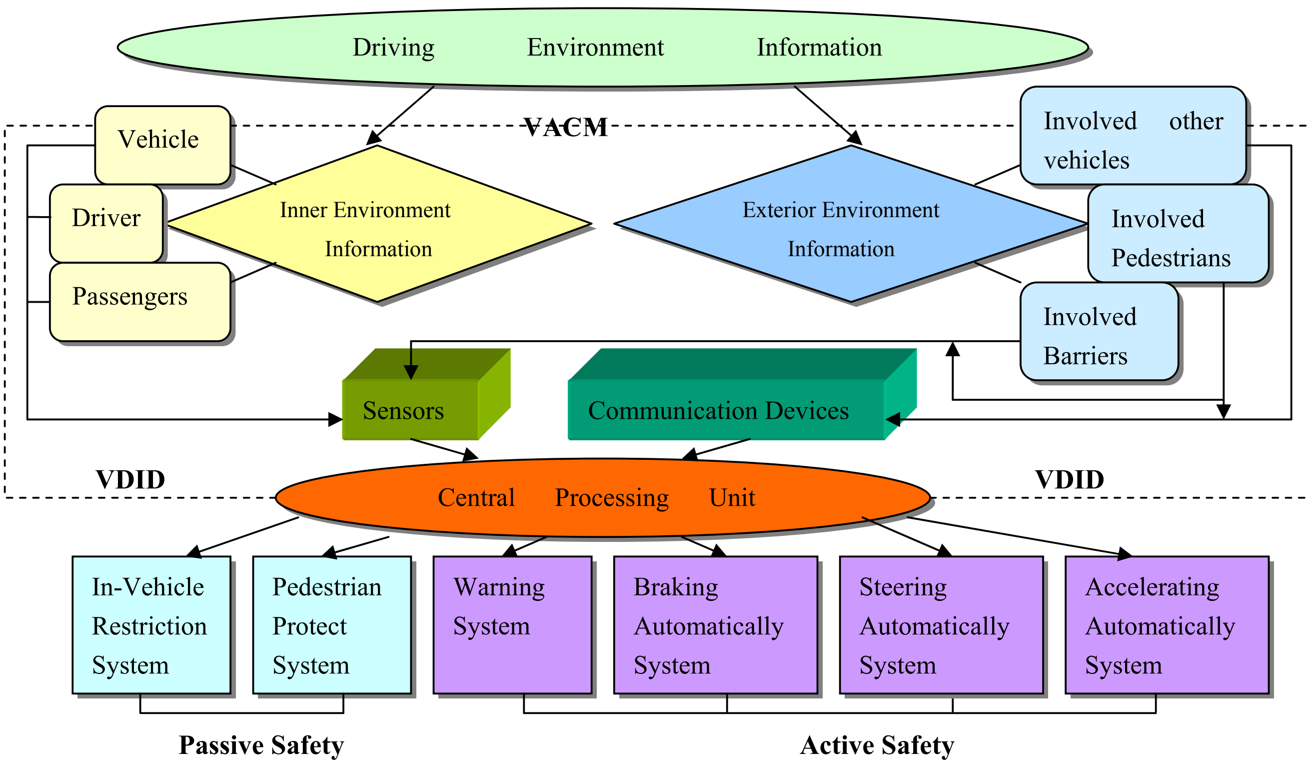


Figure 4-1 Information Flowing Between Vehicles and Their Driving Environment

5 Conclusions and Future Works

People usually think that no matter in which situation, when a crash seems to occur, braking produces always positive results and speeding up maybe too risky. To vehicles driving on parallel roads this maybe true but to vehicles driving on perpendicular roads that meet at an intersection, it is not correct. This paper concludes that braking, speeding down and speeding up are all actions which will possibly force a crash that originally will not occur, and possibly can help to avoid a crash that initially will occur. And that braking is the final way for a vehicle to avoid a crash must be corrected. Most important thing is that only through integrating vehicle's passive and active safety systems, traffic safety problem can be well solved. Sensor and communication technologies have to be used together to realize intelligent crash avoidance systems and protect systems. The results of this study may help to distinctly improve automotive safety at road intersections.

Future works involve further research on automotive safety problem at multilane road intersections with pedestrians and turning vehicles involved. The feasibility of VDID and VACM need to be further studied from effectiveness view, economic view, and environmental view.

Acknowledgements:

The work benefited from discussion with my supervisor, Prof. Zhong Zhihua, and also my parents' support and encouragement. Thank Prof. Yang Jikuang for his helpful advices. And special thanks go to Prof. Mizuno for his giving me a chance of visiting Nagoya University and Japan Automobile Research Institute (JARI) and Mitsubishi Motor Company. The visit is a significant experience for me to get an initial impression of automotive safety research.

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