Evaluation of Stopping Behavior of Drivers in Dilemma Zone Using Driving Simulator

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A traffic signal control method called Dilemma-Free has been introduced for more than fifteen years. In this method, there is an important issue about driver/vehicle behaviors involving the reaction time of a driver for braking and the deceleration rate of a vehicle. This paper describes a study of the stopping behavior of drivers in the dilemma zone using a driving simulator, and a questionnaire survey to inquire test drivers about their decision whether to cross or stop at the intersections. Results of this study show that there is no clear difference in approach speeds between stopped and passing vehicles and the drivers' decision in the dilemma zone is heavily influenced by the vehicle's distance to the stop line. Additionally, questionnaire survey confirmed that the status of pedestrian signals is one of the primary factors influencing drivers' decisions.

Keywords: *dilemma zone, driving simulator, stopping behavior, dilemma-free signal control, amber signal*

1. Introduction

Automotives have been playing an important role in Japan to support socio-economic activities, which has provided much convenience and benefits to people's daily lives. However, motor vehicles are also involved in a large number of accidents, which counts approximately 930,000 every year in Japan. Over fifty percent of the total traffic accidents occurred at or around intersections, among which more than seventy percent are rear-end or head-on collisions [1]. The statistics indicate that intersection collisions are a major safety concern. As a countermeasure to hazardous driving conditions at intersections, a traffic signal control method called Dilemma-Free has been developed to prevent accidents at signalized intersections [2]. The control method aims at easing the burden of driver decision in the so-called dilemma zone. When the traffic signal transitions to amber, drivers of vehicles in the dilemma zone have to make a decision to either stop at the stop line or to proceed through the intersection. The dilemma-free method is designed to prevent the drivers from being caught into zones where they hesitate over crossing an intersection on the phase transition. Within the dilemma zone, drivers face a highly hazardous situation where an abrupt braking may lead to a rear-end collision with the vehicle behind while proceeding to pass will result in a violation of the traffic signal when entering the intersection. It is difficult for drives within the dilemma zones to stop safely at a stop line or approach into an intersection on an amber light before it changes into red, and vehicles driving in the zones are at high risk of traffic accidents.

There are two important aspects of this dilemma-free control method. One is the estimation of approach speed at the onset of the amber phase. The other is the understanding of driver/vehicle behaviors involving the reaction time of a driver to take braking actions and the deceleration rate of a vehicle. The former issue has been extensively investigated. For example, some earlier studies led to the use of image processing sensors [3]. On the other hand, there has been limited research on the latter topic until now as it is difficult to observe the deceleration rate and the reaction time of braking in actual fields. M. Kataoka et al. (2005) analyzed the approach speed at the onset of amber signal, and proposed a new method for dilemma-free control based on the travel time from the onset of amber to arrival at the intersection [4], [5].

We constructed mixed reality traffic experimental space using a driving simulator (DS) and a traffic simulator called KAKUMO, so as to carry out the investigation of basic human factors that are difficult to be verified in actual driving conditions [6]. The experiments aim at resolving the behaviors of drivers and the motion of vehicles. With the use of the DS space, we conducted experiments to evaluate driver behaviors under the dilemma-zone situations. Besides, focusing on the stopping behaviors of drivers, we tried to extract the reaction time of braking and the deceleration rate. We also carried out a questionnaire survey to inquire test drivers about their decision whether to cross or stop at the intersections. This paper describes the results of the study and discusses issues related to the current dilemma-free signal control method.

2. Dilemma zone and dilemma-free control

This section provides an overview of the dilemma zone and the dilemma-free control method.

2.1. Dilemma zone

The location of a traveling vehicle from a stop line and the approach speed at the onset of the amber signal are expressed as x [m] and v [m/s], respectively as shown in Figure 1. It is necessary for a vehicle to travel at an upstream location of x_s [m] from a stop line in order to stop safely at the stop line, with its motion governed by Equations (1) and (2), where τ [s] and d [m/s^2] denote the reaction time of braking and deceleration rate from when they step on the brakes to the point at which they stop, respectively.

$$x_s = \tau v + \frac{v^2}{2d} \tag{1}$$

$$x \geq x_s \tag{2}$$

At the same time, it is necessary for a vehicle to cross over a stop line before traffic lights changed red so as not to violate the signal when the vehicles pass through an intersection. In other words, they need to be at a upstream location of x_p [m] from the stop line where x_p denotes travel distance that vehicles would travel during the amber interval, which is expressed as shown in Equations (3) and (4):

$$x_p = av \tag{3}$$

$$x \leq x_p \tag{4}$$

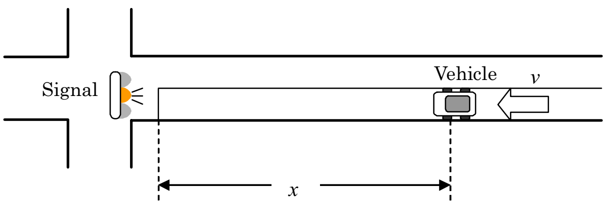

Figure 1. Distance to a stop line and approach speed of a vehicle at the onset of amber interval.

where a [s] denotes the duration of the amber phase.

Dilemma zone D, in which vehicles are not able to make a stop at a stop line safely nor drive through the intersection without violating the signal, is obtained by applying Equation (5), as shown in Figure 2.

$$D = \left\{ (x, v) \middle| av \leq x \leq \tau v + \frac{v^2}{2d} \right\} \tag{5}$$

Vehicles within the dilemma zone are at risks of causing rear-end collisions if they stop suddenly or colliding with cross-street traffic if they violate the signal and drive through the intersection.

It should be noted that there are zones where drivers are able to either stop at a stop line or drive through an intersection, which are called option zones. Option zone O is derived with Equation (6), as shown in Figure 2.

$$O = \left\{ (x, v) \middle| \tau v + \frac{v^2}{2d} \leq x \leq av \right\} \tag{6}$$

2.2. Existing dilemma-free control

The dilemma-free control method adjusts the switching time instant of traffic signals from green to amber to reduce the number of vehicles in the dilemma zones described above. It determines the time to end green interval while detecting no vehicles in the zones. The method is operated with preset upper and lower limits for the speed of approaching vehicles., The dilemma-free signal control method, currently operating in the field, covers carries out the following functions [7].

(a) Detection of Vehicles in the Zones

The passage time and speed of vehicles are measured via vehicle detectors installed at the upstream locations of a stop line. Assuming that the vehicle maintains the same speed as it approaches the intersection, the vehicle location is predicted at the onset of amber interval. Based on this input, the existence of the vehicle in the dilemma zone is checked.

(b) Signal Transition from Green to Amber

Green signal is kept as long as vehicles are detected

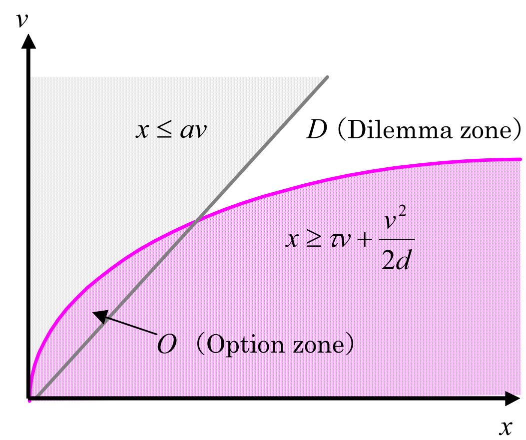

Figure 2. Dilemma zone.

in the dilemma zone, and ended as soon as no vehicle is present in the zone, then the traffic signal is switched to amber. There is a preset maximum interval allowed for the green signal phase, even though the green signal is extended by the dilemma-free control method. When the maximum interval is reached, the transition to amber will occur immediately regardless of whether there are still vehicles detected within the dilemma zone.

3. Experiments

3.1. Experimental system

The experimental system is composed of the DS and a traffic flow simulator called KAKUMO. Figure 3 and Figure 4 show the appearance of the DS and the experimental system, respectively. The DS, which offers the environment where drivers are able to drive in a virtual space, allows the assessment of driving behaviors

Figure 3 Appearance of driving simulator.

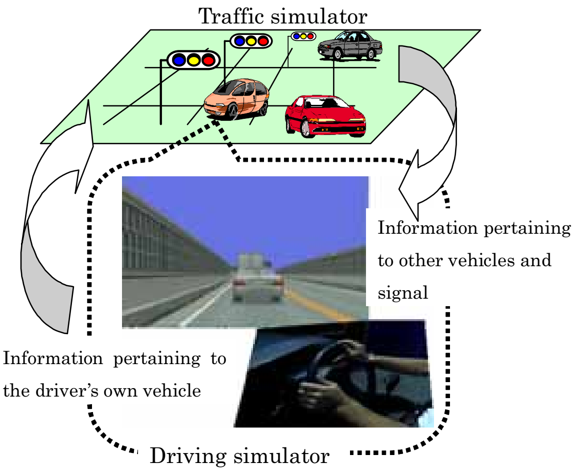

Figure 4. Experimental System.

[8]. KAKUMO is a microscopic traffic simulator that updates the status of each vehicle every 1/20 of a second [9]. The DS and KAKUMO communicate every 1/60 of a second, enabling the system to establish the travel conditions of all vehicles in a road network. The KAKUMO model provides inputs to decide the signal phase on the DS, and the signal transition from green to amber is executed based on the position and speed of the subject vehicle.

3.2. Experimental method

For the driving scenarios in DS, an experimental block of a roadway network is constructed. Each block includes ten intersections as shown in Figure 5. In Figure 5, the route composed of Intersection 2, 5, 7 and 8 indicates three-lane road. Moreover the route made up of Intersection 1, 4, 7 and 9, and the route composed of Intersection 3, 6 and 10 represent two-lane road, respectively. Blocks are connected together to form the whole experimental road, the total length of which is 12 km. Two-lane and three-lane road include 56 and 52 intersections in total, respectively. Figure 6 shows a visual image of the two-lane road indicated on the screen of the DS.

The purpose of the experiments is to control the

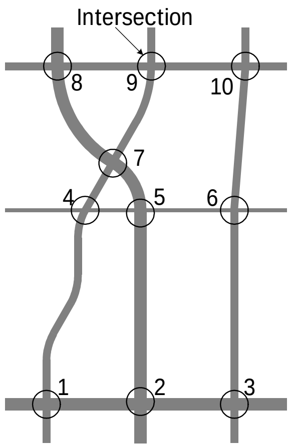

Figure 5. Basic road network (Block).

Figure 6. Screen image of experimental road.

timing of switching to the amber signal at an intersection in order to learn driving behaviors of the subject drivers when they fall into the dilemma zones. The driving scenarios are analyzed with the KAKUMO, which is linked to the DS, As shown in Figure 7, three types of green-to-amber signal-transition timing are employed to find out whether or not different vehicle position within the dilemma zones would cause different behaviors. Some intersections are controlled under any of the three types. G-type has the signal transition occurring at the downstream or leading portion of the dilemma zone, while the transition of N-type and S-type occurs at the middle and trailing portions of the dilemma zone.

We carried out the experiments for a total eighteen different intersections with five G-type, nine N-type and four S-type locations, and studied the stopping behavior of subject drivers such as the reaction time of the drivers and the deceleration rate of the vehicles at the time instant when the signal switches to amber and red. Also, we conducted a questionnaire survey of the subject drivers after the experiments to learn about their decisions when they encounter the transition of signal phases.

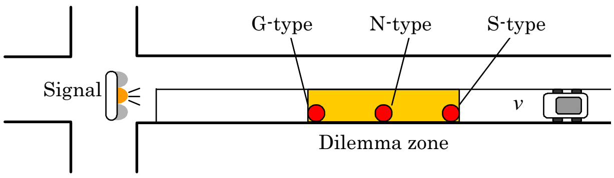

Figure 7. When to show amber indicator: Three types.

4. Experimental results

4.1. Factor analysis of stops or passage

We examined the effects of vehicle locations and speeds within the dilemma zone on the driver decisions to stop at or pass through an intersection. The data were obtained from 38 to 40 drivers on two-lane roadways and from 36 to 39 drivers on three-lane roads, respectively. The results indicated in this paper are extracted from the experimental data and presented below.

Figure 8 shows the fraction of stopped vehicles at the eighteen intersections on two-lane roads. Each bar in the figure represents the results from one intersection. The type of control methods, G, N or S, is marked along the horizontal axis for each intersection. It can be seen that the percentage of the stopped vehicles is higher when the signal transition point is located at the upstream portion of dilemma zone, though the structure of intersections are not necessarily the same. We carried out the same experiments on three-lane roads including eighteen intersections, which resulted in the similar findings as those of two-lane road.

We investigated if there was a difference in approaching speeds between vehicles stopped and passing vehicles at the onset of the amber signal phase. Figure 9 and 10 show the average speeds of stopped and passing vehicles under the three types of signal transition control at the intersections on two-lane and three-lane roads, respectively. Hypothesis testing reveals that approach speeds of the stopped and passing vehicles are not different for all roads and control methods at 5% significance level. It shows that the vehicles of both driving behaviors were traveling in almost the same speeds regardless of their locations in the dilemma zones. The approaching speed of two-lane road was relatively lower than that of three-lane road on the whole, yet the results were still similar in terms of the speed effect on driver decision to stop or to pass. These results indicate that drivers' decision to stop or to drive thorough an intersection turned out to be heavily influenced by the vehicle position at the signal transition time.

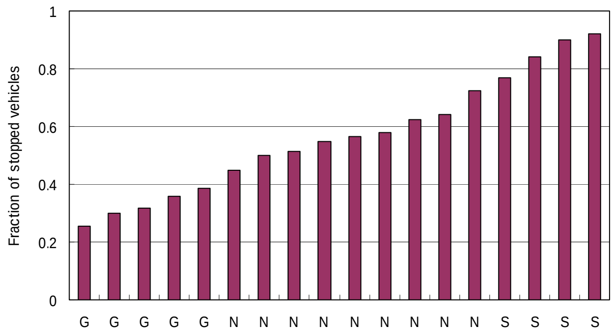

Figure 8. Fraction of stopped vehicles at two-lane intersections.

4.2. Analysis of stopping behaviors

We investigated the behaviors of the subject drivers who decided to stop at the intersections. For the analysis, we extracted the reaction time of braking and the deceleration rate, and studied whether or not there was any correlation between the driver stopping behaviors and the vehicle locations at the onset of the amber signal phase.

4.2.1 Reaction time of braking

The reaction time of braking was extracted for each subject driver, which was then used to derive an average value for each type of control methods for comparison. Note that the reaction time of braking represents the time from the onset of amber signal to the time point when the brakes are applied. Figure 11 shows the comparison of the reaction time of braking for different road types and different control methods.

Based on the results the reaction time of braking turned out to be the smallest under G-type control, followed by N-type and then S-type. The value in the case of two-lane road was relatively lower than that of the three-lane road. More specifically, the reaction time was less than one second for type-G control, whereas it was greater than one second for N-type and S-type. These observed data indicated that vehicle locations at the onset of amber phase led to differences in reaction time.

In the model adopted by the existing dilemma-free control method, the reaction time braking has been assumed to be constant (i.e., one second) to set a dilemma zone as shown in Equation (1). However, experimental results from this study indicated that it might be necessary to apply different reaction time of braking at different distances to the intersection.

4.2.2. Deceleration rate

The deceleration rate of individual subject vehicle was extracted for comparison among different control types, similarly to the analysis described in **4.2.1**. Note that deceleration rate is calculated from the time when the brakes are applied to when the vehicle stops and it is expressed using a dimension of acceleration of gravity (i.e., 9.8m/s^2). Figure 12 shows the comparison of the deceleration rate on each road.

As for the deceleration rate, it was less influenced by the control type and the number of lanes. The deceleration rate was about 0.35g in S-type and around 0.40g in N-type and G-type. This is mainly due to the fact that in S-type situations the amber signal phase begins when the subject vehicles are at the most upstream locations in spite of the approach speed in all types of control methods.

The existing dilemma-free control operation has been conducted in the real field under the assumption that the deceleration rate 0.30g with a fluctuation range of 10%. The experimental results confirmed that a higher deceleration rate may be required in the operation for vehicles traveling at the middle and the most downstream locations in the dilemma zone.

4.3. Studies on braking performances

For the third step of the analysis, we extracted the approach speeds and locations of each vehicle that

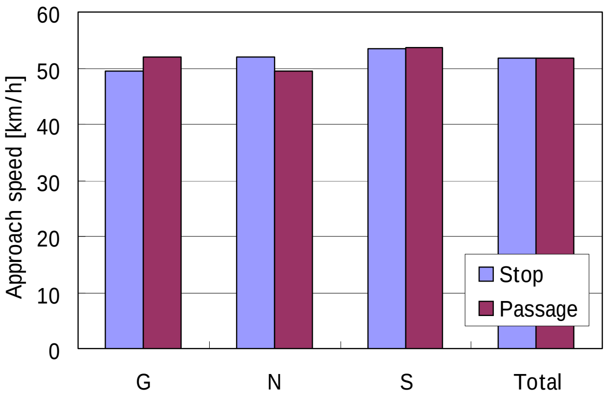

Figure 9. Comparison of approach speeds at the onset of the amber signal on two-lane road.

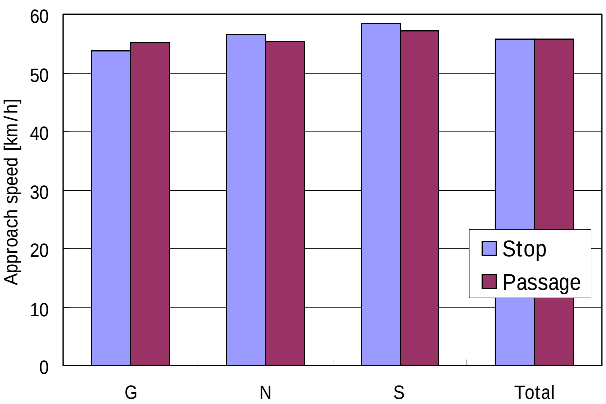

Figure 10. Comparison of approach speeds at the onset of the amber signal on three-lane road.

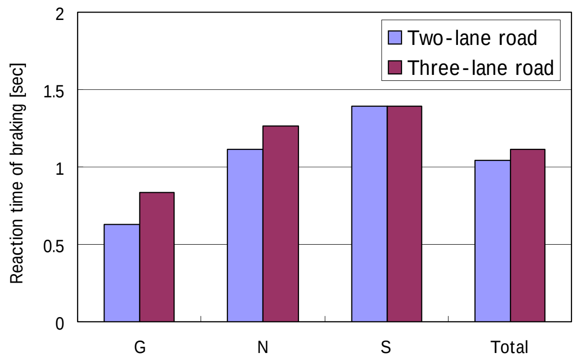

Figure 11. Comparison of reaction time of braking.

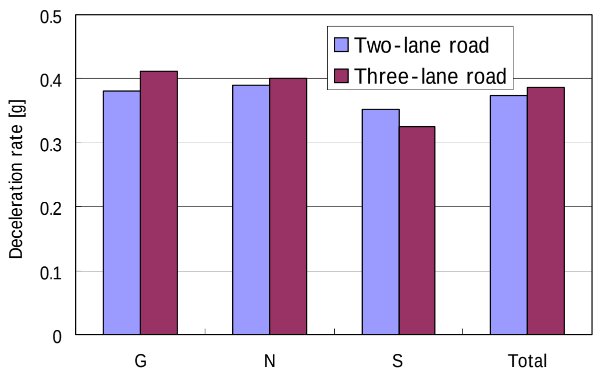

Figure 12. Comparison of deceleration rate.

stopped at the intersections at an interval of 0.1 seconds, and evaluated their braking performances. The results on two-lane and three-lane intersection are shown by curves A, B and C in Figures 13 and 14, respectively.

Using regression analysis, Curve A which is represented by the equation (7) was found to best-fit the trajectories of all stopped vehicles:

$$x = \tau v + \frac{v^2}{2d} + x_0 \quad (7)$$

where x_0 is the stopping position.

Results of regression in the two-lane and three-lane intersections are shown by equations (8) and (9), respectively.

$$x = -0.23v + \frac{v^2}{2 \times 0.42g} + 3.02 \quad (8)$$

$$x = -0.37v + \frac{v^2}{2 \times 0.38g} + 5.03 \quad (9)$$

Estimated reaction times of braking in above equations (8) and (9) are not positive. It seems not consistent with the conventional theory, however, the subject drivers who decided to stop at the intersections might begin to brake before the onset of amber signal because the pedestrian signal was already flashing or has turned red.

Curve B is drawn according to the vehicle stopping model described by model (7), with the parameters of the reaction time, the deceleration rate and stopping positions derived from the average of experimental data. Curve C is based on the stopping model (1) but with the standard parameters from the existing dilemma-free control method, which uses a reaction time of one second and a deceleration rate of 0.3g.

In addition, we analyzed the other control types as well in the similar manners. The findings can be summarized as follows:

(a) Despite no great difference between observed and estimated deceleration rate, curves A and B are quite different mainly due to the difference in reaction time of braking.

(b) The subject drivers do not necessarily stop at the stop line where $x = 0$, even though the existing control method is based on such assumptions. This results in the differences in dilemma zones defined by the model and the actual field data.

(c) The dilemma zone generated with curve A is located closer to the stop line with a higher-speed range when compared with that of curve B. On the other hand, curves B and C are very similar in their shapes, which lead to little differences in the setting of dilemma zones, in spite of the differences in model parameters between them.

(d) It is confirmed that the dilemma zones depend on the parameters representing the braking behaviors, which are influenced mostly by vehicle positions at the onset of the amber phase. Therefore it will be desirable to take these parameters into account for the effective operation of the dilemma-free control method.

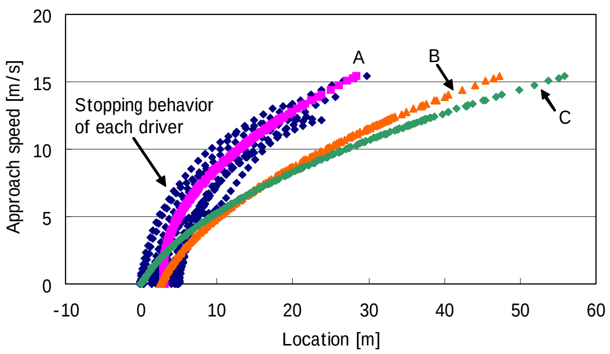

Figure 13. Comparison of braking performances at the two-lane intersection.

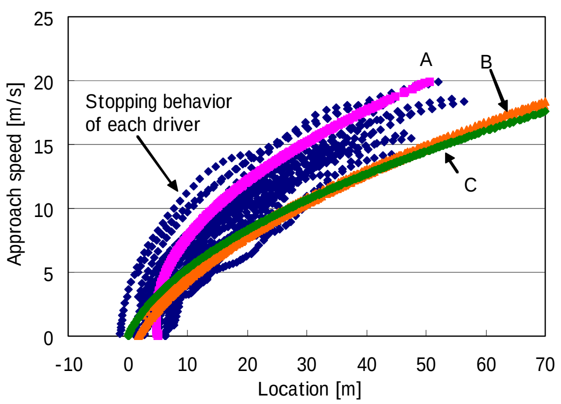

Figure 14. Comparison of braking performances at the three-lane intersection.

6. Questionnaire

We carried out a questionnaire survey among the subject drivers after the experiments. There are a total of four questions in the survey. Question 2 is multiple-choice, therefore the answers are weighted by the order given by the drivers. Figure 15 shows the results of the questionnaire. We evaluated the answers to Question 2 by giving three points, two points and one point to the top, the second and third factors mentioned in the answers, respectively, with the total score plotted in the second graph of Figure 15. The survey results are described below.

(a) In the survey, 81 percent of the drivers indicated that they had been unable to make a quick decision to stop or to proceed at the onset of the amber phase. And more specifically, the percentage of two-lane road is relatively higher than that of three lane road.

(b) The top three factors affecting their decisions included the position and speed of the vehicles as well as the status of the pedestrian signal. The top three factors represent 89% of the answers given by drivers for Question 2. In spite of some differences of ratio of respective factors between roads, these top three factors ranked in the same order.

(c) With respect to the influence of the pedestrian signal, quite a few drivers, about 29%, answered that they would mostly accelerate when pedestrian signals switched from green to flashing green while about half of the drivers indicated that the decision to accelerate or decelerate depends on the conditions at the time. Furthermore, if the pedestrian signal transitions from flashing green to red, 38% of drivers answered that they would mostly decelerate whereas about 50% of the drivers still replied that they might accelerate or decelerate, depending on the conditions.

7. Conclusions

The work described in this paper utilized the DS to examine the scenarios of dilemma zones and analyze the stopping behaviors of drivers. The results revealed that there was no clear difference in approach speeds between stopped and passing vehicles based on the hypothesis test at 5% significance level. Importantly, the driver's decision in the dilemma zone is strongly influenced by the vehicle's distance to the stop line. It is necessary to employ these results to improve the existing dilemma-free control.

It should be noted that a questionnaire survey of the drivers found out that the status of pedestrian signals was one of the primary factors influencing their decisions. Based on this understanding, further studies will be conducted to evaluate the effects of pedestrian signal on driver decisions in the dilemma zone.

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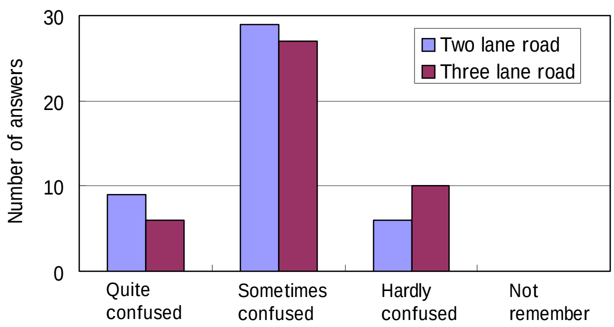
Question 1
Did you have a problem in deciding to stop or proceed through the intersections in green-to-yellow transition?



Question 2
What are the factors for you to decide to stop or proceed through the intersections?
(Maximum three answers according to your priority)

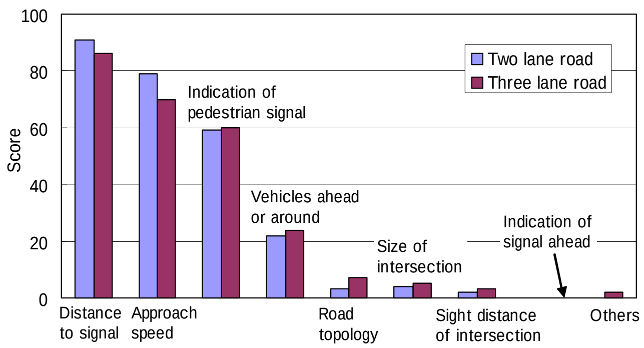
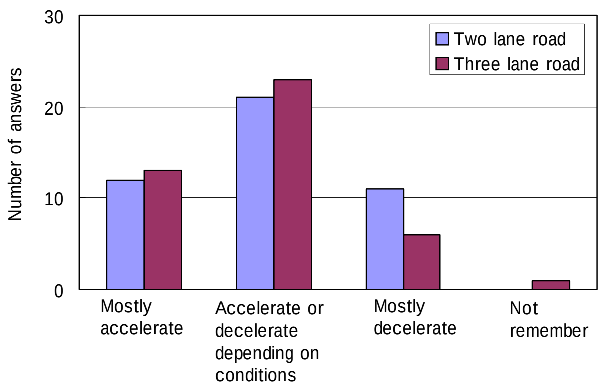


Figure 15. Results of questionnaire (1).

Question 3
How did you drive when pedestrian signal turned from green to flushing during the green interval?



Queation 4
How did you drive when pedestrian signal turned from flushing to red during the green interval?

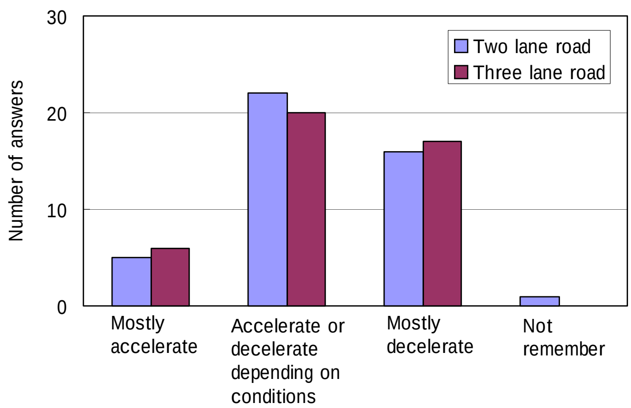


Figure 15. Results of questionnaire (2).

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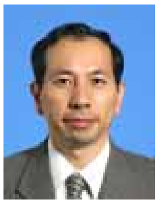

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