# A STUDY ON WARNING TIMING FOR LANE CHANGE DECISION AID SYSTEMS BASED ON DRIVER'S LANE CHANGE MANEUVER

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## ABSTRACT

The purpose of this paper is to clarify the suitable warning timing of "Lane Change Decision Aid Systems (LCDAS)" for a driver's lane change maneuver. The relationship between lane-change tasks and closing vehicles in the passing lane was investigated by field experiments on the Chuo expressway in Japan. The driver's steering during the lane change was simulated using a linear prediction model. Based on these results, the system requirements of warning timing and sensing area for LCDAS are proposed.

## INTRODACTION

Several warning systems, including Forward Vehicle Collision Warning Systems (FVCWS) and Lane Departure Warning Systems (LDWS) have been proposed as advanced vehicle safety devices using ITS technologies. A Lane Change Decision Aid Systems (LCDAS) is one of such devices that warns the subject vehicle driver of potential collisions with other vehicles in the adjacent lane during lane change maneuvers. The warning can be one of two categories: a blind spot warning that informs the driver of other vehicles on the side of the subject vehicle and a closing vehicle warning that informs of a faster vehicle closing from the rear.

For application to large trucks, several blind spot warnings using ultrasonic sensors were introduced into the market in the 1990s [1,2]. However, the obstacle detection accuracy was insufficient and there were many unnecessary or false alarms that made the warning system unsatisfactory. With the advance of sensing technologies, such as image processing and laser radar, interest in practical application of LCDAS has been rekindled [3,4], and LCDAS standardization has begun as an ITS device at ISO/TC204/WG14 [5].

The design of the warning timing is discussed in the development and standardization stage of a warning system like LCDAS. To ensure effectiveness, warnings must be presented to the driver in a timely manner. Although the warnings should be presented early when considering the driver's safety as the first priority, if warning timing is set too early, the driver may consider it unnecessary or a false alarm, reducing the effectiveness of the warning system. Therefore, it is important that the contradicting issues of establishing safety and reducing nuisance be resolved.

The purpose of this study is to clarify the suitable warning timing of the LCDAS based on the driver's lane change maneuver. The relationship between lane change tasks and closing vehicles in the right-side lane (i.e., passing lane) was investigated by field experiments on the Chuo expressway in Japan. The driver's steering when reversing a lane change based on the output warning was simulated using the driver's linear prediction model. Based on these results, the system requirements of warning timing and sensing area for LCDAS are proposed.

## INVESTIGATION OF LANE CHANGE MANEUVER

### Test Method

Ten male and five female subjects, ages 23 to 56, with valid driving licenses and normal visual and auditory senses, participated in this test. The subject drivers drove the a test vehicle that installed with four CCD cameras installed for recording of the driver's face and the traffic conditions as shown in Figure 1.

The subjects drove on the left-side lane (i.e., cruising lane) of a four-lane road, overtaking slower vehicles by changing to the right-side lane (i.e., passing lane) as shown in Figure 2. The subjects could stop the lane change task if they judged it risky based on closing vehicles in the adjacent lane. The rear-view image of the right-side lane in Figure 1 was also recorded (on different tapes) to calculate the headway distance from the subject vehicle to the target vehicle by image analysis.

The experiment was conducted using the Chuo expressway between Chofu interchange and Hachioji interchange, a distance of about 17 km. The subjects made three round trips in this section for a total distance of 100 km, and total time of 70 minutes per subject.

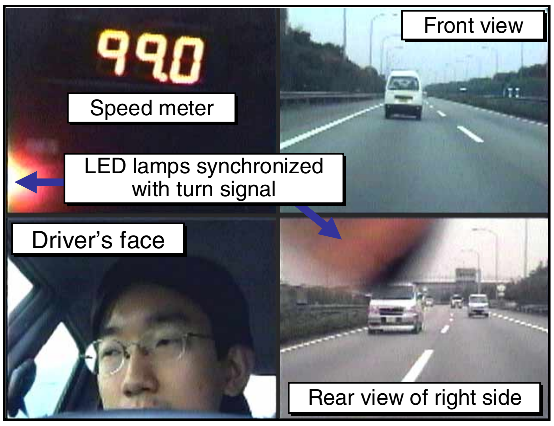


**Figure 1. Example of recorded scene using four CCD cameras.**

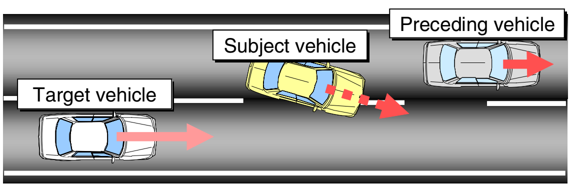


**Figure 2. Image of driving task.**

**Calculation of Headway Distance**

By analyzing the rear view image of the right side, the headway distance from subject vehicle to target vehicle in the adjacent lane was obtained for both the lane change execution and the lane change cancellation. The headway distance was measured as the drivers checked the adjacent lane from the moment the driver begins to return the viewpoint from the rear view mirror to the front. To calculate the relative velocity with respect to a target vehicle, the headway distance before one second was also measured.

A personal computer mounted to a video capture board (resolution 640×480 pixels) was used for the analysis. The corresponding tread width of the target vehicle and pixel number on the screen were used to calculate the headway distance. The accuracy of the image analysis was verified using the test vehicle placed 3.5 m to the right side of the subject vehicle with a 1.48 m tread width. Figure 3 shows that the method used to calculate headway distance using the image analysis was appropriate (full-scale error is ±3% or less).

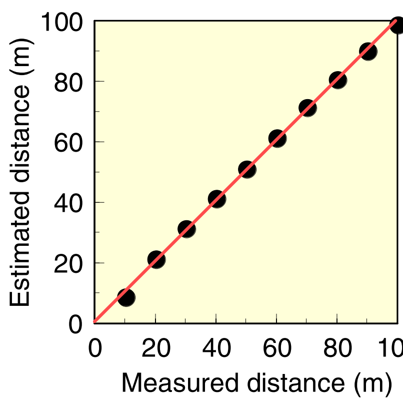


**Figure 3. Verification of headway distance calculated from video analysis.**

## TEST RESULTS

**Number of Acquisition Data**

Table 1 presents the total amount of data acquired for each subject, divided into the number of lane changes and lane-change cancellations. A headway distance of 100 m was the criterion for judging a target vehicle in the adjacent lane.

The field experiment totaled 1500 km driven by fifteen subjects, with 1097 data points obtained. There were 538 lane changes with an adjacent vehicle present, which meant that headway distance was less than 100 m. Furthermore, there were 266 instances of lane change cancellation influenced by adjacent vehicles. The average speed of all vehicles was 91.3 km/h.

**Table 1.**
**Number of experimental data**

| Subject number | Execute lane change | | Cancel lane change | Total | Average speed (km/h) |
|---|---|---|---|---|---|
| | No target vehicles (Dist.≧100m) | With target vehicles (Dist.＜100m) | | | |
| 1 | 15 | 46 | 14 | 75 | 94.3 |
| 2 | 33 | 40 | 10 | 83 | 97.2 |
| 3 | 9 | 41 | 16 | 66 | 88.9 |
| 4 | 16 | 52 | 27 | 95 | 94.3 |
| 5 | 14 | 25 | 20 | 59 | 88.0 |
| 6 | 25 | 30 | 14 | 69 | 94.4 |
| 7 | 25 | 30 | 8 | 63 | 95.0 |
| 8 | 22 | 46 | 21 | 89 | 89.3 |
| 9 | 7 | 46 | 32 | 85 | 86.9 |
| 10 | 33 | 37 | 8 | 78 | 95.3 |
| 11 | 21 | 30 | 8 | 59 | 92.7 |
| 12 | 0 | 41 | 23 | 64 | 86.2 |
| 13 | 18 | 22 | 17 | 57 | 88.1 |
| 14 | 27 | 21 | 17 | 65 | 88.3 |
| 15 | 28 | 31 | 31 | 90 | 91.1 |
| Total | 293 | 538 | 266 | 1097 | – |
| AVE | 19.5 | 35.9 | 17.7 | 73.1 | 91.3 |
| S.D. | 9.2 | 9.3 | 7.7 | 12.3 | 3.5 |

## Relationship between Headway Distance and Relative Velocity

Discriminant analysis is a technique for assigning measured values to data groups when multiple data groups exist. The boundary line to decrease the probability of the most erroneous distinction is called a discriminant function. The discriminant function with the execution group and the cancellation group is expressed as $y=0.496x-1.91$ in Figure 4, and it was found that the boundaries approximately agreed with the diagonal.

## Relationship between Lane Change Maneuver and TTC

The reciprocal of the gradient in the above discriminant function, i.e., the headway distance divided by the relative velocity, corresponds to the time to collision (TTC). The distribution of TTC for headway distance was examined by separating the execution group and the cancellation group. This facilitated understanding by using TTC in a discussion of the warning timing, which was related to the danger of collision. Figure 5 shows that the TTC for the execution group exceeded 6 seconds, regardless of the headway distance. However, TTC for the cancellation group was 10 seconds or less.

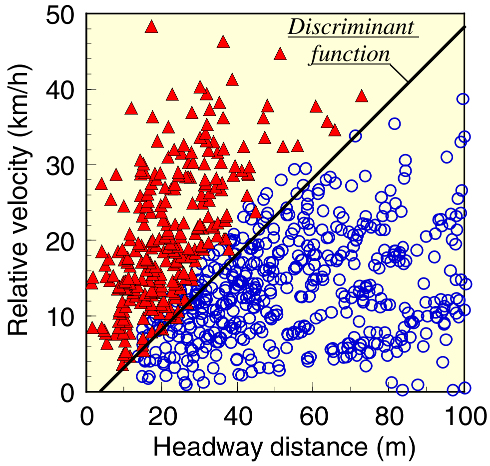


**Figure 4. Relationship between headway distance and relative velocity of target vehicles (○ :Lane change execution ▲ :Cancellation).**

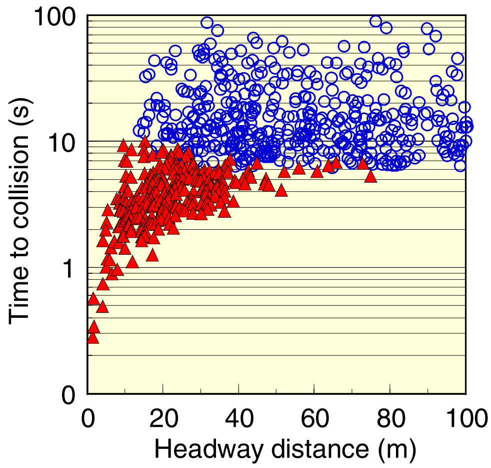


**Figure 5. Distribution of time to collision (○ :Lane change execution ▲ :Cancellation).**

### Consideration in Warning Timing

From this analysis, TTC can be used as an evaluation index for deciding the warning requirements for LCDAS. Any warning requirement established, however, must resolve the contradictory issues of establishing safety and reducing nuisance alarms.

Of the 538 data points acquired in this test, the minimum TTC of the execution group was 6.17 seconds. When TTC was 6 seconds or less, all drivers concluded that the lane change would be dangerous and abandoned execution. Therefore, the warning should be presented at this minimum threshold to keep the driver's nuisance to almost zero in theory. For all 266 data points of the cancellation group, the maximum TTC was 9.98 seconds, and lane changes were not cancelled over this value, concluding that all drivers perceived a TTC of 10 seconds or over within the safety range. Therefore, a warning issued at over this threshold will increase the driver's annoyance.

The above findings set a reasonable standard of the warning threshold for LCDAS: TTC should be set at 10 seconds if the designer gives precedence to safety and to 6 seconds in order to minimize the driver's annoyance. We now examine why the threshold of TTC ranges from 6 to 10 seconds, i.e., why the decision point for lane change or cancellation exists in this range. Drivers' predictions before lane changing greatly influence this. Figure 6 shows a histogram of required time for lane change for all 831 data points in which the driver executed a lane change. The time required is distributed between 3.1 seconds and 8.8 seconds, and the average is 5.3±1.0 seconds. Therefore, the driver estimates the positions of his own vehicle and the adjacent vehicle for a period of lane changing, from the headway distance and the relative velocity of the vehicles. We next assume that the drivers will change lanes when they judge that their own vehicle will not collide with the leading vehicle and will not interfere with the adjacent vehicle. The driver may expect about 2 seconds as a margin of safety. When an error in these predictions and judgments, including missing the adjacent vehicle, is made, the potential for accidents increases. An important role of LCDAS is to anticipate the lane change when such errors occur.

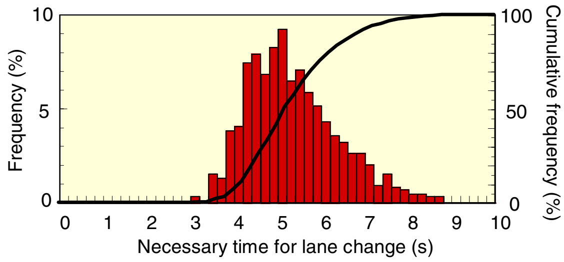


**Figure 6. Distribution of required time for lane change.**

## SIMULATION OF LANE CHANGE MANEUVER

In the previous section, the warning timing of LCDAS was investigated based on the driver's lane change judgment. By making TTC an evaluation index, a warning threshold of 6 to 10 seconds was obtained. However, we cannot conclude that the LCDAS must warn the driver within this threshold. The TTC threshold should become lower if the driver rapidly returns to the original lane after the lane-changing warning is given. In this section, the minimum TTC at which the LCDAS must give a warning is verified from the results of lane-change simulations using a driver model.

### Simulation Models and Conditions

A vehicle model with four degrees of freedom (longitudinal, lateral, yaw and roll) was used to calculate vehicle motion [6]. A passenger car of normal size (Table 2) was assumed.

The first prediction model (the most fundamental model) was used to calculate the driver's steering behavior. In this model, a driver estimates his/her vehicle's position after traveling *Tp* seconds at the present velocity and direction, then sets a steering wheel angle proportional to the error with the target course. In this study, prediction time *Tp* was set at 1 second, and the time lag of the steering input was set at 0.3 seconds. The driver gain, which is a proportional constant of the steering wheel angle to the prediction error, was obtained by optimization so that the lateral deviation between running path and target course was minimized. Although the driver gain was slightly different from each driving conditions, it was about 0.4 rad/m. The velocity of subject vehicle was set at 100 km/h, and the lane width was set at 3.5 m. The target course in lane changing was a curve connecting the start point and the end point by a half-cycle sine wave. This end point was determined according to the time required for the lane change.

**Table 2.**
**Vehicle parameters for simulation model**

| | |
|---|---|
| Total mass | 1180 kg |
| Length | 4.400 m |
| Width | 1.695 m |
| Height | 1.385 m |
| Tread (front / rear) | 1.470 / 1.460 m |
| Wheelbase | 2.550 m |
| Distance from front / rear axle to C.G. | 1.046 / 1.504 m |
| Overall steering gear rario | 17.5 |

## SIMULATION RESULTS

### Normal Lane Change

A normal lane change task is simulated in Figure 7. The horizontal axis shows the elapsed time from the start of the lane change. The vertical axis shows the steering wheel angle (upper part) and the vehicle lateral position (lower part). The necessary time for lane change was set at 5.3 seconds, which was the average of the above-mentioned field experiment.

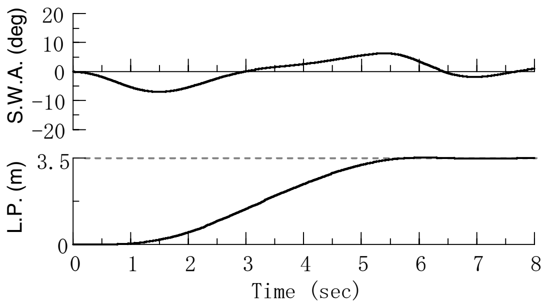


**Figure 7. Simulation of normal lane change task.**

The purpose of LCDAS is to cause the driver to steer in the opposite direction in order to return to the original lane after the warning output. Therefore, it is important to determine how long it takes the subject vehicle to return to the original lane. The situation in which the lane change was interrupted by a warning was simulated under the following conditions.

- Warning system detects the lane change with the start of steering input.
- System delay time from the lane change detection to output warning is 0.3 seconds.
- Driver's reaction time for presented warning is 0.89 seconds, which is the 95%ile of the steering reaction time for LDWS.
- Lane change time is 3.9 seconds, which is the 5%ile value of the above-mentioned field experiment.

Figure 8 shows that the maximum lateral position deviation reaches 0.50 meters 1.96 seconds after the start of lane change. If the subject vehicle is running in the center of the lane before the lane-changing starts, it can return to its original course without entering the adjacent lane. However, it risks colliding with the adjacent vehicle if the lane change is initiated from around the lane marker. In addition, if there are manifold lane widths and vehicle widths, it is more important to evaluate the delay time until the vehicle begins to return than to evaluate the vehicle's absolute lateral position. In short, the risk of collision is small if the adjacent vehicle does not catch up to the subject vehicle when the subject vehicle reaches maximum displacement. However, the risk of collision is high when the adjacent vehicle overtakes the subject vehicle before this maximum point. LCDAS should warn the driver to interrupt the lane change. Figure 8 clearly demonstrates that it is imperative for LCDAS to present a warning when the TTC with the adjacent vehicle is equal to or less than 2 seconds.

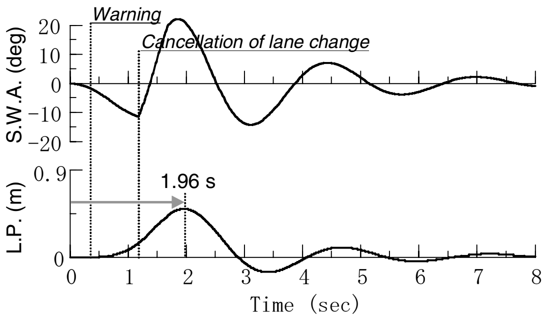


**Figure 8. Simulation of stopped lane change situation.**

From another perspective, we consider the situation in which the adjacent vehicle avoids the collision by applying the brakes when the subject vehicle changes lanes. In this case, the following conditions are required to prevent the adjacent vehicle from colliding with the preceding vehicle in the lane change, which means that the headway distance before lane changing must be less than the necessary distance for the following vehicle's deceleration.

$$\Delta V \bullet TTC > \Delta V \bullet T + \Delta V^2 / 2\alpha$$
$$TTC > T + \Delta V / 2\alpha$$

Where,

*ΔV : Relative velocity between lane-changing vehicle and following vehicle*

*TTC : Time to collision with lane-changing vehicle and following vehicle*

*T : Delay time until following vehicle starts the braking*

*α : Deceleration of the following vehicle*

When it is assumed that T=1second, ΔV=30km/h and α=4m/s$^2$, TTC required to avoid the collision is calculated to be over 2.04 seconds. Therefore, we can expect the following vehicle to avoid collision by braking, even if the warning is not presented for the lane-changing vehicle driver for TTC over 2 seconds. Braking alone will not avoid the collision when TTC is less than 2 seconds. From this perspective, it is imperative to warn the driver who initiates a lane change when the TTC with the adjacent vehicle is 2 seconds or less.

## CONSIDERATION OF SENSING RANGE

From the above analysis, three TTC thresholds (2 seconds (time required for collision avoidance), 6 seconds (minimum value at lane change execution) and 10 seconds (maximum value at lane change cancellation)) were obtained as LCDAS warning requirements. Next, we examined the required sensing range for the adjacent vehicle detection based on these results.

TTC is calculated from the headway distance and the relative velocity. The relative velocity was obtained from all 804 field test data points in which there was an adjacent vehicle. Figure 9 shows that the 90%ile speed difference between the cruising lane and the passing lane in the four-lane expressway was 30 km/h or less. The headways obtained were 17m for a TTC of 2 seconds, 50m for a TTC of 6 seconds, and 83m for a TTC of 10 seconds (calculated from the headway distance using the TTC threshold and assuming an upper relative velocity limit of 30km/h). Therefore, the range in which LCDAS should detect the adjacent vehicles is 20m as a minimum requirement, 50m for lane-changing decision support, and 80m for maximum safety.

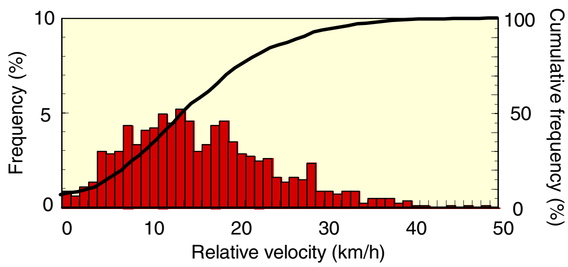


**Figure 9. Distribution of Relative velocity of adjacent vehicle.**

## CONCLUSION

In order to determine suitable LCDAS warning timings from the drivers' characteristics at the lane-changing, field experiments were conducted on an expressway and computer simulations of lane change maneuver were performed. Using TTC with the adjacent vehicle as an evaluation index, the following warning times are proposed.

• 10 seconds and over : Unnecessary
(LCDAS must not give a warning)
• 6 to 10 seconds : Adjustable range
(LCDAS may give a warning)
• 2 to 6 seconds : Recommended
(LCDAS should give a warning)
• Under 2 seconds : Imperative
(LCDAS shall give a warning)

For the range to detect an adjacent vehicle, we consider 20m for the minimum requirement, 50m for lane-changing decision support, and 80m for maximum safety, when the upper relative velocity limit is assumed to be 30 km/h.

The values obtained in this study are the results simulated from representative driving situations. The following approaches will be continuously examined: Timing of the turn signal activation, tolerances of the lateral deviation, and necessary time for collision avoidance.

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