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Accident-preventive Measure Selection Method Based on the Speed Cognition of Lead-vehicle Driver in Curved Roadway

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Abstract

To select appropriate traffic safety measures in curved roadways, we focus on the structure of drivers' cognitions of lead-vehicle speeds in curves. The purpose of this study is to propose an accident-preventive measure selection method based on the speed-cognition structure of the lead-vehicle driver in a curved roadway. In order to test the hypothetical structure of the speed cognitions, we use path-analysis approach and employ a driving simulator. And in our hypotheses about the speed-cognition structure and the curve cognition process of the driver, we focus on the relationship among a target-setting error due to the maximum safety speed (TSE), a subjective-adjustment error due to perceived speed (SAE), an "objective-adjustment error due to perceived speed (OAE) a speed-perception error due to actual speed (SPE), and a maximum-safety error due to actual speed (MSE)". In the results of our driving-simulator experiment, in the case of left-hand curves, the measures that have drivers perceive the perceived speed low during passing through the curve are effective for diminishing the actual vehicle speed. In the case of right-hand curves, on the other hand, the measures that have drivers target the target speed low before proceeding into the curve are effective for diminishing the actual vehicle speed. In the class of sharp curves, drastic measures such as improvements to the working of the curve are better than measures such as the impact on the perceived speed. In the class of gentle curves, on the other hand, even though in the same class, the measures should be handled sensitively before proceeding into the curve or while passing through the curve, depending on the degree of the change of curvature.

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Keywords: Speed cognition ; Driving simulator ; Maximum safety speed ; Target speed ; Perceived speed

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1. Introduction

Single-vehicle drivers tend to underestimate the speed in roadways (Yotsutsuji and Kita, 2010). Underestimation of speed in curved roadways may be a contributing factor necessitating speed adjustment and thus causing fatal and serious injury accidents in curves (Milosevic and Milic, 1990; Cameron and Elvik, 2010; Elvik, 2013). As the result of approaching sharp curves without realizing that current speed is dangerous to passing through the curve, when driver fails to decelerate while just realizing that, the driver feels a tense moment and traffic incidents may occur. Hence in order to prevent drivers' misperception of speed from traffic incidents in curves, it is necessary to select accident-preventive measures which reflect speed-cognition structures of the drivers toward/into the curves, in keeping with the characteristics of curves.

Studies on speed-cognition structures of drivers toward/into a curve still have unclear points. This study conducts an in-house experiment employing a driving simulator, not an in-vehicle experiment, in order to replicate driving situations toward/into curves at the risk of accidents. Targeting curved sections in a non-urban two-lane roadway, it is assumed that information by road signage is not provided to drivers before approaching the curves and each driver does not take a glance at the speedometer while looking at the curves. Under the assumption, focusing on speed cognition according to the characteristics of curves, this study examines the selection method of various preventive measures handling errors involved in the speed-cognition structure.

This study focuses on the structure of drivers' cognitions of lead-vehicle speeds in curved roadways. The purpose of this study is to propose an accident-preventive measure selection method based on the speed-cognition structure of the lead-vehicle driver in a curved roadway, while using path analysis technique to analyze data from a driving-simulator experiment. With respect to the curve-cognition process and speed-cognition structure of lead-vehicle driver, this study generates hypotheses as discussed in detail in chapter 3.

2. Relevant Studies

Vision psychology explains that motion perception in the human visual system is affected by the contrast and special frequency of a moving brightness. As for moving patterns of the black and white lines in order (i.e. moving patterns of brightness), humans are known to perceive the high contrast and high special frequency patterns faster than physical speeds of the patterns, otherwise, the low contrast and low special frequency patterns slower than physical speeds of the patterns (Weiss, Simoncelli and Adelson, 2002). Such discrepancy between perceived speeds and physical speeds are modeled by the Bayesian model (Weiss, Simoncelli and Adelson, 2002; Hurlimann, Kiper and Carandini, 2002), the ratio model (Hammet, Champion, Morland and Thompson, 2005), and the power model (Yotsutsuji and Kita, 2010). This study focuses on cognitive factors influencing the discrepancy between perceived speeds and physical speeds.

It is important for driver performance and speed adjustment in curves to estimate vehicle speed as accurately as possible. In traffic engineering, however, it is empirically known that drivers underestimate vehicle speed after deceleration (Milosevic and Milic, 1990), and is quantitatively known that underestimation of vehicle speed bears relevance to a number of accidents in curves (Cameron and Elvik, 2010; Elvik, 2013).

In Japan, Oumi et al. (2002) analyzed driver's cognition process regarding the direction of bentness and the change of curvature, and also studied how effective road signage should be in the curve detection point, while conducting an in-vehicle experiment in several curve sections of a non-urban two-lane roadway. As the result of classification of curves with respect to each impression to the change of curvature, such as "sharp" with a strong need for decelerating, "normal" with a weak need for decelerating, "gentle" with no need for decelerating, they point out that the strength of the impressions has a discrepancy between approaching to and passing through the curve and a gap between these impressions and actual driving behaviors carries latent accident risks.

3. Hypotheses

3.1. Curve cognition process

This study assumes the process of curve cognition of a lead-vehicle driver, as illustrated in Fig. 1. In Fig. 1, the driver detects a forward curvature in the straight section toward the curve, and equally aims at a target speed, $\hat{v}_S$, for passing safely through the curve, by comparing to a maximum safety speed, $\hat{v}_O$, which is determined by the radius of the curvature, R , in an objective way. The $\hat{v}_O$ is unknown for this driver, and hence the driver controls a passing speed, $\bar{v}_S$, which the driver perceives in passing through the curve, subject to the $\hat{v}_S$, and accommodates the steering angle, the acceleration/deceleration, etc. of the vehicle. When the driver does not take a glance at the speedometer while gazing at the curves, the $\bar{v}_S$ does not always coincide with the actual vehicle speed, $\bar{v}_O$.

This study posits the premise that, firstly only two of the characteristics of curves, which means the direction of bentness and the change of curvature, are dealt with, and secondly the changes of driving environments, such as weather, day-and-night, and traffic volume, are not dealt with, and thirdly the influence of other vehicle speeds on a speed cognition of the lead-vehicle driver is not dealt with.

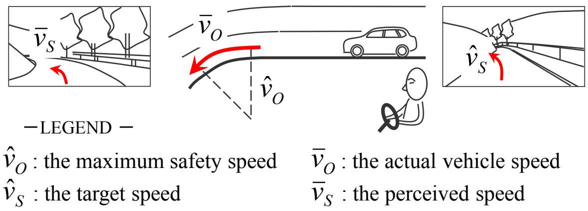

Fig. 1. Curve cognition process

3.2. Speed cognition structure

By testing a hypothesis described as a path diagram in Fig. 2, this study recursively estimates the structure of speed cognition of a lead-vehicle driver. In Fig. 2, this study terms each discrepancy among the speeds of $\hat{v}_O$, $\hat{v}_S$, $\bar{v}_O$ and $\bar{v}_S$ an "error". In particular, the discrepancy between $\hat{v}_O$ and $\hat{v}_S$, the one between $\hat{v}_S$ and $\bar{v}_S$, the one between $\hat{v}_O$ and $\bar{v}_S$, the one between $\bar{v}_S$ and $\bar{v}_O$, and the one between $\hat{v}_S$ and $\bar{v}_O$ are termed a "target-setting error due to the maximum safety speed (hereinafter referred to as TSE)", a "subjective-adjustment error due to perceived speed (SAE)", an "objective-adjustment error due to perceived speed (OAE)", a "speed-perception error due to actual speed (SPE)", and a "maximum-safety error due to actual speed (MSE)", respectively. In Fig. 2, the error of ε_1 is represented as the TSE, and the error of ε_2 is represented as the sum of the SAE and the OAE, and the error of ε_3 is represented as the sum of the SPE and the MSE.

Suppose that a representative lead-vehicle driver repeatedly experiences the drive within a curve, and then consider the relationship between speed cognition of the driver and latent accident risks of the vehicle. Now, it assumes that the driver tries to turn safely onto the curve with a target speed which the driver subjectively aims at as the maximum safety speed. As will become apparent in the next chapter, in the course setting of an in-house experiment employing a driving simulator, the appearance interval of a curve is very short, because it is a mountainous course. Hence, it is assumed that the driver cannot afford to think whether such curve is the same configuration as the past few curves, just at the moment of approaching to such a curve. In addition, it is assumed that the influence of driving habituation on the driver in such curves is quite small. Compared with the $\hat{v}_O$, there is a continuous distribution of the $\hat{v}_S$.

If there is a continuous distribution of the $\hat{v}_S$, that is a distribution of the ε_1 as the TSE, there is the case that $\hat{v}_S \geq \hat{v}_O$. Although the driver perceives the $\bar{v}_S$ under an arbitrary $\hat{v}_S$, when the $\hat{v}_S$ becomes distributed, there is also a distribution of the $\bar{v}_S$. If there is a continuous distribution of the ε_2 as the sum of the SAE and the OAE, there are the cases that $\bar{v}_S \geq \hat{v}_S$ and $\bar{v}_S \geq \hat{v}_O$. Although the $\bar{v}_O$ emerges as the result of driving skill under the $\bar{v}_S$, when the $\bar{v}_S$ becomes distributed, there is also a distribution of the $\bar{v}_O$. If there is a continuous distribution of the ε_3 as the sum of the SPE and the MSE, there are the cases that $\bar{v}_O \geq \bar{v}_S$ and $\bar{v}_O \geq \hat{v}_S$. When almost coincidentally these errors emerge, there is the case that $\bar{v}_O \geq \hat{v}_O$. In this result, accident risks are revealed. On the other hand, even though there is the case that $\bar{v}_O < \hat{v}_O$, when any of three errors composed of the ε_1 , the ε_2 and the ε_3 meets the conditions set forth above, it is assumed that the driver gets into a situation under latent accident risks.

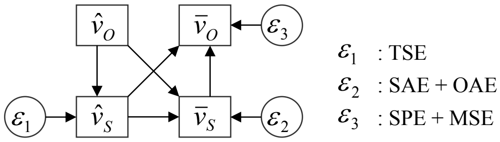

Fig. 2. Speed cognition structure

4. In-house Experiment

4.1. Driving simulator

In the in-house experiment which was conducted in this study, a driving simulator (hereinafter referred to as DS) was employed, in view of physical security for experimental participants who may feel tense moments of the accidents under a real-vehicle environment. This DS is made by Honda Motor Co., Ltd. and is set up in the Suzuka Circuit Traffic Education Center, located at Suzuka Circuit in Mie Prefecture, for the sake of training and education of driving safely.

In the DS experiment held in this study, a driving course supplied by the driving simulator was the full circuit around a virtual island, as illustrated in Fig. 3. In addition, driving time and road surface condition were set as daytime and wet, respectively.

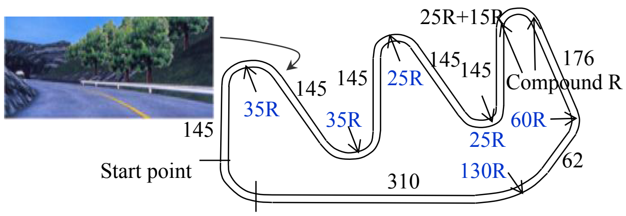

Fig. 3. Experimental course in the driving simulator

This DS is designed to experience the same feeling as driving a real-world vehicle at the moments of cornering and braking, by equipping 6-axes cylinders with the simulator vehicle. Based on information of driver's operation such as steering and accelerating, the simulator PC calculates motions of the simulator vehicle and makes driving situations pre-registered at each passing-through points, and conveys these processing results to the simulator vehicle. The simulator vehicle has automatic transmission. Although the speedometer equipped in the simulator vehicle has an analog display, the speedometer displayed in the simulator PC is with a digital display. At the moment that the simulator vehicle crashes into guardrails in the midst of driving, the motion picture displayed on the windshield restarts to just before these crashes.

4.2. Experiment description

4.2.1. Participants

Participants were composed of two members. One was a Japanese woman in her early twenties, and another was a Japanese man in his late thirties. The former had just over a few years of experience as a driver, and hence seems to show lower performance in measuring the characteristics of curves. The latter had a driver's license for many years but it had been a while since he last drove, and hence seems to estimate optimistically the safety speed because of forgetting the experience of many incidents.

4.2.2. Procedure

By letting both participants do a trial run on 3 laps clockwise from the start point described in Fig. 3, we had them adjust speed feelings inherent in the DS and also had them confirm the actual vehicle speed which was able to be obtained by the speedometer equipped in the simulator vehicle, as compared with such speed feelings inherent in the DS. Continuingly in the experiments, we had both participants drive, without watching the speedometer, on 7 curves in the circuit course clockwise from the start point, and similarly on 7 curves after turning around at the last curve. Two participants conducted these procedures one after the other in steps of 4 sets.

4.2.3. Data

In the experiment, after having each participant utter each $\hat{v}_S$ up to the entry of each curve, we had one utter each $\bar{v}_S$ perceived while passing through each curve. Simultaneously we recorded each $\bar{v}_O$ displayed in the simulator PC. After finishing all experiments, we calculated the $\hat{v}_O$ of each curve, based on the radius of curvature measured from the center position in each of inner lane and outer lane. In the result, available data set was 96, that is "2 participants" times "12 curves" times "4 tries" makes 96, as excluding 1 curve because of the compounding curvature and the hairpin.

The data obtained from the experiment are detailed in Table 1.

4.2.4. Supplement

In order to examine the effective accident-prevention measures in curves in the view points of the speed cognition and eye movement of drivers, we conducted an additional experiment in which the participants mandatorily watch the guardrail while passing through any curve. Furthermore we debriefed where the participants kept their eyes on while passing through the curve, in the case of not compelling them to watch the guardrail.

Furuichi et al. (2004) reported that, by employing a wearable eye-marker device, a driver before proceeding into a curve keeps their eyes in the distance, without taking a glance at the speedometer, and gazes narrowly and deeply at the curve, while the driver just after proceeding into the curve shifts the gaze point from the distance to the road surface in front of the vehicle. Furthermore, they reported that the driver while passing through the curve shifts their gaze point from the road surface in front of the vehicle to either the lane edge or the centerline, and if such driver feels the curve sharpen more than expected, the driver gazes widely and shallowly irrespective of distance.

In our additional experiment as mentioned above, we reconfirmed the results that Furuichi et al. (2004) reported.

Table 1. The data obtained from our experiment

Radius	Variables	Participant 1 : Woman				Participant 2 : Man			
Direction	(km/hr)	1st try	2nd try	3rd try	4th try	1st try	2nd try	3rd try	4th try
25 m	$\hat{v}_s$	45	45	60	50	50	60	50	50
Right turn	$\bar{v}_s$	45	50	45	55	40	50	40	45
Lap 1	$\bar{v}_o$	47	51	49	48	40	45	40	38
25 m	$\hat{v}_s$	50	45	45	50	45	50	55	60
Left turn	$\bar{v}_s$	60	55	55	55	50	55	55	45
Lap 1	$\bar{v}_o$	48	49	47	42	41	42	38	44
25 m	$\hat{v}_s$	50	40	50	50	50	50	50	50
Right turn	$\bar{v}_s$	45	45	45	45	50	50	55	55
Lap 2	$\bar{v}_o$	49	50	47	51	41	42	45	39
25 m	$\hat{v}_s$	45	45	50	50	50	50	60	55
Left turn	$\bar{v}_s$	55	50	55	55	55	50	60	50
Lap 2	$\bar{v}_o$	48	44	46	45	46	42	49	40
35 m	$\hat{v}_s$	45	50	50	50	60	60	60	60
Right turn	$\bar{v}_s$	40	45	50	50	65	65	60	65
Lap 1	$\bar{v}_o$	48	51	51	52	56	49	55	54

Table 1. The data obtained from our experiment (*Continue*)

Radius Direction	Variables (km/hr)	Participant 1 : Woman	Participant 2 : Man	Radius Direction	Variables (km/hr)	Participant 1 : Woman	Participant 2 : Man	Radius Direction	Variables (km/hr)
130 m Right turn	$\hat{v}_s$	60	65	65	60	60	70	65	60
	$\bar{v}_s$	65	65	65	60	60	70	70	70
	$\bar{v}_o$	59	59	60	59	62	73	73	73
130 m Left turn	$\hat{v}_s$	70	70	75	70	60	70	70	65
	$\bar{v}_s$	75	65	70	65	65	70	70	65
	$\bar{v}_o$	70	65	64	67	57	77	67	61
35 m	$\hat{v}_s$	45	50	45	40	60	60	60	60
Left turn	$\bar{v}_s$	45	55	50	45	60	60	60	60
Lap 1	$\bar{v}_o$	49	55	19	49	45	48	53	49
35 m	$\hat{v}_s$	50	50	50	50	60	40	60	55
Right turn	$\bar{v}_s$	45	50	45	45	60	45	50	60
Lap 2	$\bar{v}_o$	51	56	48	52	50	43	39	43
35 m	$\hat{v}_s$	50	50	50	45	60	50	50	40
Left turn	$\bar{v}_s$	45	55	55	50	50	55	45	45
Lap 2	$\bar{v}_o$	51	50	48	51	44	46	42	45
60 m	$\hat{v}_s$	50	60	60	50	60	60	60	60
Right turn	$\bar{v}_s$	55	55	55	65	60	65	65	60
	$\bar{v}_o$	54	58	55	57	55	58	60	60
60 m Left turn	$\hat{v}_s$	50	50	60	50	65	70	60	70
	$\bar{v}_s$	65	60	65	65	65	70	60	60
	$\bar{v}_o$	64	61	62	60	57	67	44	60

5. Analysis

5.1. Model identification

Based on the path diagram described in Fig. 2, we apply path diagram analysis techniques to data that was classified by the direction of bentness (left/right) and the change of curvature (the radii of curvature in 6 curves). After conducting a Wald test on validity of path coefficients, we omit the paths where the t value of which was less than 1.96 for the 5% level of significance, and identify path diagrams to fit the data. This study terms this identifying diagram a "model". Additionally, in the experiment in this study, both of the $\hat{v}_S$ and $\bar{v}_S$ composing the speed-cognition structure were measured by utterance data. Thus these variables are dealt with observed ones.

The results of such model identifications are shown in Fig. 4 and Fig. 5. In Fig. 4, the models classified by the direction of bentness do not reject statistically by χ^2 test for 1% level of significance, regardless of the fewness of samples, although the Goodness of Fit Index (GFI) in each of the models is not necessarily a good thing, because the data varies widely when targeting a variety of curvatures for all curves. In Fig. 5, the models classified by the change of curvature do not reject statistically by χ^2 test for 5% level of significance, regardless of the fewness of samples, although the Adjusted Goodness of Fit Index (AGFI) in each of the models is not necessarily a good thing because the number of significant paths are small, while the other indexes are good. As the result of this statistical validity, we determine that the experiment in this study is valid.

5.2. Considerations

5.2.1. Direction of bentness

In path diagram analysis techniques, the standardized solution of path coefficient indicates the intensity of correlation, while the non-standardized solution of it indicates the depth of causality. Accordingly, we can consider the indirect effect on two variables by using the product of the non-standardized solutions.

The non-standardized solutions described in the case of left-hand curve in Figure 4 show that the $\bar{v}_S$ is affected by both the direct effect of the $\hat{v}_O$ as the value of 0.292 and the indirect effect of the $\hat{v}_O$ via the $\hat{v}_S$ as the value of 0.187 (= 0.556×0.336). Accordingly, the $\bar{v}_O$ is affected by the indirect effect of the $\hat{v}_O$ via the $\bar{v}_S$ as the value of 0.238 (= 0.292×0.814). In the result, the error of ε_1 has a much greater impact from the $\hat{v}_O$ via the $\bar{v}_S$.

On the other hand, the non-standardized solutions described in the case of the right-hand curve in Fig. 4 show that the $\bar{v}_S$ is affected by the indirect effect of the $\hat{v}_O$ via the $\hat{v}_S$ as the value of 0.261 (= 0.384×0.679). In addition, the $\bar{v}_O$ is affected by both the indirect effect of the $\hat{v}_O$ via the $\hat{v}_S$ as the value of 0.296 (= 0.384×0.772) and the indirect effect of the $\hat{v}_O$ via both the $\hat{v}_S$ and $\bar{v}_S$ as the value of 0.148 (= $0.384 \times 0.679 \times 0.566$). In the result, the error of ε_3 has a much greater impact from the $\hat{v}_O$ via the $\hat{v}_S$.

In summary, the major impact on the $\bar{v}_O$ from the $\hat{v}_O$ via the process of speed cognition shows that the case of the left-hand curve, which is 0.238, is smaller than the case of the right-hand curve, which is 0.296. It should be noted that, this result requires attention to the fact that drivers in Japan keep to the left.

5.2.2. Change of curvature

In Fig. 5, the causal relationship of speed cognition to the $\bar{v}_O$ shows that there are two major classes of the speed-cognition structure as "25R or 35R" and "60R or 130R". Although there are some unclear points in the relationship between the impression on the change of curvature and the structure of speed cognition, this study terms the class of "25R or 35R" a "sharp", and terms the class of "60R or 130R" a "gentle", for convenience sake.

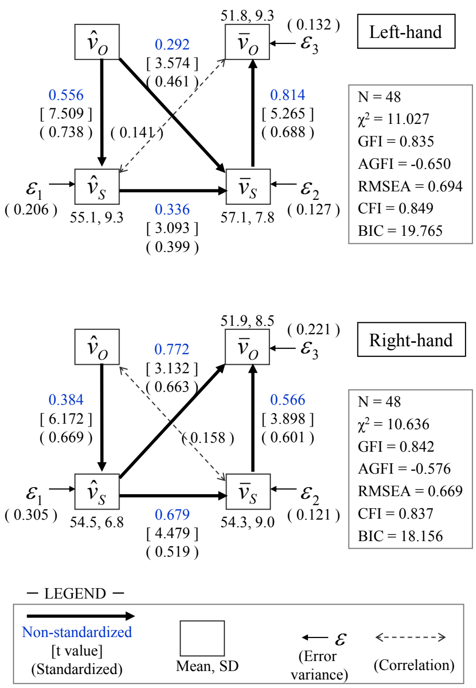

Fig. 4. Path diagrams (1)

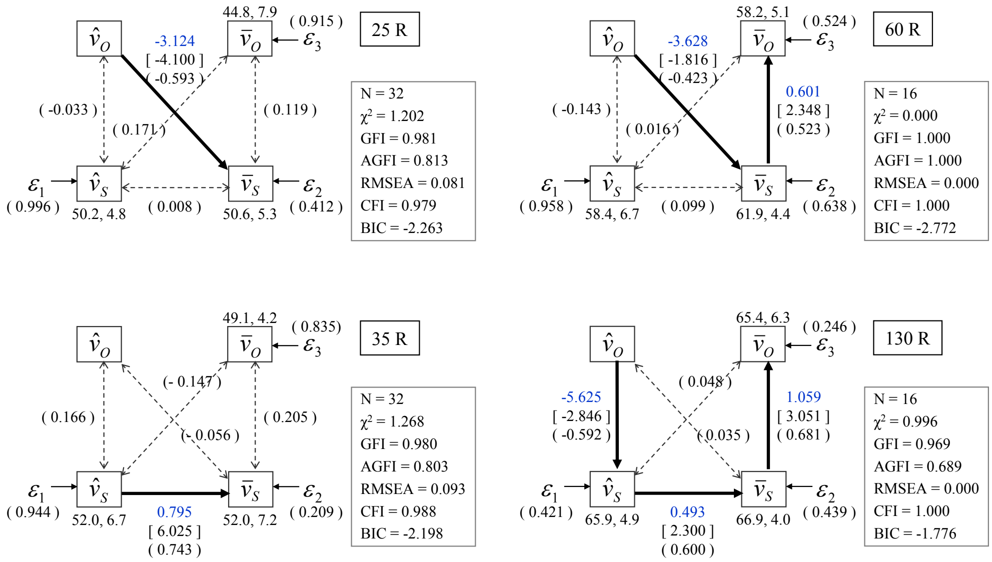

Fig. 5. Path diagrams (2)

In the “sharp” class of “25R or 35R”, the non-standardized solution of the 25R shows that the $\bar{v}_s$ is affected by the direct effect of the $\hat{v}_o$ as the value of -3.124, while the non-standardized solution of the 35R shows that the $\bar{v}_s$ is affected by the direct effect of the $\hat{v}_s$ as the value of 0.795. Because, however, the path coefficient between the $\bar{v}_s$ and $\bar{v}_o$ is of no significance for the classes of both 25R and 35R and also the correlation coefficient is small, the $\bar{v}_o$ has little impact from the $\bar{v}_s$.

In the “gentle” class of “60R or 130R”, the non-standardized solution of the 60R shows that the $\bar{v}_o$ is affected by the direct effect of the $\bar{v}_s$ as the value of 0.601, while the non-standardized solution of the 130R shows that the $\bar{v}_o$ is affected by the indirect effect of the $\hat{v}_s$ via the $\bar{v}_s$ as the value of 0.522 (= 0.493×1.059). Accordingly, even though this is the same class as “gentle” curves, the process of speed cognition to the $\bar{v}_o$ varies based on the value of curvature. By the way, both values of the direct effect of the $\hat{v}_o$ on the $\bar{v}_s$ in the 60R and the direct effect of the $\hat{v}_o$ on the $\hat{v}_s$ in 130R have negative ones. This indicates that, as the $\hat{v}_o$ of 60R and 130R lowers, either the $\bar{v}_s$ or the $\hat{v}_s$ rises. We think one of these causes regarding these negative values is our request for the two participants to approach the curves as close to the maximum safety speed as possible.

6. Discussions

6.1. Accident-preventive measures based on the direction of bentness

Our experiment showed that the error of ε_3 had a much greater impact from the $\bar{v}_s$, in the case of left-hand curves (the inner side of traffic lanes in Japan). Accordingly, the measures such as having drivers perceive the $\bar{v}_s$ low while passing through the curve are effective for diminishing the $\bar{v}_o$. Taking into account that a driver, while passing through a curve shifts their gaze point into either the lane edge or the centerline, we suggest that accident-preventive measures, such as the deceleration guide markings on the road surface, are effective.

On the other hand, our experiment also showed that the error of ε_3 had a much greater impact from the $\hat{v}_s$, in the case of right-hand curves (the outer side of traffic lanes in Japan). Accordingly, measures such as having drivers target the $\hat{v}_s$ low before proceeding into the curve are effective for diminishing the $\bar{v}_o$. Taking into account that a driver keeps their eyes in the distance before proceeding into a curve, we suggest that accident-preventive measures, such as chevron markers on guardrail (by which drivers feel that the curve is sharper than expected) are effective.

6.2. Accident-preventive measures based on the change of curvature

In the class of sharp curves, even though we have drivers feel that the curve is sharper than expected before proceeding into the curves, the $\bar{v}_O$ has little influence from the $\bar{v}_S$. Accordingly, in such sharp curves, we suggest that drastic measures, such as improvement to the work of the curve, are better than measures such as the impact on the $\bar{v}_S$.

On the other hand, in the class of gentle curves, even though in the same class, we suggest that accident-preventive measures for diminishing the $\bar{v}_O$ should be handled sensitively before proceeding into the curve or while passing through the curve, depending on the degree of the change of curvature. In the case of curves of 60R, measures with relation to the $\bar{v}_S$ while passing through the curve are effective for diminishing the $\bar{v}_O$. In the case of curves of 130R, on the other hand, measures with relation to both the $\hat{v}_S$ before proceeding into curve and the $\bar{v}_S$ while passing through the curve are effective for diminishing the $\bar{v}_O$. However, these results need to be verified through further experiments.

7. Conclusion

To select appropriate traffic safety measures in curved roadways, we focus on the structure of drivers' cognitions of lead-vehicle speeds in curves. And in this paper, we provide a method of selecting accident-preventive measures reflecting speed-cognition structure of the lead-vehicle driver in a curved roadway.

As the result of data analysis though our driving-simulator experiment, in the case of left-hand curves, the measures that have drivers perceive the perceived speed low during passing through the curve are effective for diminishing the actual vehicle speed. In the case of right-hand curves, on the other hand, the measures that have drivers target the target speed low before proceeding into the curve are effective for diminishing the actual vehicle speed. In the class of sharp curves, drastic measures such as improvements to the working of the curve are better than measures such as the impact on the perceived speed. In the class of gentle curves, on the other hand, even though in the same class, the measures should be handled sensitively before proceeding into the curve or while passing through the curve, depending on the degree of the change of curvature.

Although there are some issues in this study, such as the normality of errors, the number of samples, etc., we think a new support method for selecting traffic-safety measures as based on driver's cognition was provided.

Acknowledgements

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