ASSESSMENT METHODOLOGY FOR THE INDUCTIVE AND FORCIBLE TRAFFIC SAFETY MEASURES THROUGH SPEED-UTILITY-BASED FRAMEWORK CONSIDERING SPEED RECOGNITION STRUCTURE OF DRIVER

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ABSTRACT

In curved sections on the road, in view of mortality due to traffic accidents caused by motor-vehicles' excessive speed, it is important to control the vehicles' speed before the occurrence of the excessive speed, by means of preventive traffic safety measures. In a curved section, achieving better prevention of vehicle accidents caused by the vehicle's excessive speed needs to reflect driver's recognition for both the speed of the vehicle and the attributes of the curve into the preventive safety measures. Speed recognition structure of the driver contains various errors, one of which is the discrepancy between perceived speed of the driver and actual speed of the vehicle. The error in speed recognition results in unsafe driving because, even though the driver makes a rational judgment of speed choice and makes no mistakes in vehicle operation, the driver is not aware of the excessive speed. Among a variety of preventive traffic safety measures to avoid unsafe driving due to the excessive speed, this paper focuses on two types of the measures. One is the forcible type that prevents any occurrence of the speed recognition error forcibly before the error occurs. Another is the inducible type that stimulates a return to safe driving with the vehicle's safety speed swiftly even though the error occurs. This paper provides a methodology for assessing the effect of preventive safety measures both of the forcible type and of the inducible type, by employing uniform analytical framework that is considering speed choice behavior and speed recognition of a driver who approaches a curved section. The proposed methodology deals with both approaching speed before the vehicle enters the curve and target speed due to safe driving during the curve, so that the subjective approaching speed of the driver and the objective approaching speed of the vehicle or the subjective target speed of the driver and the objective target speed of the vehicle are included in the speed recognition structure of the driver in the curve section. In modeling of the speed recognition structure, the relationship between the subjective approaching speed and the objective approaching speed is modeled by employing the optic-flow theory in the area of the visual psychology. In modeling of speed choice behavior, the relationship between the subjective approaching speed and the subjective target speed is modeled on the assumption of discrete speed choice based on speed utility. In conclusion of this paper, preferable advantage of the inducible traffic safety measures by comparison with the forcible ones is discussed.

Key Words: Preventive traffic safety measures, Inducible type, Forcible type, Assessment methodology, Speed recognition structure, Discrete speed choice, Speed utility

INTRODUCTION

In traffic safety management on curved sections on the road, understanding the structure of each driver's recognition for the attributes of curves and the speed of motor-vehicles is fundamental to achieving better prevention of traffic accidents caused by the vehicles' excessive speed. Speed recognition structure of a driver contains various errors, one of which is the discrepancy between perceived speed of the driver for one's own vehicle and actual speed of the vehicle. When a deceleration behavior of the driver is too late to round the curve even though the driver is aware of the lateness of the deceleration behavior, under the situation that the driver is unaware of a risk of the vehicle's high speed during approaching the curve, the driver may feel chilly to the revelation of accident risks through experiences such as sudden rolling of the vehicle in the curve. Errors in speed recognition structure of the driver result in unsafe driving with accident risks, even though the driver has a rational judgment of speed choice and has no mistakes in vehicle operation. Taking preventive traffic safety measures to avoid the errors in speed recognition structure of the driver needs to reflect the speed recognition structure into preventive traffic safety measures.

Among a variety of preventive traffic safety measures to avoid unsafe driving due to the excessive speed, this paper focuses on two types of the measures. One is the type that prevents any occurrence of the speed recognition error forcibly before the error occurs. Another is the type that stimulates a return to safe driving with the vehicle's safety speed swiftly even though the error occurs. In this paper, the former is called "forcible type" and the latter is called "inducible type". This paper provides a methodology for assessing the effect of preventive safety measures both of the forcible type and of the inducible type, by employing uniform analytical framework that is considering speed choice behavior and speed recognition of a driver who approaches a curved section. The proposed methodology deals with both approaching speed before the vehicle enters the curve and target speed due to safe driving during the curve, so that the subjective approaching speed of the driver and the objective approaching speed of the vehicle or the subjective target speed of the driver and the objective target speed of the vehicle are included in the speed recognition structure of the driver in the curve section.

In modeling of the speed recognition structure, the relationship between the subjective approaching speed and the objective approaching speed is modeled by employing the optic-flow theory in the area of the visual psychology, under the hypothesis that the driver almost uses visual information during operating one's own vehicle and the diver also perceives self-motion speed on the basis of the optic-flow. In modeling of speed choice behavior, the relationship between the subjective approaching speed and the subjective target speed is modeled on the assumption of discrete speed choice based on speed utility that consists of the trade-off between both utilities for moving fast and safe. The speed utility is represented to be a utility function of the subjective approaching speed with condition of the subjective target speed, considering driver's risk-aversion attitude. In this paper, speed-utility-based analytical framework considering speed recognition structure is employed to model deceleration mechanisms both of the forcible traffic safety measures and of the inducible measures. The forcible traffic safety measures are defined to be a mechanism as making actual vehicle speed decelerated forcibly by making speed utility cut down. In contrast, the inducible traffic safety measures are defined to be a mechanism as making actual vehicle speed decelerated by changing perceived speed while a level of the speed utility holds.

In conclusion of this paper, preferable advantage of the inducible traffic safety measures by comparison with the forcible ones is discussed. This paper points out that the inducible traffic safety measures such as the involvement-in-speed-perception type can be preferable to the forcible traffic safety measures such as the enforcement-to-speed-utility type.

FRAMEWORK OF METHODOLOGY

Speed Recognition Structure

This paper assumes that there are no vehicles with the exception of single-occupant vehicle or other vehicles' speed has no influence on speed recognition of the driver in question.

Now, define $\bar{v}^o$, $\bar{v}^s$, $\hat{v}^o$, $\hat{v}^s$ as the objective moving speed, i.e., actual vehicle speed, the subjective moving speed, i.e., perceived speed of a driver, the objective target speed, i.e., the speed that is determined by geometric structure of a road section where the driver plans to pass through, the subjective target speed, i.e., the speed that the driver intends for passing through the road section, respectively. This paper assumes that the driver intends the $\hat{v}^s$ against the $\hat{v}^o$ and recognizes the $\bar{v}^s$ on the basis of the $\hat{v}^s$. The $\hat{v}^o$ is not necessarily equivalent to the $\hat{v}^s$ in case of not getting the prior information about the geometric structure of the road section. In addition, the $\bar{v}^o$ is not necessarily equivalent to the $\bar{v}^s$ in case of not paying attention to the speedometer. Then, there exist various errors in the speed recognition of the driver. This paper suggests a model of the speed recognition structure as shown in Fig.1. Fig.1 is using a drive at a curved section as an example.

If the situation of $\hat{v}^o \le \bar{v}^o$ occurs, then the accidents caused by speeding will occur. However, even though the situation of $\hat{v}^o > \bar{v}^o$ occurs, the accident risk caused by various errors in the speed recognition structure exists. This paper calls the condition of $\hat{v}^o < \hat{v}^s$ the target-speed setting error, and calls the condition of $\hat{v}^s < \bar{v}^s$ the speed adjustment error, and calls the condition of $\bar{v}^s < \bar{v}^o$ the speed perception error.

In this paper, the speed adjustment error is considered as the error which occurs in choosing the $\bar{v}^s$ on the basis of the $\hat{v}^s$, and the speed perception error is considered as the error caused by the discrepancy between the $\bar{v}^s$ and the $\bar{v}^o$ in the speed perception structure.

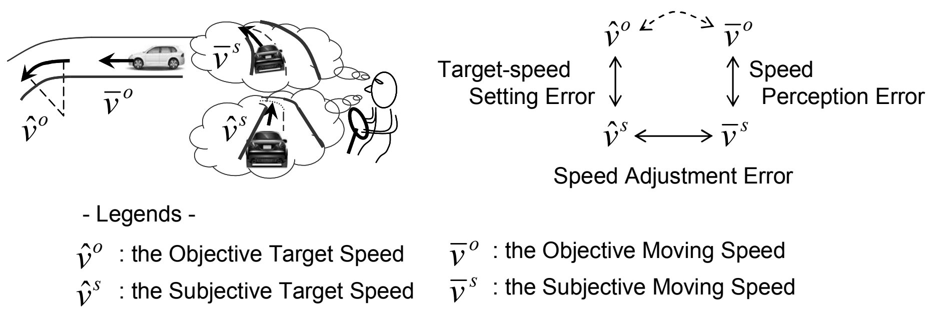


Fig.1: A model of the speed recognition structure

Speed Perception Structure

In general for the perception of a driver, it is believed that the sensory information that a driver uses in driving is almost visual (Sivak 1996). In this paper, for speed perception of the driver, it is assumed that the sensory information that the driver uses to perceive an actual vehicle speed of one's own is mainly visual. Now, define the speed perception structure, φ, against an actual vehicle speed, $\bar{v}^o$, satisfying the following equation:

$$\bar{v}^o = \varphi(\bar{v}^s, E, \varsigma) \tag{1}$$

, where the E denotes the factor affecting the sensory information but the visual one, such the as auditory or vibratory information from the vehicle body, and the ς denotes the factor affecting driver's attributes or driving skills.

In this paper, the influence of both the E and the ς on the φ separates from the influence of visual information. Marr (1982) introduced the idea that, in the modeling of human visual perception, the distinction between the detection and the cognition of visual information is needed. According to Marr, the detection of visual information represents a purely geometric computational processing on a retina at the back of human's eyeball. In this paper, on the basis of the visual information with which the optic-flow in driver's view can provide to the driver, the structure model of the φ can be mathematically derived from the purely geometric relationship between the $\bar{v}^s$ and the $\bar{v}^o$.

According to Gibson (1966), a driver can perceive a visible distance of depth to an optical stimulus, on the basis of an array of optical stimuli that has been already laid out on the road surface, such as the gradient of the density of road texture. Besides, the driver can also perceive a self-motion speed, on the basis of a velocity field of the stimuli, i.e. optic-flow, expanding all-round from a focal-point-of-view in driver's field-of-view, along the inverse direction against a moving direction of the vehicle. Considering an optic angle to an optical stimulus, this optic angle, in a precise sense, denotes the angle that is formed between a line to the focal-point-of-view and a line connecting the stimulus with the counter-image projected on the retina of driver's eye. Lee (1980) mathematically translated the optic-flow to be the temporal differentiation of this optic angle. And through modeling the optic-flow, Lee derived a model of visible distance perception structure such that a visible distance from the focal-point-of-view to an optical stimulus increases in inverse proportion to the actual distance to the stimulus on the road surface. Lee's modeling framework is easy to handle due to its simplifications. Inspired by Lee's research, a number of models that followed his framework have been suggested. However, to our knowledge, these models have yet to focus on the discrepancy between the actual vehicle speed and the perceived speed.

Considering the speed of an optical stimulus oncoming along the inverse direction against the moving direction of the vehicle, it is believed that the driver can perceive a self-motion speed, $\bar{v}^s$, on the basis of this oncoming speed, $\bar{v}^o$, indicated in the equation (1). It is also believed that the driver can perceive self-motion on the basis of this self-motion speed. In this paper, the structure model of the self-motion perception is suggested using examples from Lee's framework.

Speed Utility Structure

Kita (2000) proposed the modeling framework for driving behavior on the basis of the utility approach, and analyzed merging behavior at the entrance ramp on an expressway. Kita constructed the discrete choice model of driving behaviors, such as merging or passing, at the ramp section, under the hypothesis that the driver has an instantaneous-formed utility in case of choosing such behaviors. In this paper, it is assumed that, in case of choosing driving behaviors, such as accelerating or decelerating, the choice of such behaviors depends on the choice of the subjective perceived speed, $\bar{v}^s$. Then, the speed choice model of the rational driver, under the hypothesis that the driver choose a speed, $\bar{v}^{s*}$, satisfying the maximization of the instantaneous-formed speed utility, $U(\bar{v}^s \mid \hat{v}^s)$, on the condition of the $\hat{v}^s$, can be represented as follows:

$$\bar{v}^{s*} = \arg\max U(\bar{v}^s \mid \hat{v}^s) \qquad (2)$$

In this paper, in order to specify the speed utility function, $U(\bar{v}^s \mid \hat{v}^s)$, a model for the discrete choice of the $\bar{v}^s$ on the condition of the $\hat{v}^s$ is constructed, under the hypothesis that the driver chooses the subjective moving speed discretely.

Considering speed utility of a driver, it is believed that the driver desires to operate the vehicle while satisfying level-of-services for moving fast, safely, comfortably, and timely. Speed chosen by the driver reflects a satisfying level-of-service. This paper focuses on especially moving fast and moving safely, because it is believed that speed utility for moving fast and safely have a great influence on speed recognition of the driver.

In addition, it is assumed that there is the trade-off relationship between utility for moving fast and utility for moving safely. This relationship indicates the driver's feelings that the driver wants to avoid moving speed in excess of a maximum safety speed and to move as fast as possible. In order to express such trade-off relationship in the $U(\bar{v}^s \mid \hat{v}^s)$, the partial utility, u_1, for moving fast as a monotone increasing utility function and the partial utility, u_2, for moving safety as a monotone decreasing utility function are defined with respect to the $\bar{v}^s$. Then, it is assumed that the u_2 is subject to the $\hat{v}^s$, and the u_2 has the risk-aversion property. The proposed speed-utility function is represented as follows:

$$U(\bar{v}^s \mid \hat{v}^s, \gamma, \lambda) = u_1(\bar{v}^s \mid \gamma) + u_2(\bar{v}^s \mid \hat{v}^s, \lambda) \tag{3}$$

, where the γ is the adjusting parameter and the λ is the risk-aversion parameter. The γ, λ satisfies $\gamma > 0$, $\lambda > 0$, respectively. The $u_2(\bar{v}^s \mid \hat{v}^s, \lambda)$ is satisfies $du_2 / d\bar{v}^s < 0$ and $d^2 u_s / d(\bar{v}^s)^2 < 0$. An example of the speed-utility function of Eq.(3) is shown in Fig.2.

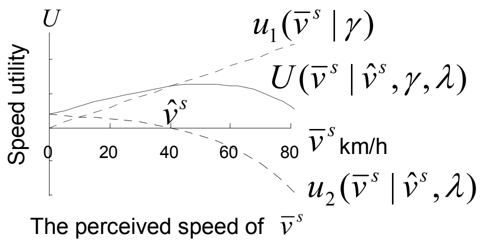


Fig.2: The proposed speed-utility function representing the speed utility structure of a driver

Deceleration Mechanisms both of Forcible Type and of the Inducible Type

Now, each deceleration mechanism of the forcible traffic safety measures and the inducible traffic safety measures is defied by employing the speed-utility-based framework considering speed perception structure, represented in Eqs. (1), (2), and (3).

Accident Risks Caused by Vehicle's Excessive Speed

Considering the speed perception structure $\bar{v}^o = \varphi(\bar{v}^s)$, where the E and the ς is omitted as a manner of convenience of representation, it is assumed that the situation of $\bar{v}^s < \bar{v}^o$ occurs. In addition, it is assumed that the situation of $\hat{v}^s = \hat{v}^o$ occurs, as the simplification of discussion. It is assumed that the driver chooses the $\bar{v}^s$ because of risk-taking attitude while the speed adjustment error of $\hat{v}^s < \bar{v}^s$ occurs, and then the $\bar{v}^o$ satisfies $\bar{v}^o > \bar{v}^s$ and $\bar{v}^o > \hat{v}^o (= \hat{v}^s)$. Such situation of the speed recognition structure is represented as follows:

$$U(\bar{v}^s \mid \hat{v}^s, \gamma, \lambda) > U(\varphi^{-1}(\bar{v}^o) \mid \hat{v}^s, \gamma, \lambda) \quad \text{if} \;\; \bar{v}^o > \bar{v}^s > \hat{v}^o = \hat{v}^s \tag{4}$$

Next, let us consider the forcible and inducible measures to make the $\bar{v}^o$ decelerated at the level of the $\bar{v}^{o*}$ that satisfies $\bar{v}^{o*} = \hat{v}^o$, in the situation represented by Eq.(4).

Deceleration Mechanism of Forcible Traffic Safety Measures

The forcible measures can be defined to be a mechanism making the $\bar{v}^o$ decelerated forcibly by making the speed utility of U^V cut off. Then, this mechanism is represented as follows:

$$U(\bar{v}^s \mid \hat{v}^s, \gamma, \lambda) - U^V = U(\varphi^{-1}(\bar{v}^{o*}) \mid \hat{v}^s, \gamma, \lambda) \quad (5)$$

Fig.3 shows this mechanism, where the γ and the λ is omitted in the $U(\bar{v}^s \mid \hat{v}^s)$ as a manner of convenience of representation. In Fig.3, the speed utility of the driver with the speed in excess of $\hat{v}_O = \bar{v}_O^1 = \varphi(\bar{v}_S^1)$ descends from the $U(\varphi^{-1}(\bar{v}_O^1) \mid \hat{v}_S)$ to the $U(\varphi^{-1}(\bar{v}_O^0) \mid \hat{v}_S)$, by making the U^V cut off from the $U(\bar{v}_S^0 \mid \hat{v}_S)$. As the result, the actual vehicle speed decelerated at the level of the $\bar{v}^{o*}$.

As the examples of the forcible traffic-safety measures to achieve the mechanisms of Eq.(5), there are campaigns against speeding cars or the intelligent speed adaptation devices, and so on.

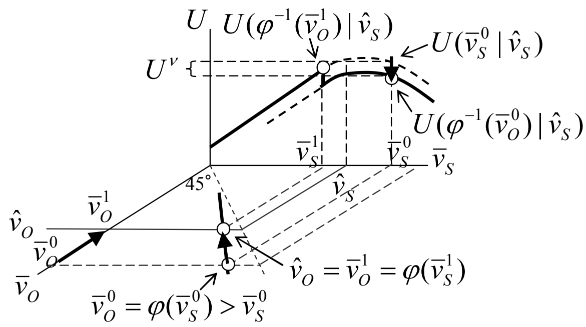


Fig.3: Deceleration mechanism of forcible measures

Deceleration Mechanism of Inducible Traffic Safety Measures

The inducible measures can be defined to be a mechanism making the $\bar{v}^o$ decelerated until the $\bar{v}^{o*}$ inductively by changing from the speed perception structure of the φ to the $\tilde{\varphi}$. Then, this mechanism is represented as follows:

$$U(\bar{v}^s \mid \hat{v}^s, \gamma, \lambda) = U(\tilde{\varphi}^{-1}(\bar{v}^{o*}) \mid \hat{v}^s, \gamma, \lambda) \quad (6)$$

Fig.4 shows this mechanism. In Fig.4, the driver confuses $U(\tilde{\varphi}^{-1}(\bar{v}_O^1) \mid \hat{v}_S)$ with $U(\bar{v}_S^0 \mid \hat{v}_S)$, by changing from the φ satisfying $\bar{v}_O^0 = \varphi(\bar{v}_S^0)$ to the $\tilde{\varphi}$ satisfying $\hat{v}_O = \bar{v}_O^1 = \tilde{\varphi}(\bar{v}_S^0)$. As the result, the actual vehicle speed decelerated at the level of the $\bar{v}^{o*}$.

As the examples of the inducible traffic-safety measures to achieve the mechanism of Eq.(6), there are road markings with the line intervals becoming narrow in increments, and so on.

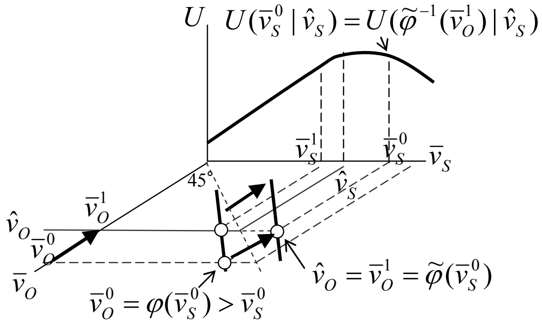


Fig.4: Deceleration mechanism of inducible measures

MODELING OF SPEED PERCEPTION AND SPEED CHOICE

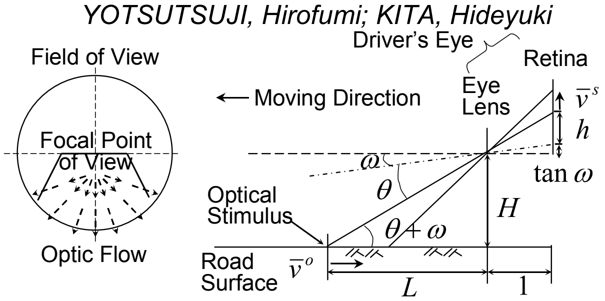
Modeling of Speed Perception Structure

The modeling framework is illustrated in Fig.5. Suppose that a driver operates a vehicle on a straight road, maintaining a constant eye-level of H, and the driver is watching a focal-point-of-view at a constant angle of ω to the moving direction of the vehicle. The left side of Fig.5 shows the optic-flow expanding from a focal-point-of-view in the driver's field-of-view. In contrast, the right side of Fig.5 shows a lateral view illustrating the geometric relationship between an optical stimulus on the road surface and the counter-image projected on the retina of driver's eye. Despite any longitudinal gradient of the road surface, the moving direction of the vehicle is always paralleled to the road surface. The distance between the eye-lens and the retina of driver's eye is standardized as 1. Assuming that the driver is operating without paying attention to the speedometer, the actual vehicle speed, $\bar{v}^o$, at the time-period t is unknown for this driver. Based on an optical stimulus located at the actual distance of L, the driver perceives the oncoming speed, $|-\bar{v}^o|$, along the inverse direction of the moving direction, while the counter-image projected on the retina at the visible distance of h from the focal-point-of-view stimulates the perceived speed, $\bar{v}^s$. Both of the stimuli can make the optic angle of θ along the direction of the focal-point-of-view. Then the temporal change of $\theta + \omega$ can form the instantaneous velocity field on the retina, namely the optic-flow. This driver can perceive the speed of $\bar{v}^s$ on the basis of the temporal change of the $\theta + \omega$.

According to Fig. 5, the derivative of the θ with respect to t can be expressed by the derivative of each of the h and the L with respect to t, respectively, as follows:

$$\frac{d(\theta+\omega)}{dt} = \frac{d}{dt}\tan^{-1}(h+\tan\omega) = \frac{1}{1+(h+\tan\omega)^2}\frac{dh}{dt} \tag{7}$$

$$\frac{d(\theta+\omega)}{dt} = \frac{d}{dt}\tan^{-1}\frac{H}{L} = \frac{-H}{(L)^2\{1+(H/L)^2\}}\frac{dL}{dt} \tag{8}$$



- Legends -

L : Actual Distance to an Optical Stimulus

h : Visible Distance to an Optical Stimulus

$|-\bar{v}^o|$: Oncoming Speed of the Optical Stimulus

$\bar{v}^o$: Actual Vehicle Speed along the Moving Direction

$\bar{v}^s$: Perceived Speed of Optic Flow

θ : Optic Angle Formed by the Optic Stimulus

H : Height of Driver's Eye (Constant Level)

ω : Optic Angle Formed by the Focal Point of View (Constant Level)

Fig.5: Geometric relationship between an optic stimulus on road surface approaching to a driver and an inverse image of the stimulus on the retina of driver's eye

Consequently, the following equations are derived from Eq.(7) and Eq.(8)

$$dh = -\frac{H}{(L)^2} dL \tag{9}$$

$$h + \tan\omega = \frac{H}{L} \tag{10}$$

Eq.(9) illustrates a model for the distance perception structure of a driver. Eq. (10) implies that the visible distance, h, from the focal point of view increases in inverse proportion to the actual distance, L, of the oncoming optical stimulus on the road surface.

Let $\bar{a}^s$, $\bar{a}^o$ be defined as $\bar{a}^s \equiv d\bar{v}^s / dt \equiv d^2h/dt^2$, $\bar{a}^o \equiv d\bar{v}^o / dt \equiv d^2L/dt^2$, respectively. The following equation is obtained by differentiating Eq. (10) twice with respect to t.

$$\frac{|\bar{a}^s|}{|\bar{v}^s|} = \frac{|-\bar{a}^o|}{|-\bar{v}^o|} + 2\frac{|-\bar{v}^o|}{L} \tag{11}$$

Provided that discrete time is applied, the difference of Eq. (11) for a given time-period, τ, is expressed as:

$$\frac{d\bar{v}^{o,\tau+1}}{|-\bar{v}^{o,\tau+1}|} - \frac{d\bar{v}^{o,\tau}}{|-\bar{v}^{o,\tau}|} = \frac{d\bar{v}^{s,\tau+1}}{|\bar{v}^{s,\tau+1}|} - \frac{d\bar{v}^{s,\tau+1}}{|\bar{v}^{s,\tau+1}|} - 2\left(\frac{dL^{\tau+1}}{L^{\tau+1}} - \frac{dL^{\tau}}{L^{\tau}}\right) \tag{12}$$

, where the time interval between τ and $\tau+1$ does not need to be coincident with dt. Now, let $\alpha_{\tau+1}$, defined as a new indicator in this paper.

$$\alpha_{\tau+1} \equiv \frac{d\overline{v}^{s,\tau+1} / \overline{v}^{s,\tau+1} - d\overline{v}^{s,\tau} / \overline{v}^{s,\tau}}{dL^{\tau+1} / L^{\tau+1} - dL^{\tau} / L^{\tau}} \tag{13}$$

The $\alpha_{\tau+1}$ defined by Eq. (13) indicates a proportion of the variation of the Weber-fractions of perceived speeds, to the variation of the Weber-fractions of actual distances, at the time period of $\tau+1$. Let us call the $\alpha_{\tau+1}$ "sensitivity" in this paper. Consequently, the following equation is derived from Eq. (12) by employing the $\alpha_{\tau+1}$.

$$\frac{|-\overline{v}^{o,\tau+1}|}{|-\overline{v}^{o,\tau}|} = c_{\tau+1}\left(\frac{|\overline{v}^{s,\tau+1}|}{|\overline{v}^{s,\tau}|}\right)^{1-\frac{2}{\alpha_{\tau+1}}} \tag{14}$$

, where the $c_{\tau+1}$ denotes a constant of integration. Eq. (8) illustrates a model for the speed perception structure. Eq. (14) implies that the mathematical relationship between the $\overline{v}^{o}$ and the $\overline{v}^{s}$ can be represented by a power function with respect to the $\alpha_{\tau+1}$, in theory.

Modeling of Speed Choice

Now, let us construct a model of the discrete choice of moving speed, under the hypothesis that the driver chooses a perceived speed satisfying the maximization of the instantaneous-formed speed utility.

In this paper, the speed utility function represented by Eq.(3) is specified as follows:

$$U(\overline{v}^{s} \mid \hat{v}^{s}, \gamma, \lambda) = \gamma\overline{v}^{s} + \exp[\lambda] - \exp\left[\lambda \frac{\overline{v}^{s}}{\hat{v}^{s}}\right] \tag{15}$$

The first term of Eq.(15) indicates the partial utility, u_1, for driving fast, and sum of the second term and the third term indicates the partial utility, u_2, for driving safely. One reason that the second and third terms are expressed by the exponential function form is that the Arrow-Pratt measure of absolute risk-aversion of the u_2 becomes a constant of $\lambda / \hat{v}^{s}$ on the condition of any $\hat{v}^{s}$. Another reason is that the parameters are computable, although the total utility of U is convex upward and single-peaked.

In order to evaluate the parameters of Eq.(15) under the hypothesis of the discrete choice of speed, the random utility model of E(15) is assumed as follows:

$$U(\overline{v}_i^{s} \mid \hat{v}_k^{s}, \gamma^{k}, \lambda^{k}) = \gamma^{k}\overline{v}_i^{s} + \exp[\lambda^{k}] - \exp\left[\lambda^{k} \frac{\overline{v}_i^{s}}{\hat{v}_k^{s}}\right] + \varepsilon_i^{k} \tag{16}$$

Each choice set of the $\hat{v}^s$ and the $\bar{v}^s$ denotes $\hat{v}^s = \{\hat{v}_k^s\}_{k=1}^K$ and $\bar{v}^s = \{\bar{v}_i^s\}_{i=1}^J$, respectively. Both of the γ^k and the λ^k becomes segmented for the latent class of k. The ε_i^k indicates the errors occurred when the driver perceives the speed rounded. It is assumed that the ε_i^k has the Gumbel distribution.

In this paper, it is assumed that the choice probability of the $\bar{v}_i^s$, $\Pr[\bar{v}_i^s]$ is obtained by the latent class logit model (Greene & Hensher, 2003) as follows:

$$\Pr[\bar{v}_i^s] = \sum_{k=1}^{K} \Pr[\bar{v}_i^s \mid \hat{v}_k^s] \cdot \hat{\pi}_k^s = \sum_{k=1}^{K} \frac{\exp[U(\bar{v}_i^s \mid \hat{v}_k^s, \gamma^k, \lambda^k)]}{\sum_{j=1}^{J} \exp[U(\bar{v}_i^s \mid \hat{v}_k^s, \gamma^k, \lambda^k)]} \cdot \hat{\pi}_k^s \tag{17}$$

$$\sum_{k=1}^{K} \hat{\pi}_k^s = 1 \tag{18}$$

The $\hat{\pi}_k^s$ indicates the choice probability of the $\hat{v}_k^s$. In this paper, it is assumed that the $\hat{\pi}_k^s$ is obtained by the logit model as follows:

$$\hat{\pi}_k^s = \frac{\exp[U(\hat{v}_k^s)]}{\sum_{l=1}^{K} \exp[U(\hat{v}_l^s)]} \tag{19}$$

, where the utility function of the $\hat{v}_k^s$ is defined in this paper, as follows:

$$U(\hat{v}_k^s) = \eta_1 \hat{v}_k^s + \eta_2^k R + \eta_0^k + \varepsilon^k \tag{20}$$

The $U(\hat{v}_k^s)$ has two explanatory variables that are composed of the $\hat{v}_k^s$ and the radius of curvature, R. The η_1, η_2^k, and η_o^k denote the parameters.

In general, it is often the case that it is difficult to estimate the parameters of Eq.(17) which is subject to Eq.(18), γ^k, λ^k and the choice probability, $\hat{\pi}_k^s$, simultaneously. In this paper, the parameters, γ^k, λ^k and the choice probability, $\hat{\pi}_k^s$ are optimized one after the another, employing the Expectation-Maximization algorithm. The EM algorithm (Train, 2008) is one of the maximum likelihood estimation methods in the case of that it is unknown where the $\bar{v}_i^s$ belongs in the class of the $\hat{v}_k^s$, because of the incomplete data.

A NUMERICAL EXAMPLE

Data Obtained from In-house Experiments

Let us show a numerical example with the proposed assessment methodology. The data were obtained from two experiments employing a driving simulator. The employed driving simulator device is Honda-Motor-Company's driving simulator device at Suzuka-Circuit Traffic-Education-Centre in Japan (Fig.6). In both experiments, a total of two participants who are the expert driving-skilled drivers participated in the experiments.

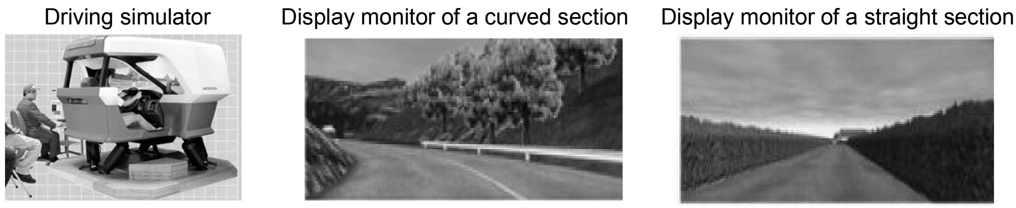


Fig.6: The appearance of the driving simulator and the display monitors in the experiment

The first experiment is aimed at evaluating the speed recognition structure of a driver at a curved section of the road. At the moment when the participant enters at the curve, operating the simulator vehicle, the participant speaks the subjective target speed, $\hat{v}^s$, that he or she intends for passing through the curve with the objective target speed, $\hat{v}^o$, determined by the radius of curvature. Successively, the participant speaks the subjective moving speed, $\bar{v}^s$, that he or she can perceive while entering at the curve, and then the experimenter monitors the actual vehicle speed, $\bar{v}^o$. The data of the $\hat{v}^s$ and the $\bar{v}^s$ with respect to the three cases of the radius of curvature R = 35m, 60m, 130m, involving both of the right-hand and left-hand directions, are shown in Fig.7.

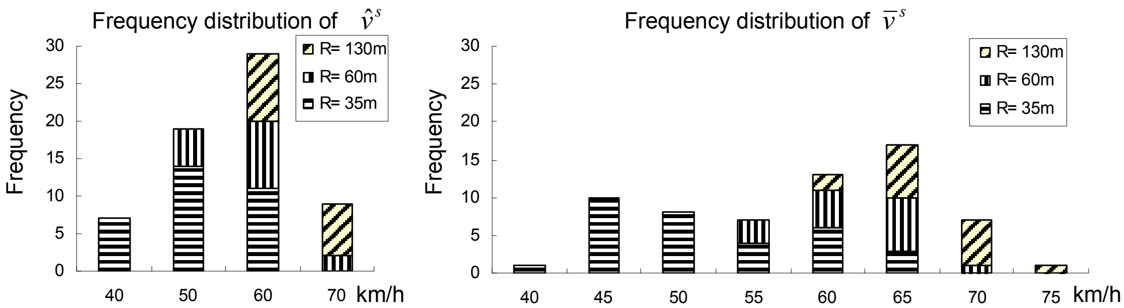


Fig.7: The data of the $\hat{v}^s$ and the $\bar{v}^s$ with respect to the radius of curvature R

Fig.7 shows that the subjective target speed, $\hat{v}^s$, is distributed for any radius of curvature, R. In this experiment, the driver drove in the round course. In this driving course, because each distance between any curve and the next curve was short, it is likely that the driver did not remember which curve the driver oneself was going to enter. This suggests that, in the curved section where the driver does not have much experience in passing through, even the target speed, $\hat{v}^s$, is distributed.

The second experiment is aimed at evaluating the speed perception error in the speed recognition structure of a driver at a straight section of the road. The participant maintains the subjective moving speed, $\bar{v}^s$, at the straight section for a few second, on the basis of the baseline speed, $\bar{v}^o$, instructed by the experimenter. Successively, after the experimenter hides the speedometer and gives the participant the instruction to gain a speed with an instructed ratio, one half, etc., the participant subjectively announces the moment that he or she evaluated the speed with the instructed ratio. Then the experimenter monitors the actual vehicle speed, $\bar{v}^o$, at the moment of the participant's announcement. The data obtained from this experiment are summarized in Fig.8.

Fig.8 shows that the speed ratio of the ex-post $\bar{v}^o$ to the ex-ante $\bar{v}^o$ has the discrepancy with the speed ratio of the ex-post $\bar{v}^s$ to the ex-ante $\bar{v}^s$. In addition, Fig.8 shows that the difference between the gradients of regression lines is more remarkable for a speed ratio equal to one half or one third, than to the double or triple.

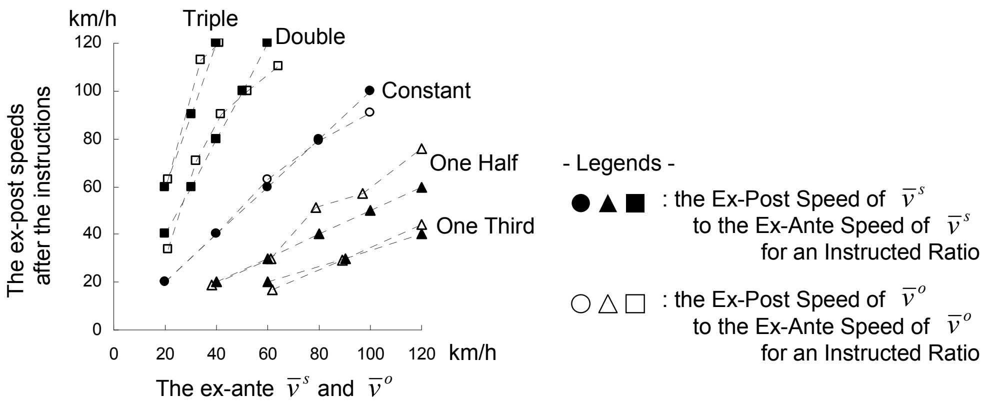


Fig.8: The data of the speed ratios of the ex-post $\bar{v}^s$, $\bar{v}^o$ to the ex-ante $\bar{v}^s$, $\bar{v}^o$

Analysis of Speed Recognition Structure

Considering the speed recognition of the driver who enters at a curve, the relation among the $\hat{v}^s$, the $\bar{v}^s$, and the $\bar{v}^o$ is analyzed. As the result of the pass analysis, Fig.9 shows the path diagrams representing the error structure for each radius of curvature, R = 35m, 60m, 130m.

Which is effective for the traffic safety measures acting on either the $\hat{v}^s$ or the $\bar{v}^s$ is examined on the purpose of making the $\bar{v}^o$ in excess of the safety speed slow down. In Fig.9, in the case of R = 35m where the curvature is large, the measures making the $\hat{v}^s$ low is effective to make the $\bar{v}^o$ slow down. In contrast, in the case of R = 130m where the curvature is small, the measures making the $\bar{v}^s$ low is effective to make the $\bar{v}^o$ slow down.

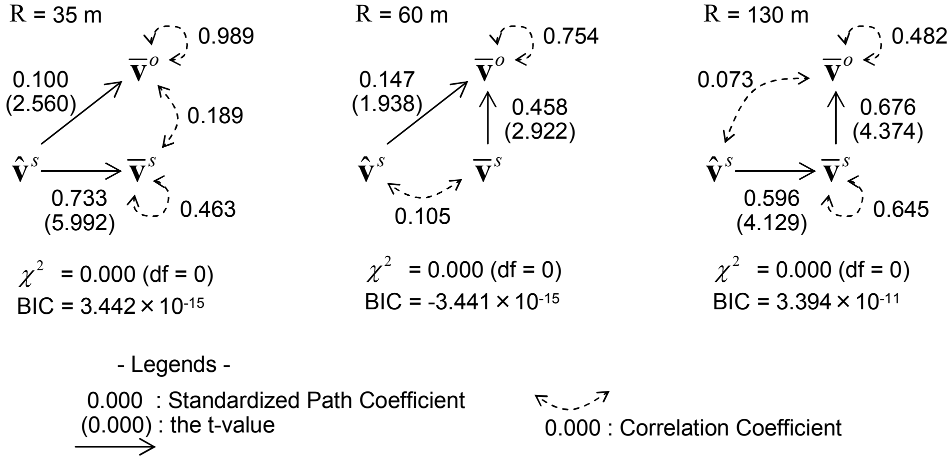


Fig.9: Path diagrams representing the error structure among the $\hat{v}^s$, the $\bar{v}^s$, and the $\bar{v}^o$

Now, the parameters of Eq.(14) are estimated using the data shown in Fig.8. By implementing the non-linear regression analysis to the following equation, the null hypothesis H_0 of β_0 = 0 is tested:

$$\frac{v_O^1}{v_O^0} = \beta_0 + \beta_1 \left(\frac{v_S^1}{v_S^0} \right)^{\beta_2} \tag{21}$$

, where the actual speeds of v_O^1 and v_O^0 used the mean value of all participants' data.

As the results of two cases where the baseline speeds are 40 km/h and 60 km/h, the t-values of $\hat{\beta}_0$ are t = 1.43, p < 0.39, in the case of 40 km/h, and t = -0.88, p < 0.5, in the case of 60 km/h, respectively. The results of t-test show that H_0 is not rejected for both cases in the significant level of 1 %. Accordingly, the functional relationship illustrated in the equation (21) is valid.

Consequently, after conducting the regression analysis setting β_0 = 0 in the equation (21), the non-linear regression analysis is implemented. The results of both of $\hat{\beta}_2$ = 0.842 in the case of 40 km/h and $\hat{\beta}_2$ = 0.873 in the case of 60 km/h can corroborate that the speed perception structure produces not "under-perception" but "over-perception of speed", because of $\hat{\beta}_2$ < 1.

Analysis of Speed Choice

The $\hat{\pi}_k^s$ in Eq.(19) and the parameters of the $U(\hat{\pi}_k^s)$ in Eq.(20) are estimated with the data shown in Fig.7. The choice set of the $\hat{v}_k^s$ is $\{\hat{v}_1^s, \hat{v}_2^s, \hat{v}_3^s, \hat{v}_4^s\} = \{40, 50, 60, 70\}$, and the data of R are the values considering either the right-hand or the left-hand direction with respect to R = 35m, 60m, 130m. The results are shown in Table 1 and Table 2.

Table 1: The estimated parameters of the $U(\hat{\pi}_k^s)$

Explanatory variable	Parameter	Estimated value (t-value)
$\hat{v}_k^s$	η_1	1.002 (2.1)
R to the $\hat{v}_1^s$	η_2^1	- 6.328 (- 6.6)
R to the $\hat{v}_2^s$	η_2^2	- 6.262 (-21.8)
R to the $\hat{v}_3^s$	η_2^3	- 6.202 (-12.6)
R to the $\hat{v}_4^s$	η_2^4	- 6.167 (-11.5)
Constant terms	η_0^1	37.793 (10.7)
	η_0^2	26.809 (24.4)
	η_0^3	14.124 (20.2)
Initial likelihood		-79.2
Final likelihood		-51.0
DF adjusting likelihood ratio		0.356
Hitting ratio		59.4%
AIC		118.0
Number of samples		64

Table 2: The estimated probabilities of the $\hat{\pi}_k^s$

	$\hat{\pi}_1^s$ $\hat{v}_1^s$ =40km/h	$\hat{\pi}_2^s$ $\hat{v}_2^s$ =50km/h	$\hat{\pi}_3^s$ $\hat{v}_3^s$ =60km/h	$\hat{\pi}_4^s$ $\hat{v}_4^s$ =70km/h
R = 35 m	0.158	0.534	0.308	0.000
R = 60 m	0.013	0.249	0.650	0.088
R = 130m	0.000	0.000	0.394	0.606

Table 3: The estimated parameters of the $U(\bar{v}_i^s \mid \hat{v}_k^s)$ in the case of R = 35m

Explanatory variable	Parameter	Estimated value (t-value)	
Partial utility for driving fast	γ^1	0.303 (7.9)	
	γ^2	0.303 (7.9)	
	γ^3	0.304 (8.0)	
Partial utility for driving safely	λ^1	1.563 (25.4)	
	λ^2	1.954 (25.2)	
	λ^3	2.345 (25.5)	
	$\hat{\pi}_1^s$	$\hat{\pi}_2^s$	$\hat{\pi}_3^s$
Prior of $\hat{\pi}_k^s$	0.158	0.534	0.308
Posterior of $\hat{\pi}_k^s$	0.231	0.449	0.320
Hitting ratio	55.0%		
Number of samples	32		

Table 4: The estimated parameters of the $U(\bar{v}_i^s \mid \hat{v}_k^s)$ in the case of R = 130m

Explanatory variable	Parameter	Estimated value (t-value)
Partial utility for driving fast	γ^1	1.109 (5.5)
	γ^2	1.109 (5.4)
Partial utility for driving safely	λ^1	2.792 (23.2)
	λ^2	3.258 (23.1)
	$\hat{\pi}_2^s$	$\hat{\pi}_3^s$
Prior of $\hat{\pi}_k^s$	0.394	0.606
Posterior of $\hat{\pi}_k^s$	0.392	0.608
Hitting ratio		62.5%
Number of samples		16

Next, the parameters of the $U(\bar{v}_i^s \mid \hat{v}_k^s)$ in Eq.(16) are estimated using the data shown in Fig.7, picking up the case of R = 35m and the case of R = 130m. In the case of R = 35m, the choice set of the $\hat{v}_k^s$ is $\{\hat{v}_1^s, \hat{v}_2^s, \hat{v}_3^s\} = \{40, 50, 60\}$, and the choice set of $\bar{v}_i^s$ is $\{\bar{v}_1^s, \bar{v}_2^s, \bar{v}_3^s, \bar{v}_4^s, \bar{v}_5^s, \bar{v}_6^s\} = \{40, 45, 50, 55, 60, 65\}$. In the case of R = 130m, the choice set of the $\hat{v}_k^s$ is $\{\hat{v}_1^s, \hat{v}_2^s\} = \{60, 70\}$, and the choice set of $\bar{v}_i^s$ is $\{\bar{v}_1^s, \bar{v}_2^s, \bar{v}_3^s, \bar{v}_4^s\} = \{60, 65, 70, 75\}$. The results are shown in Table 3 and Table 4.

After estimating the parameters, utility functions displayed in Fig.10 and Fig.11 are obtained. In the case of R = 35m in Fig.10, it seems that the speed utility function is convex upward and single-peaked within the range of $\bar{v}^s$ up to 100km/h. This result suggests that in case of that the radius of curvature is small, the speed utility descends, because of the property of driving safely with respect to the $\bar{v}^s$ in excess of the $\hat{v}^s$. Accordingly, in the case of implementing the traffic-safety measures at the rapid curved section of the road, it seems that the forcible measures making the utility of the $\hat{v}^s$ descended forcibly or the inducible measures making the perception for the $\bar{v}^s$ changed inductively by the perceptual illusions is effective.

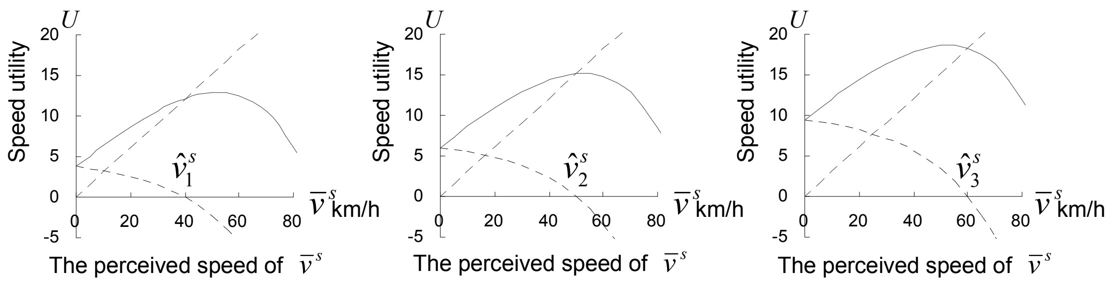


Fig.10: The speed utility functions of the $U(\bar{v}^s \mid \hat{v}_k^s)$ in the case of R = 35m

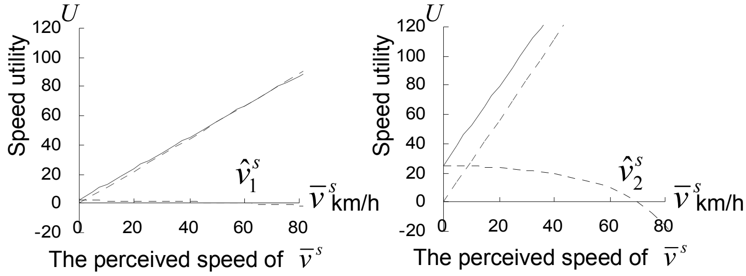


Fig.11: The speed utility functions of the $U(\bar{v}^s \mid \hat{v}_k^s)$ in the case of R = 130m

In contrast, in the case of R = 130m in Fig.11, it seems that the speed utility function is monotone-increasing within the range of $\bar{v}^s$ up to 100km/h. This result suggests that in case of that the radius of curvature is large, the speed utility do not descend, because of the property of driving fast with respect to the $\bar{v}^s$ in excess of the $\hat{v}^s$. Accordingly, in the case of implementing the traffic-safety measures at the straight section of the road, it seems that the forcible measures making the utility of the $\hat{v}^s$ descended forcibly is not effective but the inducible measures making the perception for the $\bar{v}^s$ changed inductively by the perceptual illusions is effective.

CONCLUSIONS

This paper focused on preventive traffic safety measures in curved sections on the road, while reflecting driver's recognition for both the speed of one's own vehicle and the attributes of the curve into the measures. This paper proposed a methodology for assessing the effects both of the forcible traffic safety measures and of the inducible traffic safety measures by employing uniform analytical framework. This framework is consists of speed recognition model and speed choice model. In conclusion, preferable advantage of the inducible measures by comparison with the forcible ones was discussed.

By employing this framework, the forcible measures, such as police regulations for speeding, equipments of the intelligent speed adaptation device in each vehicle, were defined to be a mechanism as making actual vehicle speed decelerated forcibly by making speed utility cut down. In contrast, the inducible measures, such as road markings with the intervals of lines becoming narrow in increments, were defined to be a mechanism as making actual vehicle speed decelerated by changing perceived speed while a level of the speed utility holds.

Which of the inducible type and the forcible type are effective for deceleration mechanisms of preventive traffic safety measures in curved sections on the road is depend on the result of comparison of switching cost contained in the speed perception structure, $\widetilde{\varphi}$, of each driver with working cost contained in the implementation of the enforcement policy making driver's utility level, U^V , cut off. The forcible type needs such an enforcement power that can give the influence over the speed utility of each driver. In contrast, the inducible type does not need such enforcement power. This means that, when road marking, which is one of the inducible traffic safety measures, is implemented on the road, each driver who drives on the marking acts as if he or she makes vehicle speed descended voluntarily. This is one of the preferable advantages of the inducible safety measures, such as the involvement-in-speed-perception type, by comparison with the forcible safety measures, such as the enforcement-to-speed-utility type.

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