Eye movement and driving behaviour in curved section passages of an urban motorway

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Abstract: This study focuses on driver eye movements and vehicle control behaviour, factors implicated in the human errors that are considered to be important factors that may cause traffic accidents. Some curved sections of urban motorways have a comparatively high frequency of accident occurrence. The authors attempted to link three factors, namely eye movement, roadway alignment, and driver speed and steering control. In order to analyse the factors that lead to human error, an in-car experiment was carried out on some routes with curved sections of the Tokyo Metropolitan Expressway. This study focuses on single-car collisions occurring primarily in free-flow regions. Using the results of the experiment, the authors were able to analyse the factors that produce human error in relation to motorway alignment, eye movement, and centrifugal acceleration in the curved sections. As a result, the authors proposed a model that evaluates the risk of curved sections in relation to the driver's eye movement and driving behaviour.

Keywords: curved section safety, driving behaviour, eye movement, driver speed and steering control

1 INTRODUCTION

This study focuses on driver eye movement and vehicle control behaviour, factors that may cause traffic accidents. Quantitative indicators of actions related to vehicle control while driving include speed, acceleration, braking, and steering angle. These indicators are output after drivers have taken in various kinds of information with their sensory organs and processed that information. During this process, perception errors sometimes occur. This study examines these kinds of human error as the latent triggers of traffic accidents.

An in-car experiment was conducted on several sections of the Tokyo Metropolitan Expressway that include curved sections. The roadway alignment of the curved sections is fairly severe, so the driver's workload is high, making it easy for human errors to occur. Using data obtained from this experiment, the authors analysed the relationship between the alignment of the roadway and eye fixation behaviour and driving behaviour on curved sections. Based on this analysis, an explanatory theory is being built regarding the mechanisms that lead to human error in drivers, which is a factor in the occurrence of traffic accidents on curved sections.

The traffic accidents presumed by this study are single-car collisions (hitting roadway structures, flipping over, etc.) occurring primarily in free-flow regions.

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2 LITERATURE REVIEW

While research on the characteristics of drivers when driving covers a wide range of areas, vision is the main sense for taking in information while driving, and therefore is one of the most vital areas of such research. Hartman reports that over 90 per cent of the information obtained while driving is taken in visually [**1**]. However, the origin of these data is very obscure and some disagreement about the exact role of vision during driving has recently appeared. For example, Sivak showed that none of these studies supports this percentage with empirical data [**2**]. Nagayama suggested that 50 per cent of accidents involve perceptual factors and 16.2 per cent of these correspond to a lack of visibility. This lack of visibility is probably one of the main causes of the higher concentration of accidents registered at corners in urban zones, specifically at junctions without signs or traffic lights [**3**]. Shinar *et al.* conducted an in-car experiment using an eye mark recorder on curved sections of a rural road with varying accident frequencies. Based on their experiments, they showed that eye fixation times on curved sections of roads with a large number of accidents tend to be longer than on curved sections with smaller numbers of accidents. They also report that there is greater variation in eye fixation activity in sections with a large number of accidents than in sections with fewer accidents [**4**]. Kageyama conducted an in-car experiment on sloping sections of road at points with high and low incidences of accidents. By looking at a driver's saccadic distance and eye fixation time, he suggests that information achieving performance is lower on curved sections with high incidences of accidents [**5**]. Contending that a driver's span of apprehension could not be fully explained by the distribution of fixation points alone, Miura conducted an in-car experiment on several roads with varying degrees of congestion. He found that a driver's depth and breadth of apprehension are not compatible, but rather that there is a trade-off between the two [**6**]. Having analysed the curve detection performance of drivers, Hagiwara *et al.* report that drivers tend to trust the information they obtain visually, regardless of whether the road alignment is gentle or extreme [**7**].

All of the above studies were based on an in-car experiment and provide valuable information regarding the eye movement and eye fixation of driving on actual roadways. The perspectives of the studies, however, barely give any consideration to an approach that grasps the driver, the vehicle, and the road as a single system. They also barely looked at the relationship between eye fixation behaviour and vehicle control, one of the factors that takes human error into consideration.

There are a number of studies on vehicle movement in curved sections. Brouce and Newton suggest that workload while driving on curved sections can be measured through experiments with altered curve radii and speeds [**8**]. Herrin and Neuhardt found that there is a limit value for how much centrifugal acceleration a driver can sustain while driving on curved sections, and that this value varies depending on the driver's situation [**9**]. Shinar reports that errors in judgement by drivers regarding curvature when driving through curved sections are compensated for based on feedback from centrifugal acceleration [**10**]. These studies focus primarily on the driver–vehicle relationship, theorizing about general trends in driver behaviour. Concrete descriptions of the roadway sections are lacking, and there are few comparisons of driver behaviour on sections with high and low incidences of accidents.

3 IN-CAR EXPERIMENT

3.1 Sites and subjects

The site of the in-car experiment was a number of S-shaped curved sections of the Tokyo Metropolitan Expressway. Accident statistics were obtained on these sections through the cooperation of the Tokyo Metropolitan Expressway Public Corporation, and then the statistics were processed and the accident rates were estimated for each curved section. The rates for most of these sections differ between the first and second curves (entry curve and exit curve) of the S-shape (see Fig. 1 and Table 3 given later). The S-shaped curved sections are characterized by repeated curving, so as long as there are no on-ramps or off-ramps, traffic conditions can be considered to be equivalent throughout.

Figure 1 is an example of a simplified representation of the horizontal alignment of the two S-shaped curves used in the experiment. The arrows in the figure show the direction that was analysed in this study. The S-shaped curves indicated in the figure contain distances (km) that are marked for both the eastbound and westbound or northbound and southbound sections used in the experiment. The values in parentheses are the accidents rates (number of accidents per 100 million vehicle-km) for the first and second curves that were estimated based on the accident statistics and traffic flow data.

The experiment was conducted when the traffic volume was relatively light and traffic conditions were such that the drivers were able to drive unencumbered. Eight drivers were used for each route and the experiment was conducted on one route per day. All drivers were males in their twenties. Each driver completed two round trips on the target sections. The first time through, driving was in the shoulder lane; the second time, it was in the median

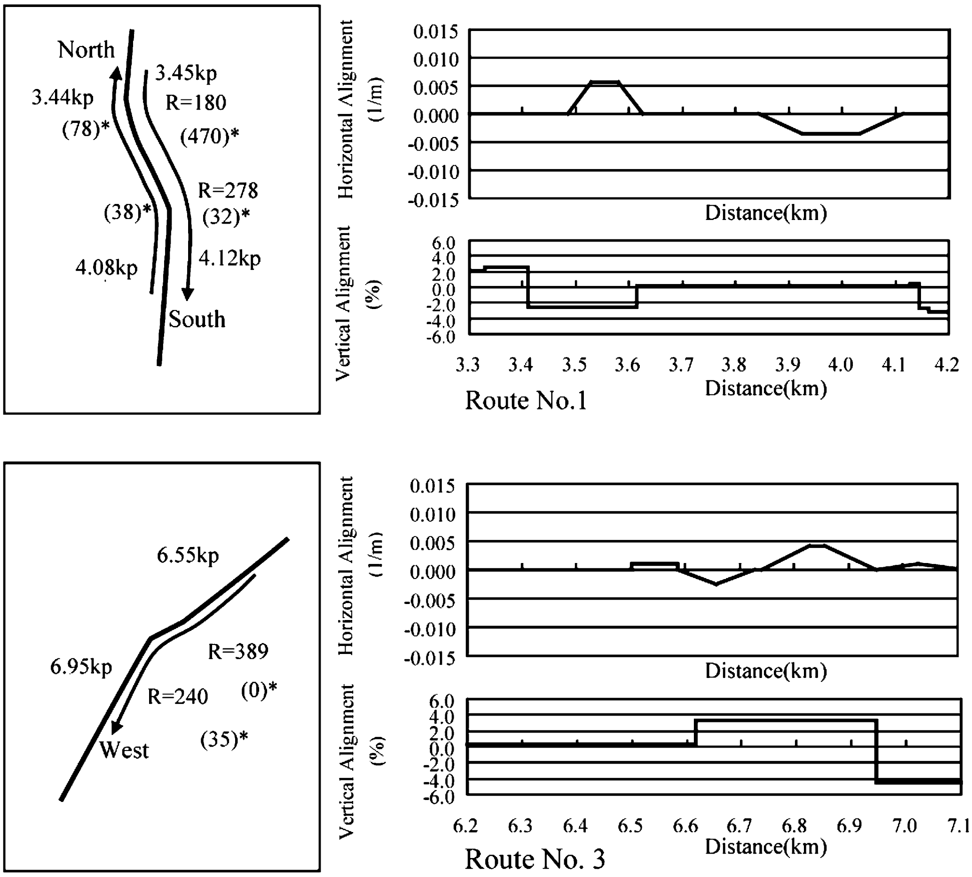


Fig. 1 Outline of study routes and alignments (routes 1 and 3)

lane. The drivers were not given any information other than instructions on which course to follow. However, they were allowed to talk to other passengers in the car, and they were instructed to drive as close to their normal driving behaviour as possible. An eye mark recorder was used to measure driver eye movement. All the experiments were conducted during the day to reduce danger to the drivers. Experiments were not conducted at night.

3.2 Measuring devices and data collection

A minivan equipped with measuring devices was used. Speed, steering angle, pressure on the accelerator, and travelling position were measured as digital data. All the data were recorded on one laptop computer. The study used the analysis items shown in Table 1. The data for speed and steering angle were measured every 10 m. The EMR-8B (NAC Image

Table 1 Data collection and measuring device

Data collection	Detailed item	Measuring device
Eye movement	Eye fixation time (s)	EMR-8B, Nac Image Technology Company Limited Method: limbus boundary method (infrared)
	Number of eye fixations (times/s)	Detection range: 0–40° Detection resolution: 0.1°
Driving characteristics	Steering angle (deg)	VTC, handmade device (Musashi Institute of Technology) Method: angle sensors by rotating pulse Detection range: 0–360° Detection resolution: 1°
	Vehicle speed (km/h)	Digital speedmeter Measures directly from an axle
	Distance from the starting point (km)	Digital range finder Measures directly from the number of rotations and turning radius of a tyre

Technology, Inc.) was used to measure eye movement. Eye fixation times and number of eye fixations for each driver were processed with NAC EMR-8B analysis software. EMR-8B irradiates a pupil near-infrared rays, detects a motion of a pupil and a corneal reflex image by an electronic circuit, and measures the horizontal direction of an eyeball and the perpendicular amount of rotations. Detection resolutions are 0.1 degree (eye movement) and 0.02 mm (pupil size).

It was not possible to obtain valid data for every driver that participated in the study because of problems with the measuring devices or because of traffic conditions at the time of the experiment. The traffic volume during the experiment time period used here was the average hourly volume (vehicle per hour per direction) on weekdays collected by vehicle detectors buried in the roadway in the target sections.

3.3 Data derivation

3.3.1 Calculation for centrifugal acceleration

Generally, a driver has the tendency to reduce speed when a curvilinear radius becomes small. A driver decides a next action (acceleration rate, deceleration rate, etc.) by the present speed and an experiential risk critical threshold. Centrifugal acceleration is a quantity determined by the speed and steering angle of a vehicle travelling through a curved section. It expresses a characteristic of the driver's speed and steering control. By the Japan Highway Geometry Design Code, the rate of centrifugal acceleration is used as one of the design indices at the curve section. Actual vehicle speeds, however, are not the design speeds and the vehicle trajectory is not the same as the alignment. For these reasons, the centrifugal acceleration, α, that occurs when an experimental vehicle passes through a curve was calculated using the following formula, which is based on spot speed, steering angle, and superelevation (see Fig. 2) [**11**]

$$\alpha = \frac{V^2}{R} \tag{1}$$

where

V = speed (m/s)
R = turning radius (m)

The turning radius is approximately

$$R = \frac{b}{\sin \varphi} \tag{2}$$

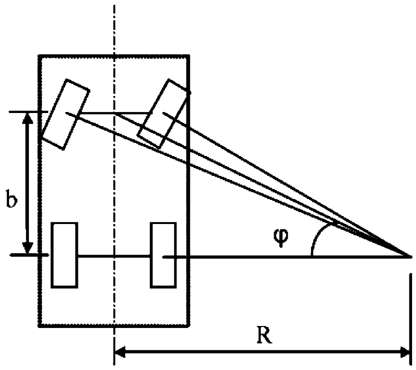


Fig. 2 A relationship between the lean of the front wheel and the turning radius

where

b = wheel base (m)
φ = turn of the front wheels (deg)

The turning radius is determined by a steering angle. If ϕ (deg) is proportional to the steering angle h, ϕ is

$$\varphi = \frac{|h|\varphi_{\max}}{h_{\max}} \tag{3}$$

where

$\varphi_{\max}$ = turn of the front wheels at the maximum steering angle (deg)
h = steering angle (deg)
$h_{\max}$ = maximum steering angle (deg)

When centrifugal acceleration takes into consideration a horizontal slope and gravitational acceleration, the centrifugal acceleration that a driver feels, α, can be taken out of the integral in equations (1) to (3). Therefore

$$\alpha = \frac{[v(1/3.6)]^2}{b/\sin(|h|\phi_{\max}/h_{\max})} \cos\theta - g \sin\theta \quad (\text{m/s}^2) \tag{4}$$

where

v = speed (km/h)
θ = superelevation (deg)
g = gravitational acceleration (m/s^2)

3.3.2 Mean eye fixation time and mean number of eye fixations

The eye movements of drivers related to visually gathering information include saccadic movement and pursuit movement. A saccade is a fast movement of an eye, head, or other part of an animal's body or of a device. It can also be a fast shift in frequency of an emitted signal, or other such fast change. Humans do not look at a scene in a steady way.

Instead, the eyes move around, locating interesting parts of the scene and building up a mental 'map' corresponding to the scene. In the human eye, one reason for saccades is that only the central part of the retina, the fovea, has a high concentration of colour sensitive photoreceptor cells, called cone cells. The fixation means the state where the saccade movement was finished. During the saccade movement, no information is passed through the optic nerve to the brain. The definition of the eye fixation time has not yet been clarified. As a general rule, saccades last from about 20 to 200 ms. Pursuit movement is the ability of the eyes to follow a moving object around. When the rate of eye movement is less than 30 deg/s, the eyes are considered to be fixed on the same object [**12**]. In this study, the eye fixation time is defined as continuously looking at the same thing for more than 0.165 s [**13**].

The mean eye fixation time and mean numbers of eye fixations, which are required by the eye mark data analysis software, are calculated using the following formula (see Fig. 3)

$$\text{Mean eye fixation time: } T_a = \frac{T_t}{N_t} \tag{5}$$

$$\text{Mean number of eye fixations: } N_a = \frac{N_t}{T_l} \tag{6}$$

where

T_a = mean eye fixation time (s)
N_a = mean number of eye fixations (1/s)
T_l = time required to pass through the curve (s)
T_t = total eye fixation time in the section (s)
$= \sum T_{ni}$ $(i = 1, \ldots, N_t)$; Fig. 3
N_t = total number of eye fixations in the section

3.3.3 Horizontal eye movement

A driver moves his or her head and eyes to collect information about the surroundings. The horizontal visual angle is defined as the angle to the eye fixation position based on the direction the vehicle is moving (Fig. 4). In this study, it was not possible to trace the

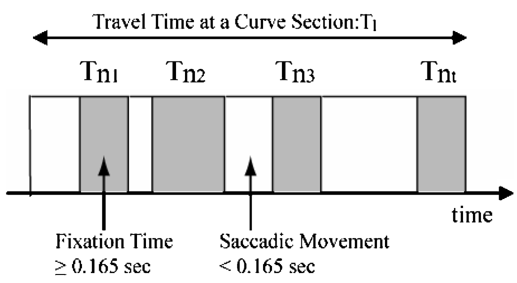


Fig. 3 Concept of fixation time

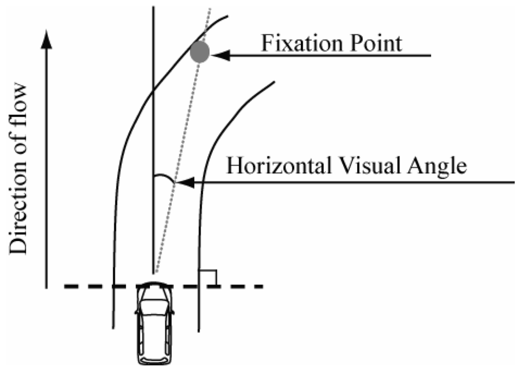


Fig. 4 Concept of horizontal eye angle definition

course of the vehicle, so the following method was used to ascertain the horizontal visual angle. Firstly, it was presupposed that every 10 metres the car moved parallel to the centre-line of the lane. Using the horizontal alignment diagram, the angle formed by the eye fixation point, which was photographed every 10 metres by the eye mark recorder, and the direction in which the vehicle was moving were then measured; this angle was made the horizontal visual angle.

3.4 Running behaviour in curved sections

3.4.1 Speed and centrifugal acceleration in curved sections

Figure 5 shows the results from route 3, westbound, and route 2, southbound. The indicators shown by the figure are, in order from the top, speed, steering angle, centrifugal acceleration, and vertical and horizontal alignment. Looking at these results, it can be seen that on route 3, each driver passed through the S-shaped sections by decelerating before entering the second curve. There were hardly any differences therefore in centrifugal acceleration on the two curves.

On route 2, there was hardly any deceleration in the S-shaped curved sections. The fact that all the drivers drove through the curved sections without decelerating means that the drivers judged that they were able to pass through the S-curves at the same speed as that when they entered. In contrast, with route 3, the steering angle while passing through the curved sections was constantly changing. In the second curve, the variance in steering angles among the drivers can be seen. The steering wheel operation indicates that the workload of the drivers was quite high.

Table 2 qualitatively summarizes the average characteristics of the drivers in terms of speed, steering, and centrifugal acceleration for all of

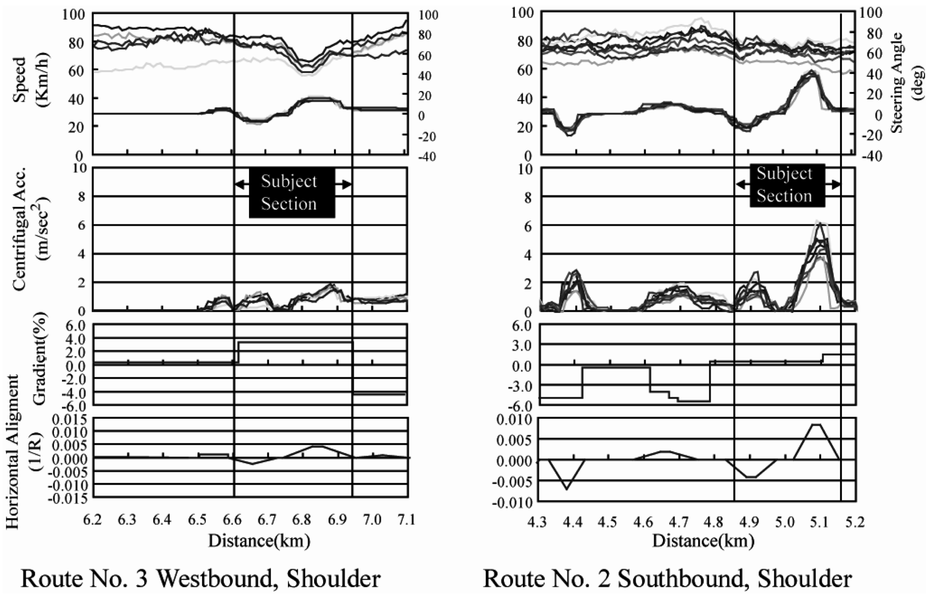


Fig. 5 Examples of speed and steering operation at curved sections

Table 2 Average running behaviour at each curved section

Route location	Route 1 Haneda line, northbound				Route 2 Haneda line, southbound			
Lane	Shoulder lane		Median lane		Shoulder lane		Median lane	
Curve	First	Second	First	Second	First	Second	First	Second
Speed change	→	→	→	↓	→	→	↓	→
Steering operation	S	U	S	U	U	S	U	U
Centrifugal acceleration	Low	High	Low	High	Low	Low	Low	Low
Route location	Route 1 Ueno line, northbound				Route 1 Ueno line, southbound			
Lane	Shoulder lane		Median lane		Shoulder lane		Median lane	
Curve	First	Second	First	Second	First	Second	First	Second
Speed change	↓	→	↓	→	→	→	→	→
Steering operation	U	S	U	U	U	S	U	U
Centrifugal acceleration	High	High	High	High	High	High	High	High
Route location	Route 2, northbound				Route 2, southbound			
Lane	Shoulder lane		Median lane		Shoulder lane		Median lane	
Curve	First	Second	First	Second	First	Second	First	Second
Speed change	→	→	↓	→	→	→	→	↓
Steering operation	U	U	U	U	U	U	U	U
Centrifugal acceleration	High	Low	High	Low	Low	High	High	High
Route location	Route 3, westbound							
Lane	Shoulder lane		Median lane					
Curve	First	Second	First	Second				
Speed change	→	↓	→	↓				
Steering operation	S	S	S	U				
Centrifugal acceleration	Low	Low	Low	Low				

Note
→ No significant change
↓ Significant change (drop)
S Stable
U Unstable

the sections driven during the experiment. The arrows in the speed column indicate acceleration or deceleration in a section. The 'stable/unstable' in the steering wheel column indicates whether or not steering corrections were made in a section. The 'high/low' in the centrifugal acceleration column shows the magnitude of centrifugal acceleration occurring in a section.

4 RELATIONSHIP BETWEEN THE MEAN EYE FIXATION TIME AND THE MEAN NUMBER OF EYE FIXATIONS

When driving on curved sections of the same distance at the same speed, if the time of each eye fixation is long, then the number of eye fixations decreases. Conversely, if the time of each eye fixation is short, the number of eye fixations increases. Figure 6 shows in a conceptual diagram the mean eye fixation time and mean number of eye fixations of drivers travelling through a curved section. Formulating the trade-off relationship between the mean eye fixation time and the mean number of eye fixations, the relationship can be expressed by

$$a = T_a N_a \tag{7}$$

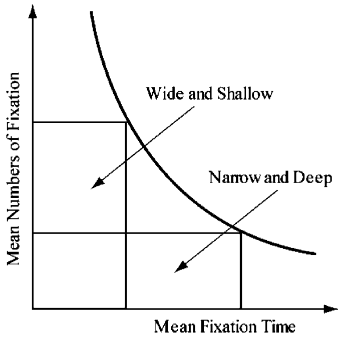


Fig. 6 Relationship between fixation and fixation duration

where

T_a = mean eye fixation time (s/fixation)
N_a = number of eye fixations (number of times/s)

The a value shows the trade-off relation between the mean eye fixation time and the number of eye fixations. When the curved section of the same distance is run at the same speed, if the eye fixation time becomes short, the number of eye fixation times increases (wide and shallow fixation). On the contrary, if the eye fixation time becomes long, the number of eye fixations will decrease (narrow and deep fixation); i.e. there is a limitation in information processing of a person and the depth and width of attention are incompatible. If the eye fixation time and the number of eye fixations increase simultaneously, a will increase.

Figures 7(a) and (b) show the results of the real relationship between the mean eye fixation time and the mean number of eye fixations, which applied the above idea to the results of experimental data. In these figures, the results have been broken up into three categories, namely the first curved section,

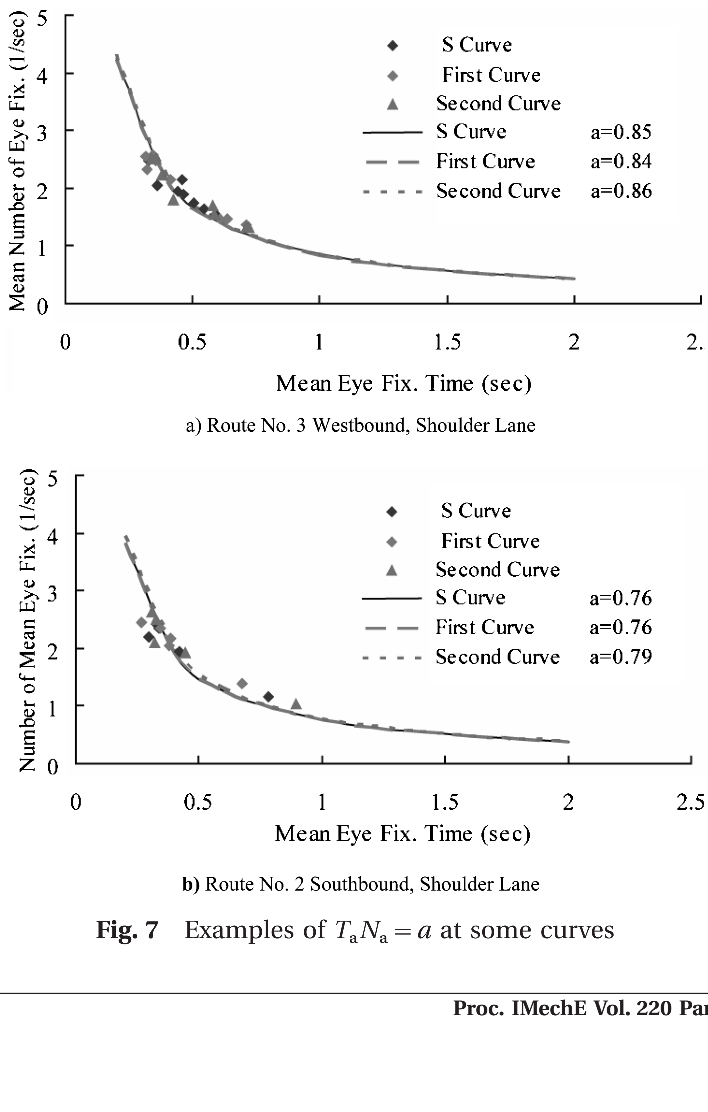


Fig. 7 Examples of $T_a N_a = a$ at some curves

the second curved section, and the whole S-curved section. Table 3 shows values of each curve as inferred from the data obtained in the experiment. As discussed above, the number of samples is the number of drivers for which the eye mark data could be used. The shaded area shows the sections of the first and second curves of the S-shape that have high estimated accident rates.

The first and second curves of the S-shaped curved sections are linked, so the traffic conditions at the time of the experiment can be considered equivalent. Comparing the relationship between estimated accident rates and the *a* value of the first and second curves, it is found that in 9 out of a total of 14, *a* is large for sections where the estimated accident rate is high. From this, the following points can be made.

Table 3 Eye fixation characteristics, estimated *a* value, estimated accident rates, and mean travel speed at each curved section

Route number	Route 1, Haneda line											
Direction	Northbound						Southbound					
Average hourly volume (vehicles/h)	2160						1260					
Number of samples	4			3			3			4		
Lane	Shoulder			Median			Shoulder			Median		
curve	S	1st	**2nd**	S	1st	**2nd**	S	**1st**	2nd	S	**1st**	2nd
Estimated acceleration rate (1/100 million vehicle-km)	39	38	**78**	39	38	**78**	210	**470**	32	210	**470**	32
Average eye fixation time (s)	0.44	0.46	**0.37**	0.44	0.41	**0.51**	0.09	**0.40**	0.45	0.45	**0.42**	0.47
SD (standard deviation)	0.06	0.06	**0.04**	0.09	0.05	**0.17**	2.03	**0.11**	0.08	0.11	**0.10**	0.16
Average number of eye fixations (1/s)	1.98	1.88	**2.41**	1.90	2.03	**1.77**	0.30	**2.37**	1.87	1.95	**2.10**	1.97
SD	0.20	0.21	**0.20**	0.21	0.08	**0.39**	0.85	**0.50**	0.17	0.34	**0.44**	0.46
a value	0.87	0.86	**0.89**	0.84	0.83	**0.90**	0.03	**0.95**	0.84	0.88	**0.88**	0.93
mean travel speed (km/h)	66.2	64.5	**63.8**	76.9	78.1	**74.6**	73.9	**74.5**	69.9	77.0	**75.4**	78.5
Route number	Route 1, Ueno line											
Direction	Northbound						Southbound					
Average hourly volume (vehicles/h)	740						360					
Number of samples	6			6			5			6		
Lane	Shoulder			Median			Shoulder			Median		
curve	S	1st	**2nd**	S	1st	**2nd**	S	**1st**	2nd	S	**1st**	2nd
Estimated acceleration rate (1/100 million vehicle-km)	225	111	**206**	225	111	**206**	995	**1291**	689	995	**1291**	689
Average eye fixation time (s)	0.46	0.54	**0.42**	0.49	0.60	**0.42**	0.43	**0.42**	0.46	0.44	**0.51**	0.35
SD	0.10	0.16	**0.09**	0.06	0.15	**0.06**	0.08	**0.08**	0.15	0.05	**0.06**	0.03
Average number of eye fixations (1/s)	1.76	1.60	**1.97**	1.64	1.45	**1.95**	1.84	**1.99**	1.69	1.72	**1.60**	1.91
SD	0.39	0.58	**0.31**	0.33	0.37	**0.36**	0.29	**0.22**	0.45	0.35	**0.43**	0.19
a value	0.81	0.86	**0.83**	0.80	0.87	**0.82**	0.79	**0.84**	0.78	0.76	**0.82**	0.67
Mean travel speed (km/h)	72.9	70.8	**75.1**	76.8	75.9	**77.7**	66.6	**64.3**	69.3	77.7	**77.8**	77.6
Route number	Route 2											
Direction	Northbound						Southbound					
Average hourly volume (vehicles/h)	760						620					
Number of samples	6			7			8			7		
Lane	Shoulder			Median			Shoulder			Median		
curve	S	**1st**	2nd	S	**1st**	2nd	S	1st	**2nd**	S	1st	**2nd**
Estimated acceleration rate (1/100 million vehicle-km)	707	**765**	175	707	**765**	175	473	95	**1001**	473	95	**1001**
Average eye fixation time (s)	0.42	**0.42**	0.42	0.49	**0.54**	0.44	0.46	0.16	**0.51**	0.38	0.40	**0.37**
SD	0.10	**0.16**	0.08	0.14	**0.17**	0.14	0.09	0.16	**0.16**	0.05	0.08	**0.07**
Average number of eye fixations (1/s)	2.09	**2.17**	2.12	1.94	**1.83**	2.15	1.93	2.04	**1.86**	2.00	2.05	**2.00**
SD	0.33	**0.44**	0.31	0.40	**0.48**	0.44	0.30	0.53	**0.49**	0.14	0.23	**0.35**
a value	0.88	**0.91**	0.89	0.95	**0.99**	0.95	0.89	0.33	**0.95**	0.76	0.82	**0.74**
Mean travel speed (km/h)	73.3	**76.5**	70	80.5	**85.0**	75.8	73.9	75.2	**71.7**	80.0	84.4	**74.6**
Route number	Route 3											
Direction	Westbound											
Average hourly volume (vehicles/h)	2700											
Number of samples	5			5								
Lane	Shoulder			Median								
curve	S	1st	**2nd**	S	1st	**2nd**						
Estimated acceleration rate (1/100 million vehicle-km)	20	0	**35**	20	0	**35**						
Average eye fixation time (s)	0.43	0.41	**0.46**	0.44	0.46	**0.43**						
SD	0.20	0.15	**0.25**	0.14	0.14	**0.15**						
Average number of eye fixations (1/s)	2.01	2.08	**2.03**	1.90	1.90	**1.96**						
SD	0.51	0.41	**0.63**	0.38	0.38	**0.42**						
a value	0.86	0.85	**0.93**	0.84	0.87	**0.84**						
Mean travel speed (km/h)	68.7	72.8	**65.5**	73.4	77.6	**70.1**						

Supposing a is in fact dependent on the estimated accident rates in each curved section; a large value would mean that the eye fixation of drivers driving on curves with high accident rates is marked by either long mean eye fixation times, large average numbers of eye fixations, or both. By extension, this would mean that the amount of information drivers take in visually increases in sections with high estimated accident rates. Consequently, in curved sections with high accident rates, drivers drive while either frequently moving their eyes or focusing on a small number of eye fixation points. In fact, when there is a large difference in the estimated accident rates between the first and second curves of an S-curve (e.g. route 1 Haneda southbound, route 1 Ueno northbound, and route 2 northbound and southbound), the value of a tends to be larger in the section where the accident rate is high. This means that in curves with high estimated accident rates, extraneous information that diverts the driver's attention is mixed in with the information taken in by the driver.

Given that during the experiment none of the drivers had an accident, and considering that the above discussion related to drivers, roadway structure, and roadside scenery, and that a values are estimates calculated on the average values of each of the drivers, it can be concluded that the range for a (0.68–0.92) shown in Table 3 is within the normal range of eye fixation behaviour and driving activity.

5 EYE MOVEMENT OF DRIVERS WHO EXCEED THE THRESHOLD

5.1 Threshold value of centrifugal acceleration

In this study, centrifugal acceleration is used as an indicator to judge the driving state. Centrifugal acceleration is a quantity that is generated by a driver using the accelerator and operating the steering wheel after recognizing and judging visually acquired information.

This study is based on the supposition that exceeding a fixed threshold for centrifugal acceleration is a latent condition for human error. Based on this supposition, driving behaviour that exceeds the centrifugal acceleration threshold on curved sections will be discussed and analysed. In the experiment, none of the drivers had any accidents. However, not all of the drivers drove in the same manner. A centrifugal acceleration threshold at or above the average $+ 1.64\sigma$ was used, which means that a 5 per cent or less probability of the centrifugal acceleration threshold value being generated was applied.

5.2 Eye movement characteristics in curved sections

As a driver drives, there is a time delay between perception and reaction. Given this time delay, the eye fixation behaviour and driving of drivers will be looked at from the point centrifugal acceleration exceeds the threshold ('section under review') to a point a distance upstream ('immediate upstream section'). Specifically, for the two sections the driver eye fixation targets and the change in the average rate of movement in horizontal eye fixation points will be analysed. Driving behaviour in the two sections will also be looked at. The average rate of movement in horizontal eye fixation points in the target sections is defined as

$$E = \frac{\sum_{j=1}^{n} \Delta e_j}{t_n - t_1} = \frac{(\beta_2 - \beta_1) + \cdots + (\beta_j - \beta_{j-1}) + \cdots + (\beta_n - \beta_{n-1})}{t_n - t_{n-1}} \tag{8}$$

where

E = average speed of movement in horizontal eye fixation points in the target sections (deg/s)
Δe_j = distance moved between two eye fixation points
j = jth eye fixation point in the target section ($j = 1, \ldots, n$)
β = horizontal eye fixation angle (deg)
t_1 = first eye fixation time (s)
t_n = last eye fixation time (s)

Table 4 shows the average rates of movement in horizontal eye fixation points in the immediate upstream sections and the sections under review. It also shows differences between the sections in average rates of movement.

With images from the eye mark recorder, first the eye fixation change was analysed between immediate upstream sections and sections under review in drivers who produced centrifugal acceleration values that exceeded the threshold at a certain point in the section under review. Based on this analysis, it was possible to classify roughly the eye movements of the driver by the location in the immediate upstream sections, and to divide them into the following four cases (Table 5):

Case A before entering the curved section and near the end of the section
Case B before entering the curved section
Case C while driving through the curved section
Case D near the end of the curved section

Table 4 Horizontal fixation point changing speed and patterns of the eye

Location	Direction	Lane	Driver	Curve (first/second)	Horizontal gaze angle speed (deg/s) Immediate upstream (A)	Review section (B)	Difference (B − A)	Case
Route 1 (Haneda line, Tenozu)	North	Median	1a-C	2	5.70	3.80	−1.80	*
Route 1 (Ueno line, Ueno)	South	Shoulder	3a-D	2	18.20	13.70	−4.40	D
			3g-B	1	4.30	4.80	0.50	B
			3g-B	1	3.30	0.00	−3.30	*
		Median	3c-E	1	8.30	2.20	−6.20	A
	North	Shoulder	3cb-A	2	7.30	12.70	5.40	C
		Median	3c-E	2	10.30	12.00	1.70	A, C
Route 2 (Gotanda)	East	Shoulder	4d-L	1	7.00	0.00	−7.00	B
			4g-D	1	6.90	2.60	−4.30	B
			4g-D	1	6.80	4.90	−1.90	B
			4g-D	1	2.30	3.20	0.90	B
			4g-D	2	7.00	8.00	1.00	D
		Median	4f-K	2	4.90	0.40	−4.50	D
	West	Shoulder	4a-D	1	4.40	2.10	−2.30	B
			4c-N	1	9.90	9.90	0.00	C
			4c-N	2	7.40	6.10	−1.30	C
			4h-I	1	6.20	1.10	−5.10	B
		Median	4e-E	1	4.90	4.00	−0.90	*
			4e-E	2	5.30	9.60	4.20	C
			4e-E	2	7.70	22.20	14.50	C

The * mark in the ‘Case’ column of Table 4 indicates samples that were not able to be classified in terms of the four cases.

Figure 8 shows typical horizontal eye fixation angles seen in some sections. In the figure, ‘2’ indicates values that exceed the threshold in the sections under review, while ‘1’ refers to immediate upstream sections for which eye movement was analysed in response to ‘2’. ‘Case’ refers to the categories of eye movement at that time, which are shown above.

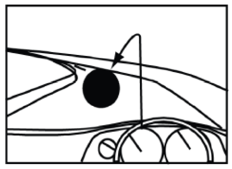
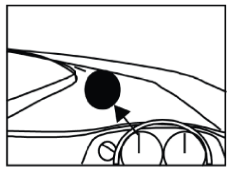
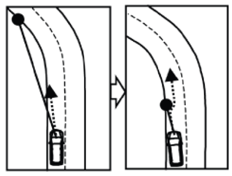
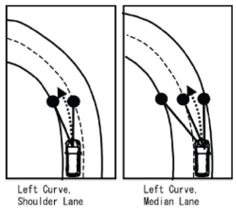
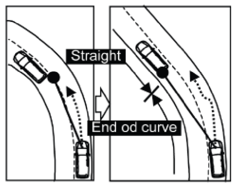
The following points can be drawn from the above cases. In Cases A, B, and D, horizontal eye movement in the immediate upstream section was relatively frequent. Conversely, there were many drivers whose range of eye fixation on this road section was narrow and whose rate of movement in horizontal eye fixation points was slow compared to the immediate upstream section. This kind of eye behaviour in the section under review can be explained by the driver trying to stabilize the driving position of his or her vehicle. Analysing the eye mark images, it was found that at this time the eye fixation is on a position directly ahead in which it is easy to confirm the driving position of the vehicle. Driving behaviour where drivers exhibit this kind of eye movement can be thought of as a driving situation where human error has been corrected.

Differing from the other cases, in Case C, horizontal eye movement was frequent in the section under review even though centrifugal acceleration was elevated. It can be hypothesized that here the driver’s workload was high compared to the other cases, and at the same the driver was making corrections with the steering wheel while driving through the section under review, meaning that there was instability in the driving of the vehicle. As can be seen from the differences shown in Table 4 between the rates of movement in horizontal eye fixation points in the immediate upstream section and the section under review, of the six drivers classified in this case, five had elevated or equalled rates of movement compared to the immediate upstream section. This supports the trend towards frequent horizontal eye movement in drivers in the section under review.

6 RELATIONSHIP BETWEEN DRIVER EYE MOVEMENT AND ROADWAY ALIGNMENT IN CURVED SECTIONS

Here the relationship will be discussed between the model constructed, $T_a N_a = a$, for the mean eye fixation time and the mean number of eye fixations, and roadway alignment and estimated accident rates for curved sections [Figs 9(a) and 9(b)]. Figure 9(a) shows that a or a variation of a increases with a lower curve radius. This means that the curve radius

Table 5 Typical eye movement of each case

Case	Location		Fixation point change and/or driving behaviour		Explanation	Ratio
A	Entrance or exit or exit of a curved section	a	Immediately before Concerned section	Fix speedmeter Fix roadway in front of a vehicle via landscape		1/75
		b	Immediately before Concerned section	Fix speedmeter Fix roadway in front of a vehicle		1/75
B	Entrance of a curved section		Immediately before Concerned section	Distance place Approaching side wall. Correct direction using steering wheel		7/75
C	In a curved section		Immediately before Concerned section	High approaching speed Unstable fixation		6/75
D	Near the exit of a curved section		Immediately before Concerned section	Fix front vehicle A front vehicle runs into a straightway A driver progresses to the direction of lane deviation Correct direction using steering wheel		3/75

becomes large and a cognitive workload (the eye fixation time, the number of eye fixations, and the number of goals) increases.

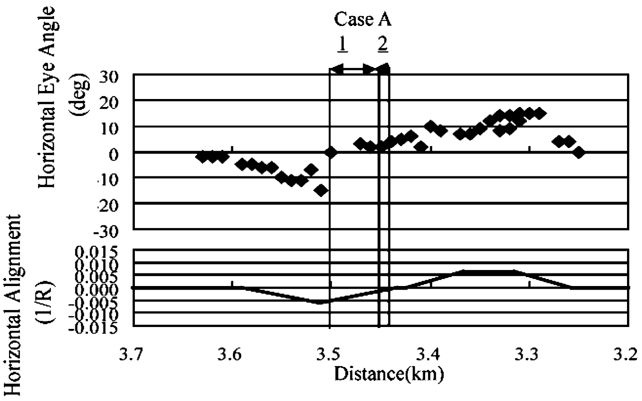
Based on the results of this analysis, it was found that a is dependent on the radius of each curve and that it tends to have a fixed upper limit [Fig. 9(a)]. It was also found that the estimated accident rate is dependent on the radius of the curve [Fig. 9(b)]. Based on the relationships shown in Figs 9(a) and 9(b), the fact that the amount of information that must be taken in by the driver in a curved section increases (that is to say, the fact that a increases in a curved section) means that the section has a high likelihood of accidents occurring.

Given the relationship discussed above between a curve's radius and a, which is determined by the estimated accident rate and the driver's eye fixation behaviour, it can be concluded that the a value, which is related to eye fixation behaviour, can be used as one of the indicators for evaluating the relationship between driver behaviour in a curved section (eye fixation behaviour and vehicle control behaviour) and the roadway alignment (in this case, the curve's radius).

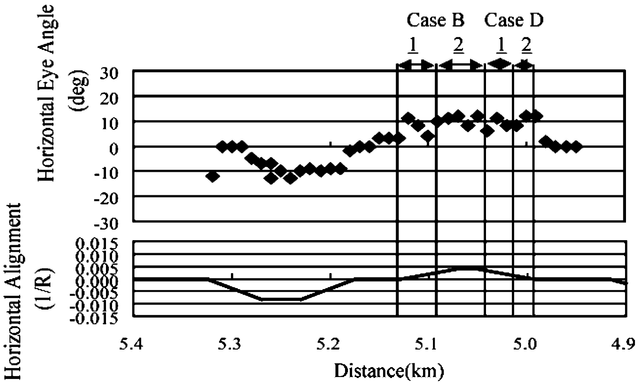
7 CONCLUSION

The analysis was able to clarify the following points:

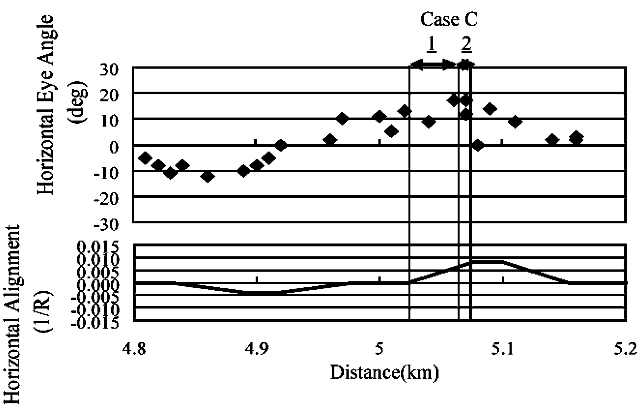
1. There were some drivers who operated a constantly changing steering angle while passing through the curved sections where there was a high accident rate. Such steering operation indicates that the workload of the drivers was quite high.
2. The trade-off relationship between the mean eye fixation time and the mean number of eye fixations can be formulated as $T_a N_a = a$.



a) Case A, Route No.1 Ueno Line, Southbound, Median Lane



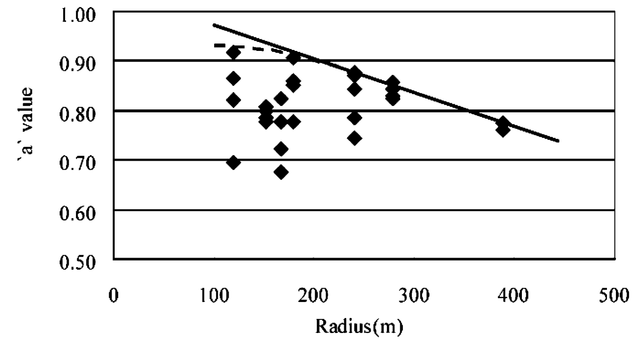
b) Case B and D, Route No.2, Northbound, Median Lane



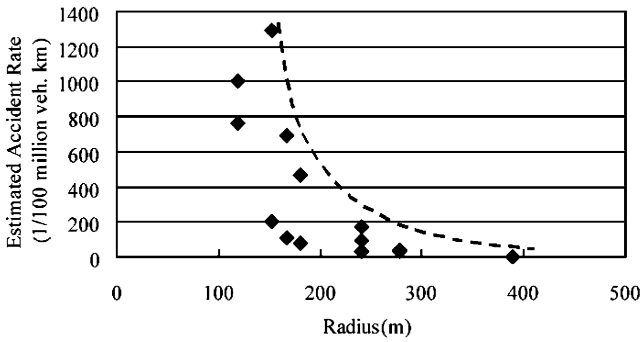
c) Case C, Route No.2, Southbound, Median Lane

Fig. 8 Examples of horizontal eye movement when threshold values are exceeded for each case

3. Centrifugal acceleration was a useful indicator to analyse driving attitude and eye movement of a driver passing through curved sections.
4. The *a* value, which is related to eye fixation behaviour, can be used as one of the indicators for evaluating the relationship between driver behaviour in a curved section and the roadway alignment.
5. The curved section where *a* is high has a tendency for unstable steering operation.



a) Relationship between 'a-value' and Curve Radius



b) Relationship between Estimated Accident Rate and Curve Radius

Fig. 9 Relationships between estimated accident rate, radius, and *a* value

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