

特集 Investigation of Headlight Swivel-angle Preference at Curves on Rural Two-lane Highways*

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We investigated drivers' preferences for headlight swivel angles as a function of curve alignment and assessment point before the curve section. In a field experiment using a test vehicle on the test track at the DENSO Abashiri Test Center in Hokkaido, 33 young drivers were surveyed on their headlight swivel-angle preference at three assessment points before each curve. The subjects stopped at each assessment point and selected the preferred low-beam swivel angle from the presented swivel angles. Curve alignment and assessment point were found to have a marked effect on the preferred swivel angle. Furthermore, we developed a multiple-regression model for estimating optimal swivel angles. It was found that headlight swivel should be predictive, toward assisting the driver's judgment of curve sharpness before the curve section. In the near future, with the aid of commercial car navigation systems headlight swivel systems incorporating a dynamic algorithm should be able to predict road geometry before arriving at curves.

Key words: Optimal swivel angle, Headlight, Curve alignment, Rural highway, Safety

1. INTRODUCTION

Various studies have addressed the degree of danger at rural highway curves at night, and many have determined dangerous curves based on traffic accident statistics. The physical relation between curve radius and travel speed is the most common index for degree of danger at highway curves. Previous studies based on traffic accident statistics show that the accident rate increases sharply once the curve radius decreases beyond a certain lower threshold.¹⁾⁻⁴⁾

Two curves with the same radius and slope may differ greatly in accident frequency, possibly as a result of the drivers' different assessments of their sharpness. The road administrator needs to provide traffic control devices appropriate to the curve sharpness and depth at night on rural highways. Suzuki et al. have investigated the qualitative relationships between various kinds of curve and subjective assessment of curve sharpness in daytime and nighttime.⁵⁾ They find that curve radius, curve length and driving speed significantly affect pre-judgment and post-judgment scores. In addition, traffic control devices and the roadscape affect subjective sharpness judgments. To determine what types of information are most effective at improving drivers' curve judgments, Hayashi et al. conducted a field experiment to investigate how judgment of curve sharpness differs according to information provision type and according to time of day (daytime vs.

nighttime).⁶⁾ These studies show that curve alignment and curve sharpness judgment both are important in determining the hazardousness of a curve. Safe driving at night on rural two-lane highways requires that the driver recognize a curve ahead and accurately estimate its sharpness and depth. It is important for the driver to see the whole curve before the beginning of the curve.

To improve nighttime curve visibility, the adaptive front-lighting system (AFS) was developed and it was put into commercial use in recent years.⁷⁾⁻¹¹⁾ **Figure 1** outlines the low beams used in the AFS. The AFS swivels the low beams right and left, usually basing the swivel angle on input from a steering wheel sensor and vehicle speed. Before a driver enters the curve, the low beams do not illuminate the curve; instead they illuminate the straight approach. The driver may expect the low beams to swivel in the curve direction to illuminate the curve ahead. However, current AFS systems do not swivel until the driver turns the steering wheel. It is thought that the driver may prefer for the swivel to occur before the car enters the curve and for the swivel angle to be greater than is executed by currently available AFS. Ibrahim proposed a method that would achieve predictive swiveling by incorporating a dynamic bending algorithm and commercially available car navigation system.¹²⁾ Sivak et al. indicated an effect of moving both lamps in parallel on visibility of objects as a

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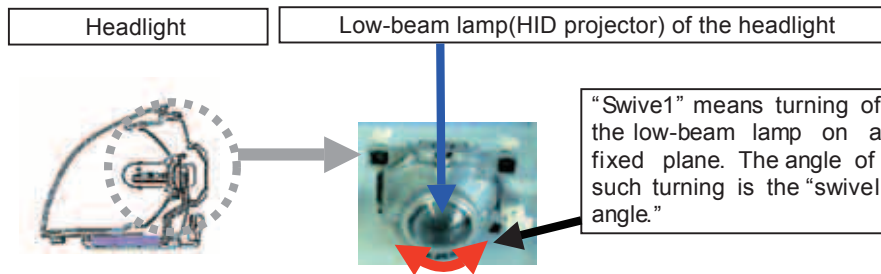


Fig. 1 Swivel headlight used in this experiment

function of curve radius.¹³⁾ However, few studies have investigated optimal swivel angles at curves in terms of subjective evaluation by drivers. For example, if the swivel system is not match with driver's viewing behavior, the swivel system can not show expected improvement effect on visibility. The present study investigates subjective evaluation by drivers of low-beam swivel angle at curves of mountain highways. The preferred swivel angle is expected to depend on the curve alignment. We measured the preferred swivel angles at various curves in the field under static condition. The objectives were as follows:

- To show how the curve alignment affects swivel-angle preference as a function of curve alignment and approach distance before the driver enters the curve.
- To develop a model for estimating the swivel angle as a function of road alignment.

(It should be noted that vehicles travel on the left side of the road in Japan.)

2. METHODS

2.1 Experimental site and date

The experiment was conducted at the DENSO Abashiri Test Center in Hokkaido, Japan. The center consists of many kinds of test track. For example, tests for high-speed driving use an oval test course. The test track there was selected mainly for its ability to provide safe testing of swivel angle under conditions that closely reproduce those on an actual roadway. The test center is equipped with a test track that simulates a typically winding rural highway. The track length is 2.8 km, and there are 21 curves whose curve radii range from 50 m to 200 m and whose grades range from -10% to 10%. We selected 10 of the 21 curves as experimental curves. The experiment was carried out from October 25 to 28 and November 7 to 10, 2005. The

weather on all the experimental dates was clear and the road condition was dry.

2.2 Subjects

Four females and twenty-nine males participated. The range of age was varied from 21 to 34 years. The average age was 22.7 years, the standard deviation was 2.9 years, and the median age was 22. Thirty of the subjects were students at Kitami Institute of Technology. All the subjects have a valid Japanese driver's license and normal visual acuity. Their average annual driving distance is 11,000 km. None of the subjects had experience with AFS.

2.3 Measurement instruments

A four-door sedan (Lexus LS430, 2003) was used as the test vehicle. The AFS system allows the left and right low-beam headlights to swivel independently. In this system, the swivel angle is controlled by the steering angle and the driving speed. The headlights use HID projector lamps. For the experiment, we developed a special electronic control unit (ECU) for remote control of the swivel angle (Fig. 2). The swivel angle can be controlled remotely through an RS-232C terminal. A laptop computer sends each swivel angle to the ECU via the RS232C terminal. LabView 7.0 was used to develop a program to control the swivel angle of the left and right headlights. The experimenter can select any of five swivel angles (-5°, 0°, 5°, 10°, 15°) by pressing the corresponding button on the computer screen. Negative swivel angles cause the left low beam to swivel left while the right low beam points forward. Positive angles cause the right low beam to swivel right while the left low beam points forward. The angle of 0° causes both headlights to move to their forward positions (Fig. 3).

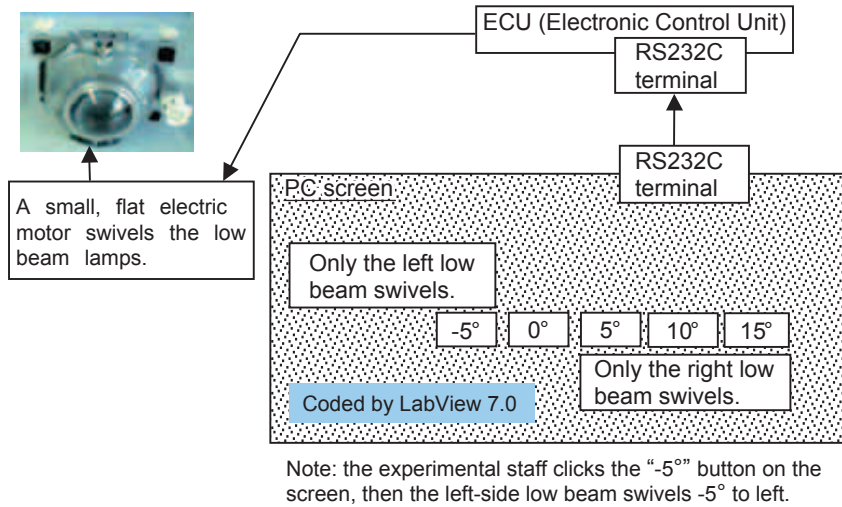


Fig. 2 System for changing between the pre-determined swivel angles

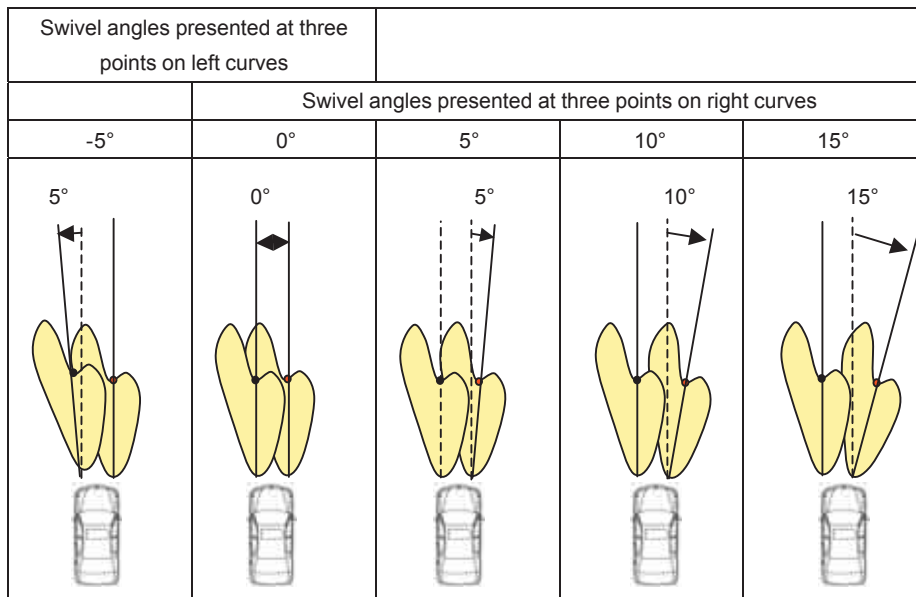


Fig. 3 The five pre-determined swivel angles

2.4 Target curves

We selected ten curves for their direction, radius and grade. All of these curves do not have any spiral entrance and exit. Five are left curves (C01 to C05) and five are right curves (C06 to C10). Curves C01 and C06 have descending grades, and curves C02, C04, C05, C09 and C10 have ascending grades. Curve C03 is at a crest on the road, and curve C08 is flat. The curve radii of the 5 left curves range from 60 m to 140 m, and the grades of those curves range from -10% to 10%. The curve radii of the 5 right curves range from 50 m to 180 m, and the grades of those curves

range from -10% to 10%. Curves C01, C06 and C08 are the second curve of S-curves. These S-curves have two continuous curves, with the curve radius of the second curve being smaller than that of the first curve. On the S-curves the driver needs to see the direction of the second curve while still in the first curve, but the steering direction causes the low beams to swivel in the direction opposite the second curve. Curve C01 is right-left S-curve, and curves C06 and C08 are left-right S-curves. We observed subjects' evaluation at the second curve of these S-curves. On these S-curves, AP1 and AP2 shown in Fig. 4 are located at the

last half of the first curve.

2.5 Measuring the preferred swivel angles at three assessment points

We surveyed test subjects for their preferred swivel angles under static conditions. Each subject was instructed to stop at an assessment point and to choose the preferred swivel angle. We assumed three assessment points for each curve: the first at 27.6 m before the curve (AP1), the second at 13.8 m before the curve (AP2) and the third at the beginning of curve (AP3) (Fig. 4). At an assumed driving speed of 50 km/h, the position of point AP1 (27.6 m) corresponds to 2 seconds before entrance into the curve and that of point AP2 (13.8 m) corresponds to 1 second before entrance into the curve.

Each subject was asked to stop at each assessment point and to choose the preferred swivel angle from swivel angles presented by the experimenters. Before the experiment we determined which swivel angles would be presented. Swivel angles opposite the curve direction were not offered as choices, because the driver usually looks at the road straight ahead and in the curve direction before entering a curve. For left curves, the experimenter presented swivel angles of 0° and -5° at each of the three assessment points. For right curves, the experimenter presented swivel angles of 0°, 5°, 10° and 15° at each of the three assessment points. The maximum angle presented at right curves is larger than that at left curves, because the driver can get a better view of right curves than of left curves (the car drives on the left side of the road). The driver can see farther ahead on roads with right curves than on those with left

curves. In addition, non-swiveling low beams are angled slightly leftward in Japan. In the case of an S-curve, the experimenter presented swivel angles of -5°, 0°, 5°, 10° and 15° at points AP1 and AP2. At point AP3 of curve C01, the experimenter presented swivel angles 0° and -5°. At point AP3 of curves C06 and C08, the experimenter presented swivel angles 0°, 5°, 10° and 15°. The 0° is the normal forward position for the low beams. The presentation order at each assessment point was the same.

2.6 Experimental procedure

We tested four subjects per day, except on October 28, when we tested five subjects. The experimenters explained the schedule and aim of the experiment. All the subjects were first given time to familiarize themselves with the test vehicle so that they might reach a certain uniformity of aptitude in driving. They drove the test course twice at dusk and twice more after dark. In the dark condition, they used the swivel system and experienced the difference between conventional low beams and AFS low beams. After driving, the experimenters instructed the drivers on how to complete the experimental tasks under static conditions. The subjects were instructed to maintain the same driving posture when stopped as when driving. Each subject drove the test course and stopped at each assessment point. To ensure that all drivers viewed from the same points, the experimental staff assisted the subjects by voice in stopping the test vehicle at the assessment point each time. After the vehicle came to a stop, the experimental staff remotely swiveled the low beams to present the pre-determined swivel angles. The presentation order at each assessment point was the same.

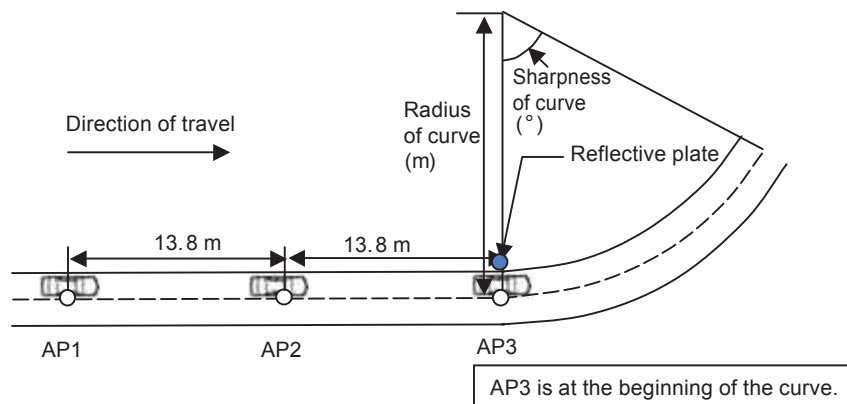


Fig. 4 The three assessment points for each curve

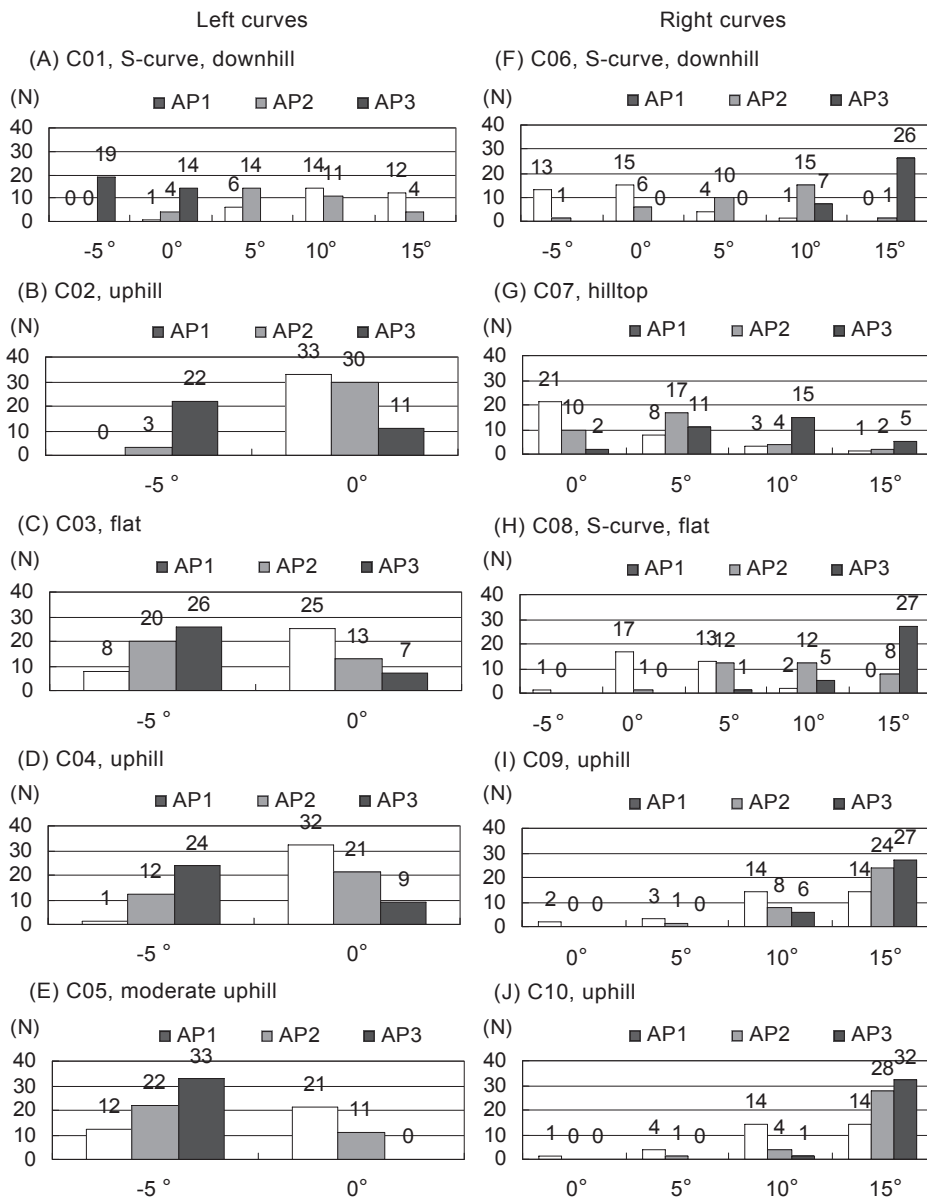
After observing all of the swivel angles, the subjects spoke the preferred angle, which was recorded by the experimenter. We repeated this procedure at each of the 30 assessment points. After finishing the run, each subject was asked several questions concerning the experimental procedure and the headlight swivel.

3. RESULTS

3.1 Preferred swivel angles

The dependent variable in this experiment is the preferred swivel angle for each assessment point. **Figure 5**

shows the number of subjects who chose each presented swivel angle for each assessment point. C01 to C05 are left curves; C06 to C10 are right curves. The top preferences are given here. At point AP1 of the left curves except C01, the top preference was 0°. At point AP2 of curves C02 and C04, the top preference between 0° and -5° was 0°. At point AP2 of curves C03 and C05, the top preference between 0° and -5° was -5°. At point AP3 of the five left curves, the predominant preference was -5°. At point AP1 of curve C01, the top preference was 10° and the second preference was 15°. At point AP2 of curve C01, the top preference was



The x-axis shows the swivel angle (0°: no swivel; negative value: left low beam swivels left; positive value: right low beam swivels right). The y-axis shows the number of subjects who chose that angle as their top preference.

Fig. 5 Preferred swivel angle at ten curves (33 subjects).

5°. At point AP3 of curve C01 the top preference was -5°. At point AP1 of curves C09 and C10, the top preference was both 10° and 15°. At point AP2 of the same curves, the top preference was 15°. At point AP3 of the right curves except C07, the top preference was 15°. Point AP3 of curve C07 is near a hilltop, so the drivers there had trouble getting a clear view of that curve.

3.2 Multiple-regression analysis

Multiple-regression analysis requires that the dependent variables be numerical values. We calculated average angles for each assessment point, and used these as dependent variables. The sum of angles at each point divided by 33 is the average angle for that point. Slope (%), curve radius (m), S-curve or simple curve, and assessment point (m) are the independent variables. The S-curve or simple curve is a categorical variable: single curve or S-curve. We used dummy variables of 0 for S-curve and 1 for simple curve. **Table 1** shows the results of the multiple-regression analysis. Left curves and right curves were modeled separately.

The regression coefficients for each of the four factors and the corresponding t statistics are shown in **Table 1**. The coefficient of determination for left curves is 0.91, and

that for right curves is 0.98. For left curves, all independent variables except slope clearly indicate significant effects on the dependent variable. For right curves, all of the independent variables except type of curve indicate significant effect. For left and right curves, preferred swivel angle increases as the curve sharpens. Also, the absolute value of the preferred swivel angle increases as the assessment point approaches the beginning of the curve, except at left-right S-curves, where the absolute value of the preferred swivel angle decreases as the assessment point approaches the beginning of the curve. At right curves, the preferred swivel angle increases as the slope sharpens.

The x-axis shows the swivel angle (0°: no swivel; negative value: left low beam swivels left; positive value: right low beam swivels right). The y-axis shows the number of subjects who chose that angle as their top preference.

3.3 Comparison between preferred swivel angle and swivel angle achieved by AFS during travel

The experiment under the static condition found that the drivers prefer large swivel angles before they enter a curve. However, current AFS do not execute a swivel until the steering wheel has been turned. Therefore, it is important to

Table 1 Results of multiple-regression analysis

(A) Left curves					
Regression statistics		Independent variable	Standardized coefficient	t value	Significance
R	0.99	Radius	0.16	2.81	0.02*
R squared	0.98	Position	-0.31	-6.02	0.00**
Adjusted R squared	0.97	S-curve	0.88	12.79	0.00 **
Number of observations	15	Slope	-0.02	-0.31	0.76

(B) Right curves					
Regression statistics		Independent variable	Standardized coefficient	t value	Significance
R	0.95	Radius	-0.38	-3.73	0.00**
R squared	0.91	Position	0.59	5.25	0.00**
Adjusted R squared	0.87	S-curve	-0.28	-2.14	0.06
Number of observations	15	Slope	0.42	3.51	0.01**

determine the degree of difference between the preferred swivel angles determined in the static experiments (preferred swivel angles) and the swivel angles executed by AFS during driving (AFS swivel angles) as a function of curve alignment and approach distance. This analysis will find more suitable control logic to achieve the preferred swivel angle on winding roads at night.

Each subject drove once on the test track using the AFS at night before the static experiment. During each run, the data recording system recorded swivel angle, steering angle, and vehicle speed using the controller area network bus (CAN Bus) of the test vehicle. It is necessary to identify an AFS swivel angle at point AP3 among the large number of recorded AFS swivel angles. We used a laser sensor to record a location signal of point AP3 with other kinds of data. A special reflecting plate is installed at the left-side shoulder of the road where is exactly the same at point AP3 in order to produce a location signal. The experimental vehicle is equipped with the laser sensor behind the left-side door mirror. The laser head equipped with the laser sensor output laser light. This laser light goes to leftward of the vehicle direction. Simultaneously, the laser sensor receives retroreflected light. At point AP3, retroreflected laser light intensity is over a critical value due to an existence of the special reflecting plate, and then the location signal is recorded in the data. We recorded these data continuously during driving on the 2.8-km test section. The sampling rate of the data recording system is 20 Hz. The number of data per run is approximately 5,000.

We read the AFS swivel angle for each assessment point from the recorded data after the experiment. When the location signal is 1, this data is recorded at point AP3. Swivel angle of this data is the AFS swivel angle at point AP3. It is possible to estimate the driving distance from points AP1 and AP2 to point AP3 based on the vehicle speed and time elapsed. Swivel angle at point AP1 is the AFS swivel angle of the data recorded at 27.6 m before point AP3. Swivel angle at point AP2 is the AFS swivel angle of the data recorded at 13.8m before point AP3. After collecting all the AFS swivel angles at points AP1, AP2 and AP3, average and standard deviation of these swivel angles at each assessment point were calculated (**Table 2**).

At left curves, there were large differences between preferred swivel angle and AFS swivel angle at each point.

The preferred swivel angles at point AP3 for five curves in the static experiment were approximately -5° . The AFS swivel angles at point AP3 of those curves were not as large. At points AP1 and AP2 of curves C01 and C02, there were small differences between preferred swivel angle and AFS swivel angle. At points AP3 of curves C03, C04 and C05, there were large differences between preferred swivel angle and AFS swivel angle. Although the subjects preferred large swivel angles at points AP1 and AP2, the AFS swivel angles were almost zero at these points. For the current AFS to achieve the preferred swivel angles, it must execute the swivel at least 1 second before the driver begins the steering operation.

At the five right curves, there were differences between preferred swivel angles and AFS swivel angles. These differences for right curves at each assessment point were larger than those for left curves. At point AP1 on the five right curves, the subjects selected large angles already as of this moment arriving at point AP1. For example, at point AP1 on curves C09 and C10, the average preferred swivel angle was almost 11° . At point AP3 on right curves except curve C07, the average preferred swivel angle was over 13° . However, the average AFS swivel angles at point AP3 on five right curves were less than 5° . At points AP1 and AP2 on curves C07, C09 and C10, the AFS swivel angle was almost 0° . For the current AFS to achieve the preferred swivel angles, the swivel must start at least 2 seconds before the driver enters the right curve.

3.4 Subjective opinions on swiveling lighting after the experiment

After the experiment, the experimental staff handed a questionnaire to each subject. There were questions regarding personal attributes and three questions regarding swiveling lighting: 1) How easy was it for you to choose a preferred swivel angle in this experiment? 2) What part of the curve do you want to see before you enter the curve? and 3) If you were driving on a rural two-lane highway, which lighting system would you prefer: swiveling low beams, or conventional fixed low beams? All of the subjects answered that it was easy to choose a preferred swivel angle in the experiment. However, a few subjects noted that the viewing duration might differ between static conditions and running conditions. At left curves, one-third

Table 2 Preferred swivel angle and AFS swivel angle at each assessment point

Left curves					
Curve No.	Assessment point No.	Preferred swivel angle	AFS swivel angle		
		Average (°)	Average (°)	Std. (°)	Number of data
C01	AP1	10.6	8.4	2.6	32
	AP2	7.3	7.7	2.7	32
	AP3	-2.9	0.6	0.7	32
C02	AP1	0.0	0.0	0.0	33
	AP2	-0.5	0.0	0.0	33
	AP3	-3.3	0.0	0.1	33
C03	AP1	-1.2	-0.5	1.9	33
	AP2	-3.0	-0.6	1.7	33
	AP3	-3.9	-1.1	1.7	33
C04	AP1	-0.2	3.0	3.7	33
	AP2	-1.8	-0.4	1.5	33
	AP3	-3.6	-0.7	1.6	33
C05	AP1	-1.8	-0.8	1.8	33
	AP2	-3.3	-0.8	1.8	33
	AP3	-5.0	-2.5	1.9	33
Right curves					
Curve No.	Assessment point No.	Preferred swivel angle	AFS swivel angle		
		Average (°)	Average (°)	Std. (°)	Number of data
C06	AP1	-1.1	-4.9	0.1	33
	AP2	6.4	-5.0	0.1	33
	AP3	13.9	-1.0	0.9	33
C07	AP1	2.6	0.2	2.3	31
	AP2	4.7	0.2	2.3	31
	AP3	8.5	0.4	2.1	31
C08	AP1	2.4	-2.7	5.4	33
	AP2	9.1	-2.6	5.3	33
	AP3	13.9	0.6	3.0	33
C09	AP1	11.1	0.6	3.5	33
	AP2	13.5	1.1	3.1	33
	AP3	14.1	1.6	3.0	33
C10	AP1	11.2	0.3	4.9	33
	AP2	14.1	1.6	4.3	33
	AP3	14.8	4.4	4.5	33

of the subjects responded that they would like to see the straight entrance to the curve and expressed a preference for conventional fixed low beams over AFS. Two-thirds of the subjects responded that they would like to see the left side of the road and expressed a preference for swiveling low beams over conventional fixed low beams. At right curves, most subjects expressed a preference for large rightward swivel, because they said that it gave them a fuller view of the entire curve. However, a few subjects reported negative opinions regarding large rightward swivel angle, due to the non-uniform illuminance that it produced on the road

surface. We must be careful to avoid dark spots between the beams. At S-curves, most subjects did not want large swivel angles.

4. DISCUSSIONS AND CONCLUSIONS

This study investigated drivers' preferences for headlight swivel angles before entering left and right curves under static condition, as a function of S-curve or simple curve, curve radius, road slope, and distance from the beginning of the curve. These dependent variables were found to profoundly affect the driver's preferred swivel angle. We

proposed a linear-regression model to predict swivel angle. A comparison between preferred swivel angles under static conditions and swivel angles observed for the current AFS during driving found that drivers prefer for the swiveling to start early during the approach to the curve. For greater safety and accessibility, AFS should incorporate predictive swiveling using car navigation data.

At points AP1 and AP2 of left curves, the average preferred swivel angles were less than -5° . At point AP3 of left curves, the average preferred swivel angles were almost -5° . There are two opinions on swivel angle at point AP3: some drivers gave a high evaluation to the 0° angle, and others gave a high evaluation to -5° . The difference might come from the difference in drivers' eye tracking behaviors. At right curves, the drivers tended to prefer earlier and sharper swiveling than that executed by the conventional AFS. This is because it is possible to get a full view of the entire curve before reaching point AP3. At point AP3 on right curves except C07, the drivers preferred the maximum swivel angle (15°). Point AP3 on curve C07 is at top of a slope. None of the drivers preferred the maximum swivel angle (15°) there. This is because it is impossible to see the curve ahead until coming over the hill. Swiveling is very effective in allowing the driver to get a full view of right curves at night except at curves with unusual alignments, such as slope-top right curves. However, it is important to consider the glare given to oncoming traffic. If the low beams swivel to a large angle before the car enters the curve, an oncoming driver might be blinded by the glare¹⁴⁾. At S-curves, the drivers prefer a small swivel angle on the first curve; i.e., at the first curve they want see the second curve. However, the low beams swivel in the direction of steering at the first curve.

Based on these results, we used multiple linear-regression models to develop a procedure for estimating the preferred headlight swivel angle before a driver enters a curve. We conducted a field experiment under static condition. It was found that at left curves, to meet driver preferences, the swiveling should begin at point AP2, i.e., before the driver enters the curve, and at right curves, the swiveling should begin by point AP1, i.e., also before the driver enters the curve. At S-curves, the drivers prefer a small swivel angle before entering the second curve. Consequently, the pre-curve swivel should consider the

average preferred angles and the interpersonal differences in preferred angles. However, variations in preferred swivel angle among subjects are not negligible. It should be noted that subjects fell into two groups: those who selected a small angle before point AP3 and those who selected a large angle before that point. Factors other than those examined in the study (S-curve or simple curve, curve radius, slope and assessment distances before each curve section) affect the determination of swivel-angle preference. In addition, we should test preferable swivel angles under dynamic condition based on the results of the current study. A full understanding of those factors and effects of dynamic condition on preferable swivel angles await future studies.

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