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Road Surface Sensor

• Keiji Fujimura • Takashi Sakamoto

We propose a road surface sensor using a near-infrared beam as another useful sensor for vehicle control. The principle is based on the reflection flux polarization when a light source and a detector are set at Brewster's angle. This means that the light flux reflected from a completely wet surface, e.g., specular surface, is horizontally polarized whereas the light flux reflected from a completely dry surface, e.g., diffusing surface, is almost unpolarized.

After testing a developed model under several typical road surface conditions, we are confident that dry, wet, frozen, and snow-covered surfaces can be classified with better than 90% accuracy.

We believe that this sensor will be applicable for a brake control system, driver's safety information system, and so on in the near future.

1. Introduction

Many control and alarm systems for improved automobile safety have been proposed, and sensors required by such systems are being aggressively developed.[1] The optical road surface sensor we are proposing is one of them.

Since road surface detection is related to all phases of vehicle control, we anticipate wide future development of its applications such as braking control, steering control, and driving control, with possible applications including not only onboard systems but also road information systems and road maintenance and control systems.

Optically speaking, road surfaces dominantly involve diffuse reflection when they are dry, while tending to have specular reflection when they are wet.

To distinguish between these two different states of road surfaces, generally two or more measuring points are necessary for each point of reflection.[2] But such a system would need equipment too complex to be used as a mobile unit.

At the same time, for a system to be valid as mobile, it must be able to observe road surfaces instantaneously without being affected by uneven road surfaces or spatial fluctuations of reflectivity, while maintaining its measurement accuracy under all environments.

To meet these requirements, the system needs to be as simple as possible and capable of real-time signal processing and decision by relative value operation.

For a solution, we directed our attention to the polarization characteristics of reflection obtained when a light source and a detector are set in such a manner that the angle of incidence and the angle of reflection make Brewster's angle. This configuration allows specular reflection on wet road surfaces to provide a polarization degree of near 1, while polarization due to diffuse reflection on dry road surfaces is near 0, thus permitting a decision on the state of road surfaces.

In assembling the sensor, we used a light source of near-infrared LEDs, which provided pulse-modulated beams to reduce the effects of external light.

To permit simultaneous observation of both vertical and parallel components of polarized reflection from the same visual field on road surfaces, we provided the detector with a lens and a prism to divide the image into two and inserted a linear polarizer in each optical path. The degree of polarization was calculated from the relative values of the two outputs to minimize the effects of fluctuations of reflection level caused by different road surfaces.

As a result of evaluation of the sensor thus assembled, conducted on various road surfaces, we verified that the sensor can distinguish dry, wet, frozen, and snow-covered road surfaces with an accuracy of 90% or more.

An overview and evaluation test results of this sensor are described below.

2. Development Target

Before starting development work, we studied possible applications and the performance required of sensors of this kind.

In an anti-skid control system, road surfaces and brake hydraulics combine to play an important role in improving automobile safety.

Among various anti-skid control systems introduced in patent journals and other similar publications, there are some that propose the use of information related to the road surface coefficient of friction. [3), 4)] However, none of them is free from certain control delay because the methods used in these systems are all based on the variation in acceleration at the time of braking.

On the other hand, the relationship between road surface conditions and the coefficient of friction varies as shown in Figure 1.

There is a report handling the wet state of road surfaces by applying the concept of the specular surface coefficient, thus verifying that the coefficient of friction decreases as road surfaces get more and more wet.[5)]

Still another source provides information that, when it first starts raining, the mud components on the road are yet afloat and function like ball bearings, thus producing a very skiddy road surface.

We could propose an anti-skid control system capable of much safer operation if these different road surface conditions and degrees of wetness were detectable in advance. Other possible applications we have in mind are also shown in Table 1.

Now focusing the sensor performance on its ability to distinguish road surface conditions, we made experiments, evaluations, and reviews, paying special attention to the transitions in road surface conditions shown in Figure 2.

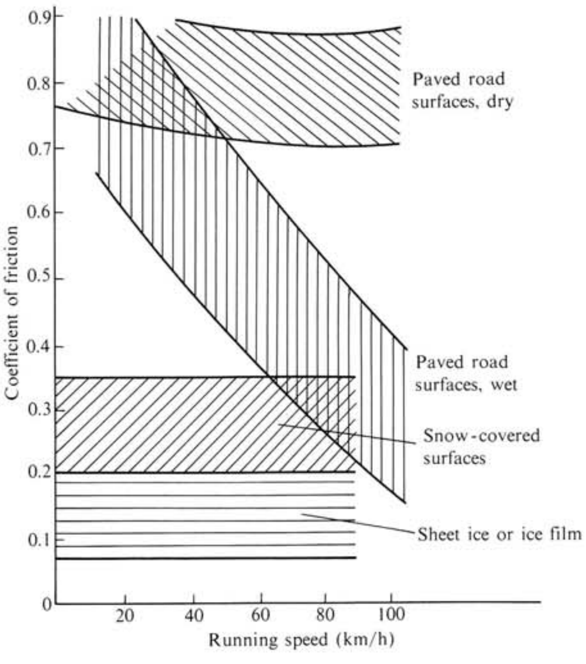


Figure 1. Relationship between road surface condititions and the coefficient of friction

Table 1. Road surface sensor applications

Applied Systems	Features
1. Anti-skid control system	Permits braking control corresponding to the road surface coefficient of friction, resulting in improved safety.
2. Anti-collision system	Allows braking control to be conducted flexibly depending on the state of road surfaces while detecting by radar the distance and relative speed between a car and the one in front.
3. Road information system	Provides drivers with real-time announcements of the state of road surfaces in front and gives alarm as necessary, with displays installed beside the highways.
4. Road maintenance and control system	Diagnoses the state of road surface deterioration by measuring polarization characteristics of the same road surface periodically.

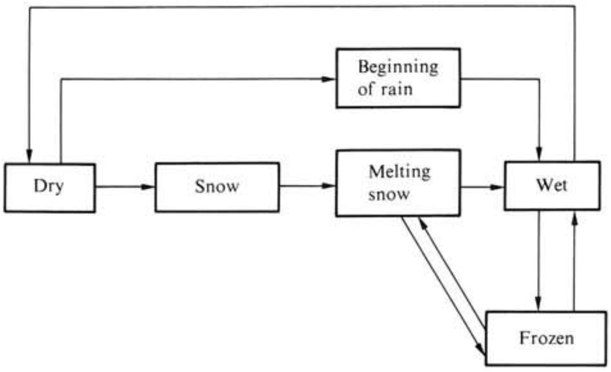


Figure 2. Transitions in road surface conditions

3. Principles of measurement

Based on the theory of electromagnetic waves, a plane wave's specular surface reflectivity, ρ, is generally given by the following formula:

$$\rho_h(\theta) = \left| \frac{\cos\theta - \sqrt{n^2-\sin^2\theta}}{\cos\theta + \sqrt{n^2-\sin^2\theta}} \right|^2$$
$$\rho_v(\theta) = \left| \frac{n^2\cos\theta - \sqrt{n^2-\sin^2\theta}}{n^2\cos\theta + \sqrt{n^2-\sin^2\theta}} \right|^2 \quad (1)$$

where,

θ: Angle of incidence
n: Relative refractive index of both media
$\rho_h(\theta)$: Parallel polarization components of reflection
$\rho_v(\theta)$: Vertical polarization components of reflection

There exists an incident angle called Brewster's angle, which satisfies $\rho_v(\theta) = 0$. Here, this is expressed as θ_b.

On the other hand, as a quantity representing the polarization characteristics of reflection, polarization degree, P, is defined by the following formula:[6)]

$$P(\theta) = \left| \frac{\rho_h(\theta)-\rho_v(\theta)}{\rho_h(\theta)+\rho_v(\theta)} \right| \quad (2)$$

Therefore, in the case of specular reflection, $P(\theta_b) = 1$ if incident angle, θ, equals Brewster's angle, and $P(\theta) < 1$ for any other incident angle.

In the case of reflection on a completely diffusing surface, $\rho_h(\theta) = \rho_v(\theta)$ because of no polarization characteristics, resulting in $P = 0$ irrespective of the light receiving angle.

In other words, variations in polarization degree caused by the state of reflective surfaces become largest when both the incident angle and light receiving angle equal Brewster's angle. For a change from specular surfaces to diffused surfaces, polarization degree, P, varies between 1 and 0. Therefore, the characteristics of reflective surfaces are made known by measuring P.

As shown in Figure 3, reflection from road surfaces can be classified into diffuse reflection when dry and specular reflection when wet. This makes it possible to presume road surface conditions from variations in polarization degree, $P(\theta)$.

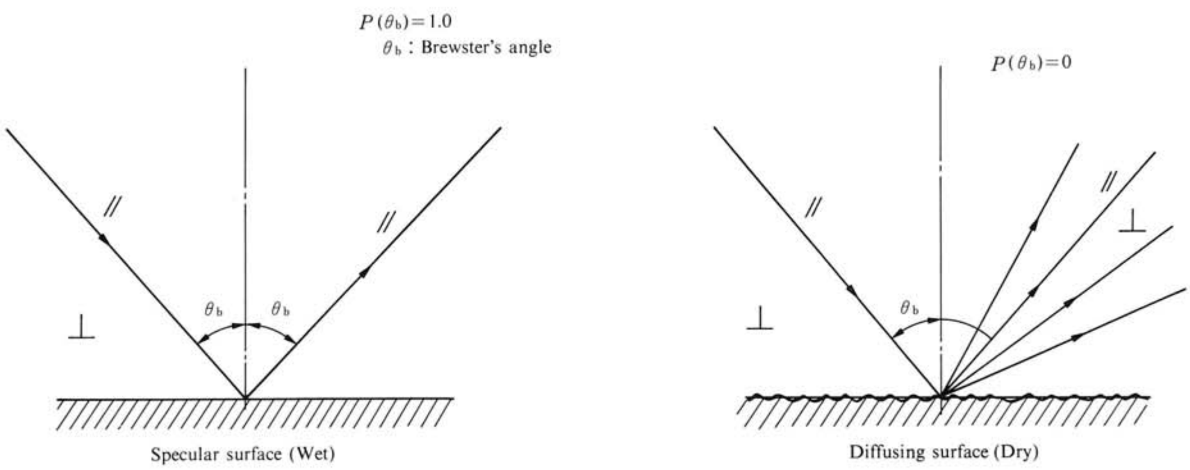


Figure 3. Specular and diffusing surfaces

4. Construction of sensor

The construction of our prototype sensor is shown in Figure 4, and its main specifications are shown in Table 2.

The light source unit employs near-infrared LEDs, the beam being pulse-modulated at 1 kHz to permit distinction from external light such as sunshine and headlights. The emitted flux of light is radiated almost as a parallel flux on road surfaces by a condenser lens.

The detector unit employs an image-dividing lens system (a plano-convex lens combined with a prism) which forms images on each light detector by

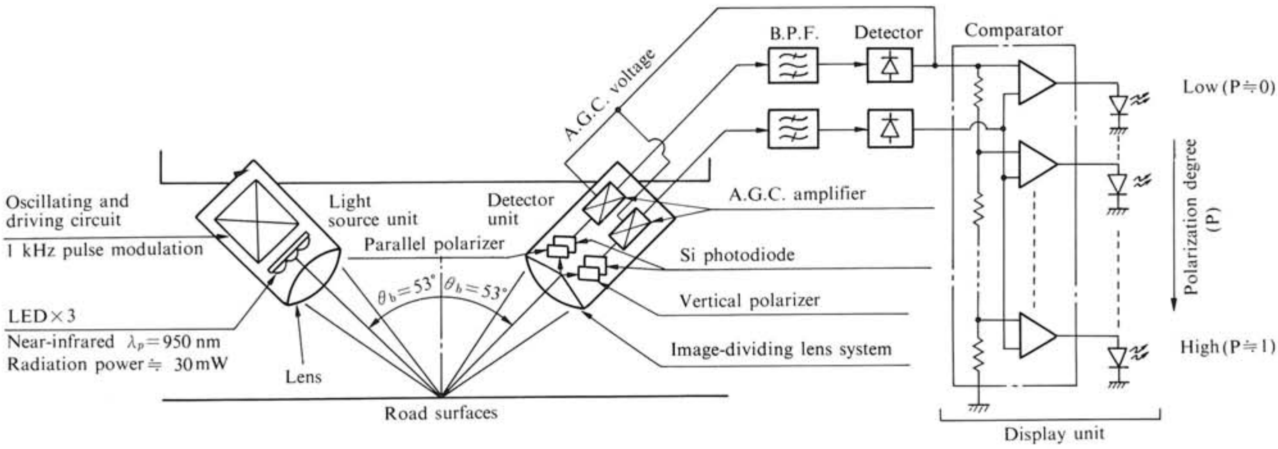


Figure 4. Construction of a sensor

Table 2. Sensor specifications

Item	Specification
Sensor mounting	Inside front bumper (Height ≑ 400 mm)
Road surface detection area	50 × 70 mm (Cross area of the light source unit and the detector unit)
Light source unit	
Dimensions	40 mm dia. × 90 mm
Weight	175 g
Light source	GaAs LED (λp = 950 nm) × 3
Light emission output	≑ 30 mW
Modulation frequency	1 kHz (Square wave)
Condenser lens	Aperture 30 mm, focal length 60 mm, convex lens
Detector unit	
Dimensions	40 mm dia. × 110 mm
Weight	210 g
Light detector	Si photocell (Light receiving area 10 × 10 mm^2)
Polarizer	Near-infrared linear polarizer (Polaroid Corp. HR Type)
Preamplifier gain	60 dB
A.G.C. range	20 dB
Frequency characteristics	f_0 = 1.0 kHz Q ≑ 10
Image-dividing lens system	Aperture 30 mm, focal length 60 mm, convex lens + vertical angle 152° prism
Display unit	LED × 12; polarization ratio (K = ρ_h/ρ_v) displayed by bar graph

dividing the same visual field on road surfaces into two.

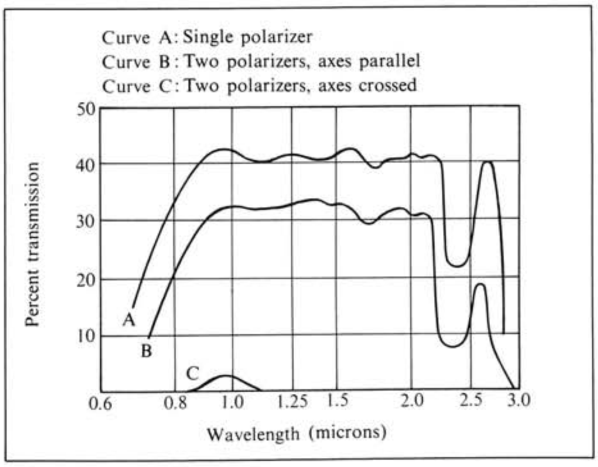
In front of the light detectors, the linear polarizers at right angles to each other permit simultaneous reception of parallel polarization components and vertical polarization components.

The polarizer used is Polaroid Corp.'s HR Type near-infrared linear polarizer. We tried several other visible light polarizers which are mainly used for liquid crystal displays, but this HR Type proved to be the only one capable of providing a sufficient extinction ratio in the near-infrared region. Characteristics of this polarizer are shown in Figure 5.

Our sensor features the ability to detect both parallel and vertical polarization components simultaneously for onboard detection of various status changes on road surfaces. Therefore, it is necessary to make the detection characteristics of the two systems as equal as possible to ensure accuracy of detection.

Variations in detection characteristics are mainly caused by ① light detector sensitivity, ② image formation balance (determined by prism precision and spherical aberration in the image-dividing lens system), and ③ electrical circuit characteristics.

After assembling the sensor, its detection characteristics must be regulated as follows by adjusting electrical circuit characteristics: First, make both detection outputs equal using sandpaper as a diffused surface. Then observe a water surface and adjust characteristics of the preamplifier and the detector to maximize the ratio of both polarization components.



HR-An infrared light polarizer which covers most of the useful response range of commercial lead sulfide photocells.

Figure 5. Characteristics of a near infrared linear polarizer[7] (Polaroid Corp. HR Type)

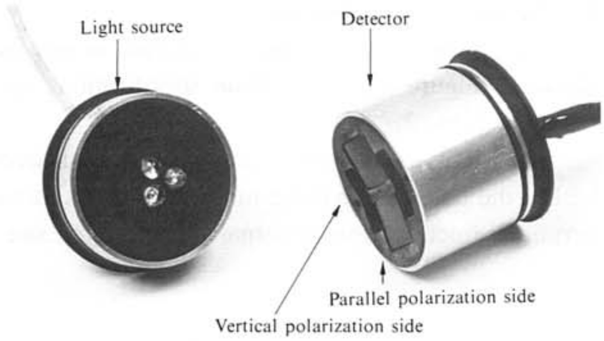


Figure 6. Inner configuration of a sensor

Detection errors are minimized by repeating the adjustments several times.

The signal processing circuit can be a simple comparator that compares the two signals and provides outputs depending on specific applications of the sensor. Figure 4 shows an example in which the polarization degree, i.e., the degree of road surface wetness, is displayed as a dot.

The ratio between parallel and vertical polarization components can express polarization degrees from low ($P \simeq 0$) to high ($P \simeq 1$) as can be easily understood by modifying the aforementioned formula (2) into:

$$P(K) = \left| \frac{K-1}{K+1} \right| \qquad (3)$$

where, $K = \rho_h/\rho_v$ (herein referred to as polarization ratio)

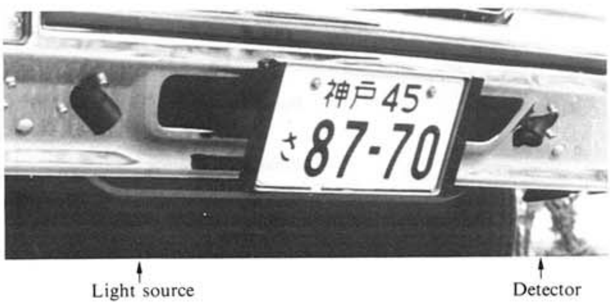


Figure 7. Installed model on an automobile

Figure 6 shows the internal construction of our prototype sensor.

Figure 7 shows an example actually mounted on the front bumper of a car. From the viewpoint of Brewster's angle requirements, the sensor can be conveniently housed inside the bumper.

5. Results of evaluation

5.1 Observation of road surfaces in the rain

To verify the theory of our sensor, a fixed point measurement was conducted before actual running evaluation. We measured the transitions in the polarization degree, P, from the time it began to rain till some time after it completely stopped raining on actual asphalt road surfaces. The results are shown in Figure 8.

It indicates very well how the polarization degree, P, increases from the time it begins to rain and gradually decreases as road surfaces get dry after it stops raining. In other words, the polarization degree, P, is a good indicator of the degree of road surface wetness.

The process may be explained by the way that rain water collected in road surface depressions would cause the diffuse surface of the dry road to change gradually into a specular surface.

5.2 Results of actual running tests on various road surfaces

Table 3 shows the polarization degree data

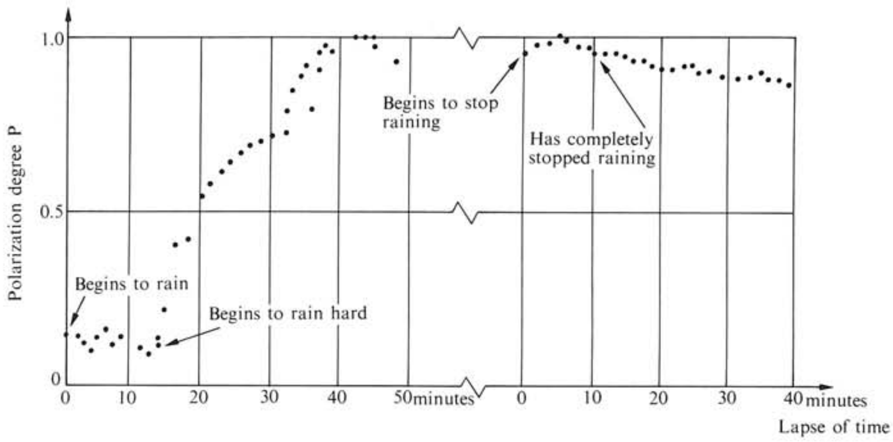


Figure 8. Transition in polarization degree in rain

Table 3. Polarization degree of various road surface conditions (Results of actual running test)

	Dry		Wet		Frozen or snow-covered		Melting snow		Running speed km/h
	$\overline{P_D}$	$\sigma/\overline{P_D}$	$\overline{P_W}$	$\sigma/\overline{P_W}$	$\overline{P_S}$	$\sigma/\overline{P_S}$	$\overline{P_S}$	$\sigma/\overline{P_S}$	
Suburban paved road	0.42	26%	0.91	0.54%	–	–	–	–	20
Urban road 1	0.33	36%	0.89	0.38%	–	–	–	–	40–50
Urban road 2	0.22	40%	0.89	0.55%	–	–	–	–	40–50
Suburban trunk road	0.53	16%	0.89	0.21%	–	–	–	–	20
National trunk highway	0.40	20%	0.89	1.2%	–	–	–	–	40–50
Metropolitan speed highway	0.39	17%	0.90	0.87%	–	–	–	–	50–60
Hokkaido – Mountainous area	–	–	–	–	0.10	32%	–	–	40
Hokkaido – Local city 1	–	–	–	–	0.07	24%	–	–	20
Hokkaido – Local city 2	–	–	–	–	–	–	0.84	40%	40
Hokkaido – Trunk road	–	–	–	–	–	–	0.92	13%	40

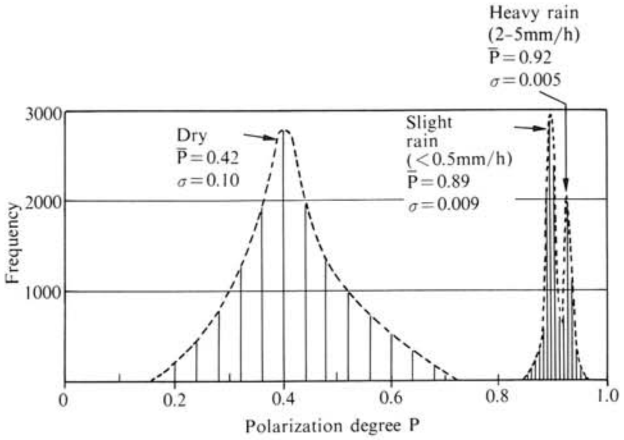


Figure 9. Distribution of polarization degree

a) Frozen road surface
(Polarization degree $\overline{P}=0.12$)
Near Nakayama Pass,
Sapporo City, Hokkaido.

b) Snow-covered surface
(Polarization degree $\overline{P}=0.13$)
Near Hanakawa,
Sapporo City, Hokkaido.

c) Melting snow
(Polarization degree $0.18<\overline{P}<0.9$)
Near Teine, Sapporo City, Hokkaido.

Figure 10. Examples of a few typical tested roads

obtained from running tests we conducted on various road surfaces using our sensor mounted near the front bumper of our car. Based on this data, we discuss below how different states of road surfaces — "dry", "wet", "frozen or snow-covered" and "melting snow" — can be decided.

Since the sensor is designed to have a response speed of about one second, the average length of road surfaces measured when running at 20 to 50 km/h is about 5.6 to 14 m.

1) Decision of dry or wet road surfaces

From Table 3, the mean value of the polarization degree for dry road surfaces, $\overline{P_D}$ = 0.22 to 0.53, with variations $\sigma_D/\overline{P_D}$ = 14 to 40%.

For wet road surfaces, $\overline{P_W}$ = 0.89 to 0.91, $\sigma_W/\overline{P_W}$ = 0.38 to 1.2%.

Thus, the polarization degree can clearly distinguish between dry road surfaces and wet road surfaces. Here, wet road surfaces are defined as ones in such a state of rain that the car may require wiper operation.

Furthermore, taking the "suburban paved road" in Table 3 as an example, the polarization degree can be expressed in a histogram as shown in Figure 9. From this, it is seen that the distribution of the polarization degree can be approximated by a normal distribution and that the decision of dry or wet road surfaces can be made with an accuracy of 99.99% or higher.

2) Decision of frozen or snow-covered road surfaces and melting snow road surfaces

In cold areas, there are many such frozen,

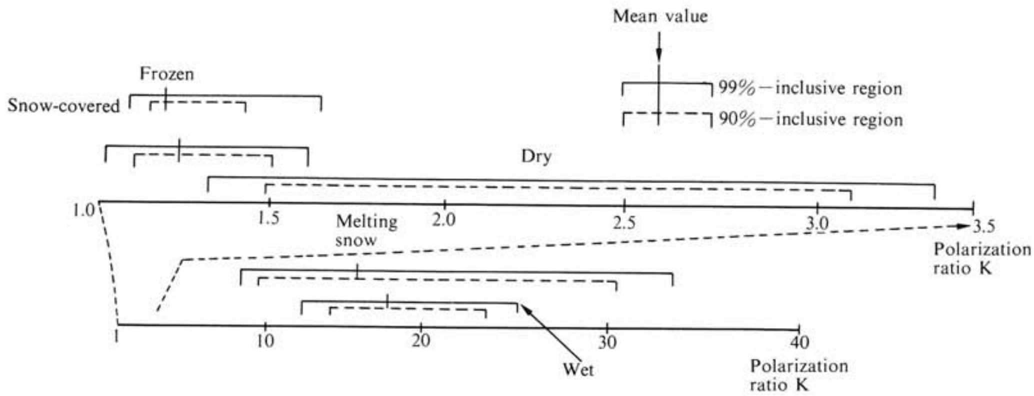


Figure 11. Distribution of polarization ratio for a few typical tested roads

snow-covered or melting snow road surfaces as shown in Figure 10. Our data, obtained from a few typical tested roads in Hokkaido, has been compiled and is shown in Figure 11. From this data, features of each different road surface condition can be described as follows:

① Melting snow road surfaces naturally have the same tendency as wet road surfaces, but the former has a wider range of variation in the polarization ratio, K, than the latter.

② Frozen or snow-covered road surfaces have a still smaller polarization ratio than dry road surfaces and are close to completely diffused surfaces. The reason may be that frozen surfaces have been finely shaved by spike tires or the like.

③ The polarization ratio can distinguish between frozen or snow-covered road surfaces and dry road surfaces with a decision accuracy of 90% or so.

3) Proposed algorithms for decision of road surface conditions

Based on the experimental data mentioned above, we have studied basic algorithms to distinguish various road surface conditions from one another. In the study, we considered the following points and made the model shown in Figure 12:

① We paid special attention to the tendency for the polarization ratio to change in relation to time, for improved identification of melting snow road surfaces.

② Outdoor temperature information was used in addition to the polarization ratio to enhance the distinction between a simply wet state and a specularly frozen state. In actual running tests, we observed no case of specularly frozen road surfaces, but we confirmed that rain water collected in road depressions would cause such a state.

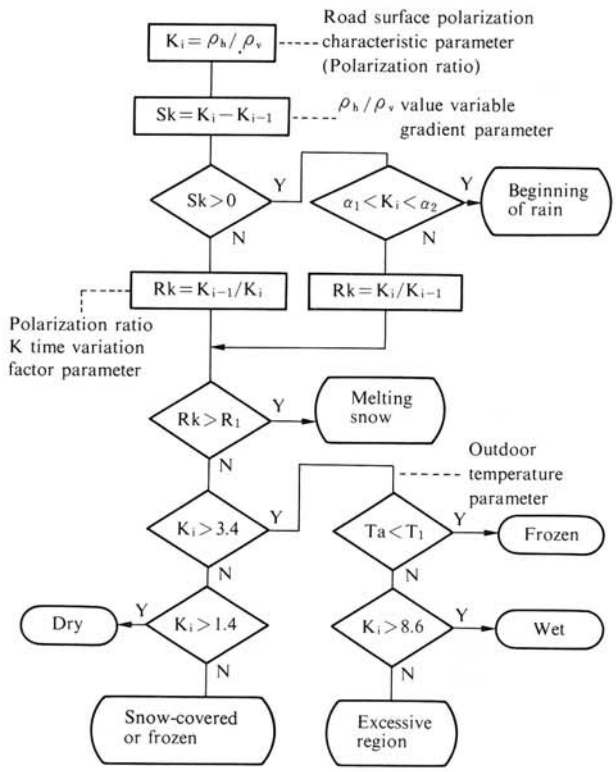


Figure 12. Basic algorithm to discriminate surface conditions by polarization ratio

③ For detection of the beginning of raining, we paid special attention to the polarization ratio's tendency toward a gradual increase.

6. Conclusion

With our mobile road surface sensor developed utilizing the polarization characteristics of reflection, we have verified that this sensor can accurately detect such different states as dry, wet, frozen and snow-covered road surfaces.

Many tasks yet to be done before this sensor can be put into regular service include: ① efforts in the pursuit of reliability, ② working out of simplified methods of installation and adjustment, and ③ verification of effectiveness when combined with applied systems.

However, since there are no special future difficulties observed in the availability of parts and materials used and the sensor is of quite simple construction, we believe the day for its implementation will not be too far ahead.

With a wider scope of applications other than mobile use, such as for road information systems foreseen, there is every reason to expect the soonest possible commercialization of this type of sensor.

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Keiji Fujimura

Entered the company in 1978, where he has been engaged in optical application device R&D. He is currently with the Vehicle Electronics Division's Engineering Department.

Takashi Sakamoto

Entered the company in 1967, where he has been engaged in millimeter-wave optical application device R&D, and, since 1984, in vehicle electronics products R&D. He is currently with the Vehicle Electronics Division's Manufacturing Engineering Department.