Ice Detection, Prediction, and Warning System on Highways

Motoya Inoue, Kozaburo Baba, and Yoshiharu Takada

A system has been developed by which antifreezing action can be taken, e.g., spreading chemicals, and warnings can be provided to drivers to force slow driving. The system consists of the following 5 parts: (a) meteorological observation devices installed on roadway or roadside for measuring air, pavement, and underground temperature, wind direction, wind velocity, radiation, and humidity; (b) road surface moisture meter installed on roadside for measuring scattering of light and electric conductivity; (c) data processing equipment installed in the control center for use in predicting temperature transition and discriminating road surface moisture state; (d) data transmitter consisting of A-D converters and wireless or wire transmitters for transmitting data between observation sites and control center and between control center and warning signs; and (e) warning sign that has a changeable message and provides drivers with information on slippery conditions. With the use of this system we failed only once in 43 times (a skill score of 0.86) to predict at 5:00 p.m. that ice would form the following morning; we had a skill score of 0.96 in predicting 2 hours beforehand that ice would be forming.

Meteorological phenomena such as rain, snow, ice, fog, and wind occurring on highways present obstacles for road maintenance and driving. In particular, ice film forming on road surfaces, snowfall, and snow coverage are directly connected with possible traffic accidents, so that countermeasures against these obstructions are of particular importance. An information system has been developed to detect, predict, and give warning of road icing.

Prior to the development of this system, extensive survey and study were carried out. These included a meteorological survey of highways throughout Japan; a survey of traffic and snow removal and ice control; a theoretical analysis of predicting meteorological phenomena on highways; the development of meteorological instruments, system design, and operation of meteorological information; and similar considerations.

COMPOSITION OF ROAD ICING INFORMATION SYSTEM

The information system connected with slippery roads consists of the following 5 units: meteorological observation instruments, road surface moisture meter, data processing equipment (data controller), data transmitter, and electric warning signs. A diagram of the system is shown in Figure 1.

Meteorological Observation Devices

These instruments (Fig. 2) are used to observe meteorological elements that have a potential effect on roads and the detection and prediction of road icing. These elements include: pavement temperature (-0.5 cm), underground temperature (-5, -10, -20, and -50 cm), air temperature (+150 cm), dew point temperature (+150 cm), net radiation (+200 cm), wind direction (+200 cm), wind velocity (+200 cm), and road surface moisture.

These observations are recorded and converted into electric signals that serve as input signals for the data processing equipment.

Road Surface Moisture Meter

This device (Fig. 3) uses 3 kinds of observations as input: electrical conductivity, the scattering of light, and the temperature of road surfaces. It compares the input

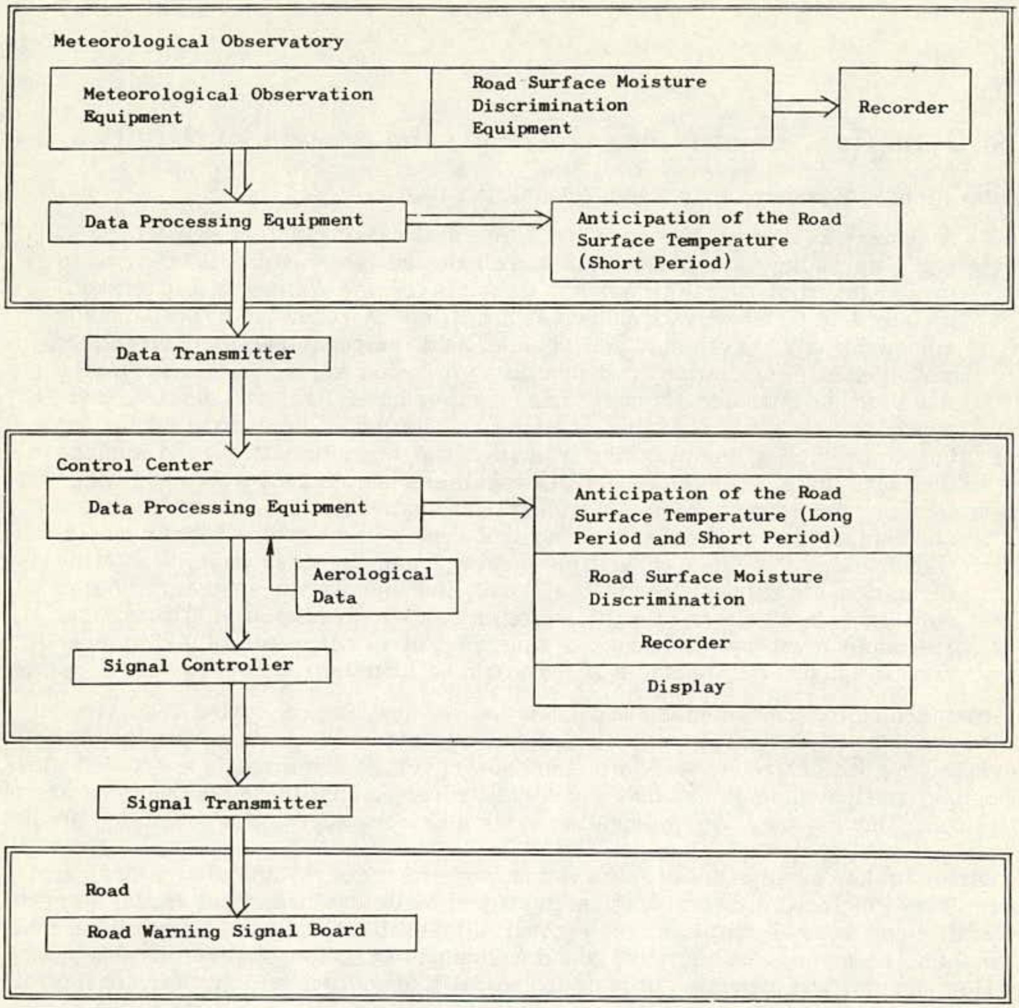

Figure 1. Diagram of the ice detection, prediction, and warning system.

Figure 2. Meteorological observation devices.

Figure 3. Road surface moisture meter.

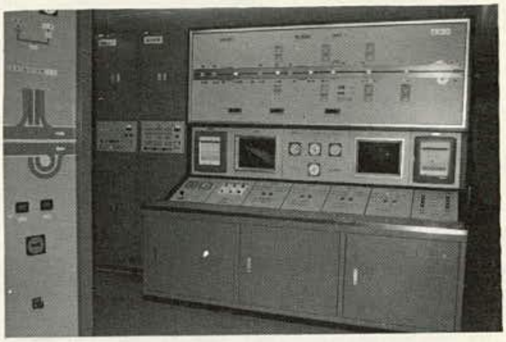

Figure 4. Data processing equipment installed in control center.

with standard values that have been preset empirically and indicates 4 kinds of road conditions by discriminating through a matrix circuit.

1. Dry—There is no danger of icing because there is little moisture on the road surface.

2. Wet—Some moisture is on the road surface, but it is not freezing. The road temperature is above 1.5 C.

3. Prestage of freezing—The road is slushy with snow and water or some moisture is present at a surface temperature of 0 to 1.5 C. This also includes the situation where icing is prevented even at subzero temperatures by spreading a high density chloride.

4. Ice—There is a danger of icing, or the road is already icy with moisture at subzero temperatures.

Data Processing Equipment

This equipment, installed at the control center (Fig. 4), indicates and processes data obtained at each observatory, and also predicts pavement temperatures with a built-in pavement temperature prediction device.

The prediction is made in 2 ways depending on the time involved. A long-range forecast of pavement temperatures covers up to 15 hours from 5:00 p.m. to 8:00 a.m. the following day; a short-range forecast predicts temperatures continuously 2 to 4 hours in advance of a given time between the hours of 5:00 p.m. and 8:00 a.m.

A prediction formula is previously prepared by analysis of meteorological data obtained at the observatories, and the prediction simulator provides a short forecast of pavement temperatures. In the case of long-range predictions, some types of upper air information are added to the meteorological data fed on-line from each ground observatory. A discriminant method is used here to distinguish whether pavement temperatures are above or below freezing. Whenever pavement temperatures are forecast to fall to freezing degrees, in both methods of prediction, a warning sign appears on the control panel.

Data Transmitter

The device transmits signals from meteorological observatories to the data processing system at the control center or from the control center to the warning signs along the roadside. Observations are wire-transmitted as analog signals when short distances are involved and as digital signals converted by an A-D converter when long distances are involved.

Electric Warning Sign

When moisture appears, such as snow coverage of the road surface, a warning sign is indicated on the roadside sign boards according to the ice prediction. Sign messages, formed by electric variable letters, may be slow-down, ice, fog, snow, gales, and the like. Selection and flashing of the electric letters are controlled from the operation board located at the control center. Automatic control of these signs is also possible. A warning sign is shown in Figure 5.

STUDY OF PREDICTION METHOD OF PAVEMENT TEMPERATURES AND RESULTS

Ice film on road surfaces is formed when pavement temperatures fall to freezing in the presence of moisture on the road surface. Because moisture on a road surface is a result of extremely complicated phenomena, prediction of pavement temperatures is much more difficult than an ordinary weather forecast. The observation stage, therefore, was previously confined to detection.

Detailed surveys and studies have been carried out on icing phenomena on road surfaces throughout Japan. In addition, a study on methods of predicting pavement temperatures was also conducted using analytical methods of heat balance, thermal conductivity, pattern, and statistics on the basis of road and air meteorological data of the particular district.

Figure 5. Warning sign.

Pavement Temperature Forecast Through Heat Balance and Heat Conductivity Analyses

The heat balance on a road surface is not only a basis for clarifying the phenomena of road icing but also a prerequisite for controlling road snow and ice by road heating, using sprinklers, and spreading chemicals (chlorides). An equation of the heat balance is expressed as a summation of a certain amount of time in regard to the total heat flux between unit area of the road surface and space.

$$R = LE + P + A + X$$

where, in this case,

R = net radiation ly/min,
LE = heat loss by evaporation,
P = heat flux caused by advection between the road surface and air,
A = heat flux between the road surface and underground, and
X = direct contact heat transfer caused by rain showers and such.

The heat sum of the empirical formula is calculated according to each term. The heat flow several hours in advance can be estimated from the heat flow at the time of observation, thus enabling a forecast of road surface temperatures to be given by the simulator.

Prediction Through Pattern Analysis of Pavement Temperatures

This prediction method enlists the aid of harmonic analysis using a diurnal fluctuation of road surface temperatures according to the weather as a periodic curve.

$$Y = a_0 + \sum_{n=1}^{\infty} (a_n \cos nx + b_n \sin nx)$$

TABLE 1

HARMONIC ANALYSIS OF DIURNAL FLUCTUATION OF ROAD TEMPERATURES

Type of Day	a_0	a_1	a_2	a_3	b_1	b_2	A_1	A_2	a_1/b_1	φ_1 (deg, min)	a_2/b_2	φ_2 (deg, min)
Clear	4.07	9.52	4.32	1.32	5.57	2.19	11.03	4.85	1.71	59 40	1.97	63 06
Fine	5.80	7.64	4.42	1.66	5.05	2.01	9.16	4.85	1.51	56 31	2.20	65 31
Cloudy	7.62	5.32	3.01	0.85	4.54	1.55	6.99	3.38	1.17	49 33	1.95	62 48
Rain	13.52	4.46	1.88	0.24	2.53	0.92	5.12	2.09	1.77	60 28	2.04	63 56
Snow	5.81	3.58	1.57	0.85	2.09	0.26	4.14	1.59	1.71	59 43	5.98	80 31

TABLE 2

ALLOCATION OF VARIATES

No. of Data	Symbol	Kinds of Data	No. of Regression Elements		
1	TR1	Pavement temperature	6	16	32
2	TR2	Underground temperature, -5 cm	6	16	32
3	TR3	Underground temperature, -10 cm	6	16	32
4	TR4	Underground temperature, -20 cm	6	16	32
5	TR5	Underground temperature, -50 cm	6	16	32
6	TA2	Temperature, 1.5 m	6	16	32
7	TD2	Dew point temperature, 1.5 m		16	32
8	TTy 850	Temperature, 850 mb (Yonago)		16	32
9	hhy 700	Altitude, 700 mb (Yonago)		16	32
10	hhy 500	Altitude, 500 mb (Yonago)		16	32
11	hhs 700	Altitude, 700 mb (Shionomisaki)		16	32
12	hhs 500	Altitude, 500 mb (Shionomisaki)		16	32
13	TTw 850	Temperature, 850 mb (Wajima)		16	32
14	hhw 700	Altitude, 700 mb (Wajima)		16	32
15	hhw 500	Altitude, 500 mb (Wajima)		16	32
16	TTw 500	Temperature, 500 mb (Wajima)		16	32
17	R	Radiation			32
18	Difference of temperature	TA1 (0.5 m) - TA2 (1.5 m)			32
19	TTs 850	Temperature, 850 mb (Shionomisaki)			32
20	Difference of altitude	hhy 700 - hhs 700			32
21	Difference of altitude	hhy 700 - hhw 700			32
22	Difference of altitude	hhs 700 - hhw 700			32
23	Difference of altitude	hhy 500 - hhs 500			32
24	Difference of altitude	hhy 500 - hhw 500			32
25	Difference of altitude	hhs 500 - hhw 500			32
26	Components of wind velocity	ffy 850 × cos ddy 850			32
27	Components of wind velocity	ffy 700 × cos ddy 700 (dd = wind direction (angle))			32
28	Components of wind velocity	ffs 850 × cos dds 850			32
29	Components of wind velocity	ffw 850 × cos ddw 850			32
30	Hikone	Dew point temperature			32
31	Hikone	Wet bulb temperature			32
32	Hikone	Air temperature			32

Table 1 gives a harmonic analysis of diurnal fluctuation of road surface temperatures observed in Tsuru City along the Chuo Express Highway in fiscal 1967. Constants are classified according to weather.

Prediction Through Statistical Analysis

Structural fluctuation of pavement temperatures and spatial and time relationships among meteorological elements are understood from physical and meteorological concepts. On this basis, a statistical process can be applied to forecasting pavement temperatures. Two methods were examined for this purpose: multiple linear regression and categoric classification.

Prediction by Multiple Linear Regression Method—Among local and aerological data intimately related to the prediction of pavement temperatures, 180 elements were selected. Out of these, 32 elements were chosen as the most effective variates to form a 32-element regression formula. Discussion was also carried out on the basis of 16- or 6-element formulas from a practical point of view. Allocation of the variables of these multiple regression methods is given in Table 2.

This type of study is painstaking. It requires sorting through those factors most directly related to the physical phenomena that this system attempts to predict and arriving at a conclusion through a painful trial-and-error process. Moreover, the method of reaching a conclusion is necessarily dependent on a basic understanding of the mechanism appropriate for determining meteorological phenomena.

Spot observation data are sufficient for the short-period forecast of road surface temperatures. However, regional meteorological data are necessary in order to make reliable predictions, and aerological data are indispensable for long-period predictions.

Prediction of pavement temperatures, using the meteorological variables described, can be written in the following multiple linear regression formula:

$$Y = A_0 + \sum_{t=1}^{N} A_i X_i + \epsilon$$

where, in this case,

Y = road surface temperature to be predicted,
A_i = regression coefficient,
A_0 = constant,
X_i = value of variate observed at the time of prediction, and
N = number of dimensions.

Table 3 gives an example of regression coefficients obtained from a 16-element regression formula produced on the basis of observations at Hatasho along the Meishin Express Highway.

The standard deviation of errors involved in the multiple regression formula was computed in order to obtain more knowledge about the prediction accuracy. The errors originated in the 6- and 16-element regression formulas are shown in a sequence of time in Figure 6. Pavement temperatures were predicted by means of the road surface temperature predictor according to the 16-element regression formula. The prediction formula, worked out with data obtained during a winter season (60 forecasts), was applied in predicting pavement temperatures in the following winter. Actual results of the prediction (from 5:00 p.m. to 8:00 a.m. the next day) were 0.86 C in the mean error and 1.8 C in the standard deviation of error. A comparison of observations versus the results of forecasts with 6 and 16 elements is shown in Figure 7.

TABLE 3

REGRESSION COEFFICIENTS IN 1966 OBTAINED FROM 16-ELEMENT FORMULA

Constant	18:00	20:00	24:00	04:00	06:00	08:00
A_0	-4.8533	5.2374	-12.5220	-28.6821	-31.9767	-30.0362
A_1	1.1640	0.6687	0.2761	0.2009	-0.1699	-0.0519
A_2	-0.8531	-0.9415	-0.9358	-0.5689	-0.1629	0.3094
A_3	0.2797	0.8416	1.1168	0.4906	0.5204	-0.2913
A_4	0.3550	-0.0120	-0.2504	0.0492	-0.0839	0.2238
A_5	-0.0312	0.0398	0.0847	0.2330	0.2895	0.3423
A_6	0.0845	0.2290	0.3378	0.3364	0.3365	0.1928
A_7	0.0612	0.1864	0.2313	0.2164	0.2360	0.2003
A_8	-0.0012	-0.0891	-0.0883	-0.1408	-0.1281	-0.0442
A_9	0.0043	0.0011	0.0058	0.0095	0.0005	0.0179
A_{10}	0.0004	0.0054	-0.0020	-0.0003	0.0002	0.0000
A_{11}	0.0029	0.0015	0.0009	-0.0000	0.0023	-0.0003
A_{12}	-0.0034	-0.0043	0.0013	0.0035	0.0054	0.0075
A_{13}	-0.0051	0.0577	0.0824	0.1211	0.1038	0.0857
A_{14}	-0.0096	-0.0069	-0.0129	-0.0084	0.0051	0.0261
A_{15}	0.0049	0.0002	0.0062	0.0011	-0.0044	-0.0067
A_{16}	-0.0244	0.0303	-0.0042	0.0100	0.0099	-0.0008

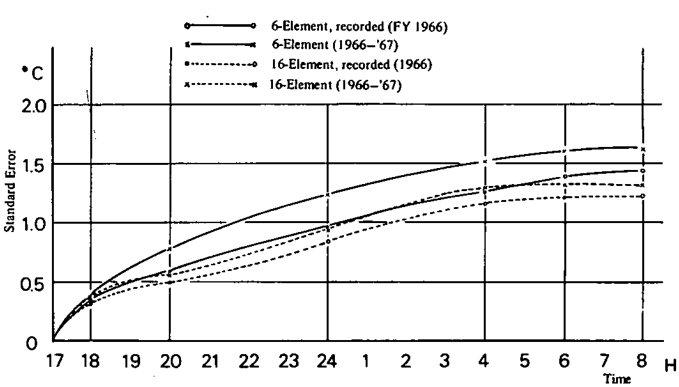

Figure 6. Standard deviation of errors.

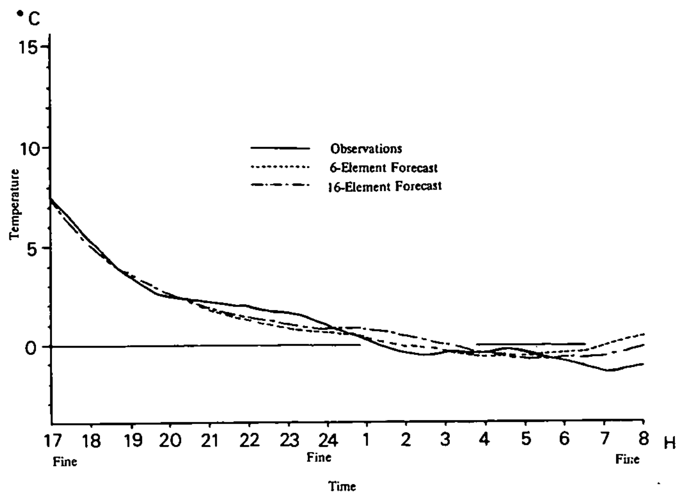

Figure 7. Prediction versus observations.

Prediction by Category Classification Method—In order to discriminate whether pavement temperatures fall below the freezing point, 5 elements including pavement temperature, underground temperature, air temperature, dew point temperature, and net radiation were chosen as prediction factors to allow a category classification of 5-dimensional space. This enabled discrimination and prediction of road icing according to category. The category classification is in this case a kind of discriminant analysis. A variate is divided at a point in order to discriminate which division an amount required belongs to. Accordingly, categories of $2^5 = 32$ are produced in the 5 dimensions. The classification points and groups in each category are determined by physical observation and by statistical treatment.

As an example, take 3 variates with prediction factors of x, y, and z. If the classification points of the prediction factor values are taken as x_0, y_0, and z_0 respectively, the number of categories classified are $2^3 = 8$.

1. $x \geq x_0,\ y \geq y_0,\ z \geq z_0$
2. $x \geq x_0,\ y \geq y_0,\ z < z_0$
3. $x \geq x_0,\ y < y_0,\ z \geq z_0$
4. $x \geq x_0,\ y < y_0,\ z < z_0$
5. $x < x_0,\ y \geq y_0,\ z \geq z_0$
6. $x < x_0,\ y \geq y_0,\ z < z_0$
7. $x < x_0,\ y < y_0,\ z \geq z_0$
8. $x < x_0,\ y < y_0,\ z < z_0$

TABLE 4

SKILL SCORE OF PREDICTIONS AT HATASHO, MEISHIN

Observed	Predicted		Total	Comment
	Above 0 C	Below 0 C		
Above 0 C	327	9	336	Short period prediction by time, every 2 hours, unit = 2 hours
Below 0 C	0	149	149	
Total	327	158	485	Skill score: 0.9571
Above 0 C	30	5	35	Short period prediction by day, unit = a night
Below 0 C	0	26	26	Skill score: 0.8324
Total	30	31	61	
Above 0 C	34	6	40	Long period prediction, 1967
Below 0 C	0	20	20	Skill score: 0.7750
Total	34	26	60	
Above 0 C	36	1	37	Long period prediction, 1968
Below 0 C	1	21	22	Skill score: 0.9275
Total	37	22	59	

If categories 4, 6, and 8 are taken as groups to reach the freezing point, they are predicted to reach the freezing point when the predicted time (x, y, and z) falls on 4 or 6 or 8. Other multidimensional category classification was conducted in this same way.

Table 4 gives a skill score that compares actual pavement temperatures with those that had been predicted. The first 2 cases are examples of short-range predictions within 2 to 4 hours, and the other 2 cases are long-range predictions from 5:00 p.m. to 8:00 a.m. the next day. In the latter cases, 2 variables of aerological data were added to the prediction factors. Rather good prediction results were achieved by using this method.

This sort of statistical prediction depends completely on the accuracy of the method applied. Moreover, meteorological data covering 2 to 3 years are necessary in order to provide stabilized forecasts with a minimum of errors.

CONCLUSION

Various methods have been examined empirically with specially designed simulators for each method to obtain an optimal prediction of pavement temperatures. It is very important that the temperature of paved surfaces be predicted automatically and mechanically without depending on meteorological knowledge if snow and ice on roads is to be effectively controlled. No practical inconvenience is presented by the alternative type of prediction of whether pavement temperatures, which are closely connected to road icing, fall below freezing point or not.

On this basis, the category classification method has been adopted as a means of making an objective prediction system of pavement temperatures. The system attained good results in its predictions, with skill scores of 0.775 in 1967 and 0.927 in 1968 for long-range predictions and 0.957 through 1967 and 1968 for short-range ones. The state of moisture on paved surfaces was detected accurately and reported to the control center.

The salient point of this system is not only to provide the men in charge of road maintenance with appropriate information but to alert drivers to the conditions by the warning signs. For this purpose, prior to the development of software that could ensure an effective system operation, surveys were carried out repeatedly on the distribution of temperatures on paved surfaces in road sections where snow and ice could be formed.

Informal Discussion

Glenn G. Balmer

Can you give us a little more detail on the moisture detector?

Inoue

We are making 3 kinds of observations: electrical conductivity measurements to detect surface moisture; scattering of light to determine the presence and state of surface moisture; and measurements of pavement temperature.

Balmer

What does the system cost?

Inoue

This system costs $300,000 per 40 km.

Ambrose Poulin

It seems to me that instead of looking at the entire heat balance equation for the surface affected, you could possibly use one or two sensors, which might give you practically all the information, and introduce logic into your computer program. Do you think that you could come up with a prediction system that instead of being 100 percent accurate and costing $300,000 might be 95 percent accurate and cost maybe $50,000 to $60,000? The point is, do you think that with one or two measurements, say surface temperature and the moisture condition, you could come up with the same information even though it might not be accurate 100 percent of the time?

Inoue

This might be possible.

Chesley J. Posey

Do you anticipate any problem from vandalism?

Inoue

We do not know.

Leonard H. Watkins

Along these 50 km where this system is installed, how many sensing stations are there? How far apart are they, and how do you determine their locations? Do you put them in known danger spots, or do you study the microclimate of the road?

Inoue

We have 30 of these different sensors in this 60-km section. The points are not the most dangerous because we studied the road surface with infrared telemeters and we know the performance of the road. The choice was based on the easiest point to maintain.

Thad M. Jones

How do you transmit the information from the individual meteorological station to the central control? Is it radio link or land line?

Inoue

We use cable, a telephone line.

Jones

Do the individual meteorological stations and warning signs have a power source independent of the main distribution 50-cycle current, or does the entire system require for its operation your regular power line voltage, or is it operated completely from batteries?

Inoue

We use a common commercial power source, not a special one, and the individual meteorological stations do not have standby power.

Don L. Spellman

I notice this system has a fairly new element, a direction and wind velocity indicator. How important is this in prediction of icing?

Inoue

In this system the radiation is a measured factor, and the wind direction and speed are secondary factors.

Balmer

On a second installation, would you install your stations as close as they are on this installation or would they be farther apart? For a 50-km section, would you have 7 stations, 3 stations, or 10 stations?

Inoue

If we installed a second system, the number of individual stations might be less than in this system. In this system we can accumulate the data, so the error can be reduced.

John A. Cook

At what height do you measure wind velocity?

Inoue

About 2 meters above the road surface.

Cook

Do you take into consideration dew point at the same time as you measure the wind velocity?

Inoue

It happens that dew point is important because of the radiation element of this point.

James A. Roberts

Do you have specific, significant evidence of the usefulness or effectiveness of the system in reducing accidents?

Inoue

We have had only one season and little experience with this system, but we have reduced traffic accidents markedly.