Field Survey Equipment and Data Analysis for Highway Rehabilitation Planning

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Highway systems are deteriorating at a rapid rate due to increased traffic loads and severe climatic conditions. In order to keep these highways in good condition, maintenance and repair strategies must be based on the precise understanding of pavement conditions. Visual observations of pavement distress by trained engineers is the most common practice for monitoring and evaluating pavement surface conditions. Since pavement management needs are great, alternative methods of data collection and evaluation are needed to manage the data rapidly and accurately. In response to this need, the Japanese were among the first to develop high-speed photographic methods that successfully measure cracking and rutting. The Japanese were also successful in the development of field equipment for longitudinal profile surveys made with a three-laser sensor system. In a parallel effort, the development of an overall Road Surface (Pavement) Condition Evaluation System for Japan was begun in 1975. The application system was combined with the field hardware to form an integrated system of pavement performance modeling. In this paper, a typical application of the road surface condition survey and data reduction in Japan is discussed. An example of actual use of the high-speed photographic recorders for surface distress and the longitudinal profile measuring device with three laser sensors is presented.

Many pavement systems are deteriorating at a rapid rate due to increased traffic loads and severe climatic conditions. Highway agencies are now facing reduced budgets and a shortage of experienced engineering staff. The combination of these trends can create difficult operating requirements for the highway agency. Within the past few years, many of these agencies have begun to implement pavement management systems (PMS) to help organize and manage their highway infrastructure.

Most PMS require that a centralized database be established as a repository for all information pertaining to the highway system. This database is then used to provide information which is used to improve management of the highway network. Data such as geometric design information, accident statistics, construction costs, and maintenance records can be found in the database. All of this information is important to the agency; however, some specialized data are more specific for PMS, including pavement condition surveys, rut depth measurements, longitudinal roughness, skid measurements, deflections, and drainage.

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Considering the size and geographic distribution of highway networks, it can be seen that data collection and management can become an enormous task for a typical highway agency. This paper discusses equipment which is available to collect PMS data at normal highway speeds. The paper also discusses a decision-analysis process which can be used to assess network- and project-level PMS needs. At this time, only rutting, longitudinal roughness, and surface conditions lend themselves to high-speed data collection techniques. Skid resistance, drainage, and other parameters such as deflections do not lend themselves to continuous data collection methods. Consequently, they will not be addressed in this paper.

The equipment and data analysis techniques that are described in this paper were developed in Japan. Feasibility studies and the design of the equipment began in the early 1970s. The system description in this paper is a summary of the state of the art of the Japanese pavement management system. Concepts, equipment, and algorithms are applicable, however, to any PMS.

PAVEMENT SURFACE CONDITION SURVEY EQUIPMENT AND DATA REDUCTION

Field Survey Equipment

The field survey equipment is mounted on a single-survey vehicle chassis. A major component of the data collection system is an automatic, photographic recording system which is used for surface distress measurements. Distress types such as cracking, patching, joint deterioration, and potholes can be measured with continuous photo equipment. Other photo instrumentation (pulse) is used to measure rut depths. Noncontact sensors are used to measure longitudinal roughness. The complete field survey system is shown, in schematic form, in figure 1. Since all of the measurement equipment is mounted on a single vehicle chassis, the data collection can be done at normal highway speeds. This is an advantage since the data collection does not interfere with traffic flow. The data collection is also much safer than manual data collection, which often requires that a rater walk along the pavement or drive at slow speeds.

Surface Distress with Photographic Recorder

The surface distress of the pavement is measured with a high-speed photographic system. The recording system utilizes a 35-mm slit camera that continuously photographs the pave-

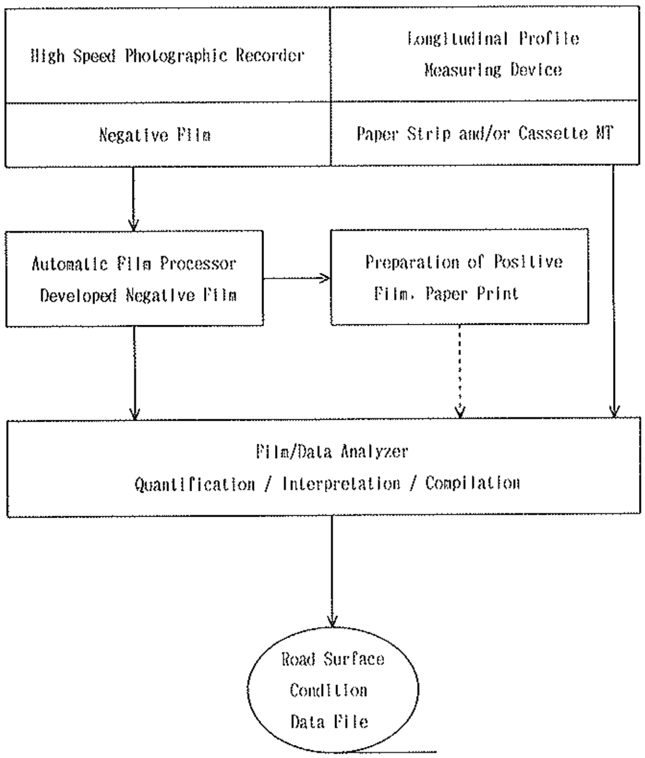


FIGURE 1 Outline of field survey and data reduction procedure.

ment surface. Pavement widths of up to 16 feet can be photographed in a single pass. This enables a travel lane and a shoulder to be filmed at the same time. A single roll of film can capture approximately 37 miles of pavement for analysis. The operating principle and configuration of the system are shown in figures 2 and 3.

As can be seen in figure 2, an image, which is the size of the slit, is formed on the film as the object is projected on the film by the lens. The film speed is synchronized with the vehicle speed so that a continuous photograph can be recorded. The photo becomes an actual record of the condition of the pavement surface. This type of record is very useful to the highway engineer and administrator, because it can be used to create digital information pertaining to the distress. The photo also becomes a historical record of the pavement condition. Pavement deterioration over time can be seen with a series of plots.

The surface distress measurements are made at night, because the pavement surface must be illuminated to maintain a high degree of photographic detail. Because the lighting is constant (no shadows, for example), the various distress types can be easily determined from the photos. A typical photograph of a highway section is shown in figure 4.

Surface Distress Data Processing

The exposed film is processed by an automatic film processor which develops, fixes, washes, and dries the film in one unit.

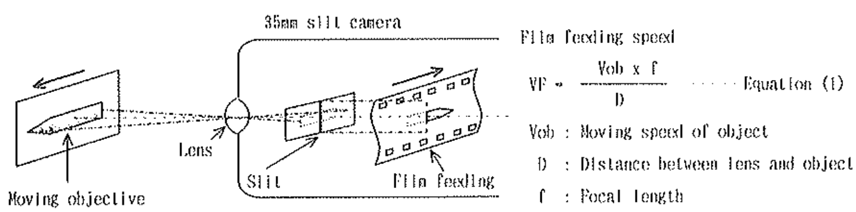


FIGURE 2 Operating principle of photographic recorder for surface distress.

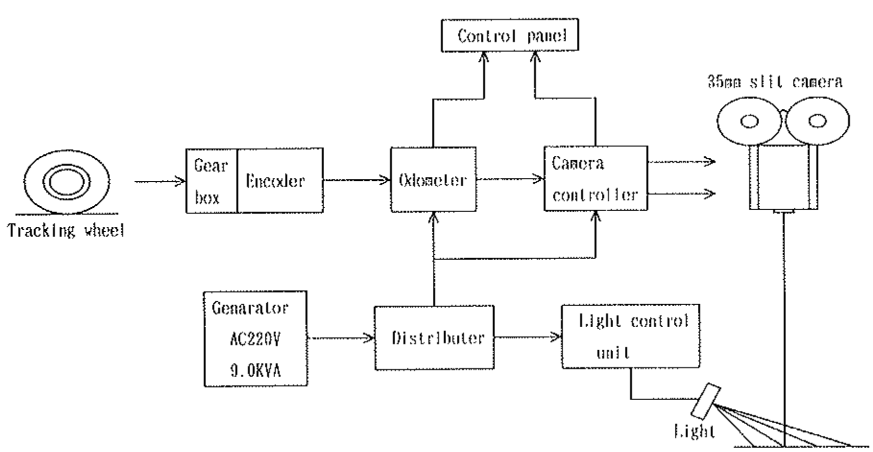


FIGURE 3 Configuration of high-speed photographic recorder for surface distress.

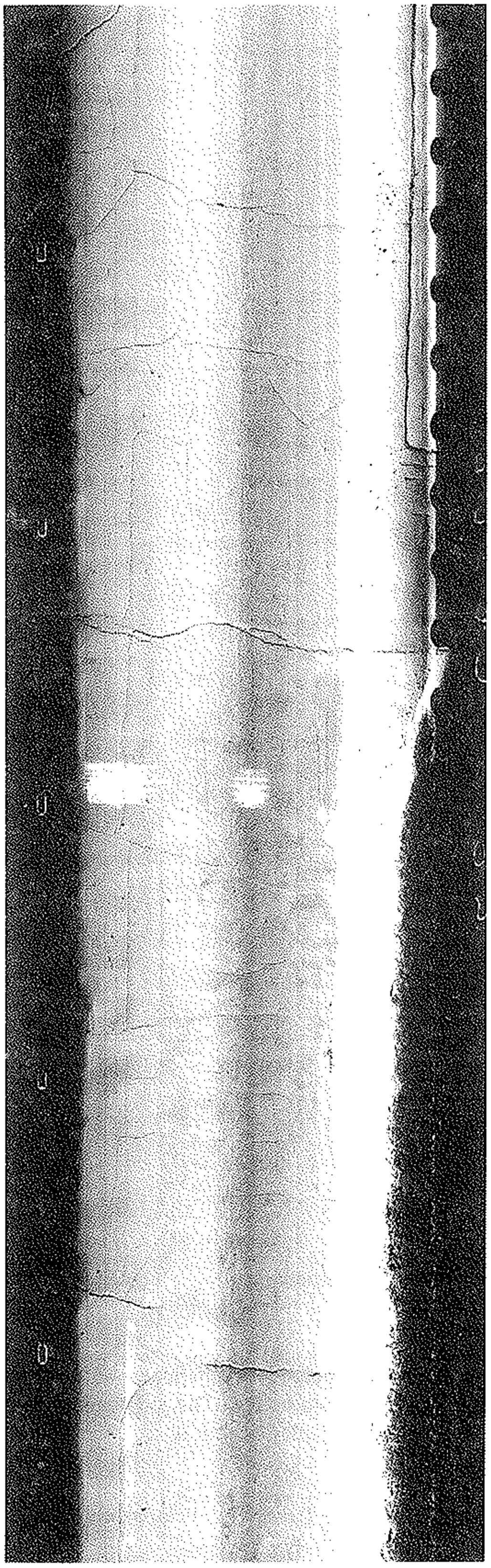


FIGURE 4 Part of continuous photo taken by high-speed photographic recorder for surface distress.

The 35-mm film is then in negative form, but it can be easily developed on positive paper if needed. After the film is in negative form, pavement cracking can be digitized.

Quantification of the cracking is performed by a grid-cell method based on the images of ten magnification. The grids can be imposed on the negative film as shown in figure 5. Digitized data can then be used to develop a cracking ratio. The cracking ratio (percent) and cracking index (in^2) are quantified by the following formulas:

Asphalt Pavement

$$\text{Cracking Ratio} = \text{Crack Ratio (percent)} + \text{Patching Ratio (percent)}$$

$$\text{Crack Ratio (percent)} = \frac{\text{Crack Area (yd}^2\text{)}}{\text{Observed Area (yd}^2\text{)}}$$

$$\text{Patching Ratio (percent)} = \frac{\text{Area of Patching (yd}^2\text{)}}{\text{Observed Area (yd}^2\text{)}}$$

Cement Concrete Pavement

$$\text{Cracking Index (in./yd}^2\text{)} = (\text{Total Length of Linear Crack} + \text{Area of Patching} \times 100/1.0\ \text{ft}) \div \text{Observed Area (yd}^2\text{)}$$

Rut Depth with Photographic Record

Rut depth surveys can also be carried out at normal highway speeds with photographic techniques. The system is designed to identify photographically the sectional profile of the pavement with a 35-mm pulse camera. The pulse camera is mounted on the front of the vehicle and operates as shown in figure 6. The camera photographs hairline optical bars which are projected onto the pavement surface. The camera shutter and hairline projector are synchronized according to the distance covered by the vehicle.

In this projection transformation method, a straight dark line is projected at an angle of 26°33′. Since the pulse camera is mounted vertically, the distortions of the photograph line are the rutting in the pavement. The operating principle of the rut depth measurements is presented in figure 7.

Rut Depth Data Processing

The film taken with the pulse camera is developed by an automatic film processor. A typical rut depth photo is shown in figure 8. The rutting can have several definitions, depending on the agency preference, as shown in figure 9. The rut depth photos are enlarged to ten times the negative size and then digitized. The complete sequence for the digitizing of the rut depth information is presented in figure 10.

Longitudinal Roughness Using Laser Sensors

Pavement longitudinal roughness is measured with three non-contact laser sensors. This enables a continuous record of the

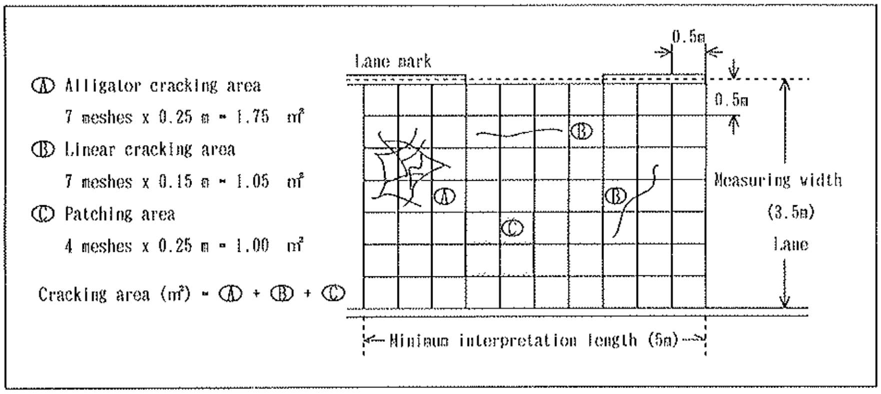


FIGURE 5 Measurement of cracking area by mesh method.

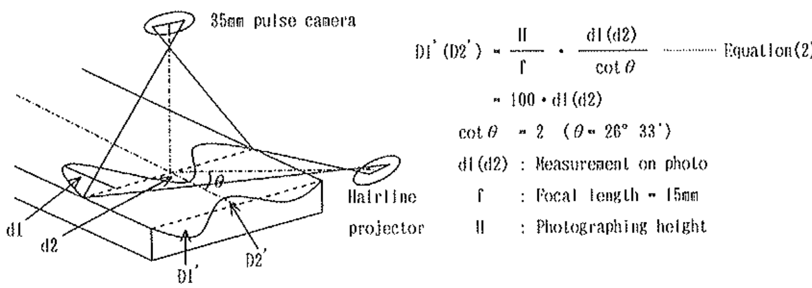


FIGURE 6 Operating principle of high-speed photographic recorder for rutting.

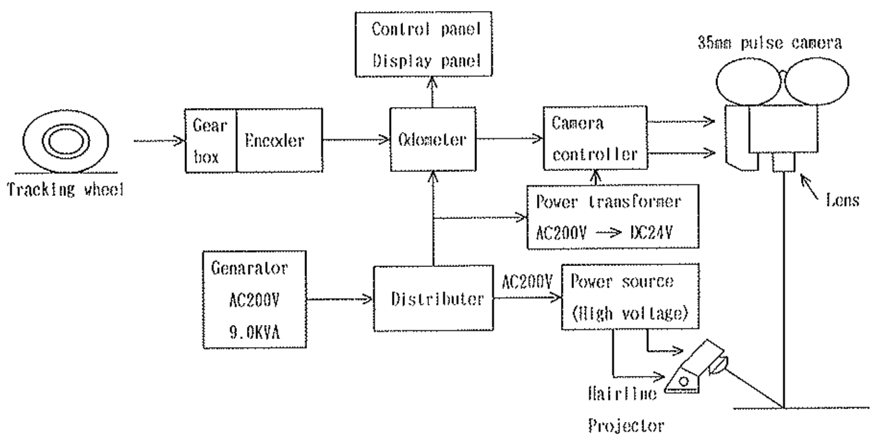


FIGURE 7 Configuration of high-speed photographic recorder for rutting.

longitudinal profile. The roughness measurement is also made at normal highway speeds.

The operating principle of the roughness measuring system is shown in figure 11. The three laser sensors are installed on the vehicle 4.9 feet apart in the longitudinal direction. The operation configuration is presented in figure 12. As can be seen, the encoder detects the distance traveled and conveys a signal to the input/output (I/O) controller to generate basic signals for equal interval data acquisition. Each time a certain interval is covered, the I/O controller and the system controller are activated to permit differential measurement from the noncontact laser sensor. The differential measurements are then processed. An example of the roughness data is shown in figure 13. Longitudinal data are recorded on magnetic tape, which is then edited. The longitudinal roughness is represented by the standard deviations for the unit pavement sections.

Application System for Pavement Surface Condition Data

The application system is designed to provide necessary information for the effective implementation of pavement maintenance and rehabilitation programs. The analysis system efficiently and effectively applies the road surface condition data to the schedule of repair and rehabilitation treatments. It

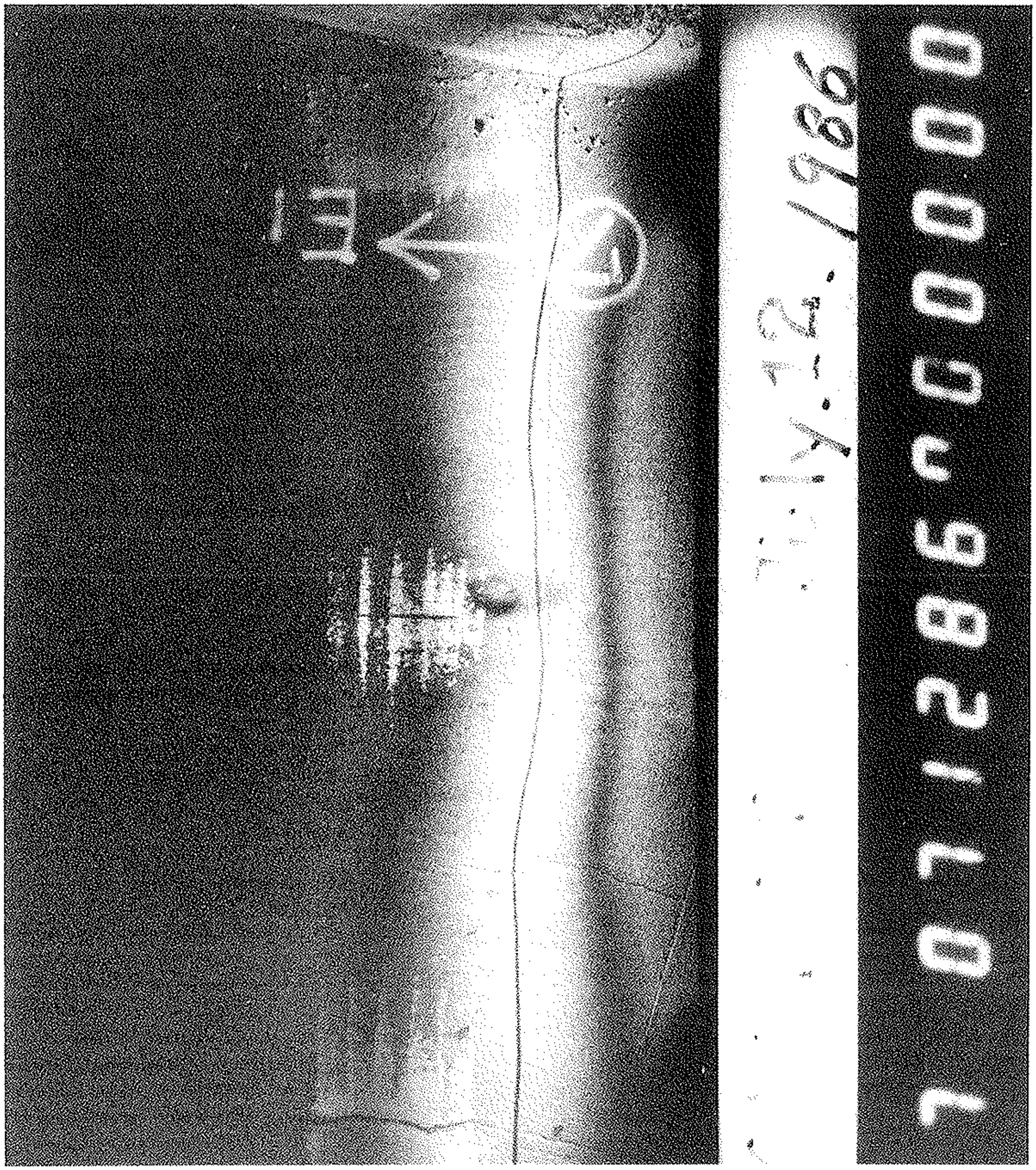


FIGURE 8 Example of photo taken by high-speed photographic recorder for rutting.

consists of the three parts which are explained further in the following sections in terms of concept, methodology, and present status of application.

Pavement Condition Evaluation System

In the past, many evaluation formulas were often based on regression analysis. AASHO road test design equations and the Japanese construction ministry evaluation formula are all based upon field experiments and statistical analysis. The regression type of analysis requires a large number of sample highway sections that are selected and evaluated for pavement conditions. Ultimately, the engineer expects to use the evaluation formulas to predict performance of the pavement system. Consequently, a relationship must be established to relate the subjective rater evaluations to the mechanical measurements of rutting, cracking, and roughness.

A long-term study was conducted in Japan to determine the relationship between the rater and the data collected with the equipment described above. Pavement evaluations were visually made to rate overall pavement conditions in five categories (A, B, C, D, and E) with five numerical values (5, 4, 3, 2, and 1). In general, these methods attempt to establish relationships between the evaluation values and the data obtained with the survey vehicle.

The first question concerning the relationship was whether human judgment is discriminative enough to distinguish among

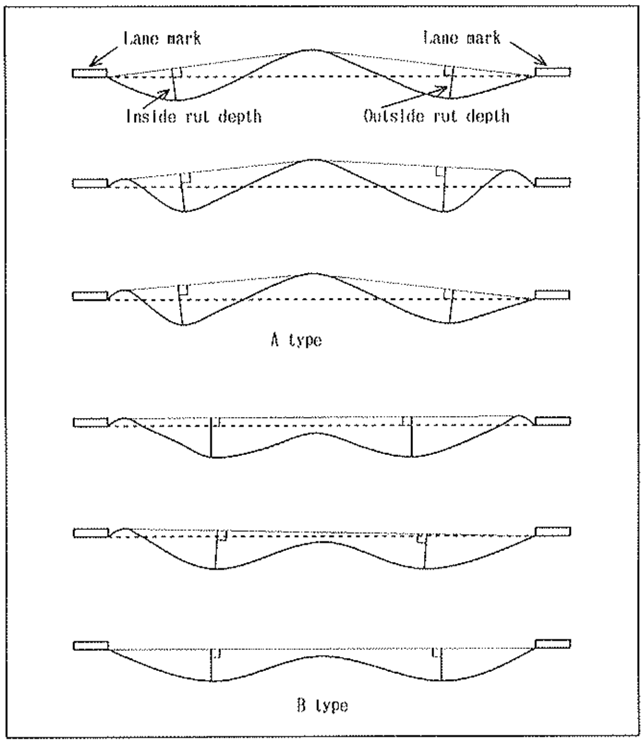


FIGURE 9 Definition of rutting volume (rut depth).

as many as five levels of condition. The study involved the one-pair comparison method, the Hayashi method, and the multidiscriminant analysis. It was concluded that the multidiscriminant analysis approach was the most rational method. It was determined that it is beyond human capability to discriminate rationally among five categories. Therefore, it was decided to use three levels for condition surveys.

This final selection of three levels was based upon a Japanese study involving fifty asphaltic, concrete pavement sections, which was used to form the basis for the development of evaluation formulas and predictive models in Japan. A panel of twenty-one expert highway engineers visually rated the pavements and ranked them into five categories. The same pavements were then evaluated with the equipment for rutting, cracking, and roughness. The data were studied with the multidiscriminant method. As is shown in figure 14, groups C, D, and E overlapped and were indistinguishable from each other. Therefore, in this study, it appeared more reasonable to combine C, D, and E into one group, F. This resulted in the formation of the three groups: A, B, and F.

Development of Performance Prediction Evaluation Formula

In the development of accurate, overall evaluation formulas, the reliability of visual observation by pavement ratios is a

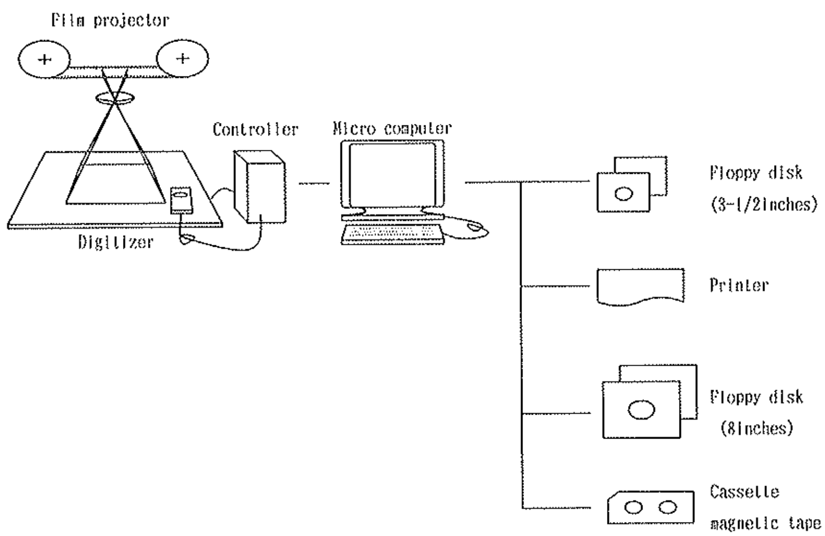
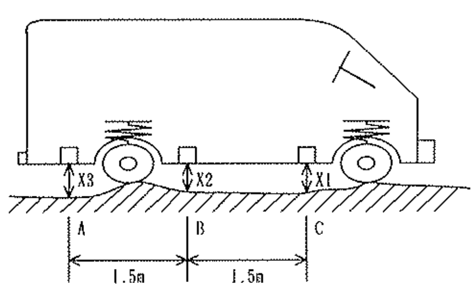


FIGURE 10 Film and data analyzer.



$$Xn = \frac{X1n + X3n}{2} - X2n \quad \text{Equation(3)}$$

X1n : Distance at 1st Sensor

X2n : Distance at 2nd Sensor

X3n : Distance at 3rd Sensor

n = Sampling No.

(n=1,2,3,4,...)

$$= \frac{L}{l} + 1$$

L :Evaluation Unit Length

FIGURE 11 Operating principle of measurement.

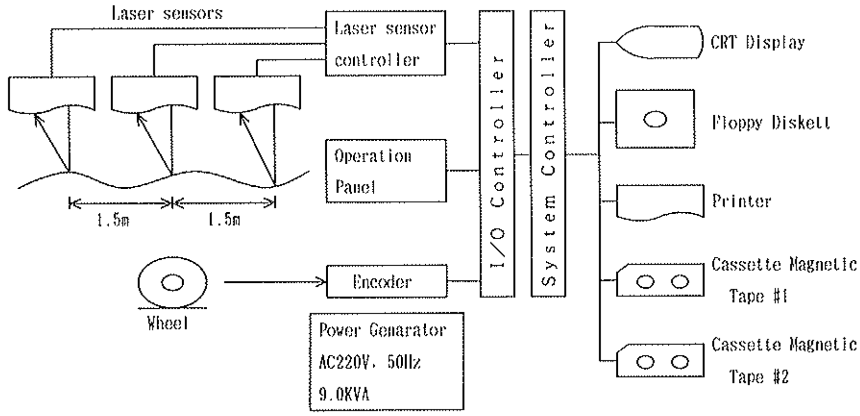


FIGURE 12 Configuration of longitudinal profile measuring device.

critical factor. Consequently, there was a need to examine the reliability of individual evaluation data. Individual visual evaluation ratings were compared in terms of correlation ratios. The ratings of inspectors with an exceptionally small ratio were deleted since they were considered unreliable.

In the next step, these visual ratings were related to the survey data on cracking, rutting, and longitudinal roughness by discriminant analysis (as discussed earlier). The relationship was then expressed as a polynomial. The formula, thus developed by discriminant analysis, was then compared with the one based on regression analysis. It was found that the multidiscriminant method performed better in matching visual ratings with manual data.

Example of Overall Evaluation Formula Development

Thirty-nine asphalt concrete pavement sections were studied in Switzerland during an investigation of the Japanese system. Eleven raters visually surveyed the pavement for overall condition rating. Subsequently, the pavement was surveyed with the equipment for cracking, rutting, and longitudinal roughness. The following formulas were developed from the discriminant analysis:

Asphalt Concrete Pavement

$$EVA = 5 - 0.0489X1 - 0.0279X2 - 0.1257X3 - 0.0532X4$$

PCC Concrete Pavement

$$EVA = 5 - 0.1306X1 - 0.0378X2 - 0.2915X3 - 0.2229X4$$

where

EVA = General evaluation rating,
$X1$ = Cracking (percent),
$X2$ = Rutting (mm),
$X3$ = Longitudinal roughness (mm), and
$X4$ = Pothole (percent).

Visual ratings by individual inspectors were compared by correlation ratios, as shown in table 1. It can be seen that inspectors 5 and 9 had exceptionally low ratio values. These ratings were determined to be biased and were, therefore, deleted.

In the next step, the data from the remaining eight inspectors were used for a discriminant analysis. A discriminative distribution of the data is seen in figure 15. The data were found to be distributed distinctly among A, B, and C.

The rates of matching (rates of samples whose categorization of visual evaluation ratings matches those of the evaluation formula) were sought and compared with the rates of matching obtained from the same data using an evaluation formula based on regression analysis. The results show that the rates of matching are higher for the evaluation formula based on discriminant analysis (66.7%) than for the formula based on regression analysis (60.2%).

Road Surface Condition Forecast System Model

To develop a forecast formula, road surface condition data values as they relate to the factors that are accountable to them were theoretically classified. The relationships, however, are actually extremely complex and almost impossible to explain (as discussed above). Therefore, an attempt was made to approximate a relationship by building a mathematical model that was simple but accurate enough to be applicable in a practical manner.

The model was constructed in the following manner. Assuming an arbitrarily chosen road section, i, with a potential for deterioration, D_i, and that the load it receives for the first year, α_2, results in cracking, C_{i1}, their relationships are expressed as

$$C_{i1} = \alpha_1 D_i$$

and similarly,

$$C_{i2} = \alpha_2 \alpha_1 D_i \quad \text{for the second year}$$

$$C_{ij} = \alpha_j \ldots \alpha_2 \alpha_1 D_i \quad \text{for the } j \text{ year}$$

and further,

$$C_{ij+1} = \alpha_{j+1} \alpha_j \ldots \alpha_2 \alpha_1 D_i$$

therefore,

$$C_{ij+1} = \alpha_{j+1} C_{ij}$$

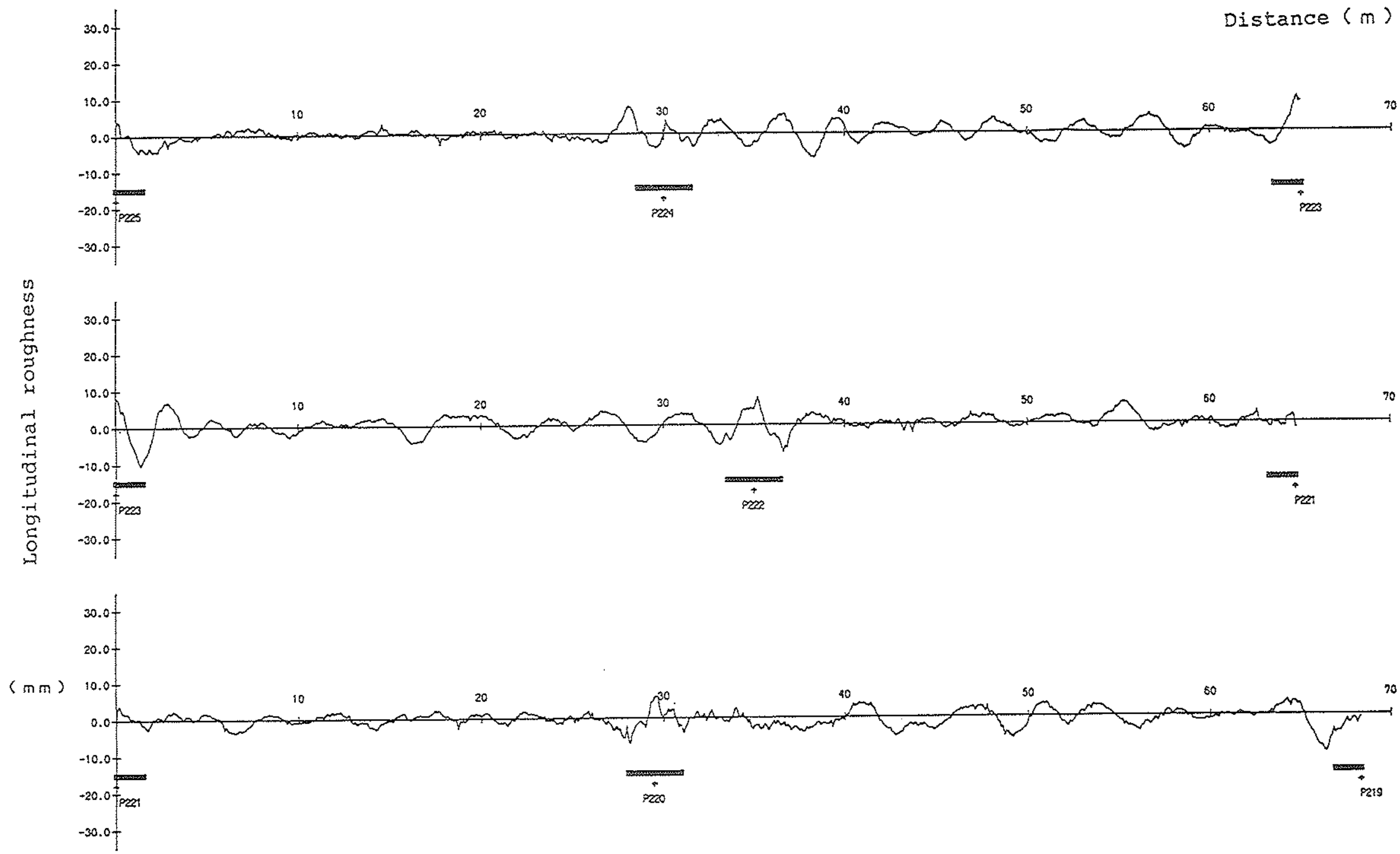


FIGURE 13 Longitudinal profile surveyed by three laser sensors.

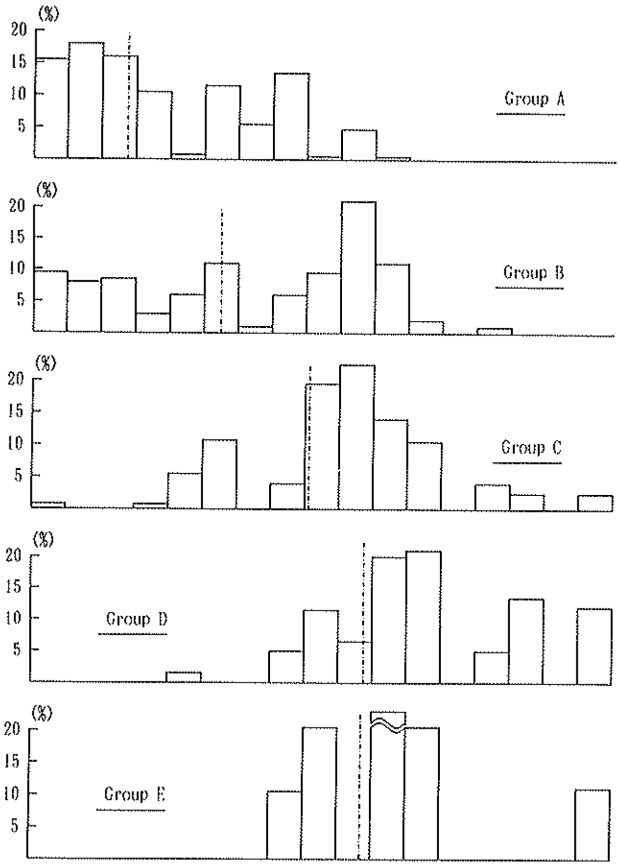


FIGURE 14 Frequency distribution of engineering judgment.

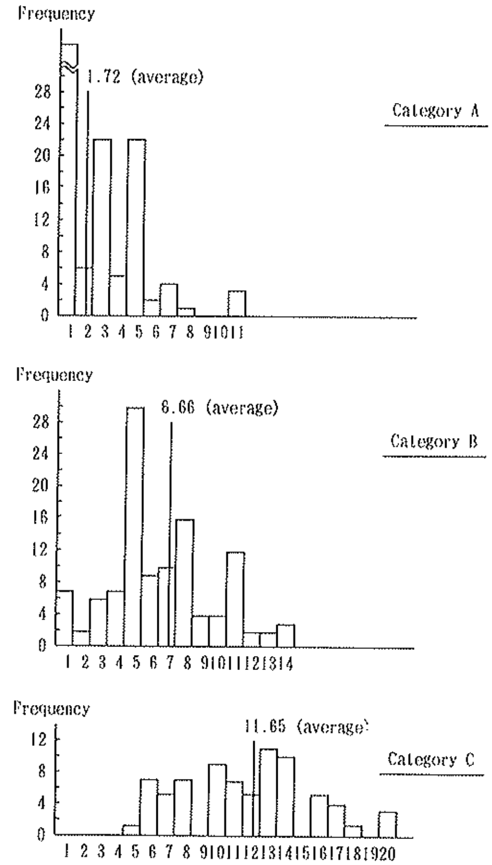


FIGURE 15 Frequency distribution.

TABLE 1 VISUAL EVALUATION DATA CORRELATION RATIO MATRIX

NO	1	2	3	4	5	6	7	8	9	10
1	1.000	0.880	0.779	0.863	0.529	0.898	0.908	0.797	0.543	0.690
2	0.870	1.000	0.743	0.891	0.651	0.817	0.870	0.847	0.553	0.833
3	0.749	0.733	1.000	0.767	0.435	0.569	0.834	0.852	0.507	0.646
4	0.872	0.920	0.842	1.000	0.575	0.870	0.910	0.847	0.495	0.720
~~5~~	~~0.542~~	~~0.671~~	~~0.450~~	~~0.576~~	~~1.000~~	~~0.468~~	~~0.542~~	~~0.586~~	~~0.557~~	~~0.449~~
6	0.889	0.818	0.683	0.871	0.434	1.000	0.857	0.705	0.480	0.714
7	0.908	0.880	0.855	0.917	0.529	0.829	1.000	0.887	0.461	0.690
8	0.790	0.857	0.858	0.882	0.579	0.712	0.884	1.000	0.501	0.638
~~9~~	~~0.497~~	~~0.518~~	~~0.461~~	~~0.556~~	~~0.556~~	~~0.446~~	~~0.442~~	~~0.457~~	~~1.000~~	~~0.391~~
10	0.694	0.870	0.659	0.703	0.442	0.807	0.694	0.634	0.414	1.000

TABLE 2 COEFFICIENT α: ASPHALT PAVEMENT

Year \ Crack (%)	0.0-0.9	1.0-9.9	10.0-19.9	20.0-29.9	30.0-
1	4.37	1.94	1.38	1.31	1.27
2	4.12	1.92	1.36	1.29	1.25
3	4.06	1.89	1.35	1.28	1.23
4	4.01	1.86	1.33	1.26	1.21
5	3.95	1.84	1.31	1.24	1.20
6	3.89	1.81	1.29	1.22	1.18
7	3.84	1.78	1.27	1.21	1.16
8	3.78	1.76	1.25	1.19	1.14
9	3.72	1.73	1.23	1.17	1.13
10	3.67	1.70	1.21	1.15	1.11
11	3.61	1.67	1.20	1.13	1.09
12	3.55	1.65	1.18	1.12	1.08
13	3.49	1.63	1.16	1.10	1.06
14	3.44	1.60	1.14	1.08	1.04
15	3.38	1.58	1.12	1.06	1.02
16	3.32	1.55	1.10	1.05	1.01
17	3.26	1.52	1.07	1.03	
18	3.20	1.49	1.05	1.02	
19	3.15	1.47	1.04		
20	3.09	1.44	1.03		

Coefficient α represents such factors as pavement structure, traffic volume, years in service, and surface deterioration. Of these factors, it can be assumed that traffic volume is, in general terms, proportional to the number of years the road has been in service and the deterioration as represented by cracking.

The coefficient α was expressed by a two-dimensional matrix of pavement structure, years in service, and cracking rate. Forecast values obtained from this table were examined, and results showed that forecast values projected three years into the future were good enough for practical application. Similarly, forecast formulas were developed for rutting and longitudinal roughness.

In 1977, 423 pavement sections were surveyed in Japan, and a matrix was developed for coefficient α with respect to cracking (tables 2 and 3). The values illustrated in tables 2 and 3 were used to forecast cracking rates for 1979. In 1979, the same road sections were surveyed, and the survey results were compared with the forecast values, as shown in table 4. The results show a close relationship, which is acceptable for practical application. The accuracy of the forecast formula was tested several more times with similar results.

Application of Forecast Formula

When the field survey of road surface conditions involves extensive lengths of pavements, in many cases, the entire roadway cannot be analyzed at one time due to budgetary constraints. In such cases, the entire road length can be equally

TABLE 3 COEFFICIENT α: CEMENT PAVEMENT

Crack (%) / Year	0.0-0.9	1.0-9.9	10.0-19.9	20.0-29.9	30.0-
1	3.70	1.63	1.25	1.18	1.14
2	3.68	1.63	1.24	1.18	1.14
3	3.67	1.62	1.23	1.17	1.13
4	3.66	1.62	1.23	1.17	1.13
5	3.65	1.61	1.23	1.16	1.12
6	3.63	1.60	1.22	1.16	1.12
7	3.62	1.60	1.22	1.16	1.11
8	3.69	1.59	1.21	1.15	1.11
9	3.59	1.58	1.21	1.15	1.11
10	3.57	1.57	1.20	1.14	1.10
11	3.56	1.57	1.20	1.14	1.10
12	3.54	1.56	1.19	1.13	1.09
13	3.53	1.56	1.19	1.13	1.09
14	3.51	1.55	1.16	1.12	1.08
15	3.50	1.55	1.18	1.12	1.08
16	3.48	1.54	1.17	1.11	1.07
17	3.47	1.53	1.17	1.11	1.07
18	3.45	1.52	1.16	1.10	1.06
19	3.44	1.52	1.16	1.10	1.06
20	3.42	1.51	1.15	1.09	1.06

TABLE 4 ACCURACY ANALYSIS OF CRACKING FORECAST

(Asphalt Pavement)

Cracking rate / Item	5.0-14.9	15.0-24.9	25.0-34.9	35.0-
Average ($\bar{x}$)	8.05	18.64	29.15	40.39
Standard deviation of error (σ)	2.84	2.87	4.87	3.45
$\sigma/\bar{x}$	0.35	0.15	0.17	0.09
Sampling size	179	30	12	14

(Concrete Pavement)

Rutting / Item	5.0-14.9	15.0-24.9	25.0-34.9	35.0-
Average ($\bar{x}$)	8.55	17.04	30.65	38.83
Standard deviation of error (σ)	2.59	1.84	1.32	3.68
$\sigma/\bar{x}$	0.30	0.11	0.04	0.09
Sampling size	66	36	24	18

TABLE 5 LIST OF SECTIONS TO BE REPAIRED

NO ROUTE NAME
1 ROUTE 16 (GUIDE LINE >= 1 L = 300m / 500m)

NO	CP NAME	DIS. KP	L.	CR	PH	RD	SO	SR	DEF	EVA		
10	KP151	100	500	7.2	0.02	16	3.71	0.39	1.54	3.75	100	6
10	KP151	600	594	1.6	0.00	23	2.85	0.67	0.82	3.86	100	6
1	KP146	0	500	0.5	0.00	24	3.35	0.29	0.73	3.68	100	6
1	KP146	2000	502	0.6	0.10	16	3.14	0.32	0.77	4.17	100	6
6	KP149	500	583	0.1	0.00	16	1.20	0.65	1.61	4.38	100	6
7	KP149	1100	500	0.1	0.08	22	3.02	0.48	1.19	4.00	100	5
7	KP149	1600	508	0.8	0.14	19	3.38	0.08	1.41	4.00	100	5
13	KP152	200	500	1.1	0.02	21	2.29	0.81	0.46	4.08	100	5
1	kP146	500	500	0.4	0.03	17	2.83	0.31	0.31	4.14	100	5
7	KP149	600	500	0.2	0.00	18	2.69	0.82	2.05	4.14	100	5
7	KP149	100	500	0.5	0.02	19	2.38	0.24	0.60	4.14	100	5
1	KP146	1500	500	0.0	0.00	13	1.64	0.50	0.50	4.43	100	5
1	KP146	1000	500	0.1	0.02	9	2.34	0.87	0.87	4.45	60	3

NO. 1 ROUTE NAME: D ROUTE 16

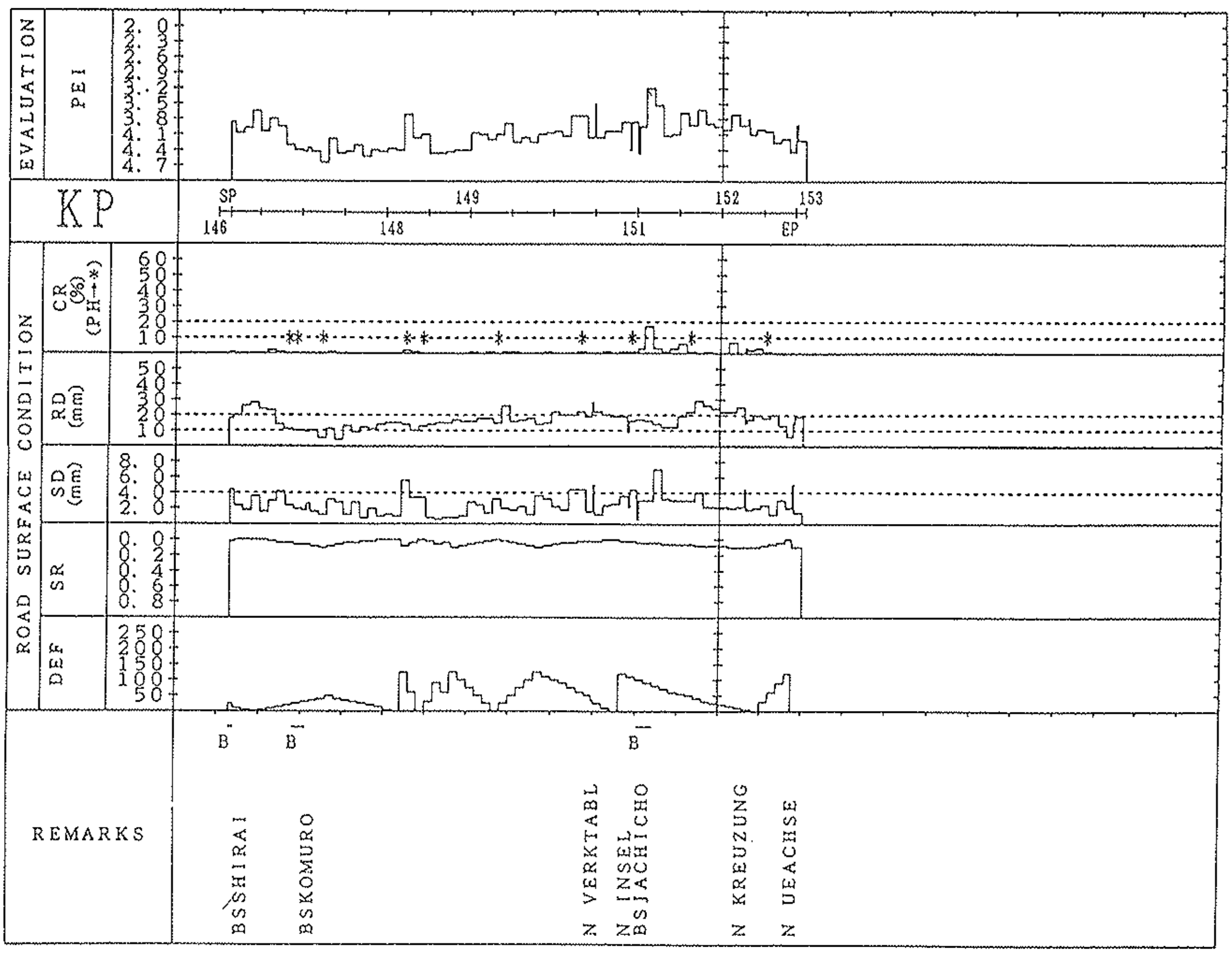


FIGURE 16 Pavement performance chart.

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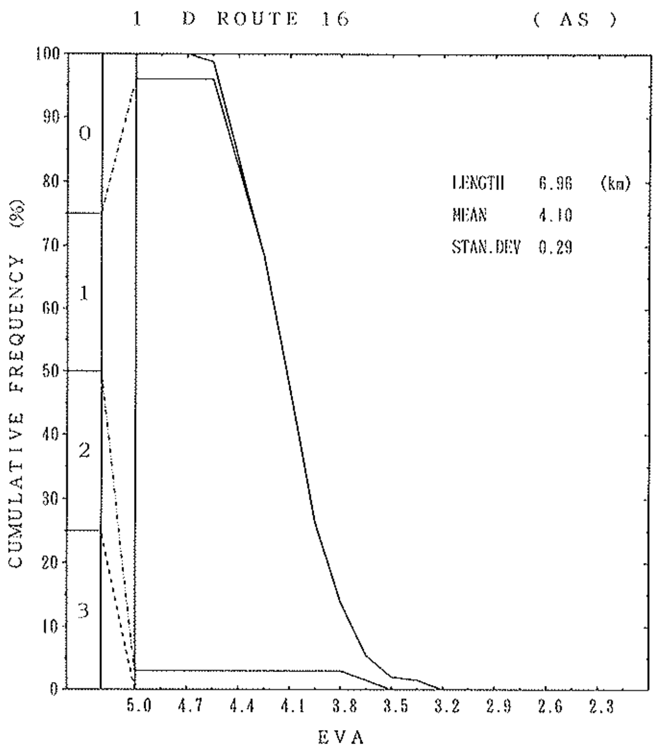

FIGURE 17 Cumulative frequency diagram.

divided into three parts, so that surveying can be conducted on one part while forecasting is done on the remaining two-thirds. Thus, the entire length of the road is constantly and conveniently monitored in one way or another.

In order for the highway agency to make the best use of the limited funds available each year for pavement maintenance and repairing, it is important for it to determine efficiently and effectively the locations of highway sections which require maintenance. The methodology used to identify such locations consists of (1) identifying from the pavement surface condition data those sections of the road that require maintenance and repair; (2) establishing priority for each of the road sections on the basis of overall evaluation data; and (3) combining both of these techniques, which results in the selection of the road sections for which maintenance and repair will be conducted.

In order to facilitate this procedure, pavement performance charts (figure 16) can be developed. Cumulative frequency diagrams from overall evaluation data (figure 17), a list of sections to be repaired, and a tabulation of overall evaluation data (table 5) can also be developed.

CONCLUSION

Based upon this study, the following conclusions can be made:

1. It is possible to photograph a continuous section of pavement using a 35-mm slit camera. The photographs can be digitized and a surface condition survey can be obtained from the photos.
2. A pulse camera can be used to measure rut depths in a pavement. The data can be digitized from the photos.
3. The surface condition slit camera and the pulse camera can be mounted on a single vehicle with laser sensors so that rutting, surface condition, and roughness can be measured at highway speeds with one vehicle.
4. Visual conditions survey data can be related to field measurements with a multidiscriminant analysis method. The data can then be used to develop prediction formulas for pavement rehabilitation and repair scheduling.

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