Development of the three-dimensional road surface measurement technology by the high-speed road surface measurement vehicle

T. Kijima, N. Miya & H. Katakawa
Central Nippon Highway Engineering Tokyo Company Limited

ABSTRACT: We have developed technology that incorporates Inertia Measurement Unit (IMU) and Global Positioning System (GPS) data with an existing high-speed road surface measurement vehicle, enabling detailed measurements of extensive three-dimensional road surfaces at any speed up to a maximum of 100 km/h (60 mph).
This measurement technology can be used in place of leveling to regulate conventional traffic lanes, with the benefits of both ensuring safe measurements and eliminating any inconvenience to road users.
It also allows for swift and accurate measurement of deteriorating road conditions and areas where structures are subject to impact shocks, standing water on road surfaces, driving safety, and disaster prediction, from which problematic areas can be identified and evaluated, leading to enhanced repair strategies and designs for roads.
Since 2004, we have measured in excess of 3,400 km of road surfaces at 187 locations.
In future, we will strive to implement additional tasks beyond the existing measurement targets, measurement in low-speed regions, and designing both up and down lanes at the same point, which have proved impossible until now.

KEYWORDS: GPS, IMU, three-dimensional, repair strategy, repair design.

1. Introduction

Expressways in Japan are periodically inspected to check their road surface properties (rutting, cracks, international roughness index (IRI), etc.) in order to maintain good surface conditions. Vehicles that can measure the road surface while traveling at high speed have been developed and put into service to prevent causing congestion and minimize the risk of accidents during inspection. In recent years, expressway corporations have investigated a Pavement Management System (PMS) that takes into account various kinds of road surface evaluation data, as well as the conventional control standards shown in Table 1, to draw up highly detailed pavement repair plans.

Deformation of road surfaces, such as are caused by the road settlement at the boundary between a bridge and earthworks and between cut and embanked sections, becomes increasingly apparent the longer the roads are used. Such deterioration not only makes the road uncomfortable to drive on, but may also aggravate damage to road structures and deterioration of the roadside environment. Poor longitudinal and cross-sectional profiles caused by such settlement may also inhibit the smooth discharge of rainwater, resulting in water remaining on the road surface, which destabilizes and endangers driving. Therefore, understanding the longitudinal and cross-sectional profiles of the road surface is essential to construct an advanced PMS.

Deformation of road surfaces over relatively long distances has ordinarily been measured by restricting lanes. Thus, measurement has been difficult on heavy traffic routes such as the Tomei and Meishin Expressways because any lane restriction is likely to cause congestion, and on sections with temporary service, where the traffic volume may be small but taking the measurements can be dangerous.

Against such a background, we developed a system that can measure the three-dimensional profiles of the road surface while traveling at speeds of up to 100 km/h without needing to restrict lanes. This was achieved by adding a global positioning system (GPS) and an inertial measurement unit (IMU) to the vehicles previously developed by us to measure road surfaces. This system has been used since 2003.

Similar road surface measuring vehicles equipped with GPS and IMU are available. No organization other than us, however, has used these measuring vehicles to conduct longitudinal and cross-sectional measurements on expressways under the control of NEXCO group companies. The measurement technology has no compare anywhere else in the world.

This paper gives an overview of the technologies used in the new road surface-measuring vehicle and exemplifies various utilization methods, such as for leveling during restoration works, which was established by subsequent improvements and investigations.

Table 1: Target values in road surface repairs adopted by expressway companies

	Rutting (㎜)	Level difference (㎜)		Skid resistance coefficient (μ V)	Roughness (σ 3m) or IRI (㎜/m)	Cracking ratio[a] (%)
		Joint to a bridge	Joint to a traverse structure			
National expressways Motorways	25	20	30	0.25	3.5	20

[a] We analyzed the road in one-meter* sections – a quarter of the lane width.
Then the cracking ratio was calculated as the number of sections with cracking divided by the number of sections analyzed.

2. Overview of the technologies

2.1 Vehicle for measuring road surfaces (Pavemeter Ver. IV)

In 1982, we developed the first version of the road surface-measuring vehicle, whose technology was assessed and approved by the then Ministry of Construction (present-day Ministry of Land, Infrastructure, Transport and Tourism) in 1983. The vehicle has undergone various improvements ever since. The vehicle used today can measure: 1) rutting, 2) cracking, 3) international roughness index (IRI), 4) flatness (σ3m), and 5) longitudinal and cross-sectional profiles; all simultaneously while traveling at speeds of up to 100 km/h, and thus does not cause traffic congestion. (Photo 1) (Table 2) (Figure 1)

Photo 1: New road surface-measuring vehicle “Pavemeter Ver. IV”

Table 2: Basic specifications of the "Pavemeter Ver. IV"

	Measuring method	Detecting device	Range of measurement	Measurement intervals (longitudinal)	Precision of measurement
Rutting	Multiple-point displacement measurement method	CCD camera	5.2 m (0.1-m intervals)	0.5m、1m、10m、20m	Not exceeding ±2 mm
Cracking	Continuous photographing	Streak camera	4.5 m	Continuous	Width: 1 mm or larger
IRI	Double integration of acceleration	Non-contactlaser displacement meter	One survey line (OWP)	0.1m	Within ±15%
Flatness σ 3 m	Non-contact 3-m profile meter	Non-contact laser displacement meter	One survey line (OWP)	1.5m	Within ±15%
Longitudinal and cross section profiles	Global positioning data/ Inertial measurement unit	GPS/IMU	5.2m (0.1-m intervals)	0.5-m intervals	Mean vertical error: ±11 ㎜

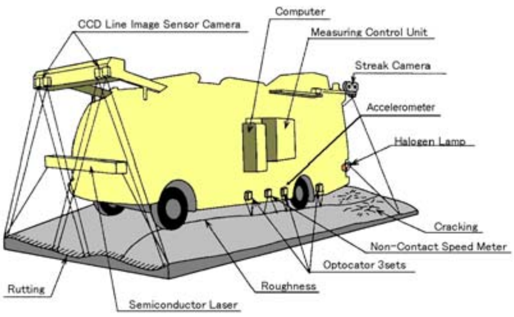


Figure 1: Schematic diagram of the "Pavemeter Ver. IV"

2.2 Rut-measuring device

In the development of a three-dimensional road surface measurement system, the most critical of the existing technologies was the multiple-point displacement measuring technique used in the rut-measuring device, which has been used since our first road surface-measuring vehicle was developed in 1982. The technique requires a device with a complicated structure, which is thus difficult to calibrate, but it was the only mean by which we could obtain the correct vertical coordinate across the traveling direction at the necessary points, which is achieved by distance pulse control. Therefore, this technology was a prerequisite for the establishment of a three-dimensional road surface measurement system able to function at high speeds. The technology is described below.

The rut-measuring device consists of two laser slit projectors at the front of the vehicle and line sensor cameras. Each of the laser slit projectors projects 54 beams of light at 100-mm intervals across the road, with the two projectors combined covering a width of 5.2 meters. The light beams are projected diagonally toward the road surface, and thus the resultant shadows due to unevenness in the road surface are cast left and right. Their movement is detected by the line sensor cameras installed on the top of the vehicle. Because the positions from which the laser light beams are projected, the projection angles, and the angle of the line sensor cameras are mechanically determined, the changes in the positions of the light beams are monitored as observed angles, and the positions of the light beams (unevenness of the road surface) can be determined as intersections between projection and observation lines using the following equations (Figure 2).

$$Ys = \frac{\tan(\theta_1)\cdot Y_1 - \tan(\theta_m)\cdot Yc + X_1 - Xc}{\tan(\theta_1) - \tan(\theta_m)} \quad (1)$$

$$Xs = -\tan(\theta_1)\cdot(Ys - Y_1) + X_1 \quad (2)$$

where:

Xs, Ys: coordinates of light beam,

Xc, Yc: central coordinates of the lens of line sensor camera,

X1, Y1: central coordinates of the light projected from laser slit projector,

θ1: projection angle of laser slit light, and

θm: observation angle of light beam.

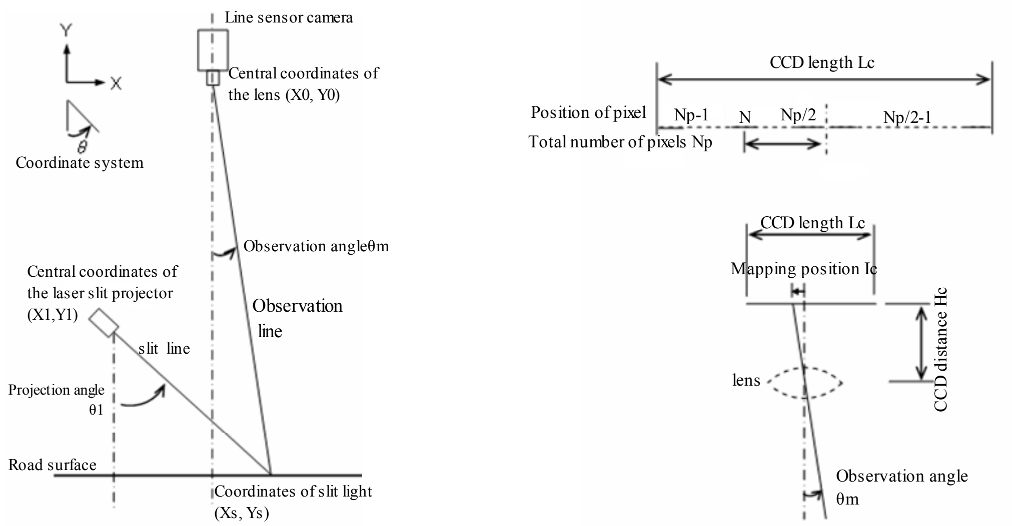
The observation angle is determined from the mapping position of the CCD (Charge Coupled Device) pixels of the line sensor camera by the following equations.

$$lc = \frac{Lc}{Np} \times \left[N - \frac{Np-1}{2} \right] \tag{3}$$

$$\theta_m = \tan^{-1}\left[\frac{lc}{Hc} \right] \tag{4}$$

where:

lc: mapping position, Lc: CCD length,
Np: total number of CCD pixels,
N: mapping position of pixel, and
Hc: distance between CCD and the lens.



a) Principle of measurement b) Observation angle and mapping position of pixels

Figure 2: Principle of rutting measurement

High resolution is achieved by using a CCD that features as many as 5,150 pixels. Mechanical errors and optical strain of the lens are corrected by the measuring control unit and host computer, and excellent overall precision of ±2 mm is achieved.

In order to measure rutting, a measuring range of about ±100 mm was considered necessary to deal with the unevenness of the road surface and vibration of the vehicle. Such a large measuring range causes light beams projected at 100-mm intervals to interfere with the adjacent beams. The system manages to achieve a measuring range of ±100 mm while retaining the small cross-sectional measuring intervals by emitting alternate beams of red (690 nm) and infrared (780 nm) light and detecting the beams using line sensor cameras with optical filters installed that preclude one of the wavelengths (Photo 2).

Photo 2: Exterior view of the vehicle in measurement mode
Note: Only the 26 red light beams are visible (690 nm @ 200 mm)

The system can determine the vertical coordinates of the road surface across the traveling direction independently from the traveling speed by sampling 54 light beams simultaneously, which minimizes the effects of vehicular vibration while traveling at high speeds.

2.3 Longitudinal and cross-sectional measuring technology using GPS and IMU

The basic technology for this measuring system is kinematic GPS under the interferometric positioning method, which involves conducting measurements at unknown observation points using a traveling vehicle, receiving signals from GPS satellites based on known fixed electronic datum points, movable ground stations and virtual reference stations, and correcting errors using the phases of the carrier waves. Moreover, the inertial measurement unit (IMU), which consists of a triaxial optical gyro and three silicon accelerometers, precisely records the position and inclination of the vehicle at 200 Hz. The post-processing system combines the resultant longitudinal and cross-sectional measurements, enabling the road surface to be precisely assessed in three dimensions (at 0.5-meter intervals longitudinally and 0.1-meter intervals across the road) (Figure 3).

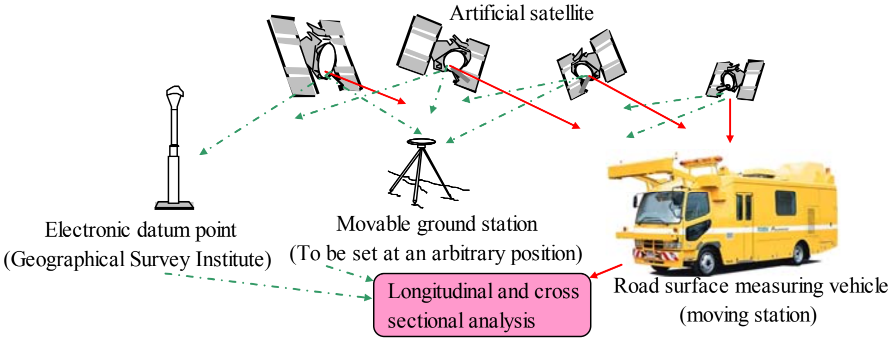


Figure 3: Kinematic GPS measurement using the road surface-measuring vehicle

A prominent characteristic of the system is that the IMU technology enables the road surface to be measured even in areas where GPS satellite signals are weak, such as in steeply sided sections, near tall noise barriers, and underneath overhead bridges, as well as in places devoid of signals, such as in tunnels.

Coordinates are determined by calculating the origin of measurement (X0, Y0, Z0) from the position of the IMU in relation to the vehicle axis, which is determined from the position of the unit and the posture data of the vehicle (pitching, rolling and direction), adding the calculated rutting data (0, Yn, Zn) to the origin, and computing the position of each laser beam (Xi, Yi, Zi). From this position (Xi, Yi, Zi) and the data of the posture of the vehicle, the coordinates are converted into those of the North-East-Down coordinate system* to calculate the absolute coordinates of the points (three-dimensional data link; Figure 4).

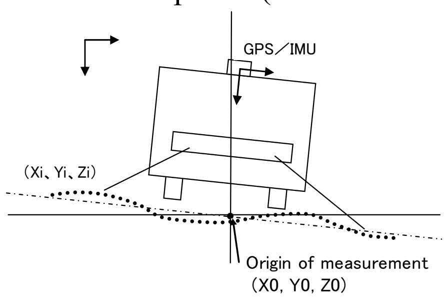


Figure 4: Schematic diagram of three-dimensional data link

*North-East-Down coordinate system

North axis: Line that passes through the origin, is on a plane parallel to the tangent plane to a reference ellipse at the geographical position of the origin, and is positive towards true north

East axis: Line on the same plane as that of the North axis and is positive toward the east

Down axis: Line that is positive vertically downward to the NE plane

The kinematic method is believed to be accurate to within about 2 to 3 cm. However, this measurement system achieves vertical errors caused by relative displacement of only 11 mm on average with the post-processing system and IMU correcting the GPS data and thus improving precision. The accuracy has been confirmed on expressways in service. This degree of precision is likely to be adequate to understand changes in the three-dimensional profile of road surfaces from the time of completion, but errors are further minimized by installing temporary benchmarks.

3. Use on expressways

3.1 Identifying and assessing points that require particular improvement

The measuring system has enabled important information, which leads to advanced PMS, to be collected without restricting lanes. This section exemplifies its utilization.

(1) Measuring expressway sections that are uncomfortable to drive on and of large impacts on structures

The earth works section before the abutments of a bridge subsided resulting in the road surface having a steep incline toward the bridge. Thus, this section was uncomfortable to drive on, causing concern about the horizontal and vertical impacts on the bridge. Elevation measurements revealed that a short transition area would be insufficient and provided information on the appropriate improvement area (Photo 3, Figure 5).

Photo 3: Bump in the road and impact on the structure

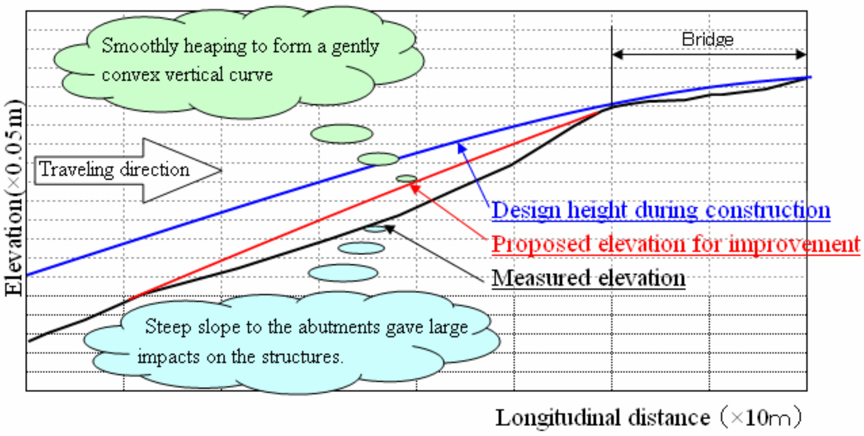


Figure 5: Determination of the present longitudinal profile and a proposed improvement plan

(2) Detecting points prone to puddle formation

Sections of cross-sectional profiles that would result in poor discharge of water were detected to identify sections that were prone to collecting water when it rains, which would cause passing vehicles to splash water (Figure 6 and 7).

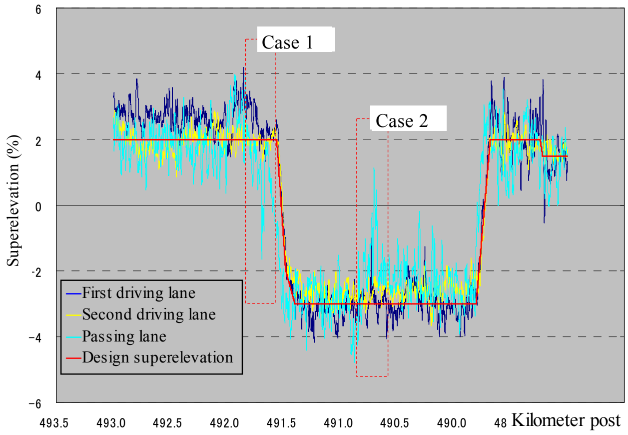
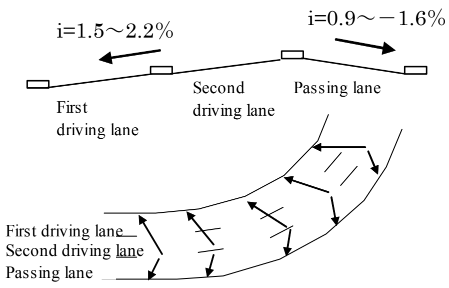
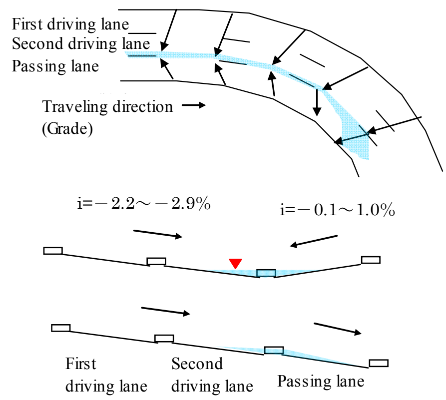


Figure 6: Detecting points of puddle formation from cross grade diagrams



Case 1
Specifying points where the grade of the passing lane is adverse



Case 2
Extracting points where the cross grade changes from “bucket (bad)” to normal and water film is formed

Figure 7: Detecting poorly graded sections and points prone to collecting rainwater

(3) Assessing driving safety

The driving safety was assessed by measuring the cross super-elevation to extract points where the resistance toward the valley side dropped during rains (Figure 8).

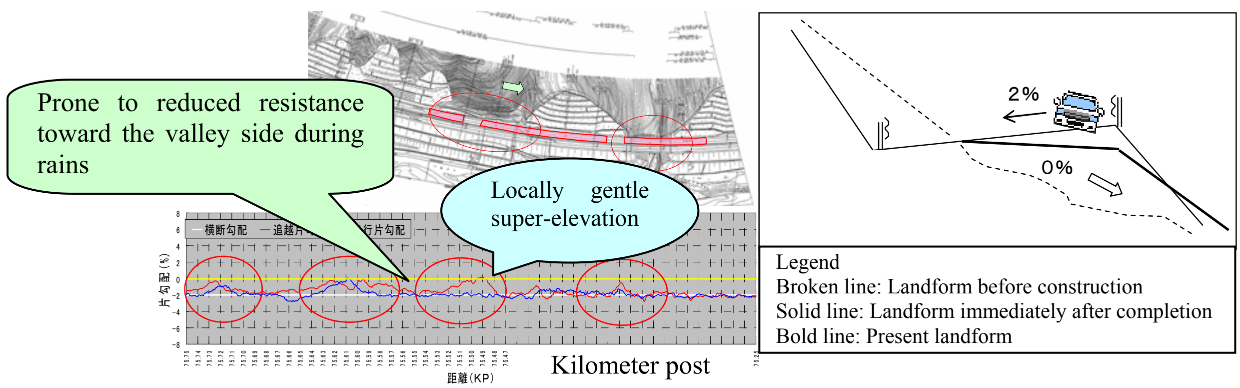


Figure 8: Assessing driving safety by measuring cross super-elevation

3.2 Restoration of expressways damaged by earthquakes

The three-dimensional road surface measurement system was used to help design the restoration of the road surface on the Hokuriku Expressway, which was damaged by the Niigata Chuetsu-Oki Earthquake (M 6.8) in July 2007.

(1) Conditions, needs and problems of the site and effects of the system

Conditions

Level differences of up to 50 cm were generated between structures and earthworks along many sections of the Hokuriku Expressway in the area affected by the earthquake (Photo 4). Emergency work was conducted to tentatively restore the highway (speed limit: 50 km) with lane restrictions in some sections to enable the road surface to be measured using the system

Photo 4: Hokuriku Expressway immediately after the Niigata Chuetsu-Oki Earthquake

Needs and problems of the site

The damage to the expressway needed to be quickly identified and restored. Moreover, drawings of the road surface after the emergency repairs, which were scheduled to be executed after the first temporary restoration works and completed before the first snowfall, were needed for the full-scale restoration project that was to start in the spring of the following year.

In conventional designs to modify the longitudinal and cross-sectional profiles of road surfaces, leveling has been performed while regulating traffic in the section being maintained. However, ordinary leveling would: 1) take too long to understand the condition of the damaged section, as it was 23 km long (with a total lane length of 92 km), and 2) not be able to prepare the necessary drawings for designing the full-scale restoration works if the leveling was to be performed after completion of the emergency repairs.

Effects of the system

The new road surface-measuring vehicle was used to measure the longitudinal and cross-sectional profiles about one month after the earthquake when traffic control was temporarily eased for road users during a busy season. The data was used to understand the road surface condition, identify sections that needed improvement, and design the improvements. The system was found to have the following benefits:

1) Highly detailed measurements of the coordinates of the temporarily restored road surface (speed limit: 50 km) were completed in only two nights, which ensured safety while taking the measurements and avoided disturbing regular traffic.

2) Comprehensive assessment using changes in longitudinal and cross-sectional profiles from the time of completion (visual evaluation) and simultaneously determined IRI values (numerical data) enabled efficient and effective assessment of the road surface and efficient and effective identification of sections that required improvements (Figure 9).

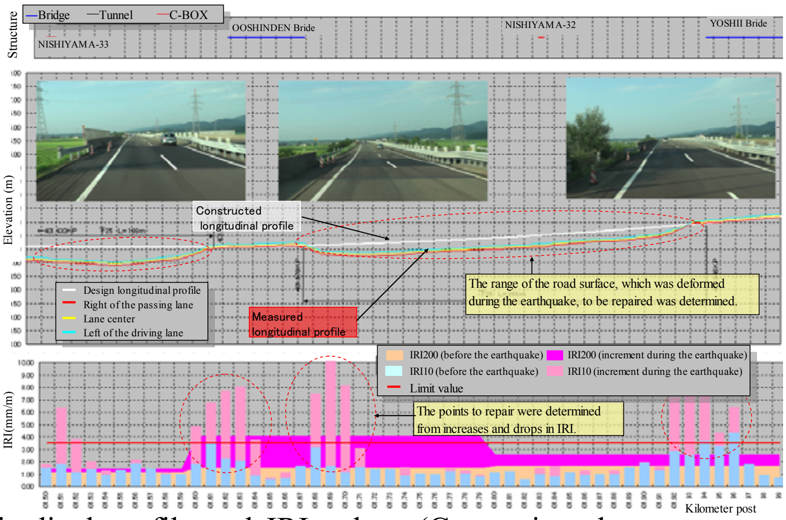


Figure 9: Longitudinal profile and IRI values (Comparison between before and after the earthquake)

3) The design modification aid system for the three-dimensional road surface measurement system enabled drawings for full-scale repairs to be completed quickly and before completion of the emergency repairs by estimating values after the completion of such repairs from those measured in the middle of the process and substituting them for ground values in the subsequent process (Figure 10 and 11).

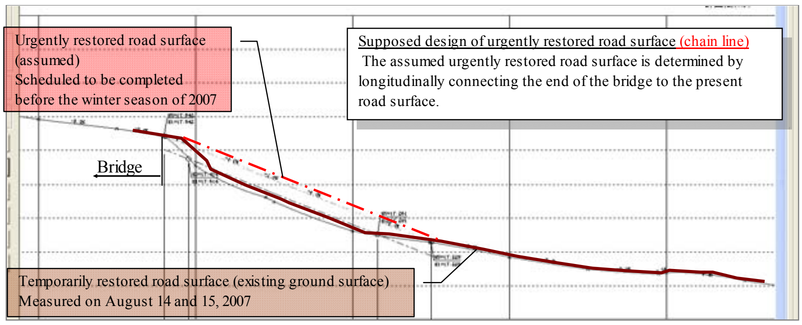


Figure 10: Temporary and emergency repairs to road surface

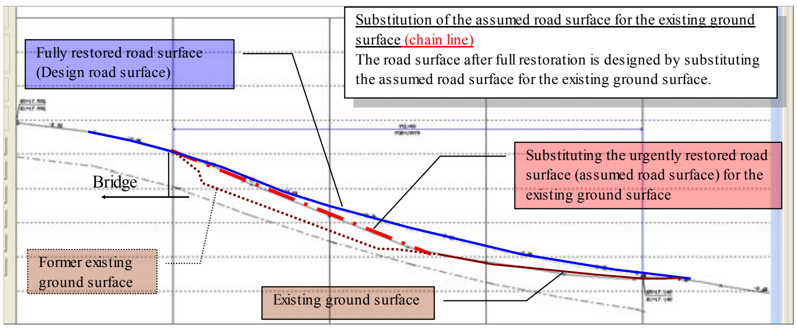


Figure 11: Emergency repairs and fully restored road surface

(2) Example of longitudinal and cross-sectional design modification

Several display images of the system while designing the profiles are shown in Figure 12. The longitudinal and cross-sectional profiles were designed so as to satisfy the standards (minimum radius of vertical curve or design speed for 100 km/h and vertical curve length) specified in NEXCO’s design guidelines, to approximate the cross slope to that at the time of initial construction, and to improve driving comfort.

Figure 12: Example of modification design
(Three-dimensional diagram of the road surface, design longitudinal profile and design cross-sectional profile)

4. Conclusions

The three-dimensional road surface measurement system on a new measurement vehicle can measure and assess the present longitudinal and cross-sectional profiles of the road surface, and the measurements can be used to improve designs (profile modification) when restoring road surfaces that have been deformed by settlement of weak ground or earthquakes. The system is a completely new technology for measuring and designing road surfaces as it not only measures changes in road surface conditions, but can also use the measured coordinates as design data – unlike conventional methods, which only compare road surface data, such as rutting, cracks and IRI, with standard values.

The system has numerous advantages over leveling, which requires lane restrictions, including: 1) ensuring safety while taking measurements, 2) maintaining traffic convenience by not restricting lanes while reducing the risk of congestion and traffic accidents, 3) improving the efficiency and reducing the costs of taking measurements by enabling long sections to be measured quickly, 4) facilitating the work involved when ordering improvement projects, and 5) increasing the precision of road maintenance technologies through comprehensive assessment with conventional road control indices.

The system has already been developed and is in use on actual roads. With the original design modification aid system, the system can estimate future ground surface conditions from its measurements and calculate the costs for different profile designs freely. It has been used to measure the profiles of some 3,400 km of roadway, and design surface modifications for 187 sections.

The system still has several points to be improved, such as: 1) ranges outside the measurement width of 5.2 m need to be designed using estimated values, 2) it is difficult to measure sections at low speeds, such as at ramps, due to the properties of the measuring instruments, and 3) up and down lanes cannot be designed as a single profile due to measurement properties. These topics will be actively investigated.

Acknowledgements

The authors wish to thank staff at NEXCO Group for providing precious advice, photographs, and other references.

REFERENCES

1) Takeishi, A., 2004. *The Recent trends of GPS technology and Its Future Use in the Field of Surveying*. Soils & Foundations, 52-6, Japan

2) Ohashi et al., 2007. *Utilization of moving-GPS-based three-dimensional road surface measurement technology for highway maintenance and control (in Japanese)*, Proceedings of the 27th Japan Road Congress, Japan

3) Toyama et al: 1997. *Development of road surface measuring vehicle (in Japanese)*, Technical Bulletin of Mitsubishi Heavy Industries, Vol. 34-2, Japan