The Accuracy of Road Surface Profilers in TRUE Project
Experiment to Compare Test Methods for Surface Roughness under Actual Road Environment

Kazuya TOMIYAMA, Dr. Eng., Assistant Professor *
Department of Civil and Environmental Engineering
Kitami Institute of Technology
165 Koen-cho, Kitami, 090-8507 Japan
Tel/Fax +81-157-26-9496; tomiyama@mail.kitami-it.ac.jp

Hiroyasu NAKAMURA, Research Engineer
NIPPO Corporation
6-70 Mitsuhashi, Nishi-ku, Saitama, 331-0052, Japan
Tel +81- 48-624-0755; nakamura_hiroyasu@nippo-c.jp

Hiroyuki MASHITO, Senior Researcher
Toa Road Corporation
315-126 Kaname, Tsukuba, 300-2622, Japan
Tel +81-29-877-4150; h_mashito@toadoro.co.jp

Masakazu JOMOTO, Dr. Eng., Researcher
Taisei Rotec Corporation
1456 Oaza-Kamiya, Konosu, 365-0027, Japan
Tel +81-48-541-6511; masakazu_jomoto@taiseirotec.co.jp

Kazuhiro WATANABE, Senior Researcher
Public Works Research Institute
1-6 Minamihara, Tsukuba, 305-8516, Japan
Tel +81-29-879-6789; k-watanabe@pwri.go.jp

* Corresponding author

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ABSTRACT

A number of surface roughness measuring devices has been introduced in Japan since the Road Bureau of Ministry of Land, Infrastructure, Transport and Tourism has issued a strategy for inspection of the whole road stock and has provided an implementation guide for evaluating roughness by means of the International Roughness Index (IRI) in 2013. Against this background, the specified nonprofit organization Pavement Diagnosis Researchers Group (PDRG) in Japan conducted the experiment to compare test methods for surface roughness under actual road environment (TRUE Project). Thirty-four devices including high- and low- speed profilers and response type systems participated in the first experiment of the project held at Hokkaido, Japan in 2014. This paper analyzes the accuracy of the high- and low speed profilers in terms of repeatability and reproducibility as well as portability for both IRI and profile measurements. The influence of operating speed on the measurements is also considered for the high-speed profilers. The final purpose of this study is to provide the essential information for associating different profilers so that profiler users and developers can assess the accuracy of each profiler to produce standard measures of roughness to interchange inspection results. For this purpose, we demonstrate a tolerance of the repeatability, reproducibility, and portability and the influence of operating speed for the high-speed profilers in respect to the IRI and profile measurements obtained in the experiment. The information described in this paper is of benefit to profiler developers as well as users for development and improvement of their profilers.
INTRODUCTION

Surface roughness is a critical concern of road users as well as administrators because it degrades not only structural but also functional performance of a pavement. In today’s socio-economic situations, as pavement infrastructures have aged, road administrators are obliged to monitor their pavements to locate unacceptable surfaces in terms of the roughness for the welfare of road users. The Road Bureau of Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan has issued a strategy for inspection of the whole road stock and has provided an implementation guide for evaluating roughness by means of the International Roughness Index (IRI) since 2013.

The strategy has accelerated the development of a large variety of roughness measurement devices corresponding to the needs for inspection purposes. As a result, the relationship between each measurement obtained with different devices on the same profile has become an important matter of profiler users to provide standard measures of roughness. In the light of this background, the specified nonprofit organization Pavement Diagnosis Researchers Group (PDRG) in Japan conducted the experiment to compare Test methods for surface Roughness Under actual road Environment (TRUE Project) since 2014.

A well-known experiment to compare profile measures is the EVEN project performed by the Permanent International Association of Road Congresses - World Road Association (PIARC), which was conducted in the United States, Japan, and Europe [1-4]. Seven devices participated in the second experiment of the project conducted in Japan in 1998 [3]. After 16 years, in the TRUE project, 34 devices including high- and low-speed profilers, and response type systems participated in the first experiment in 2014. Forty-four participants from twenty-five organizations including academies, industries, and governments took part in the experiment. This enthusiastic participation in the experiment infers a great concern and demand for the roughness investigation and its methods.

The TRUE project received profile and IRI measurements obtained with high- and low-speed profilers, and IRI measurements obtained with response type systems after the experiment. For each test section, the reference profiles were measured using hand-operated profiling devices that were verified prior to the experiment. This paper analyzes the accuracy of the high- and low speed profilers in terms of repeatability and reproducibility as well as portability for the IRI and profile measurements. For the high-speed profilers, the influence of operating speed is also analyzed. Table 1 summarizes the condition of the analysis such as the type of error (random or systematic), comparison factor (within or between devices), and data averaging method. The analysis is intended to evaluate the profilers rather than response type systems. IRI is used as the roughness index for the evaluation. Profile measurements are assessed by means of profile agreement between a pair of different measurements based on the cross-correlation method [5]. The final purpose of this study is to provide the essential information for associating different profilers so that profiler users and developers can assess the
accuracy of each profiler to produce standard measures of roughness to interchange the inspection results.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Condition of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Error</strong></td>
<td><strong>Comparison Factor</strong></td>
</tr>
<tr>
<td>Random</td>
<td>Within</td>
</tr>
<tr>
<td>Systematic</td>
<td>Between</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**OVERVIEW OF THE EXPERIMENT**

**Test Sections**

The first experiment of the TRUE project was performed on four test sections in Hokkaido, Japan considering the variety of roughness level. Each test section is 200 m with 20 m and 5 m additional extents from the beginning and end points, respectively. The sections were established on in-service arterial and residential roads. Table 2 summarizes the test sections with the IRIs calculated from the reference profiles called the true profiles.

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Summary of Test Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Section</td>
</tr>
<tr>
<td>1</td>
<td>Section 1-1</td>
</tr>
<tr>
<td>Section 1-2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Section 2-1</td>
</tr>
<tr>
<td>Section 2-2</td>
<td></td>
</tr>
</tbody>
</table>

**Participated Devices**

As mentioned earlier, thirty-four devices including high- and low-speed profilers and response type systems participated in the first experiment. The devices are grouped into the following four classifications on the basis of how directly their measures pertain to the IRI [6].

- Class 4 – A roughness measure is not reproducible or stable with time, and can only be compared to IRI by subjective estimation.
- Class 3 – A measure obtained from a response type system is calibrated to the IRI scale by correlation with reference measures from a Class 1 or 2 system.
- Class 2 – A profile-based method is used that is reproducible and stable with time, and that is calibrated independently of other roughness measuring instruments.
Class 1 – A profile-based method similar to Class 2 is used. A profile-based measurement qualifies as a Class 1 measure if it is so accurate that further improvements in accuracy would not be apparent.

Twenty-nine devices out of thirty-four participated devices including high- and low-speed profilers are classified into Class 2 while the rest of the device such as a response type system is classified into Class 3. Reference profiles were measured with Class 1 devices. This paper deals with the Class 2 profilers with Class 1 reference devices because this paper aims to analyze profile measurements as well as IRIs. Although the details of measurement principles for each device are not open to the public, the Class 2 profilers are grouped further into two categories based on the measurement method: non-contact measuring by laser sensors with a gyro unit or an inclinometer (Group A) and contact measuring by the movement of a driving wheel or an extra wheel (Group B). Table 3 shows the list of profilers for the analysis of this paper. In the table, the reported data set from H15, L2, and L4 include numerous measurement errors and/or missing data. Therefore, the measurements obtained with these devices are excluded from the analysis. The low-speed profilers L1 and L3 are also excluded because few devices are in the same group; thus, all of the low-speed profilers used in this study are classified into Group A.

### TABLE 3  List of Profilers

<table>
<thead>
<tr>
<th>No</th>
<th>Group</th>
<th>Sampling Interval (m)</th>
<th>No</th>
<th>Group</th>
<th>Sampling Interval (m)</th>
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<tbody>
<tr>
<td>H1</td>
<td>B</td>
<td>0.25</td>
<td>L1</td>
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<tr>
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</tr>
<tr>
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<td>L4</td>
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<td>0.10</td>
</tr>
<tr>
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<td>0.025</td>
<td>L5</td>
<td>A</td>
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</tr>
<tr>
<td>H6</td>
<td>A</td>
<td>0.05</td>
<td>L6</td>
<td>A</td>
<td>0.25</td>
</tr>
<tr>
<td>H7</td>
<td>A</td>
<td>0.05</td>
<td>L7</td>
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<td>0.25</td>
</tr>
<tr>
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<td>A</td>
<td>0.05</td>
<td>L8</td>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
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<td>0.10</td>
<td>L9</td>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
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<td>L10</td>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
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<td>B</td>
<td>0.25</td>
<td>L11</td>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
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<td>&lt;0.05</td>
<td>L12</td>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
<td>H13</td>
<td>B</td>
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<td>L13</td>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
<td>H14</td>
<td>B</td>
<td>0.10</td>
<td>L14</td>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
<td>H15*</td>
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<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The measurements include numerous measurement errors and/or missing data.

True Profile Measurement using Reference Devices

Each test section shown in Table 2 was measured with reference devices to provide the true
profiles. Each true profile consists of the combination of measurements obtained with three different reference devices: a Rod and Level, a Static Dipstick and a walking profiler as shown in Figure 1. The ability of these devices to produce a true profile has been verified prior to the experiment. The combination of the measurements by these three devices allows creating a true profile with a sampling interval of 0.01 m. The steps for measuring a true profile that are depicted schematically in Figure 2 are as follows:

- The Static Dipstick measures the sensitive wavelength ranges of IRI at an interval of 0.25 m,
- The Rod and Level measurements adjusts longer wavelength ranges than the Static Dipstick at an interval of 10 m, and
- The walking profiler compensates shorter wavelength ranges than the Static Dipstick at an interval of 0.01 m.

![FIGURE 1 Reference Devices for Measuring True Profiles.](image)

![FIGURE 2 A Schematic Illustration of Measuring a True Profile.](image)

Data Recording and Reporting Procedure

The participants made three runs for their profilers. The high-speed profilers were also required to obtain data at the following different operating speeds depending on the regulation speed of each site: 40 km/h, 50 km/h, and 60 km/h on Site 1 and 20 km/h, 30 km/h, and 40 km/h on Site 2.
The participants reported IRI and profile measurements with file extensions of “.csv” and “.xlsx”, respectively, in accordance with specified formats of the project. The averaging distance of IRI is set as 200 m for the present research.

ANALYSIS OF IRI MEASUREMENTS

Influence of Operating Speed

The high-speed profilers made three repeated runs at the specific speeds on each site for assessing the influence of operating speed on the measurement result. Since the influence of operating speed is assumed to be a systematic error within a device, the mean IRI for the three repeated runs at each speed is considered against the mean IRI for all data provided by the participants as the target IRI. Figure 3 shows the result of linear regression between the mean IRI of all measurements and the measurements obtained at different speeds for each site. In the figure, operating speed can be assessed by a systematic discrepancy and a random variation that correspond to a slope of the regression equation and a coefficient of determination, respectively. To reveal the influence statistically, we performed a one-way analysis of variance (ANOVA) with post-hoc Tukey’s honestly significant difference (HSD) test at the 1% statistical significance level. As the result, the Group A profilers on Site 2 only had significant differences between the measurements obtained at the operating speed of 20 km/h and 40 km/h. However, no statistical significant difference was observed on all pairs of comparisons between the target IRI and the mean for each operating speed. This means that the measurement variations due to operating speed are averaged out because the data measured at different speeds gather around the line of identity in Figure 3. Thus, the operating speed has no significant influence on IRI measurements at the range of speeds used in the experiment; accordingly it would be removed from variables for subsequent analyses.

(a) Group A
(b) Group B

FIGURE 3  Influence of Operating Speed on IRI Measurements.
**Repeatability for IRI measurements**

Repeatability of a profiler is the ability to obtain repeat measures with the same device at the same time [7], which is the random error corresponding to the precision within the device. In general, it can be evaluated by the standard deviation of IRI measurements obtained by repeated runs. Figure 4 shows the repeatability for IRI measurements of the profilers used in this study. In the figure, the result of a two-way ANOVA with post-hoc Tukey HSD test at the 1% significance level is also illustrated to examine the effects of the roughness level and the profiler class on the IRI measurements.

![FIGURE 4  Repeatability for IRI Measurements.](image)

As shown in Figure 4, the standard deviation for repeatability increases proportionally with increasing IRI. The difference between the high- and low-speed profilers was statistically significant. This could be anticipated that it is more difficult to trace the same line between repeated runs with high-speed profilers than low-speed ones. However, the measurement principle of the high-speed profilers had no significant influence to obtain repeat measurements of IRI precisely.

**Reproducibility for IRI measurements**

Reproducibility of a profiler is the ability to repeat the measures with a different profiler of the same basic design [7], which is the systematic error corresponding to the bias of measurements between devices. According to the literature [7], for profilers, reproducibility is not of as much interest as portability that is the ability to repeat the measures with completely different profiler design. The standard for portability is generally the true profile. On this account, we propose to simultaneously analyze the reproducibility and portability in this study by the graphical representation shown in Figure 5.
FIGURE 5 Reproducibility and Portability for IRI Measurements.

The figure indicates the percentile levels of the mean of measured IRIs for the repeated runs obtained with the participated profilers corresponding to the reference IRIs obtained from the true profiles. The spread of a box-plot along x-axis denotes the reproducibility of profilers. The degree of reproducibility increases with decreasing the spread. The deviation of a mean from a line of identity represents the portability of profilers. The degree of portability increases with decreasing the deviation. This representation contributes to demonstrating the position of a candidate profiler in pavement inspection activities. As shown in Figure 5, the following findings are obtained:

- For the high-speed profilers in Group A (non-contact measures), the reproducibility is spread within the error of 30%, while the portability has the bias of +10% in average,
- For the high-speed profilers in Group B (contact measures), the reproducibility is spread over a broad range with which a half of profilers exceed the error of 30%, and moreover, the portability has the maximum bias of approximately -30%, and
- For the low-speed profilers, both the reproducibility and portability are within the spread and bias of 10% errors, respectively.
However, the degree of reproducibility and portability depends on the application. This result would be a benchmark to assess profilers depending on the application. For example, the high-speed profilers in Group B are generally less expensive than the other Class 2 profilers.

ANALYSIS OF PROFILE MEASUREMENTS

A profile has more information that can distinguish bumps and depressions as an example than summary indices such as IRI. If a profiler is valid for measuring profiles, it is a great advantage in considering pavement maintenance and rehabilitation strategies. This study assesses the profilers for measuring profile in terms of profile agreement (hereafter, PA) between a pair of different measurements based on the cross-correlation method [5]: the rating of PA represents repeatability when it is applied to two measurements of the same profile by the same device and it represents reproducibility when it is applied to two measurements of the same profile by different devices. The influence of operating speeds is also analyzed by use of PA as the index. Prior to the analysis, the profiles were resampled at an interval of 0.01 m, if necessary. After that, they were filtered to gain the wavelengths of interest within a range from 0.5 m to 50 m for the wavy characteristics of roughness [8].

Overview of Profile Agreement (PA)

PA is calculated based on a cross correlation function between analyzed two profiles. A cross correlation function $r_{xy}$ of two profiles denoted as $x(t)$ and $y(t)$ that are the function of distance $t$ with a given length $T$ and longitudinal offset $\tau$ is defined as:

$$r_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)y(t+\tau)dt$$

(1)

Since actual measures of road profile are discrete and finite in length, a cross correlation function $r_{pq}$ of profiles $p$ and $q$ that are sampled at an interval of $\Delta$ for data length $N$ can be estimated by:

$$r_{pq}(\tau) = \frac{1}{N} \sum_{i=1}^{N} p_i q_{i+\tau/\Delta}$$

(2)

As shown in Equation 2, a cross correlation function is in units of elevation squared. In a profile analysis, a cross correlation function normalized to produce a value of 1 for perfect correlation ($\rho_{pq}$) are used as an index of profile agreement:
\[ \rho_{pq}(\tau) = \frac{1}{\sigma_p \sigma_q} \sum_{i=1}^{\infty} \hat{p}_i \hat{q}_{i+i/\Delta} \] (3)

where the hats over the letters \( p \) and \( q \) indicate that the profiles are offset vertically to have a mean value of zero. The values \( \sigma_p \) and \( \sigma_q \) represent the standard deviation of profiles \( p \) and \( q \), respectively. Equation 3 produces a \(-1\) to \(1\) rating of the correlation, and will only produce a value of \(1\) when the shape of both profiles are exactly the same and they are synchronized [5].

In Equation 3, differences in overall roughness are not penalized by the standard cross correlation function. Two profiles that have the exact same shape but very different amplitudes would be rewarded with a perfect rating by Equation 3. To compensate for this, the following adjustment factor \( f \) has been proposed to the normalized cross correlation function [5]:

\[
f = \frac{\min(\sigma_p, \sigma_q)}{\max(\sigma_p, \sigma_q)} \] (4)

Finally, an index of PA (\( R_{pq} \)) can be defined by the cross correlation at the optimum longitudinal offset (\( \rho_m \)) as:

\[
R_{pq} = \rho_m \cdot f \] (5)

**Influence of Operating Speed**

Since the influence of operating speed is assumed to be a systematic error within a device, the mean PA of the three repeated runs at each speed is considered against the mean PA for all data measured on each test section to be the target PA. Figure 6 shows the results of linear regression of the mean PA obtained between the target and each operating speed. To compare the results statistically, we performed a one-way ANOVA with post-hoc Tukey HSD test at the 1% significance level for each profiler group on each test site. As the result, the Group A profilers on Site 2 had significant differences between the operating speed 20km/h and 30km/h, and 20 km/h and 40 km/h. On the other hand, the Group B profilers on Site 2 had a significant difference between the operating speed of 20 km/h and 40 km/h. However, no statistical difference existed on all pairs of comparisons between the target and the mean for each operating speed. This result implies that the variations of profile measurements owing to operating speed can be averaged out because the data measured at different speeds gather around the line of identity in Figure 6.
Repeatability for IRI measurements

Repeatability of the profilers for measuring a profile can be evaluated by PA applied to two measurements of the same profile obtained by the repeated runs for the same profiler. Figure 7 shows the repeatability of the profilers used in this study. In the figure, the result of a two-way ANOVA with post-hoc Tukey HSD test at the 1% significance level is also illustrated to examine the effects of roughness level and profiler class on the profile measurements. As shown in Figure 7, the PA for repeatability is not corresponding to the roughness level. The difference between the high- and low-speed profilers is statistically significant. However, the measurement principle of the high-speed profilers has no significant influence to obtain repeat measures of a profile precisely. As a result, the low-speed profilers have the ability to obtain the repeat measures by an almost perfect correlation, whereas some high-speed profilers are difficult to make them. This result can be anticipated because some devices are intended to survey condition of a network by a summary index such as IRI. In the purpose of network monitoring,
repeatability is not of great concern because variations of measurements average out. Instead, the low-speed profilers are valid for a project use as well.

Reproducibility for Profile measurements

Reproducibility of the profilers for measuring profiles was considered with portability of them by comparing the measurements of the true profiles. Figure 8 shows the percentile level of PA against the true profiles for the mean of repeated runs obtained with the profilers used in this study. In the figure, the spread of a box-plot along y-axis denotes the reproducibility of profilers, and the deviation of a mean from a line of perfect correlation (PA=1.0) represents the portability of profilers. In the analysis, we performed a one-way ANOVA with post-hoc Tukey HSD test at the 1% significance level to reveal the effect of roughness level on PA for each profiler class. This illustration would contribute to providing the basic information about a candidate profiler for a profile measuring survey.

As shown in Figure 8, the following findings are obtained:

- For the high-speed profilers in Group A (non-contact measures), the profile obtained with a profiler is hard to reproduce by another; the profile obtained with upper 25% devices correlates well with the true profile as a PA level over 0.8 except for the worst IRI case; the roughness level has no significant influence on PA,
- For the high-speed profilers in Group B (contact measures), The profile obtained with a profiler is hard to reproduce by another; the profile obtained with 75% devices correlates seldom with the true profile as a PA level no greater than 0.8; the mean PA for portability decreases with increasing roughness level, and
- For the low-speed profilers, the profile obtained with a profiler is reproducible by another; the profile obtained with every device correlates well with the true profile as a PA level greater than 0.8; the effect of roughness level is significant only on the comparison between the rough surfaces.
(a) High-speed Profilers (Group A)           (b) High-speed Profilers (Group B)  
(c) Low-speed Profilers

FIGURE 8  Reproducibility and Portability for Profile Measurements.

Figure 9 shows the absolute percentage error in IRI versus PA level for all measurements obtained with the high- and low speed profilers. The figure also plots the 95th percentile level of IRI disagreement within a PA range of 0.05. As shown in Figure 9, a clear relationship exists between PA and the 95th percentile level of IRI disagreement as shown by the regression curve for the plots. Although some high-speed profilers were unsuitable to measure profiles, they provided the accurate measurements of IRI. This can be supposed due the various design concepts of high-speed profilers for measuring a profile as well as the IRI. These profilers may potentially involve one or more specific filters to gain profile characteristics of interest. Further studies accompanied with a waveband analysis for profiler measurements should be done. The threshold of PA level, then, should be set depending on the application of a profiler.
CONCLUSIONS

This paper has analyzed the accuracy of high- and low-speed profilers participated in the first experiment to compare test methods for surface roughness under actual road environment (TRUE Project) in 2014. Not all of the profilers used in Japan, but a number of them have been included in this study. The analysis has focused on repeatability and reproducibility as well as portability for the IRI and profile measurements obtained with the profilers. The influence of operating speed on the measurements has also been considered for the high-speed profilers. In conclusions, the following findings are acquired:

・ Although the operating speed has significant influence on the IRI measurements obtained with the non-contact high-speed profilers in Site 2, the variations of data due to it are averaged out because the data measured at different speeds gather around the target IRI. Thus, the operating speed has no influence on IRI measurements.

・ The degree of repeatability for measuring IRI indicated by the standard deviation of repeated runs decreases inversely with increasing IRI. The difference of repeatability between the high- and low-speed profilers is statistically significant, whereas the measurement principle of the high-speed profilers has no significant influence on repeatability.

・ The high-speed profilers with the non-contact and contact measures have the bias of +10% and -30%, respectively, for portability. They involve the error of 30% or more for reproducibility. On the other hand, the low-speed profiler is reproducible and portable within the error of 10%.

・ The high-speed profilers have significant influence on the profile measurements in some cases. However, the variations of profile measurements owing to operating speed can be averaged out because the data measured at different speeds gather around the target PA.

・ Some high-speed profilers with both no-contact and contact measures are difficult to make
the repeat measures of a profile because they are developed for network condition survey. Instead, the low-speed profilers can make the repeat measures of a profile valid for a project use.

- The profile obtained with a high-speed profiler of both the non-contact and contact measures is hard to reproduce by another. A quarter of the high-speed profilers with the non-contact measures have portability for measuring a profile that corresponds to the true profiles with a PA level over 0.8. Three quarters of the high-speed profilers with the contact measures have no portability for measuring a profile with a PA level less than 0.8 against the true profile.

This paper provides the informative resources to establish a realistic tolerance of the accuracy required to profilers for measuring IRIIs and profiles. This information is of benefit to profiler developers as well as users for development and improvement of their profilers.

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