Improved Calibration Procedure for British Pendulum Tester

Weiwei Guo, L. Chu, and T. F. Fwa

Abstract Regular periodic calibration is important to ensure the accuracy of measurements of British pendulum test (BPT). The current standard calibration procedures of BS EN 13036 and ASTM E303 are widely adopted by pavement engineering community. Studies by different research groups have shown that test results of BPT devices complying with standard calibration requirements have good repeatability, but could have deviations of 10% or more. The present research presents a detailed examination of the impact of the limiting values of the main calibration parameters of BPT devices. Since it is difficult to study by means experimental measurements the impact of any pendulum parameter value within the allowable range on BPN (British pendulum number), a finite element model was adopted in this research based on the mechanics of the BPT test process. The simulation results showed that BPT devices satisfying the calibration requirements of any standard could produce measurements with uncertainty of more than 23% of their mean test value. By tightening the calibration parameter range according to the actual needs of the user, this study shows that the uncertainty of the BPT measurements can be controlled within an acceptable range.

Keywords British pendulum test · British pendulum number · Pendulum test value · Calibration procedure · Finite element model · Pavement skid resistance

1 Introduction

The British pendulum tester (BPT) is an easy-to-operate and robust piece of portable test device testing of surface friction of pavement materials. The accuracy and the reproducibility of the BPT measurements are critical factors for evaluating the friction coefficient of the test surface. More than 60 years of experience of laboratory and field

W. Guo · L. Chu (✉) · T. F. Fwa
School of Highway, Chang'an University, Xi'an, China
e-mail: longjiachu@chd.edu.sg

T. F. Fwa
National University of Singapore, Singapore, Singapore

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BPT measurements by users in different parts of the world have shown practically no difficulty in achieving the precision required by standard specifications [1–4], such as the allowable error of 1.0 BPN (British pendulum number) unit at 95% confidence level specified by ASTM E303 [5].The calibration procedures and requirements specified by ASTM E303 [5] and BS EN 13036-4 [6] standard are generally adopted by most highway engineering practitioners and organizations in the world. Most of the verification requirements of the two calibration procedures are the same, but the calibration limit ranges are different.

Reproducibility studies on interlaboratory BPT measurements have shown some unsatisfactory results Strautins and Daniel [7] conducted an inter-laboratory study involving 5 laboratories and found that, for a reference specimen with a mean BPN of 27.4, the laboratory measurements varied from 17 to 44. The range of measured BPN values was from 49 to 65 for another reference specimen with a mean BPN of 56.6. Hiti and Ducman [3] tested a surface using four BPT devices. Eight BPN measurements were made per BPT device, each time setting the device to a different slider force-deflection curve within the allowable ASTM calibration limits. It was found that the BPN value measured on a referenced test surface by different BPT units varied from 44 to 60, resulting in a mean percentage difference higher than 28%. Such differences are undesirable for practical operations. These results show that the parameter calibration method cannot ensure satisfactory reproducibility in BPN measurements made by different BPT devices that follow the calibration standards of either ASTM or BS.

In order to reduce the variability of measured BPN values caused by calibration parameters, Hiti and Ducman [3] proposed strict requirements on the slider force-deflection curve. The research by Strautins [9] also showed that a reduction of tolerance limits for all calibration parameters can reduce the uncertainty of the measurements. By means of a finite element simulation model of the BPT test, Guo et al. [8] identified the limits of slider force-deflection curve as the single most influencing calibration requirement, and proposed a procedure to determine the limits to achieve a pre-specified level of measurement variability.

Given the current limitations of the calibration parameters specified by ASTM E303 and BS EN 13036-4, it is necessary to re-evaluate the impact of the uncertainty of the BPN value caused by the specified calibration parameter limits. In the impact evaluation, analyses are made on the effects of various influencing calibration parameters on the variability of BPT measurements. In view of the relatively large number of equipment parameters involved, and some parameters are unique for each equipment at the time of manufacture, it is practically impossible to experimentally perform the evaluation using physical pendulum equipment. Therefore, this research resorted to developing a computer simulation model to achieve the research goals. The BPT model developed by the finite element method provides a convenient tool that can conveniently vary the values of different parameters to provide a comprehensive evaluation of the impacts of different parameters on the measured BPT values.

2 Objectives and Method of Study

2.1 Research Objectives

The conventional approach of calibrating a given type of device is by setting control limits for selected device parameters. This is also the practice in use today by the pavement engineering community in the case of BPT. Currently, the two most commonly adopted BPT calibration methods are the ones published by ASTM and the British Standards Institute as standard procedures ASTM E303 [5] and BS EN 13036-4 [6] respectively. Although the two standards are largely similar, there are differences in the specific control limits of some calibration parameters. Table 1 highlights their main differences and their impacts on BPT measurements.

Comparing the entries in the second and third columns of Table 1, it can be seen that there are only slight differences between the two standards in the calibration requirements, except for item 5 concerning the slider force-deflection characteristic. Items (1) and (2) of Table 1 are fixed manufactured parameters that could not be corrected by users during calibration. For BPT with unworn rubber sliders, the impact of items (3) and (5) specified by the two standards are worthy of detailed analysis. This study employed a computer simulation model to evaluate the variations in the measured BPN values according to the parameters required by the two calibration standards.

Table 1 BPT device calibration requirements by ASTM E303-18 and BS EN 13036-4

Item	ASTM E303-18 Requirements	BS EN 13036-4 Requirements
1. Radius of pendulum swing	Sliding edge is 508 mm from the axis of rotation	Sliding edge is (514 ± 6) mm from the axis of rotation
2. Mass of pendulum arm with slider assembly	(1.50 ± 0.03) kg	(1.50 ± 0.03) kg
3. Center of gravity of pendulum arm	(411 ± 5) mm from axis of rotation	(410 ± 5) mm from axis of rotation
4. Width of rubber pad striking edge	Wear on striking edge shall not exceed 3.2 mm in slider plane or 1.6 mm vertical to it	Not more than 2.5 mm
5. Slider force-deflection requirements	Average vertical slider force of (2500 ± 100) g	Static force shall be (22.2 ± 0.5) N when deflected 4.5 mm. Change in static force shall be not greater than 0.2 N per mm deflection of the slider. Slider force at 0 to 8 mm deflection shall be within the envelope specified

2.2 Research Method

It is impractical to test a BPT device to cover all possible calibration ranges required for calibration by means of physical testing. However, the test mechanism of the pendulum instrument can be easily simulated by means of computer simulation. So far, researchers have developed two finite element simulation models of BPT. One is the NUS model developed by Liu et al. [10], and the other is an upgraded model based on the NUS model by Chu et al. [11]. The upgraded model shown in Fig. 1 more accurately expresses the friction performance of the rubber slider, and can completely simulate the entire test process of the pendulum.

In the finite element model, the aluminum beam is connected to the upper truss structure through hinge constraints and nonlinear springs to simulate the combined action of the spring and lever mechanism of the actual BPT pendulum assembly. In addition, the friction coefficient needs to be entered in advance to characterize the interaction between the slider and the pavement surface. The simulation model finally outputs the dwell height of the pendulum arm. The predicted BPN is obtained by using the conversion relationship between height and BPN. After calibration, the model can be applied to simulate a BPT test and calculate BPN value and other output information, such as contact pressure, sliding speed and friction at each point along the contact path. It can be used either to obtain the BPN value of a test surface with a known coefficient of friction, or to back-derive the coefficient of friction of

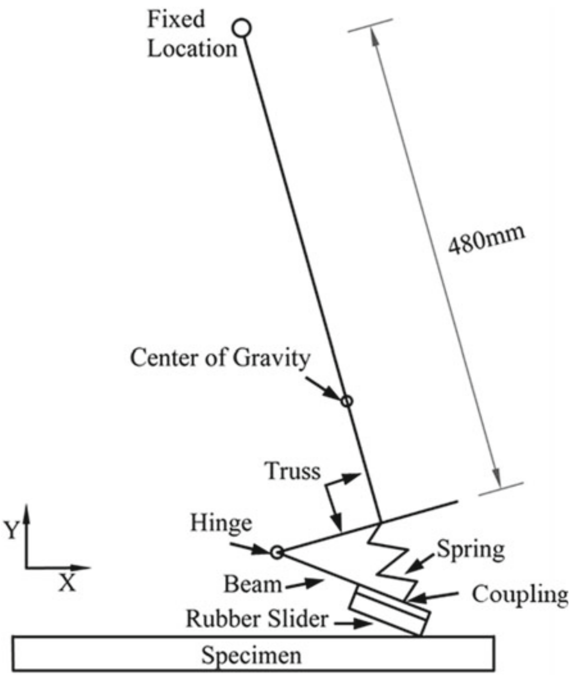

Fig. 1 Computer modeling of BPT pendulum-slider assembly [11]

a test surface with a known BPN value. The improved BPT finite element model was adopted in this study. Readers interested in the construction of 3D finite element simulation model can refer to Chu et al.'s work for more details [11].

3 Analysis of Impact of Improved Calibration Parameters

The focus of this research is to explore the variation range of the test results corresponding to the calibration requirements of ASTM E303 and BS EN 13036-4. Specifically, they are (i) the position of pendulum center of gravity, and (ii) the slider force-deflection characteristics. Improvement suggestions for these two parameters from different research will be used as the basis of comparison to illustrate the potential of the improved method to reduce the uncertainty of BPT measurements. The impact of the friction coefficient of the test surface in the range of 0.2–1.0 was considered for all the cases. This range covers all pavement friction coefficients that may be encountered in practice.

3.1 Center of Gravity of Pendulum Arm

The distances of the center of gravity (CG) from fixed location stipulated by ASTM E303 standard and BS EN 13036-4 standard are 411±5mm and 410±5mm, respectively. A narrower tolerance (410±3 mm) of the distance of center of gravity was proposed in Strautins [9] to reduce the uncertainty of BPT measurements. Therefore, in order to explore the impact of the change of the center of gravity on the measured BPN value, the simulation experiment is divided into three cases: the limit conditions of the two standards and narrower tolerances (410±3mm) are selected as parameters. The slider force-deflection curve is set as the lower limit of BS EN 13036-4.

The results of the analysis are shown in Figure 2. The curve shows the calculated BPN for all the cases analyzed. The vertical bars give the maximum differences $\Delta(BPN)_I$ in BPN value between BPT devices that meet the requirements of pendulum center of gravity position. The differences for ASTM E303 and BS EN 13036-4 standards were of the same order of magnitude. The absolute value of $\Delta(BPN)_I$ vary from 0.6 to 2.0 BPN units. The mean percentage of difference, i.e. percentage calculated based on the mean of the two BPN values, is less than 3% overall. As an improvement, the narrower tolerance method can reduce the uncertainty caused by the center of gravity to 1.8%. From the perspective of actual calibration, the position of the center of gravity is relatively easy to adjust, so it is worthwhile to adopt a stricter interval to reduce the uncertainty of the BPN value.

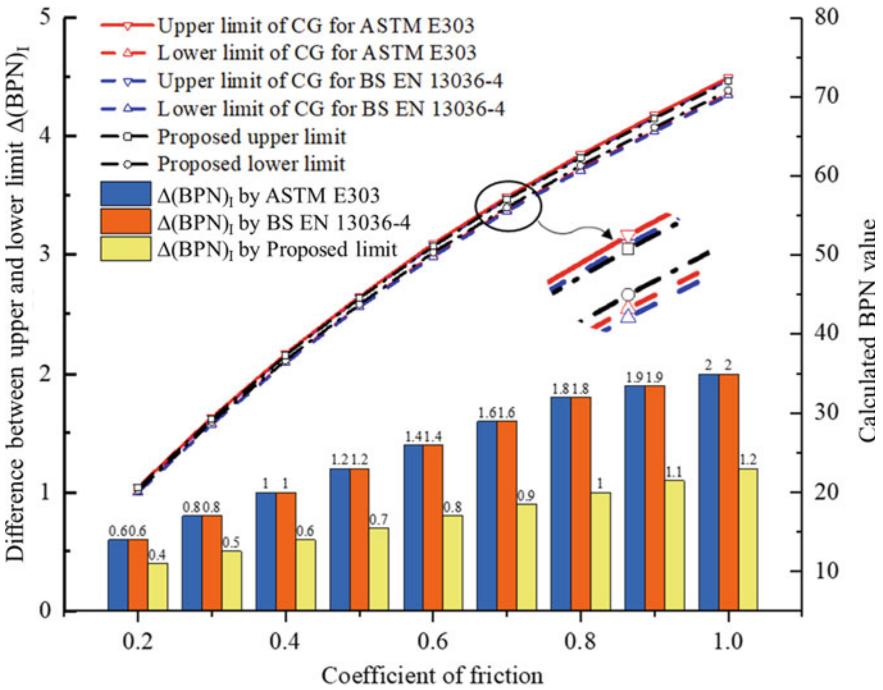

Fig. 2 Differences in BPT measurements due to different pendulum center of gravity (CG) positions

3.2 Slider Force-Deflection Requirements

The ASTM E303 standard only specifies the average slider force at the maximum slider displacement. The BS EN 130306-4 standard is stricter than the ASTM E303 standard. It clearly defines the upper and lower allowable limits for the calibration of the slide force-deflection curve, as shown in Fig. 3. For comparison, Fig. 3 also shows the implied upper and lower limits of the slider force-deflection relationship that meets the ASTM E303 maximum slider force-deflection calibration requirements. Both Guo et al. [8] and Strautins [9] recommended more stringent specific requirements for the slider force-deflection curve. The former stated a complete slider force-deflection calibration limit range in its recommendation. This section adopts the improvement recommendation of Guo et al. as the basis for comparison. Guo et al proposed to use the lower limit of BS EN 13036-4 standard as the lower limit of the improved calibration requirement. The lower limit of BS EN 13036-4 is valid, because any slide force-deflection curve below this limit will violate the slider force requirement with a maximum deflection of 3.9 mm. A trial-and-error analysis was performed using the computer BPT simulation model for the comparison study. Figure 3 also shows two proposed upper limits for calibration. In order to illustrate the impact of the slider force-deflection curve, the two sets of limits were analyzed for the ASTM E303 standard and the BS EN 130306-4 standard respectively.

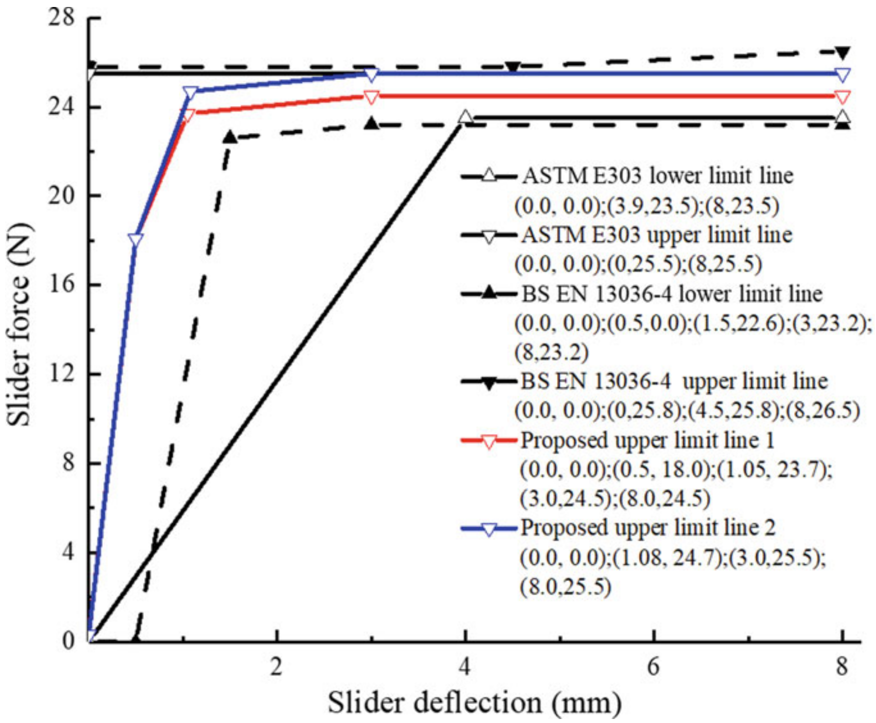

Fig. 3 Limits of calibration requirement for slider force-deflection relationships

Detailed measurement values calculated using the simulation model of the above four cases are plotted in Fig. 4. The maximum differences $\Delta(\text{BPN})_{\text{II}}$ in BPN values between the upper and lower limits of slider force-deflection curve for four cases are shown in Fig. 5. The absolute value $\Delta(\text{BPN})_{\text{II}}$ varies from 10.7 to 30.9 BPN units for the ASTM E303 standard, and 5.2–20.4 BPN units for BS EN 13036-4 standard. $\Delta(\text{BPN})_{\text{II}}$ of the proposed limits 1 and 2 can be reduced to about half of the BS EN 13036-4 standard, corresponding to 2.1 to 8.9 BPN units and 2.9 to 10 BPN units, respectively. In terms of the maximum percentage difference, the range varies from 56.2 % to 58.0 % for ASTM E303 standard and 21.9 and 25.1% for BS EN 13036-4 standard. Over the range of friction coefficient from 0.2 to 1.0, the maximum percentage difference are 10.5%, and 13.3% respectively. The magnitude of these differences is a significant improvement over the standard calibration procedures by ASTM E303 and BS EN 13036-4.

In the above analysis, it is obvious that the slider force-deflection curve has the largest impact on the BPN value. The possible absolute difference and maximum percentage difference based on the allowable range of the slider force-deflection curve of the current ASTM and BS standard are beyond the acceptable range for practical purposes. The position of the center of gravity is comparatively less important, but the adjustment of its value should also be taken into consideration to reduce measurement

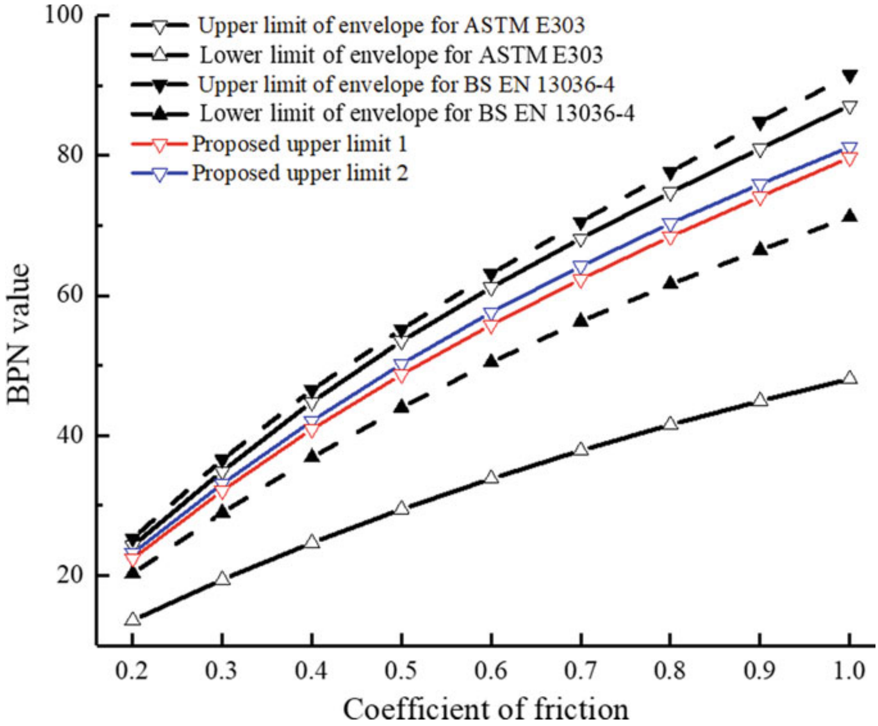

Fig. 4 Impacts of calibration limits of slider force-deflection relationship

uncertainty. Overall, reducing the allowable range of calibration parameters would reduce the uncertainty of measured BPN values, but it also means more stringent calibration limits. The allowable range of calibration parameters should be adjusted from the perspective of road maintenance and management.

4 Conclusion

This study adopts the finite element model to show that the uncertainty of the BPT test results within the allowable range of calibration parameter could reach at least 56.2 % for ASTM E303 standard and 21.9 % for BS EN 13036-4 standard. The uncertainty of the BPT measurements are much too large for effective pavement friction management. Tightening the allowable range of various calibration parameters has been shown to be feasible in this study to reduce the uncertainty of BPT measurements. The calibration limits can be determined according to the needs of a user in order to meet the user's operation requirements.

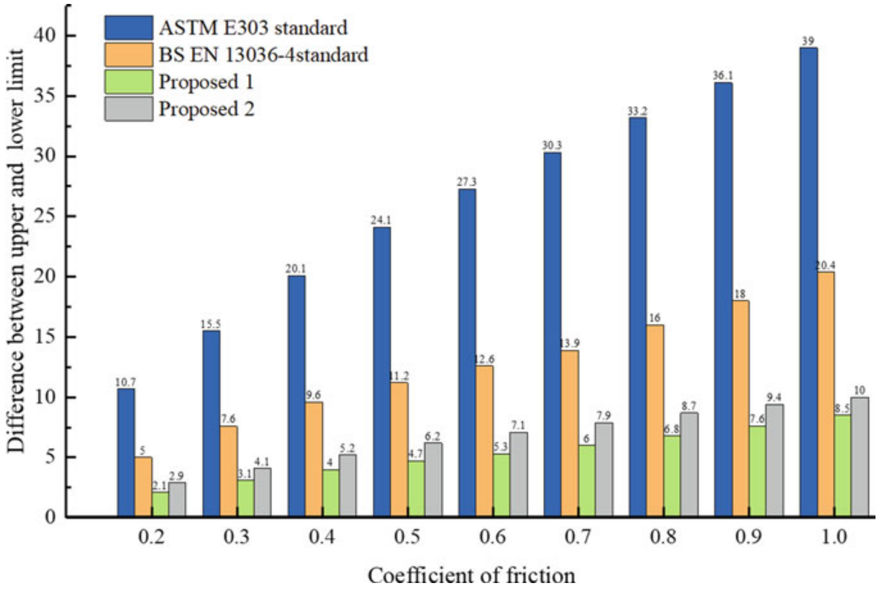

Fig. 5 Differences $\Delta(\text{BPN})_{\text{II}}$ in BPN values between upper and lower limit range of slider force-deflection curve

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