CROW Falling Weight Deflectometer Correlation Trial 2023

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- Research in the area of traffic, transport and infrastructure
- Standardisation in this sector
- Transfer of knowledge and knowledge management

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CROW
Horaplantsoen 18, NL-6717 LT Ede
P.O. Box 37, NL-6710 BA Ede
The Netherlands
Telephone: +31 381 69 53 00
Fax: +31 318 62 11 12
E-mail: klantenservice@crow.nl
Website: www.crow.nl

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CROW Falling Weight Deflectometer Correlation Trial 2023

Report D23-04

Preface

The currently most common device for non-destructive deflection testing of road pavements is the Falling Weight Deflectometer (FWD) although the Traffic Speed Deflectometer (TSD) is gaining monitoring market especially for collecting data of the arterial roadway network. FWD data are used to calculate pavement layer moduli and to assess the structural condition of roads. The properties of the constituent layers of the pavement structure, traffic data and most of all the deflection bowls form the basic set of data used in the analysis. For any FWD it is absolutely necessary that the test results are accurate and unbiased. This necessitates proper FWD calibration. Inaccurate and biased data can lead to incorrect conclusions about the structural condition of the pavement and serious errors in estimates of the properties of the pavement layers.

This report presents the test programme, the analysis and the results of the 2023 CROW FWD correlation trial held among 15 European FWDs on November 8th, 2023. The trial was tailored to collect data on the repeatability of each participating device and on the computation of the FWD correlation factor. The test programme was based on Protocol 10 of the CROW FWD Calibration Guide (CROW Report D11-07).

The organisation, analysis and reporting of the trial were conducted by Daisy Bouwmans, MSc and Dr. Christ van Gurp, both associated with Kiwa KOAC, the Netherlands. This project was conducted under contract with CROW. The preparation of the test, the analysis of the data, and presentation of the results were conducted under the aegis of the CROW Platform Road Testing.

We wish to acknowledge the departments of Public works of the Municipalities Bunschoten, Barneveld and Nijkerk for their permission to conduct the FWD surveys on their road network. We also appreciate the effort of all participating crew to make the day of the trial to a success.

P. Litjens, Executive Director, CROW

Summary

This report presents the results of the CROW FWD correlation trial organised among 15 European Falling Weight Deflectometers (FWDs) at November 8th, 2023. The trial was held in Bunschoten-Spakenburg on asphalt roads with a poor subgrade and on asphalt roads just south of Nijkerk, where the subgrade varied between moderately stiff to very stiff. The purpose of the trial was to determine: a) the repeatability of each FWD, and b) the FWD correlation factor of each FWD. Protocol 10 of CROW-report D11-07 Falling Weight Deflectometer calibration guide, August 2011, was used for the trial.

This report presents the structure of the trial, the test programme and test route and all common public results and data. The confidential FWD related data and results are reported in separate annexes submitted to the respective FWD users only.

The report also touches on the accuracy and precision of the measurement of asphalt temperatures during the day of the trial.

One participant asked to analyse their results twice in order to test their new algorithm. This means, although there were 15 participants, this report contains the results of 16 FWDs. This resulted in tags ranging for A to P.

Two FWDs failed to comply with the requirements of Protocol 10 of CROW-report D11-07 Falling Weight Deflectometer calibration guide. As a result, 13 out of the 15 participating FWDs met the specifications for obtaining the CROW FWD calibration certificate.

Samenvatting

Dit rapport bevat de resultaten van een ringonderzoek georganiseerd onder 15 Europese valgewichtdeflectiemeters (VGD's) op 8 november 2023. Het ringonderzoek is gehouden in Bunschoten-Spakenburg op asfaltwegen met een samendrukbare grondslag en op asfaltwegen net ten zuiden van Nijkerk. De ondergrond was daar redelijk stijf tot erg stijf.
Het doel van de studie was om: a) de herhaalbaarheid van elke valgewichtdeflectiemeter te bepalen en b) de VGD correlatiefactor voor ieder apparaat vast te stellen. De vergelijking is uitgevoerd conform Protocol 10 uit CROW-report D11-07 Falling Weight Deflectometer calibration guide, August 2011.

Dit rapport presenteert de opzet van de studie, het testprogramma en de testroute en verder alle openbare resultaten en data. De vertrouwelijke data en resultaten van iedere VGD afzonderlijk zijn in aparte bijlagen gerapporteerd die alleen aan de betreffende VGD-gebruikers zijn toegezonden.

Dit rapport gaat ook beknopt in op de juistheid en precisie van de meting van de asfalttemperatuur op de dag van het ringonderzoek.

Een deelnemer heeft gevraagd om hun resultaten tweemaal te analyseren om hun nieuwe algoritme te testen. Dit betekent dat, ondanks dat er 15 deelnemers waren, dit rapport de resultaten bevat van 16 VGD’s. Dit resulteert erin dat de tags van A tot P lopen.

Twee VGD’s voldeden niet aan de eisen met betrekking tot Protocol 10 uit CROW-report D11-07 Falling Weight Deflectometer calibration guide. Uiteindelijk kwamen 13 van de 15 deelnemende valgewichtdeflectiemeters in aanmerking voor het CROW valgewichtdeflectiemetercertificaat.

Contents

1. Introduction

1.1 General

The currently most common device for non-destructive deflection testing is the Falling Weight Deflectometer (FWD). Hundreds of these devices have been sold worldwide. FWD data are used to calculate pavement layer moduli and to assess the structural pavement life of asphalt and cement concrete roads. The most important input data for the structural analysis are the properties and thicknesses of the constituent layers, traffic data and most of all the deflection bowls measured by the FWD. For any FWD, it is absolutely necessary that the measured load and deflection data is accurate and unbiased. This necessitates proper calibration. Inaccurate and biased data can lead to incorrect conclusions about the structural condition of the pavement and serious errors in estimates of the properties of the pavement layers.

Figure 1 ***Various types of Falling Weight Deflectometers (2015 trial)***

1.2 History

Since the nineties, several FWD calibration procedures have been issued. The main drive for issuing these procedures was to endeavour comprehensive and easy-to-use calibration procedures. Especially the lack of reproducibility among FWDs was seen as a major handicap in the exchange of deflection data.

Since 1987, various FWD test trials were held in The Netherlands, roughly at a biennial basis. In the beginning, the tests were focused on acquisition of knowledge. In the interim test held in 1991, particular attention was paid to the influence of the type of pavement structure and the type of subgrade on the shape of the FWD load pulse and the peak readings of deflection. This test led to the conclusion that the differences among devices could not be explained from variations among load pulse shapes alone. Other factors seemed to have their effect as well. The 1993 test revealed that especially at low-support subgrade quite some variability among the peak readings of deflections could be observed. For some of the devices at that time, a distinct relationship was found between the deflection pulse duration (is equivalent to the structural support of the subgrade) and the difference between the peak reading of deflection and the average value measured by the fleet of participating equipment. For reasons of accuracy, deflection pulse duration should have no effect on the accuracy of the peak reading of deflection [1]. In other words, procedures and software used by FWD manufacturers for capturing accurate peak values of deflection at soft subgrade were not always correct in those days. Since that time, all major FWD manufacturers have developed processing software for converting velocity data of the geophone into deflection data in a correct and accurate way.

Based on the results of the trials conducted in 1997 and earlier, COST Action 336 of the European Commission started with the development of an updated set of FWD calibration procedures, resulting in a set of twelve protocols published in the second edition of the final report of COST336 'Use of Falling Weight Deflectometers in Pavement Evaluation' [2]. Experience with the application of this report and findings by the US Federal Highway Administration [3] led to the issue of an updated version of the CROW Falling Weight Deflectometer calibration guide [4].

This report focuses primarily of the aspects of short-term repeatability and reproducibility of FWD data. The CROW-report Falling Weight Deflectometer calibration guide, Protocol 10, formed the basis of the FWD Correlation Trial. The report also presents results of analyses of reproducibility or robustness of the FWD field calibration factor for each FWD. These analyses are not actually needed for determination of the FWD correlation factor but give insight in the degree of accuracy and reproducibility of this factor.

Since the deflections measured at asphalt roads also depend on the asphalt temperature, measurement of this temperature should be as accurate as practically possible. This report presents a brief analysis of the accuracy and precision of the asphalt temperatures measured by the participants.

2. Test programme

2.1 Objective

The programme of the FWD correlation trial had three objectives:

- determination of repeatability of each FWD;
- computation of the FWD correlation factor;
- accuracy and precision of temperature recordings.

Protocol 10 of CROW-report D11-07 Falling Weight Deflectometer calibration guide describes the short-term repeatability test and the determination of the FWD correlation factor in a single protocol.

Deflection results are defined as being repeatable when a single FWD, operated by one and the same crew, is capable of reproducing the deflection bowl collected in a sequence of multiple drops at a specific test site without lifting the loading plate. Deflection results are defined as reproducible when various FWDs operated by various crews, are capable of reproducing a deflection bowl at a specific test site under identical testing conditions.

This report presents a description of the test programme, the participating FWD equipment and the conditions during the day of testing. It also provides a summary of the test results. The test results are presented in more detail in the separate annexes. Some annexes contain confidential data and are for that reason only submitted to the users of the respective equipment and the supervisor of CROW.

2.2 Test set-up

Two test areas were selected with respectively three and four test sites each. 40 test stations were used for reproducibility purposes and three for verification of the repeatability. Multiple drops were requested for both the repeatability and reproducibility experiment. Seating errors may occur at the first drop due to loose debris and rough texture. Therefore, it is common practice to drop the weight at least one time before beginning to record data. This effect was accounted for in both experiments.

The target load level was set to 50 kN for the whole day of testing. Only the deflections measured at spatial distances of 300 mm, from the load centre up to an offset of 1800 mm were analysed. Results from other offsets were omitted from analysis. All participating FWDs but one used trailer mounted FWDs with the deflection bar pointing to the direction of travel. One device used a van mounted FWD with the deflection bar pointing backward. This participant drove over each section in reverse. The details of the test programme are presented in Annex I of this report.

Operators were explicitly asked to switch on the peak smoothing option (when available) for both the load and the deflection signal. A cut-off frequency of 60 Hz was requested. Experiences from previous trials showed that differences in construction of the various models of FWDs may lead to introduction of high frequency effects in the load and deflection signal. These high frequencies can never find their origin in the road under test. Prior to the trial, operators were asked to adjust types and number of rubber buffers, drop mass and drop height in such a way that the load pulse duration would be close to 26 ms.

2.3 Repeatability experiment

Three test stations were selected for the repeatability experiment. The stations were chosen for their differences in structural support. The load-carrying capacity of the three stations is given in the presentation of the results. All FWDs were requested to conduct twelve drops in one sequence without lifting the loading plate. The target load level was set at 50 kN. Operators were asked to switch off the load targeting feature in the repeatability experiment. The peak values of load and deflection of all sensors were recorded at each drop. The first two drops were omitted from analysis. All deflections were normalised to a 50 kN load level prior to evaluation. No actual time of testing or temperature data was needed for this experiment, because the data were not compared among FWDs. For full details, see Annex Protocol 10 of [4].

2.4 Reproducibility experiment

In aggregate 40 test stations spread over seven test sites were selected and marked (see figure 2) for the reproducibility experiment. All test stations were visited twice. As in the repeatability experiment, all stations were chosen for their variation in asphalt thickness, pavement structure, load-carrying capabilities and subgrade support.

Figure 2 Test stations 122 and 222 with 400 mm diameter circle

In the morning sessions, test sites consisting of asphalt roads on a clay to peat subgrade with low structural support were used. In the afternoon session, the selected test sites comprised asphalt roads on a moderate to very stiff subgrade. FWDs were requested to conduct five drops at each station in one sequence without lifting the loading plate. The loading plate had to be positioned entirely within the marked circle (see figure 3). The target load level was set at 50 kN. The operators were allowed to use load targeting features in this experiment.

Figure 3 Positioning of loading plate in circle at test station 121 and 221 (2021)

At each drop, peak values of load and deflection of all sensors were recorded. When possible, the load time history (or the whole time history) was asked to be recorded at the last drop for any deeper analysis of the test results. The first drop was omitted from analysis. All deflections were linearly normalised to a 50 kN load level prior to evaluation. In a second step, the mean of the drops 2, 3, 4 and 5 was calculated. The resulting deflection bowl was used in the analysis procedure.

The actual time of testing and temperature data was needed for this experiment, because the FWD data had to be compared to each other. Each participant was requested to record pavement temperature in a predrilled hole at each location (see figure 4). Previous experiments and trials revealed that substantial variation in temperature data may be expected due to use of various types of temperature recording instruments. For this reason, the asphalt temperature was also measured by a temperature logger in a hole situated a few centimetres away from the other temperature test point.
The temperature logger sampled temperatures at an interval of one minute. The pavement temperature was measured at a depth of approximately 0.07 m. Variation of this independently recorded pavement temperature was used in the verification whether temperature did not vary too much between the first and last visitor per test site and round of testing.

Since only three temperature loggers were available during the day of the trial, and the afternoon had four sites, no temperature data was recorded at site 7.

Figure 4 ***Asphalt temperature recording***

Testing was conducted as rapidly as possible at each location to constrain the adverse effect of temperature differences among devices. For this reason, FWDs were grouped into three groups. There were no restrictions set to the sequence of testing within each group. Queuing was nevertheless unavoidable.

2.5 Test conditions

The FWD correlation trial was conducted at November 8th, 2023 between 9:00 and 16:00. It was a rainy day, especially towards the end of the day. Air temperatures ranged from about 8°C in the morning to about 11°C in the afternoon. Asphalt temperatures varied between 8.3°C and 9.5°C in the morning, and 9.8°C and 13.1°C in the afternoon. The differences among temperatures between the first and last visiting FWD per loop and site did not exceed the value of 2.4°C. Since this value is lower than 3°C, no centre deflections needed to be removed from analysis.

All FWDs used temperature recording devices with measuring probes, which were inserted into holes that were predrilled into the pavement.

Not all test sites were visited by all the participants. It is unknown whether these drops were not executed or the data was not stored.

3. Test location

3.1 General

Two test areas were selected in the area of Hilversum and Amersfoort, more precisely in the municipality Bunschoten in the morning, and in the municipalities Barneveld and Nijkerk in the afternoon. The test areas selected in the FWD correlation trial allowed usage of an orbital route. This made it possible to: a) visit the test stations twice, and b) to break down the fleet of participants into groups and having each group started at different test sites. Annex I shows how the FWDs were broken down into groups. This annex also displays the basic layout of the test sites per test area.

3.2 Selection of test sites

The objective of the selection was to choose sufficient test sites and test stations that would cover a wide range of load-carrying capacity and deflections. A total number of 70 to 80 test stations were expected to be the maximum obtainable number for a one-day test programme. Since all stations were to be visited twice, not more than 40 stations should be included in the test programme. Bearing capacity of the roads should vary from thick and thin asphalt roads on a soft subgrade, and thick and thin asphalt roads on a stiff subgrade. The test stations were all copied from previous CROW FWD correlation trials. The stations were spread over seven test sites. Some hindrance could be observed at the busy road at site 6 and the narrow road at site 7. The exact location of the test stations is presented in Annex I.

4. Participating equipment

4.1 Participating organisations, makes and models

In total 15 FWDs participated in the FWD correlation trial. Full names and FWD types and serial numbers are listed in Annex II. This chapter presents brief information on the participating organisations and their equipment. All participants are presented below. The 15 devices came from three manufacturers, nine FWDs were made by Dynatest, four from Sweco, and two from Rincent Technologies. One of the participants requested analysis of their data processed by two different algorithms. This explains why the following tables and figures contain data of 16 FWDs.

The numbers 1 to 7 were assigned to the FWDs from the Netherlands carrying a valid CROW certificate, since they were the eligible devices for defining the reference deflection bowls. The numbers 8 to 15 were randomly assigned to the other participants.

FWD01: Asset Insight (NL)
Dynatest 8012 Fast FWD

FWD02: Kiwa KOAC (NL)
Dynatest 8002

FWD03: Kiwa KOAC (NL)
Dynatest 8081 HWD

FWD04: Kiwa KOAC (NL) (2021)
Sweco PRIMAX 1500

FDW05: Qroad BV (NL)
Dynatest 8082 HWD

FDW06: Qroad BV (NL)
Dynatest 8082 HWD

FDW07: Unihorn BV (NL)
Dynatest 8012 Fast FWD

FDW08: TPA HU Kft. (H)
Dynatest 8012 Fast FWD

FDW09: Vlaamse overheid (BE)
Sweco PRIMAX 1500

FDW10: STAC (FR)
Rincent Heavydyn

FDW11: Heijmans (NL)
Sweco PRIMAX 2500

FDW12: BRS Infra (NL)
Dynatest 8002

FDW13: Rincent NCT (FR)
Rincent Heavydyn

FDW14: Nievelt Ingenieur GMBH (A)
Sweco PRIMAX 3500

FDW15: Civil Engineering Institute CPL (SRB)
Dynatest 8082 HWD

4.2 Anonymisation

The FWD tags A to P were used to anonymise presentation of the confidential results of all 16 analyses FWDs. Tags were assigned in order of decreasing overall accuracy and precision rating. Three rating subjects were used for this purpose. The rating procedure is explained in table 1. Linear interpolation was used for rating intermediate test results. All ratings were rounded to the nearest integer. A theoretical maximum of 300 points could be achieved by the really optimal functioning FWD. The higher the overall rating, the better the FWD complies with the specifications presented in table 1.

Table 1 ***Rating procedure in anonymisation***

Rating subject	Rating	Requirement
Repeatability	100	if the ratio of the standard deviations of the load and all normalised deflections and their requirement averaged over the two best performing stations is equal to zero
	0	if the ratio of the standard deviations of the load and all normalised deflections and their requirement averaged over the two best performing stations is equal to or greater than one
Variability of deflection sensor correlation factor	100	if the ratio of the standard deviations of all normalised deflections and their requirement averaged over all stations is equal to zero
	0	if the ratio of the standard deviations of all normalised deflections and their requirement averaged over all stations is equal to or greater than 0.090
Value of FWD correlation factor	100	if the FWD correlation factor is equal to 1.000
	0	if the absolute difference between the FWD correlation factor and one is equal to or greater than 0.2

5. Overall performance

Figure 5 presents the ratings of the participating FWDs for the three subjects listed in table 1. The FWDs are tagged in order of decreasing overall rating. The overall rating of the best performing FWD is 240 (was 249 in 2021, 241 in 2019, 252 in 2017, and 242 in 2015).

Two FWDs (Tag D and Tag N) failed to comply with the requirements set to the determination of the repeatability results during the trial. Furthermore, three FWDs (Tag L, Tag N and Tag O) failed to comply with the requirements set to the determination of the FWD correlation factor in terms of the variability. However, some of these FWDs belong to the same participant.

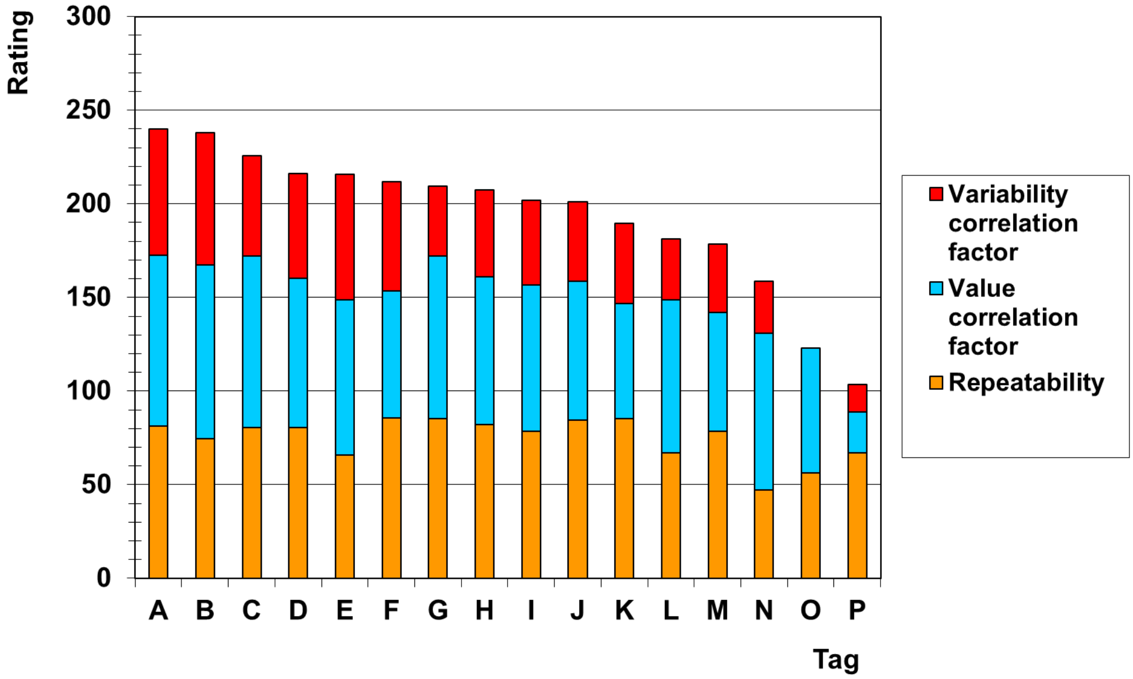


Figure 5 ***Overall rating of FWDs***

6. Repeatability

6.1 Processing of raw data

Deflection results are defined as being repeatable when a single FWD, operated by one and the same crew, reproduces the deflection bowl collected at a test site in a sequence of multiple drops without lifting the loading plate. The number of drops to be performed was set at twelve. The first two drops were omitted from analysis. All FWDs were requested to conduct this experiment on the stations 301, 302 and 303. Table 2 lists the mean deflection bowls measured by FWD Tag A. All drops were normalised to a load level of 50 kN. The three stations are quite different in terms of structural support of the asphalt layers and subgrade.

Table 2 ***Reference (FWD tag A) mean deflections on repeatability stations***

Station	Deflection sensor offset (mm)						
	0	300	600	900	1200	1500	1800
301	223	194	170	151	135	120	107
302	265	230	189	147	111	84	65
303	324	235	142	80	42	24	18

All data have been processed and analysed in accordance with Protocol 10 of [4]. There was no need to erase very distinct single outliers from the data sets presented.

6.2 Repeatability verification

The tolerances set to variation in load and deflections in a repeatability experiment in the FWD correlation trial, as specified in Protocol 10, are copied below.

- The standard deviation of the load recorded in the series of ten drops shall be less than, or equal to two percent of the mean of the recorded values. If the actual standard deviation exceeds the specified value, the load variation acceptance criterion is not complied with.
- The standard deviation of the normalised deflections, recorded in the series of ten drops shall be less than, or equal to 2 µm or the sum of 1.0 µm and 0.75 percent of the mean of the recorded normalised values, whichever is greater. If the actual standard deviation of one or more deflectors exceeds the specified values, then the deflection variation acceptance criterion is not complied with.

An example of the approach: A sequence of multiple drops has resulted in a mean of 360 µm and a standard deviation of 3.1 µm. The specifications tolerate a standard deviation of 1.0 + 0.0075 x 360 = 3.7 µm. Since the actually measured standard deviation is smaller than the limit value, the FWD under test complies with the criteria.

Any FWD passes the repeatability criteria if full compliance with load and deflection requirements is achieved for at least two of the three test stations (see figures 6 and 7). Not all FWDs succeeded in meeting with these criteria, FWD Tag D and N did not comply. Figures 6 and 7 show that this trial complying with the criteria was not significantly more difficult for specific sensors, whereas generally it is more difficult for the remote sensors. The variability of the load of FWD Tag C and Tag D was higher than those of the other equipment. Perhaps the drop height was not kept constant enough. The load variability remained within the tolerances.

Annex IV lists the load and deflection data of each FWD used in the analysis. The suffix 'x' equals the FWD number in the test. The deflections listed are the normalised data whereas the load is the actually measured value. The bottom lines of each table show the result of the verification. This table contains confidential data and is for this reason not included in the main report.

Figures 6 and 7 and Table 3 present an anonymous overview of the principal results of the repeatability experiment. The graphs and table list the ratios of standard deviation actually measured and allowed. The lower this ratio is, the better the repeatability is. Repeatability specifications require that the ratios shall be less than 1.00. Only the best two results per FWD are displayed.

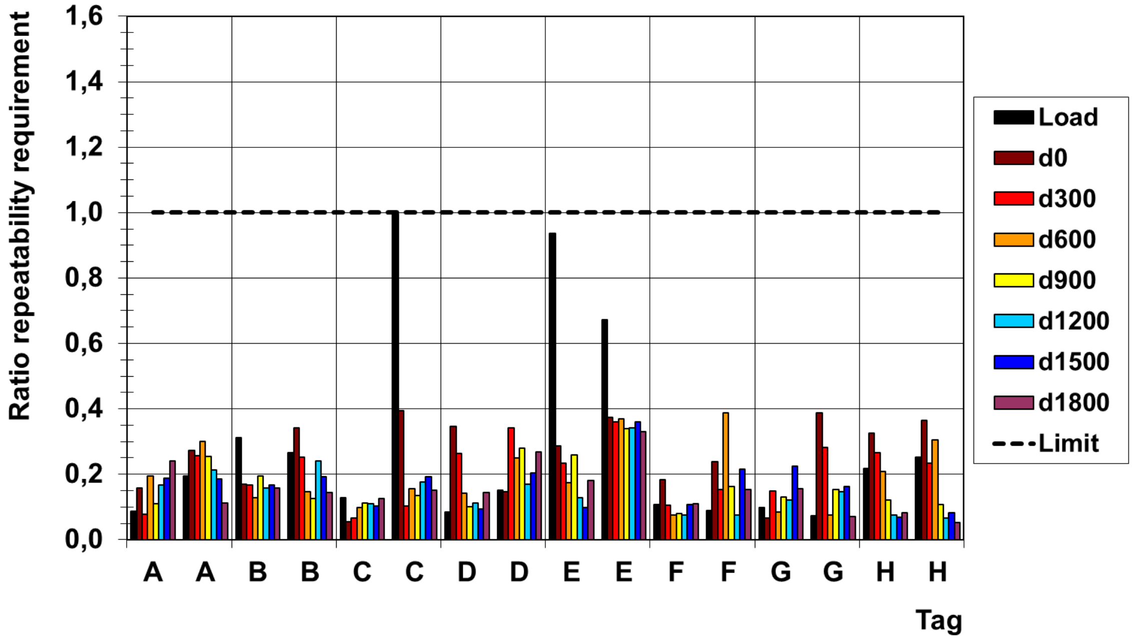


Figure 6 ***Results of best two stations in repeatability experiment for FWD tags A-H***

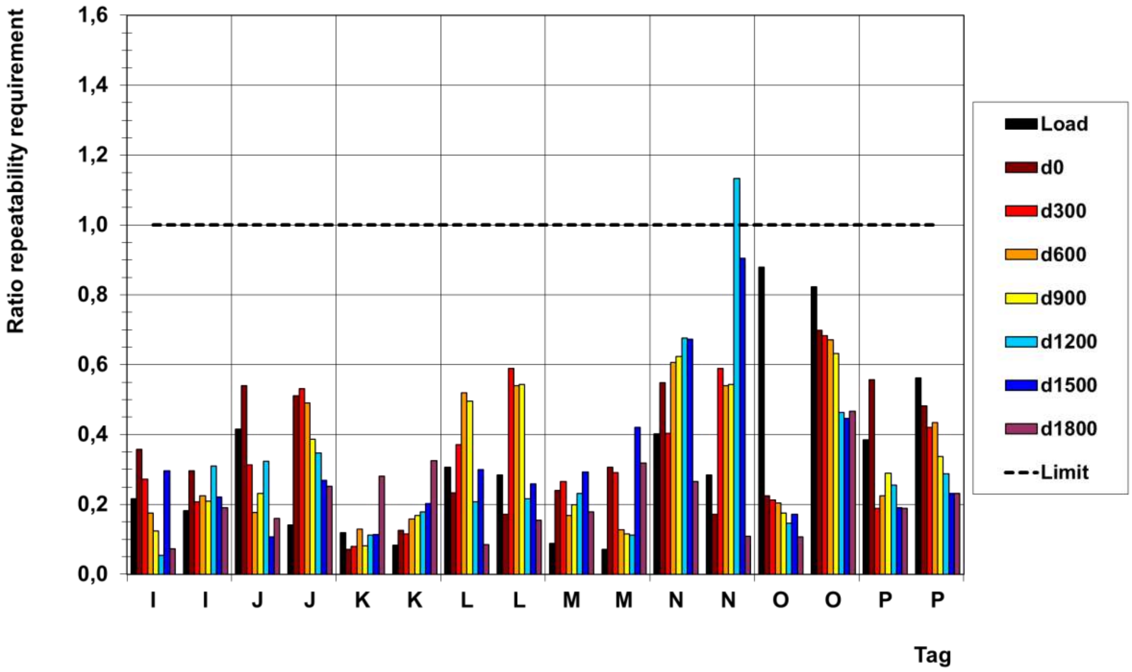


Figure 7 ***Results of best two stations in repeatability experiment for FWD tags I-P***

Table 3 ***Summary of results of repeatability experiment***

FWD Tag	Test station	Repeat. Load	Repeatability deflections						
			d0	d300	d600	d900	d1200	d1500	d1800
A	303	0,09	0,16	0,08	0,19	0,11	0,17	0,19	0,24
	302	0,19	0,27	0,26	0,30	0,25	0,21	0,19	0,11
B	302	0,31	0,17	0,17	0,13	0,19	0,16	0,17	0,16
	303	0,27	0,34	0,25	0,15	0,13	0,24	0,19	0,14
C	301	0,13	0,05	0,07	0,10	0,11	0,11	0,10	0,13
	302	1,00	0,39	0,10	0,16	0,14	0,18	0,19	0,15
D	303	0,08	0,35	0,26	0,14	0,10	0,11	0,09	0,15
	301	0,15	0,15	0,34	0,25	0,28	0,17	0,20	0,27
E	302	0,94	0,29	0,23	0,17	0,26	0,13	0,10	0,18
	303	0,67	0,37	0,36	0,37	0,34	0,34	0,36	0,33
F	302	0,11	0,18	0,10	0,08	0,08	0,07	0,11	0,11
	301	0,09	0,24	0,15	0,39	0,16	0,07	0,22	0,15
G	301	0,10	0,07	0,15	0,08	0,13	0,12	0,22	0,16
	303	0,07	0,39	0,28	0,08	0,15	0,15	0,16	0,07
H	302	0,22	0,33	0,27	0,21	0,12	0,08	0,07	0,08
	303	0,25	0,37	0,23	0,31	0,11	0,07	0,08	0,05
I	303	0,22	0,36	0,27	0,17	0,12	0,05	0,30	0,07
	301	0,18	0,30	0,21	0,23	0,21	0,31	0,22	0,19
J	303	0,12	0,07	0,08	0,13	0,08	0,11	0,11	0,28
	301	0,08	0,13	0,12	0,16	0,17	0,18	0,20	0,33
K	302	0,31	0,23	0,37	0,52	0,50	0,21	0,30	0,08
	301	0,28	0,17	0,59	0,54	0,54	0,22	0,26	0,15
L	303	0,41	0,54	0,31	0,18	0,23	0,32	0,11	0,16
	302	0,14	0,51	0,53	0,49	0,39	0,35	0,27	0,25
M	301	0,09	0,24	0,27	0,17	0,20	0,23	0,29	0,18
	303	0,07	0,31	0,29	0,13	0,12	0,11	0,42	0,32
N	303	0,40	0,55	0,40	0,61	0,62	0,68	0,67	0,27
	301	0,28	0,17	0,59	0,54	0,54	1,13	0,90	0,11
O	303	0,88	0,23	0,21	0,21	0,18	0,15	0,17	0,11
	301	0,82	0,70	0,68	0,67	0,63	0,46	0,45	0,47
P	301	0,38	0,56	0,19	0,22	0,29	0,26	0,19	0,19
	302	0,56	0,48	0,42	0,43	0,34	0,29	0,23	0,23

7. Reproducibility

7.1 General and eligibility

Deflection results are defined as being reproducible when various types of FWD, operated by various crews, produce similar deflection bowls for a specific test station under identical testing conditions. Verification of reproducibility can be achieved only, when a reference system has been defined. In the 1993 FWD comparative study, the mean of the deflections measured by the Dynatest 8002 type FWDs, normalised to a load level of 50 kN, was taken as reference. This selection was considered to be appropriate at that time because of the capability of this type of non-destructive testing (NDT) device of producing almost identical results among four devices for the wide variety of pavement structures and subgrade types. The drawback of this approach is that the reference is labelled to a specific manufacturer, which may cast some problems towards a generally acceptable reproducibility verification procedure.

A theoretically better technique is the choice of the deflections measured under a standard load pulse shape (e.g. sine-shaped pulse) as reference data. This approach requires sampling and processing of whole history deflection data. This also requires adequate and accurate modelling of the pavement structure. Linear elastic modelling is simply not sufficient. Current modelling procedures are not evolved to a satisfactory degree to be used for this purpose. Consequently, a more modest approach needs to be applied.

In this correlation trial the approach as specified in Protocol 10 of [4] was used for determination of the reference deflection bowl. Prior to the test the organisation of the trial CROW issued that all Dutch FWDs holding a valid CROW certificate would form the eligible group as defined in Protocol 10. Based on the 2021 correlation trial, the participating FWD01 through FWD7 would form the eligible group. The mean of this group serves as basis of the reference deflection bowl per station. A precise description of the determination of the reference deflection bowl is presented in Protocol 10.

7.2 Smoothing technique

When the weight of the FWD drops on the set of rubber buffers, several factors may cause some distortion in the load pulse shape. This distortion might be due to non-linearity, damping, and temperature dependency of the rubber buffers but also because of the properties of the ribbed rubber pad under the loading plate and the pavement structure. Any pavement will have some mass and damping. This damping may vary from pavement to pavement and from subgrade to subgrade. This implies that any pavement structure will act as a filter and that it will have a reduced response to fast or high-frequency components of the load signal. As a result, high frequencies may be observed in the spectrum of the load signal. These high frequencies were erased from the spectrum of the deflection signal, because the pavement cannot react that quickly to the high frequency components of the load.

If the peak values of the load time history and deflection time histories distorted by high frequency disturbance are used, we might actually compare incorrect values to each other. This might in turn have its impact on calculation results. For that reason, it is welcomed to erase the distorting effect of the high frequencies by smoothing both the load pulse and the deflection pulse. If we do not smooth both pulses, we erroneously introduce extra phase lag between the two signals. Dynamic analyses of the deflection data are based on whole time histories and need correct phase lag data to generate correct analysis results.

Distorted pulses may have a significant number of components above 60 Hz. Because most pavements do not respond to the frequencies above 60 Hz, and because 60 Hz is the lowest frequency that might be ignored in a perfect sine-shaped shock pulse, this frequency is often used as cut-off frequency. More precise load and deflection pulses will be obtained by smoothing. For this reason, Article 10.7.1 of Protocol 10 [4] requires smoothing for the devices participating in the FWD correlation trial.

7.3 Asphalt temperature

According to Article 10.10.4 of Protocol 10 [4], pavement temperature should not vary more than 3°C during the period of testing at a specific test site per round of testing. If the variation exceeds this limit, the centre deflection should not be submitted for analysis. Table 4 shows the lowest and highest asphalt temperature recorded by the temperature loggers within the time interval of the earliest and latest visiting FWD. The table shows that the temperature variation stayed within the allowed tolerances.
Since only three temperature loggers were available, no temperature data were recorded at site 7, as the afternoon session had four sites.

Table 4 ***Asphalt temperatures recorded by loggers***

Test	Asphalt temperature by logger (°C)		
Station	Minimum	Maximum	Difference
111	8,3	9,1	0,8
121	8,3	9,2	0,9
131	8,4	9,2	0,8
141	10,7	11,3	0,6
151	10,7	13,1	2,4
161	10,1	11,4	1,3
171		no data	
211	8,8	9,4	0,6
221	9,1	9,5	0,4
231	8,9	9,4	0,5
241	10,5	10,8	0,3
251	10,2	10,6	0,4
261	9,8	10,3	0,5
271		no data	

7.4 Deviation ratio and reference deflection bowl

As stated before, the determination of the reference deflection bowl was performed according to the procedures specified in Protocol 10 of [4]. All submitted deflection data were screened for apparent errors prior to analysis. No such errors were found.

The seven Dutch devices FWD01 – FWD07 holding a valid CROW certificate formed the eligible group for determination of the reference deflections. From this eligible group, FWD01 did not meet the criteria of Article 10.10.7 of Protocol 10 and was erased from the reference group [4]. The lowest and highest normalised deflection of the reference group were removed from the dataset prior to computation of the reference. This implies that a systematic difference from one of the eligible devices is automatically accounted for in the technique of computing the reference. Annex III lists the reference deflection data.

7.5 Correlation factors

Annex V lists the deflection ratios of each deflection sensor under analysis. This ratio shall be used as the multiplication factor for converting the measured deflection to the reference deflection. Good reproducibility is achieved if all factors wander narrowly around the value one. The standard deviation in each column of deflection ratios should be less than 0.090. Presence of a higher standard deviation invalidates the test results. The mean value per sensor is termed ‘deflection sensor correlation factor’. These factors may only range from 0.80 to 1.20. The values resulting from the analysis are printed at the bottom of Annex V.

The mean of the deflection sensor correlation factors is defined as the FWD correlation factor according to Article 10.10.11 of Protocol 10 [4]. This factor needs to be multiplied by the deflection data produced by the device under analysis to obtain the reference deflection data. Tables 5 and 6 list anonymous overviews of the deflection sensor correlation factors and the FWD correlation factors of the reproducibility experiment.

The standard deviations listed in Table 5 should all remain below the 0.090 level. Values not passing this criterion are marked. Figure 8 displays the results of Table 5 graphically. The graph clearly illustrates the tendency of many FWDs to provide increasing standard deviation with sensor offset, or perhaps better defined with decreasing sensor reading. This pattern was observed in previous trials as well.

Table 5 ***Standard deviation of deflection ratios per sensor***

FWD Tag	Standard deviation of deflection ratio						
	d0	d300	d600	d900	d1200	d1500	d1800
A	0,023	0,024	0,027	0,029	0,031	0,034	0,038
B	0,018	0,019	0,020	0,020	0,024	0,037	0,046
C	0,041	0,037	0,039	0,039	0,040	0,046	0,051
D	0,031	0,032	0,036	0,040	0,042	0,046	0,051
E	0,024	0,023	0,023	0,027	0,028	0,032	0,050
F	0,029	0,029	0,034	0,035	0,040	0,044	0,051
G	0,042	0,044	0,047	0,052	0,058	0,070	0,080
H	0,041	0,041	0,040	0,042	0,041	0,049	0,082
I	0,043	0,043	0,047	0,051	0,053	0,056	0,053
J	0,045	0,045	0,049	0,053	0,061	0,056	0,056
K	0,041	0,044	0,048	0,054	0,052	0,055	0,066
L	0,056	0,052	0,052	0,052	0,048	0,059	0,107
M	0,037	0,042	0,052	0,057	0,064	0,070	0,076
N	0,056	0,052	0,052	0,052	0,055	0,072	0,116
O	0,038	0,073	0,144	0,157	0,166	0,146	0,093
P	0,067	0,072	0,075	0,076	0,077	0,083	0,086

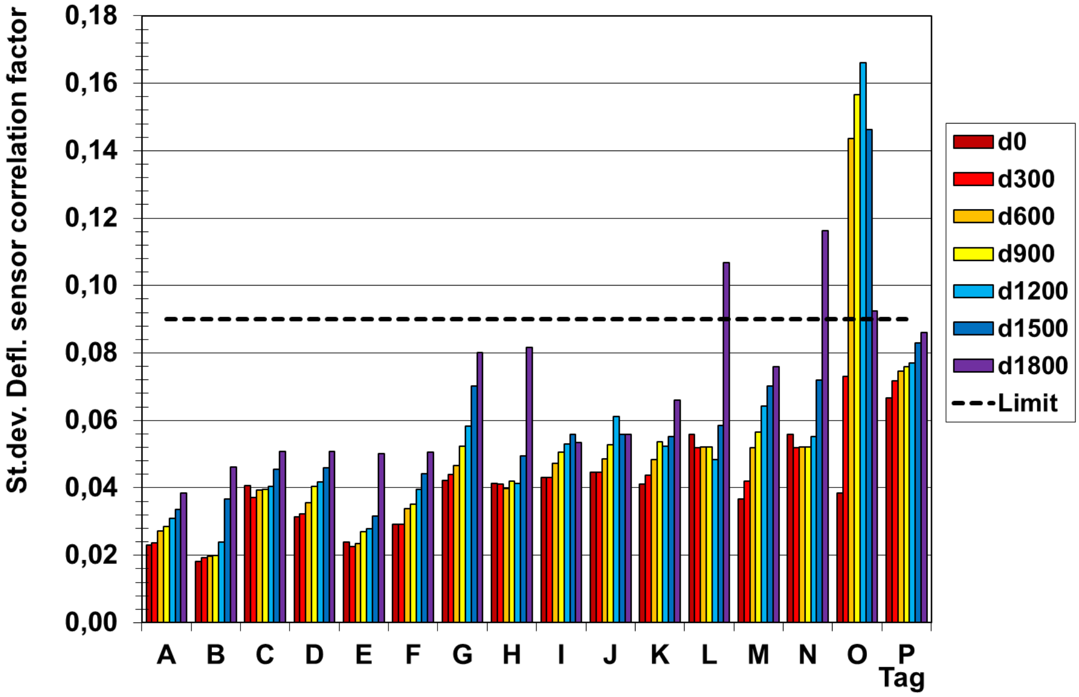


Figure 8 ***Standard deviation of deflection ratio per sensor***

Table 6 lists the deflection sensor correlation factors and in the last column the FWD correlation factor.

Table 6 Deflection sensor correlation factors and FWD correlation factor

FWD Tag	Deflection sensor correlation factor							FWD Correlation factor
	d0	d300	d600	d900	d1200	d1500	d1800	
A	0,968	0,983	0,983	0,981	0,985	0,990	0,992	0,983
B	1,016	1,022	1,021	1,017	1,027	1,006	0,994	1,015
C	1,022	1,008	1,021	1,010	1,022	1,022	1,014	1,017
D	0,964	0,954	0,954	0,953	0,952	0,966	0,972	0,959
E	1,043	1,027	1,019	1,039	1,022	1,032	1,060	1,035
F	0,942	0,938	0,933	0,932	0,931	0,938	0,937	0,936
G	0,980	0,974	0,984	0,974	0,970	0,968	0,967	0,974
H	0,947	0,951	0,919	0,943	0,956	0,963	1,022	0,957
I	0,965	0,956	0,958	0,954	0,954	0,958	0,950	0,956
J	0,950	0,949	0,952	0,944	0,950	0,946	0,948	0,948
K	1,073	1,066	1,079	1,072	1,083	1,088	1,077	1,077
L	0,967	0,954	0,945	0,936	0,924	0,944	1,077	Not valid
M	0,932	0,929	0,930	0,925	0,917	0,931	0,921	0,926
N	0,967	0,954	0,945	0,936	0,943	0,953	1,074	Not valid
O	1,107	1,021	0,883	0,874	0,867	0,879	0,903	Not valid
P	0,862	0,848	0,844	0,834	0,833	0,840	0,842	0,843

Computed FWD correlation factors between 0.995 and 1.005 inclusive are considered to be equivalent to 1.000. In other words: no adjustment is required. FWD correlation factors should not be smaller than 0.80 and not be greater than 1.20. Table 6 shows that all FWDs meet this requirement. No FWD correlation factor was computed for FWD Tag L, N and Tag O, since some of their deflection sensors did not meet the variability requirement.

8. Extended analysis of test results

8.1 Robustness of FWD correlation factor

The two rounds of visiting of each test station allow comparison of the results of the first loop to the second loop. If the analysis results are identical, the conclusion can be drawn that the FWD correlation trial provides accurate and robust data. Data of the first loop and second loop were combined in the determination of the FWD correlation factor. In this chapter, this factor will be based per loop separately. The analysis investigates the differences of deflection sensor correlation factors and FWD correlation factors between the two loops of testing. Table 7 present the differences between the two loops of testing.

Table 7 ***Differences between deflection sensor correlation factors and FWD correlation factors in loop #1 minus loop #2***

FWD Tag	Difference between deflection sensor correlation factors							FWD Correlation factor
	d0	d300	d600	d900	d1200	d1500	d1800	
A	-0,003	-0,005	-0,005	-0,002	-0,003	-0,004	-0,002	-0,004
B	-0,001	0,001	0,000	0,001	0,002	0,004	-0,002	0,001
C	-0,005	-0,013	-0,017	-0,017	-0,018	-0,014	-0,019	-0,015
D	-0,002	-0,003	-0,003	-0,001	-0,002	-0,003	-0,003	-0,002
E	-0,001	-0,003	-0,002	-0,001	-0,002	-0,001	0,003	-0,001
F	-0,002	-0,006	-0,007	-0,008	-0,010	-0,009	-0,008	-0,007
G	0,011	0,008	0,009	0,009	0,006	0,007	0,002	0,007
H	0,002	0,008	0,010	0,019	0,023	0,028	0,039	0,018
I	-0,019	-0,023	-0,022	-0,019	-0,017	-0,014	-0,014	-0,018
J	0,002	-0,001	-0,001	-0,002	-0,003	-0,002	0,004	-0,001
K	-0,009	-0,009	-0,011	-0,009	-0,009	-0,010	-0,008	-0,009
L	-0,008	-0,011	-0,013	-0,008	-0,005	-0,003	0,001	-0,007
M	0,001	-0,003	-0,003	-0,002	-0,010	0,004	0,004	-0,001
N	-0,008	-0,011	-0,013	-0,008	-0,008	-0,007	0,005	-0,007
O	-0,007	-0,010	-0,010	-0,009	-0,008	-0,008	-0,003	-0,008
P	-0,034	-0,040	-0,043	-0,040	-0,039	-0,041	-0,035	-0,039

Table 7 shows that the calibration factors found in the first round of testing usually do not depart too much from those found in the second round of testing. Preferably the ranges should not be more than 0.010. However, for some FWDs slightly larger differences were found (see marked cells). FWDs Tags C, I, and P consistently produce higher deflection sensor correlation factors (i.e. lower deflection than reference) in the second loop than in the first loop, whereas for FWD Tag H, this is more the other way around. These small differences did not lead to a too high overall variability. No apparent reason could be found for the observations.

8.2 Repeatability and reproducibility indicators

The FWD correlation factors presented in section 7.5 were used to convert the inputted normalised deflections into adjusted normalised deflections. Ideally, the deflection bowls should be identical per station for each of the FWDs. The mean deflection was calculated per geophone and station. In a next step the mean of the two loops was determined. Subsequently, the difference between the adjusted deflection and the mean of the adjusted deflection was determined for each of the FWDs. The standard deviations repeatability and reproducibility were computed based on these differences, according to ISO 5725-2. Beware that this repeatability is the indicator for consistency of measuring the same deflection at a station after leaving the station and returning to it.

The figures 11 and 12 show the standard deviations for repeatability and reproducibility for each station and for the geophone offsets 0, 300, 900 and 1200 mm. The graphs clearly demonstrate that the standard deviation increases with peak value of deflection. The sets of computed standard deviations were used to calculate the values of the repeatability r and reproducibility R. These predictive lines of r and R run therefore not through the centre of the data clouds of sr and sR (see the solid black lines in the figures 10 and 11).

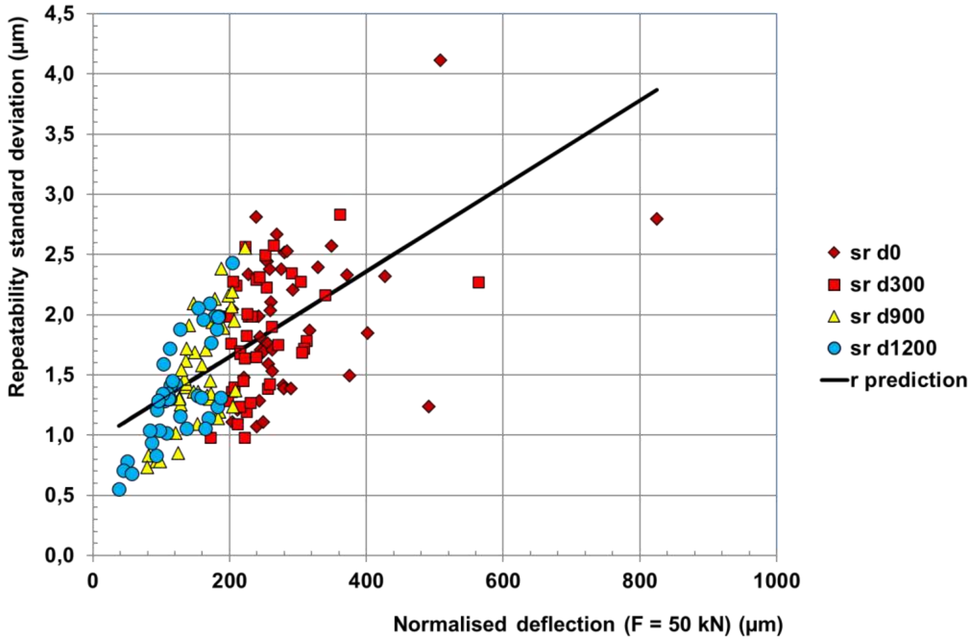


Figure 9 ***Repeatability (standard deviation) data***

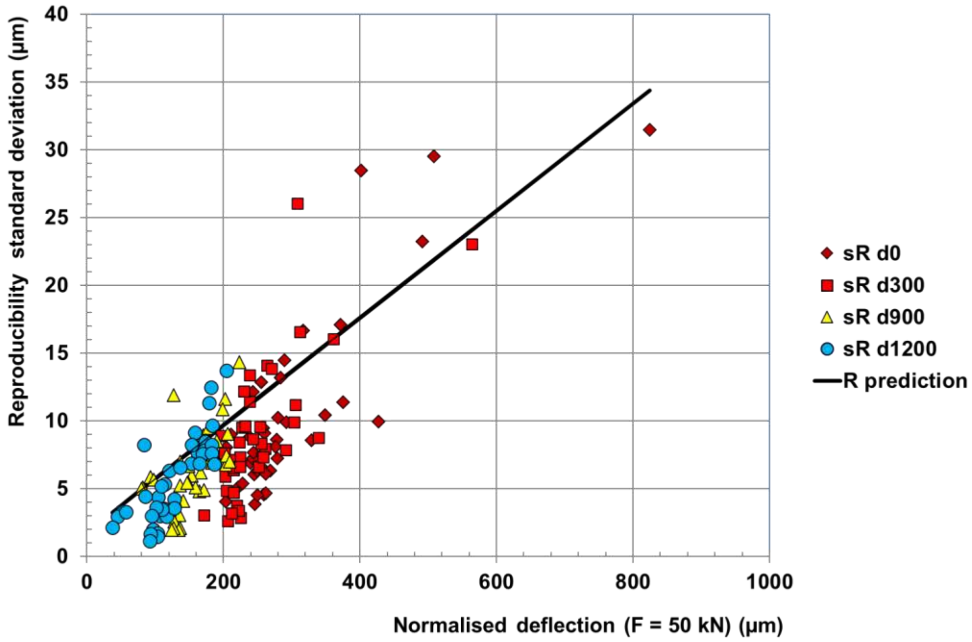


Figure 10 ***Reproducibility (standard deviation) data***

The repeatability r and reproducibility R, as indicated by the solid black line in figures 10 and 11, can be predicted approximately as follows:

$$r = 0.94 + \frac{d}{282}$$

$$R = 1.77 + \frac{d}{25{,}3}$$

where r = repeatability when leaving and returning to a test station (µm)
R = reproducibility (µm)
d = deflection (µm)

8.3 Asphalt temperature

Assessment of the structural condition of asphalt roads requires accurate data on deflections, layer thicknesses, material properties, traffic but also on asphalt temperatures. The response of the asphalt pavement structure under an FWD impact load does not only vary with structural support and load pulse characteristics, it also strongly depends on the asphalt temperature because asphalt is a visco-elastic material.
All participants of the FWD Correlation Trial were asked to record the asphalt temperature in a predrilled hole at the first station of the test sites 1 through 6. No hole was drilled on site 7 simply due to lack of sufficient temperature loggers. All sites were visited twice. This double round of testing led to a set of 12 temperatures per FWD. All FWDs used a temperature sensitive probe. For FWD08 no temperature data was recorded.
Each operator registered not only the asphalt temperature but also the clock time at each station. This clock time was matched to the clock time of the project leader and the temperature loggers. The temperature loggers stored the asphalt temperature each minute.

Figures 12 and 13 present box plots with the differences between the asphalt temperature recorded by the FWD and the reference temperature recorded by the temperature logger at the same clock time. A positive value means that the FWD recorded a higher temperature than the logger did. Figure 12 presents all data, including outliers, whereas figure 13 presents the data without outliers.
The box plot is a convenient way of graphically depicting groups of numerical data through their quartiles. The box plot has lines extending vertically from the boxes (whiskers) indicating variability outside the upper and lower quartiles, hence the terms box-and-whisker plot and box-and-whisker diagram. Outliers may be plotted as individual points. Box plots display differences between populations without making any assumptions of the underlying statistical distribution: they are non-parametric. The spacing between the different parts of the box help to indicate the degree of dispersion (spread) and skewness in the data, and to identify outliers.
The bottom and top of the box are the first and third quartiles, and the red band inside the box is the second quartile (the median). The ends of the whiskers represent highest and lowest datum.

Two outliers (data more than 3 times the interquartile range above the upper quartile, or more than 3 times the interquartile range below the lower quartile) were found: for FWD04 at station 211; FWD05 at station 111; FWD09 at station 261; and FWD12 at stations 111, 121, 131, 221, and 231. These were considered outliers, mainly not because a large difference from the average, but because a small interquartile range for these temperature sensors, and hence tight outlier limits. No extreme values were found for any FWD as can be seen in figure 12 .

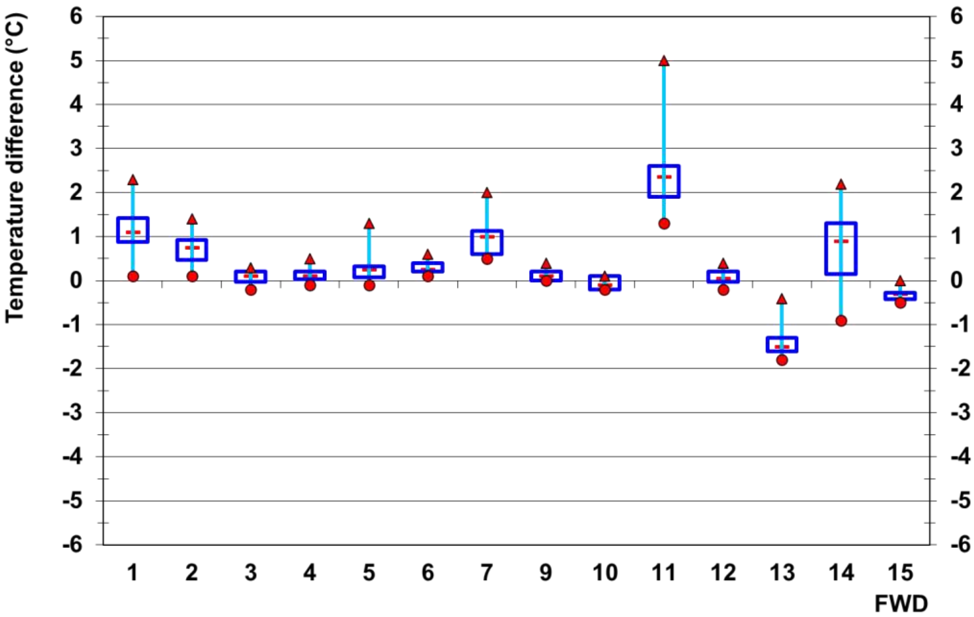


Figure 11 ***Box-and-whisker plot of asphalt temperature, including outliers***

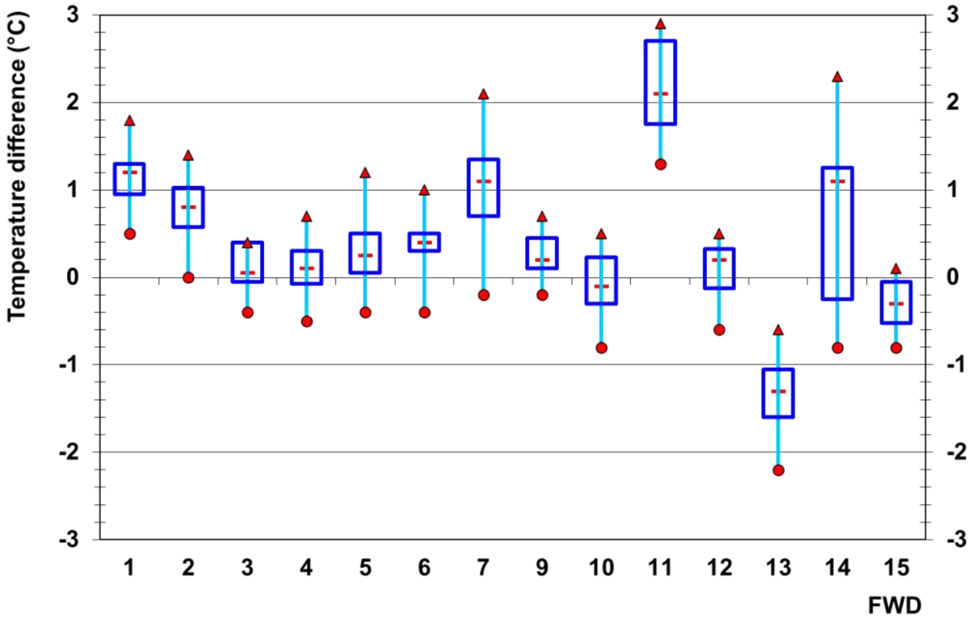


Figure 12 ***Box-and-whisker plot of asphalt temperature, excluding outliers***

Table 8 displays the standard uncertainty of the asphalt temperature recording by each FWD. The sheet with asphalt temperature recordings of FWD 8 was missing and is therefore not included in table 8. The repeatability and reproducibility of the difference between the manually recorded temperature and the logger temperature was analysed according to ISO 5725-2. The repeatability r appears to be 1,26°C. The reproducibility R equals 2,67°C. Both the repeatability indicators per station and the reproducibility indicators per station varied narrowly around the presented values. Both the repeatability and reproducibility of temperature recording are better than in the 2021, 2019 and 2017 trials.

Table 8 ***Standard uncertainty in asphalt temperature recording***

FWD	Standard uncertainty (°C)
1	0,61
2	0,39
3	0,16
4	0,18
5	0,36
6	0,16
7	0,46
8	-
9	0,12
10	0,13
11	0,93
12	0,18
13	0,40
14	0,91
15	0,15

9. Conclusions and recommendations

9.1 Conclusions

Two FWDs failed to comply with the requirements of Protocol 10 of CROW-report D11-07 Falling Weight Deflectometer calibration guide. As a result, 13 out of the 15 participating FWDs met the specifications for obtaining the CROW FWD calibration certificate.

The valid FWD correlation factors ranged from 0,843 to 1,077. This range is much greater than in 2021 (0,949 to 1,102) and in 2019 (0,928 to 1,077).

Use of two rounds of testing in the reproducibility experiment made comparison of results between the two rounds of testing possible. The analyses showed that differences between the two series are usually limited but that in some cases peculiar differences could be observed, similar to the 2021 results.

The accuracy of all asphalt temperatures recordings was more or less of the same magnitude for the temperature sensitive probes. The precision of all asphalt temperature recording had a greater deviation. The repeatability and reproducibility values are r = 1,26°C and R = 2,67°C.

Repeatability r (in terms of a single FWD leaving and returning to a test station) and reproducibility R of the deflection recordings were computed: r = 0,94 + deflection/282; R = 1,77 + deflection/25,3.
All values are expressed in µm.

9.2 Recommendations

The test sites have been used for many years and most recommendations from previous trials were accounted for in the 2021 trial. Nevertheless, some points for improvement could be found.

- Consideration should be given to use of an extra temperature logger in the afternoon session; only three loggers were available for four test sites.
- The test protocol should be more explicit in the direction in which the deflection bar should point. Although most FWDs have their deflection bar pointed into the direction of travel, still the possibility exists that FWDs might participate in the correlation trial having the deflection bar pointing to the rear. Having the offsets of the geophones under analysis on identical positions from the load centre facilitates assessment of the accuracy and precision of all geophones and not only those in the near field. Although one participant had the deflection bar pointed to the rear, the participant decided to do the test while driving in reverse to avoid producing potential deviating test results.

References

1 Van Gurp. C.A.P.M.. Characterization of seasonal influences on asphalt pavements with the use of Falling Weight Deflectometers. PhD thesis. Delft University of Technology, Delft, 1995.

2 Use of Falling Weight Deflectometers in Pavement Evaluation. Final Report. 2nd Edition. COST Action 336. European Commission, Brussels, 2005 (Available via FEHRL website).

3 FWD Calibration Center and Operational Improvements: Redevelopment of the Calibration Protocol and Equipment. Publication FHWA-HRT-07-040. Federal Highway Administration, McLean, VA, USA. October 2011.

4 Falling Weight Deflectometer calibration guide. Report D11-07. CROW, Ede, August 2011.

Annex I Test programme FWD correlation trial

This annex presents the test protocol for Group A. The test protocols for Groups B and C are identical except for the order in which the test sites are visited in the two trial loops.

I-1 General and test information

Date and time of testing: 8 November 2023; 8:30 - 17:00.

Test area: Two test areas with three test sites at low-volume roads west of Bunschoten-Spakenburg and four test sites south of Nijkerk. Both locations are in a range of 15 km from Amersfoort.

Location of venue: Denksport En Passant
Bikkersweg 90
3752 WV Bunschoten-Spakenburg

For route from motorway A1 to venue, see Figure I-1

Figure I-13 Route from Motorway A1 exit 12 to venue of FWD correlation trial

Project leader: Daisy Bouwmans
Kiwa KOAC
Nevelgaarde 20
NL-3436 ZZ Nieuwegein
The Netherlands

Contact data: Mobile: +31 6 51122920
Email: Daisy.Bouwmans@kiwa.com

Assistant: Christ van Gurp
Mobile: +31 6 2043 8375

Traffic safety: Please use the required traffic warning devices (flashing lights, traffic signs, etc.) when testing at all sites. Even though traffic intensity on most sites is low, the test sites are open to public traffic (with 1 exception in 2023) and therefore the normal safety regulations are applicable.

Number of test sites: Seven; All test sites are situated at asphalt pavement structures with low traffic intensities. The number of test stations will vary from four to seven per test site. All test stations will be visited twice except for the three stations selected for repeatability testing. The number of test stations is about 40.

Reference point and zero point:	The exact location of each test station is given in metres from the zero point for that specific test site. The zero point is not always easy to detect when approaching the test at normal travel speed. For that reason each test site has its own reference point. The reference point is easy to see (house, bridge, lamppost, etc). GPS coordinates are given for each reference point. The reference point serves as reference for the zero point. The zero point serves for referencing the test stations.
Test station markings:	The test stations are marked by white or yellow chalk or paint. The mark is a circle with a diameter of 400 mm. Position the FWD loading plate entirely in this circle;
Direction of deflection sensor bar:	The raise/lower bar with the deflection sensors shall be pointed into the direction of travel. Experience has shown that deflection sensors, especially at the larger geophone distances from the load, pointed against the direction of travel are likely to have problems meeting the reproducibility criteria.
Target load level:	Use a target load level of 50 ±5 kN for all test sites, to be set at the first test station. Do not change the load level, drop height, or drop mass during the day of the trial. The load targeting feature (when available) may be switched on at the reproducibility stations but not at the repeatability stations.
Target load pulse duration:	Use a load pulse duration of 26 ±1 ms when possible.
Deflection sensor offset:	Measure the deflections at spatial distances of 300 mm, starting from the load centre up to 1800 mm. In case of more than seven sensors, positioning of the extra sensors may be freely chosen by the operator. The extra deflections will not be analysed.
Time of drop:	Record the exact time of each drop in HHMMSS when possible, otherwise in HHMM.
Temperature:	Record the pavement temperature near the first station of each test site. Holes will be predrilled and marked for this purpose. Register the temperature (with one digit placed beyond the decimal point) and the clock time on the temperature sheet. During the trial the clock time of each FWD shall be compared to the clock time of the project leader (see temperature sheet). Independent temperature logging will be arranged for comparative reasons.
Load:	Record the load of each drop in kN with one digit placed beyond the decimal point.
Deflections:	Record the deflections of each deflection sensor and each drop in micrometres with no digits placed beyond the decimal point. Do not submit normalised deflections for analysis!
Filter and smoothing options:	Switch on the peak smoothing option (load and deflections) and set the cut-off frequency at 60 Hz. Contact your manufacturer in case you need assistance.
Reproducibility stations:	Apply 5 drops in one sequence at the selected test stations. The small pre-drop (if available) may not be counted. Store all drops. The last 4 drops will be analysed.
Repeatability stations:	Apply 12 drops in one sequence at the selected test stations. The small pre-drop (if available) is not counted. Store all drops. The last 10 drops will be analysed. Do not use the load targeting feature at these stations.
Deflection history:	When possible, store load and deflection history of the last drop at each test station of the reproducibility series. This information is used for explanation of any anomalies found in the analysis phase.

Data storage:	Test data may be stored in any format. Dynatest FWD users are asked to deliver the data in MDB format. Sweco FWD users are kindly requested to present the data in F25 format. Submit the FWD data and temperature data to the supervisor at the end of the day.

I-2 Organisation

The organisation of the FWD correlation trial 2023 consists of the following members:

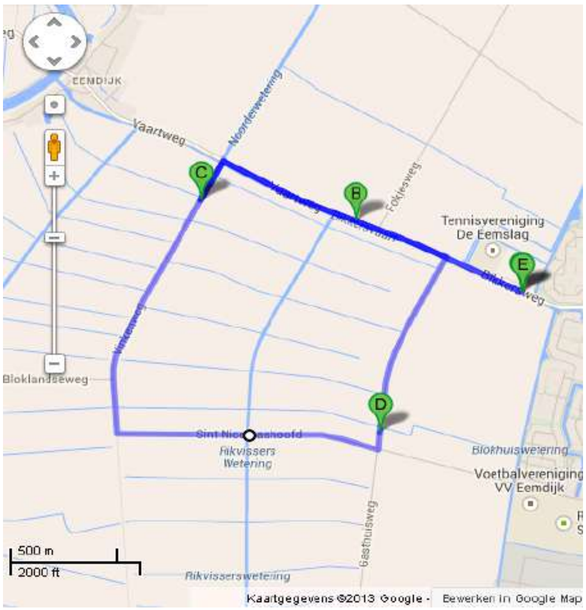
Supervisor:	Leonie de Kleijn (CROW)
Executive officer:	Daisy Bouwmans (Kiwa KOAC)
Assistant:	Christ van Gurp (Kiwa KOAC)

I-3 Test sites

The FWDs will be divided over three groups to reduce traffic congestion and to speed up testing over the whole day of the trial. All test sites will be visited twice. Each group will start at a different test site. Table I-1 lists the test order per group. Within each group participants may freely choose test order.

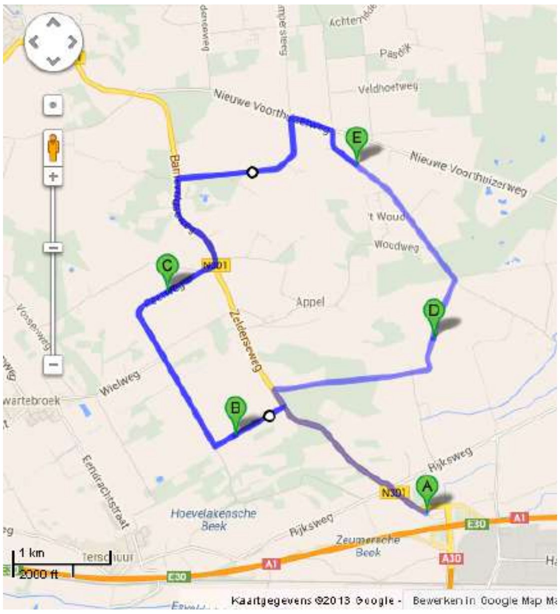
Table I-1 Sequence of test sites

Stop	Loop	Group A	Group B	Group C
1	1	Site 1	Site 2	Site 3
2	1	Site 2	Site 3	Site 1
3	1	Site 3	Site 1	Site 2
4	2	Site 1	Site 2	Site 3
5	2	Site 2	Site 3	Site 1
6	2	Site 3	Site 1	Site 2
7	1	Site 4	Site 5	Site 6
8	1	Site 5	Site 6	Site 7
9	1	Site 6	Site 7	Site 4
10	1	Site 7	Site 4	Site 5
11	2	Site 4	Site 5	Site 6
12	2	Site 5	Site 6	Site 7
13	2	Site 6	Site 7	Site 4
14	2	Site 7	Site 4	Site 5



E	Start and finish morning session
B	Test site 1
C	Test site 2
D	Test site 3

Figure I-14 Location of test sites in the morning session



A	Start afternoon session (= lunch)
B	Test site 4
C	Test site 5 and finish
E	Test site 6
D	Test site 7

Figure I-15 Location of test sites in the afternoon session

I-4 Test route

Route to Test Site

- Leave car park and turn right;
- Follow road for 700 m until first road to the right (this is the reference point).

I-4.1 Stop 1

Loop 1 / Site 1: Vaartweg in Bunschoten-Spakenburg;
Reference Point: Road called “Fokjesweg” at right-hand side;
GPS coordinates: N 52.14.839’ E 5.20.979’;
Zero Point: First lamppost to the right after reference point.

Station	Distance (m)	Test
111	80	Apply 5 drops and measure temperature
112	125	Apply 5 drops
113	150	Apply 5 drops
114	175	Apply 5 drops
115	200	Apply 5 drops
116	225	Apply 5 drops
117	250	Apply 5 drops

Route to next site

- First turning to the left to Vinkenweg;
- Reference point just after bridge.

I-4.2 Stop 2

Loop 1 / Site 2: Vinkenweg in Bunschoten-Spakenburg;
Reference Point: Sign “Bikkersvaart” just at the beginning of the road;

GPS coordinates: N 52.15.015’ E 5.20.337’;
Zero Point: 4 m after reference point.

Station	Distance (m)	Test
121	100	Apply 5 drops and measure temperature
122	150	Apply 5 drops
123	200	Apply 5 drops
124	225	Apply 5 drops
125	275	Apply 5 drops
126	300	Apply 5 drops
127	325	Apply 5 drops

Route to next site
- First turning to the left to Sint Nicolaashoofd;
- First crossing to the left to Gasthuisweg;
- Reference point just after crossing.

I-4.3 Stop 3

Loop 1 / Site 3 Gasthuisweg in Bunschoten-Spakenburg;
Reference Point: Green electricity supply box just after entrance to farm “Hoeve 't Hart”;
GPS coordinates: N 52.14.254’ E 5.20.992’;
Zero Point: Equal to reference point.

Station	Distance (m)	Test
131	200	Apply 5 drops and measure temperature
132	225	Apply 5 drops
133	250	Apply 5 drops
134	300	Apply 5 drops
135	325	Apply 5 drops
136	350	Apply 5 drops
301	525	Repeatability: apply 12 drops

Route to next site
- Turn left at end of road;
- Reference point after 300 m.

I-4.4 Stop 4

Loop 2 / Site 1 Vaartweg in Bunschoten-Spakenburg;
Reference Point: Road called “Fokjesweg” at right-hand side;
GPS coordinates: N 52.14.839’ E 5.20.979’;
Zero Point: First lamppost to the right after reference point.

Station	Distance (m)	Test
211	80	Apply 5 drops and measure temperature
212	125	Apply 5 drops
213	150	Apply 5 drops
214	175	Apply 5 drops
215	200	Apply 5 drops
216	225	Apply 5 drops
217	250	Apply 5 drops

Route to next site
- First turning to the left to Vinkenweg;
- Reference point just after bridge.

I-4.5 Stop 5

Loop 2 / Site 2: Vinkenweg in Bunschoten-Spakenburg;
Reference Point: Sign “Bikkersvaart” just at the beginning of the road;
GPS coordinates: N 52.15.015’ E 5.20.337’;
Zero Point: 4 m after reference point.

Station	Distance (m)	Test
221	100	Apply 5 drops and measure temperature
222	150	Apply 5 drops
223	200	Apply 5 drops
224	225	Apply 5 drops
225	275	Apply 5 drops
226	300	Apply 5 drops
227	325	Apply 5 drops

Route to next site
- First turning to the left to Sint Nicolaashoofd;
- First crossing to the left to Gasthuisweg;
- Reference point just after crossing.

I-4.6 Stop 6

Loop 2 / Site 3: Gasthuisweg in Bunschoten-Spakenburg;
Reference Point: Green electricity supply box just after entrance to farm “Hoeve 't Hart”;
GPS coordinates: N 52.14.254’ E 5.20.992’;
Zero Point: Equal to reference point.

Station	Distance (m)	Test
231	200	Apply 5 drops and measure temperature
232	225	Apply 5 drops
233	250	Apply 5 drops
234	300	Apply 5 drops
235	325	Apply 5 drops
236	350	Apply 5 drops

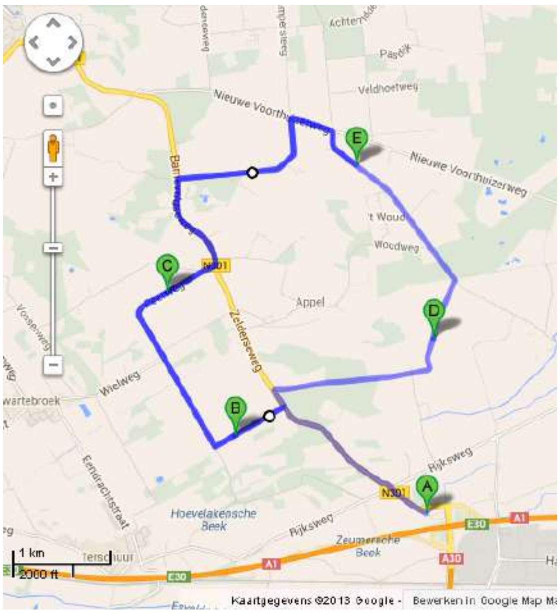
Route to finish of morning session

- Turn right at end of road;
- Turn left to car park at venue of start of morning session for forming convoy to lunch.

Route to lunch (21 km)

- Turn left at exit of car park;
- Turn right at second roundabout;
- Follow road for 4 km to Motorway A1;
- Underpass motorway and turn left at traffic lights to Zwolle, Apeldoorn;
- Follow motorway A1 to Hengelo, Apeldoorn;
- Leave motorway A1 after 15 km at Exit 15 “Barneveld, Ede, Arnhem”;
- Turn left at end of exit (traffic light), direction Terschuur (N301);
- Turn left at end of road (traffic light), direction Putten;
- Turn left after 250 m;
- Take first turning to the left at Tango petrol station;
- You enter the car park of Restaurant Goudreinet - Zelderseweg 63, Terschuur.

Figure I-16 **Route from morning session to restaurant for lunch**



A	Start afternoon session (= lunch)
B	Test site 4
C	Test site 5 and finish
E	Test site 6
D	Test site 7

Figure I-5 **Location of test sites in the afternoon session**

After lunch, go to exit of car park, turn right;

- After 100 meters turn left at the T-crossing and follow road N301 direction Putten;
- After 400 m straight ahead at roundabout (N301);
- Follow road for 1.4 km and turn left to Diepenrustweg;
- Reference point after 100 m.

I-4.7 Stop 7

Loop 1 / Site 4 Diepenrustweg in Zwartebroek;
Reference Point: Centre of entrance to House nr. 2;
GPS coordinates: N 52.10.666’ E 5.32.342’;
Zero Point: Traffic sign to the left 60 m after reference point.

Station	Distance (m)	Test
302	90	Repeatability: Apply 12 drops
141	120	Apply 5 drops and measure temperature
142	150	Apply 5 drops
143	180	Apply 5 drops
144	210	Apply 5 drops
145	240	Apply 5 drops

Route to next site

- Turn right at end of road to Leemweg;
- Straight ahead for 1.5 km and follow bend to the right;
- Reference point immediately after bend.

I-4.8 Stop 8

Loop 1 / Site 5 Peerweg in Zwartebroek;
Reference Point: Centre of entrance to House nr. 13;
GPS coordinates: N 52.11.276’ E 5.31.249’;
Zero Point: 50 m after reference point.

Station	Distance (m)	Test
151	120	Apply 5 drops and measure temperature
152	150	Apply 5 drops
153	180	Apply 5 drops
154	210	Apply 5 drops
155	240	Apply 5 drops

Route to next site

- Turn left at end of road (CAUTION: Give way)
- Follow road for 1.1 km and turn right to Bulderweg (200 m after windmill);
- Follow road for 1.6 km (two bends to the left) and turn right at traffic bump to Nieuwe Voorthuizerweg;
- Turn right after 500 m at traffic bump to Schoenlapperweg;
- Reference point just after bend to the left.

I-4.9 Stop 9

Loop 1 / Site 6 Schoenlapperweg in Nijkerk;
Reference Point: House number sign 7A;
GPS coordinates: N 52.12.119’ E 5.32.949’;

Zero Point: Equal to reference point.

Station	Distance (m)	Test
303	240	Repeatability: Apply 12 drops
161	280	Apply 5 drops and measure temperature
162	320	Apply 5 drops
163	360	Apply 5 drops
164	440	Apply 5 drops
165	480	Apply 5 drops

Route to next site

- Follow road for 1.3 km and turn right to Akkerweg;
- Reference point after 450 m.

I-4.10 Stop 10

Loop 1 / Site 7 Akkerweg in Nijkerk;
Reference Point: Entrance to House nr. 22;
GPS coordinates: N 52.11.111’ E 5.33.808’;
Zero Point: First lamppost after reference point.

Station	Distance (m)	Test
171	120	Apply 5 drops and measure temperature
172	150	Apply 5 drops
173	180	Apply 5 drops
174	210	Apply 5 drops
175	240	Apply 5 drops

Route to next site

- Follow bend to the left and to the right;
- Turn left after 1.6 km (CAUTION: Give way);
- Turn right after 200 m to Diepenrustweg;
- Reference point after 100 m.

I-4.11 Stop 11

Loop 2 / Site 4 Diepenrustweg in Zwartebroek;
Reference Point: Centre of entrance to House nr. 2;
GPS coordinates: N 52.10.666’ E 5.32.342’;
Zero Point: Traffic sign to the left 60 m after reference point.
Note: Skip station 302

Station	Distance (m)	Test
241	120	Apply 5 drops and measure temperature
242	150	Apply 5 drops
243	180	Apply 5 drops
244	210	Apply 5 drops
245	240	Apply 5 drops

Route to next site

- Turn right at end of road to Leemweg;

- Straight ahead for 1.5 km and follow bend to the right;
- Reference point immediately after bend.

I-4.12 Stop 12

Loop 2 / Site 5 Peerweg in Zwartebroek;
Reference Point: Centre of entrance to House nr. 13;
GPS coordinates: N 52.11.276’ E 5.31.249’;
Zero Point: 50 m after reference point.

Station	Distance (m)	Test
251	120	Apply 5 drops and measure temperature
252	150	Apply 5 drops
253	180	Apply 5 drops
254	210	Apply 5 drops
255	240	Apply 5 drops

Route to next site
- Turn left at end of road (CAUTION: Give way);
- Follow road for 1.1 km and turn right to Bulderweg (200 m after windmill);
- Follow road for 1.6 km (two bends to the left) and turn right at traffic bump to Nieuwe Voorthuizerweg;
- Turn right after 500 m at traffic bump to Schoenlapperweg;
- Reference point just after bend to the left.

I-4.13 Stop 13

Loop 2 / Site 6 Schoenlapperweg in Nijkerk;
Reference Point: House number sign7A;
GPS coordinates: N 52.12.119’ E 5.32.949’;
Zero Point: Equal to reference point.
Note: Skip station 303

Station	Distance (m)	Test
261	280	Apply 5 drops and measure temperature
262	320	Apply 5 drops
263	360	Apply 5 drops
264	440	Apply 5 drops
265	480	Apply 5 drops

Route to next site
- Follow road for 1.3 km and turn right to Akkerweg;
- Reference point after 450 m.

I-4.14 Stop 14

Loop 2 / Site 7 Akkerweg in Nijkerk;
Reference Point: Entrance to House nr. 22;
GPS coordinates: N 52.11.111’ E 5.33.808’;
Zero Point: First lamppost after reference point.

Station	Distance (m)	Test
271	120	Apply 5 drops and measure temperature
272	150	Apply 5 drops
273	180	Apply 5 drops
274	210	Apply 5 drops
275	240	Apply 5 drops

Route to finish
- Follow bend to the left and to the right;
- Turn right after 1.6 km (CAUTION: Give way);
- Turn left after 1.4 km;
- Finish after 670 m: N 52.190854, E 5.528866 near Peerweg 4, Zwartebroek

Finish; hand over data and temperature registration sheet to supervisor.

Annex II List of participants

Number	Group	Participant	Country	FWD maker	FWD model	Serial number	Licence plate
1	A	Asset Insight	Netherlands	Dynatest	8012 Fast FWD	30	55-WS-GH
2	B	Kiwa KOAC	Netherlands	Dynatest	8002	8002-205	WJ-RB-11
3	C	Kiwa KOAC	Netherlands	Dynatest	8081	8081-004	WJ-RB-07
4	A	Kiwa KOAC	Netherlands	Sweco	Primax 1500	0611-441	23-WH-RR
5	B	Qroad BV	Netherlands	Dynatest	8082 HWD	107	76-WJ-BX
6	C	Qroad BV	Netherlands	Dynatest	8082 HWD	154	56-WP-TV
7	A	Unihorn bv	Netherlands	Dynatest	8012 Fast FWD	8012-040	47-WS-DK
8	B	TPA HU Kft.	Hungary	Dynatest	8012 Fast FWD	UH980121651DN1024	WBW-085
9	C	Vlaamse overheid	Belgium	Sweco	Primax 1500	1992-600	UKG-162
10	A	STAC	France	Rincent	Heavydyn	VGTP114RN013M0013	GE-055-FQ
11	B	Heijmans	Netherlands	Sweco	Primax 2500	0303-483	WH-JD-09
12	C	BRS Infra	Netherlands	Dynatest	8002	8002-222	40-WDG-6
13	A	Rincent NCT	France	Rincent	Heavydyn	HVY-10C-C	FS-711-DR
14	B	Nievelt Ingenieur GMBH	Austria	Sweco	Primax 3500	0816-604	ZNL116
15	C	Civil Engineering Institute CPL	Serbia	Dynatest	8082 HWD	8082-186	AP-592 NS

Annex III Reference deflections

Deflections (µm) normalised to load level of F=50 kN

Station	d@0	d@300	d@600	d@900	d@1200	d@1500	d@1800
111	279	252	225	201	179	157	139
112	248	231	214	193	174	156	140
113	202	195	187	172	159	146	135
114	241	226	208	189	171	155	138
115	242	225	210	191	173	155	139
116	288	258	231	204	182	163	143
117	266	250	227	202	181	161	144
121	279	260	240	220	201	182	166
122	218	201	183	166	152	139	128
123	209	195	183	169	157	145	135
124	238	220	203	184	168	153	139
125	276	253	229	203	181	160	141
126	277	256	231	206	185	164	145
127	241	223	204	183	164	145	129
131	241	199	159	134	119	105	93
132	252	211	174	150	134	120	106
133	280	246	210	181	156	136	118
134	241	204	164	134	111	92	76
135	251	203	169	143	124	108	92
136	201	170	140	119	106	93	83
141	243	213	174	135	104	79	60
142	227	203	172	139	111	88	70
143	257	229	189	147	112	84	64
144	326	288	227	163	115	83	64
145	345	301	230	170	126	98	79
151	249	214	169	128	97	73	56
152	257	223	178	135	101	76	57
153	257	220	176	136	104	80	61
154	261	221	169	126	93	69	52
155	250	212	165	124	92	69	52
161	371	270	164	93	50	28	21
162	318	238	146	82	44	26	19
163	292	232	158	98	57	33	20
164	824	565	323	173	86	49	39
165	491	309	159	79	37	22	21
171	402	308	198	126	83	61	49
172	375	304	217	152	109	82	67
173	427	338	233	158	109	81	63
174	507	360	227	147	102	78	64
175	261	223	174	129	95	72	57

Station	d@0	d@300	d@600	d@900	d@1200	d@1500	d@1800
211	288	260	235	209	188	167	146
212	269	252	232	209	188	170	152
213	209	204	195	180	168	154	141
214	251	236	218	198	180	163	145
215	240	226	210	191	175	159	143
216	303	270	242	215	192	171	152
217	277	259	236	210	189	169	151
221	293	275	254	232	212	194	176
222	227	208	188	171	156	144	132
223	215	202	189	174	162	150	138
224	245	228	209	190	174	159	145
225	285	262	237	210	188	166	147
226	285	265	240	214	191	170	151
227	248	230	209	187	168	149	132
231	253	209	169	142	126	111	98
232	267	223	184	160	143	127	113
233	276	244	208	178	154	133	116
234	253	212	171	141	117	96	79
235	268	217	181	153	133	115	98
236	208	176	145	124	110	97	86
241	248	219	180	140	107	81	62
242	231	208	177	143	115	91	71
243	265	236	196	153	116	87	65
244	335	297	235	168	119	86	66
245	356	309	238	176	131	100	80
251	254	218	172	130	98	74	56
252	264	230	184	140	106	79	59
253	257	222	176	135	103	78	60
254	265	226	174	129	95	71	53
255	252	214	166	126	94	70	53
261	375	273	166	94	51	29	20
262	316	239	146	82	45	26	19
263	289	231	158	99	58	33	20
264	834	572	327	174	86	49	39
265	496	317	164	81	38	22	21
271	404	311	202	129	85	63	51
272	381	312	226	158	113	85	68
273	435	347	240	163	113	83	65
274	507	361	228	148	103	78	65
275	267	228	179	132	98	74	58